The Role of Memory and Restricted Context in Repeated Visual Search

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Abstract

Previous studies have shown that the efficiency of visual search does not improve when participants search through the same unchanging display for hundreds of trials ("repeated search"), even though participants have a clear memory of the search display. In this paper we ask two important questions: Firstly, why are participants not using memory to help search the repeated display? Secondly, can context be introduced so that participants are able to guide their attention to the relevant repeated items? Experiments 1-4 show that participants chose *not* to use a memory strategy because under these conditions repeated memory search is actually less efficient than repeated visual search, even though this latter task is in itself relatively inefficient. However, when the visual search task is given context so that only a subset of the items are ever pertinent, participants can learn to restrict their attention to the relevant stimuli (Experiments 5 and 6).

Introduction

To interact with the world we often have to perform visual search tasks on a regular basis. For example, in our daily lives we may try to find a car in a car park or a face in a crowd. Moreover, we create artificial visual search tasks of great social importance (e.g. finding a tumor in a mammogram or a hidden weapon in an airport baggage scan). In order, to improve upon these tasks we need to understand the mechanisms that occur when we search for an item. For this reason researchers have investigated the process of visual search in the laboratory. Typically participants are asked to respond to a pre-specified target item among a variable number of competing distractor items. The reaction time (RT) taken to respond to the target item is used as a measurement of search speed. If we plot RT against the number of items in a display (the set size), we can plot the slope of the RT x set size function, which gives us a measure of search efficiency. If attention can be deployed readily to the target item, independent of the number of distractor items, then we expect the search slope to be shallow, approaching 0 msec/item. Efficient slopes are characteristic of feature searches, where a target item can be separated from the distractors by means of a unique and salient feature (e.g. a red circle among green circles or a horizontal line among vertical, see Treisman & Gelade, 1980).

In other visual search tasks, there is a cost of adding more distractor items to the search task and slopes are significantly greater than zero. Such displays include search for a target that is made up of a conjunction of features (e.g. search for a red circle, among green circles and red squares) or search for a target letter among heterogeneous distractor letters. In conjunction search tasks, where some feature information can *guide* search (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989), slopes are intermediate in their efficiency; around 5-15 msec/item (e.g. Treisman & Sato, 1990; Wolfe, 1998). Tasks like letter search, lacking guiding features, tend to produce inefficient search slopes of around 30–50 msec/item (e.g., Kunar & Humphreys, 2006; Theeuwes et al., 1998). These slopes are typical of tasks involving stimuli that are large enough to be identified in peripheral vision. If each item must be fixated, search is much less efficient, because efficiency is limited by the relatively slow rate of saccadic eye movements.

In earlier work, Wolfe, Klempen and Dahlen (2000) investigated how the efficiency of a heterogeneous letter search task changed over time in two search conditions: a repeated search task and an unrepeated search task (see Figure 1). In this variant of a standard visual search task, a target probe was presented at the beginning of each trial to identify the target letter for each trial. In both conditions, participants had to indicate whether the target probe was present or absent from the search set on each trial. A target was present on 50% of trials. In the repeated search task, the search display remained the same throughout a block of trials. The identity and location of the search stimuli did not change and the search stimuli did not disappear from the screen between trials. In the unrepeated search condition, participants again had to search for a target probe that changed from trial to trial. However, here the search display also changed from trial to trial. In the repeated search condition, familiarity with the display and/or repeated attention to specific letters in the display might be expected to lead to an improvement in search efficiency over time. One might imagine that less searching would be necessary on the tenth search for the same "F" at 3 o'clock in same display. However, search in the repeated condition did *not* become more efficient over time, but remained consistent at around 50 msec/item even after 350 searches through the same, unchanging display. Repeated search efficiency was not significantly different from the unrepeated conditions.

Figure 1 about here

This result seems counter-intuitive in two ways. First, observers come to learn and remember that “F” was at 3 o’clock. Why did they not use this memory to speed search when the target was an “F”? Second, one would think that repeated search would be an efficient way to search. In the real world, when a scene becomes familiar, we reduce the effective set size and only search where we learn that things are likely to be. Why do we not see this apparent reduction of potential target locations in repeated search tasks? This paper addresses these two puzzles.

The first question was actually made more puzzling by the original Wolfe et al. (2000) work. The paper included a memory search condition, where participants committed the letter display to memory. The search stimuli were removed and participants indicated whether the target probe item was present or absent from the memorized search display. In this case, repeated search from memory *did* become more efficient. This replicates an established result in memory search. Previous work on memory search has found that initial search slopes for a task like this lie in the range of 20–50 msec/item (see Sternberg, 1975 for a review). With repetition, these search slopes become more efficient and in some instances asymptote at around 0 msec/item (e.g. Logan, 1992). These memory searches are said to have become automatized. Schneider and Shiffrin (1977) explained this as a form of consistent mapping where a target-present response and a target-absent response are mapped respectively to one set of letters (if present) and another set (if absent). Given that memory search could apparently proceed efficiently, why didn't observers use that memory to guide the visual search?

Wolfe et al. (2000) argued that vision was given priority over memory in a visual search task. Oliva, Wolfe & Arsenio (2004) asked whether inefficient visual search had a *mandatory* priority over efficient memory search. They found that this was not the case. In their research, using a variation of the repeated search task in which the participants searched a fixed display but that display was larger than the current field of view (dubbed a "panoramic" search display), participants were able to search from memory once they had been extensively trained to do so. On any one trial, participants viewed a subset of the whole visual display as a viewing window panned back and forth over a larger scene. During a series of experiments participants could be asked to respond to (i) items that were present in the display and also currently visible, (ii) items that were present in the overall display but were currently hidden from view (i.e., in a section that had previously been seen but was now not part of the panned visible section; here they had to use their memory) or (iii) items that were absent from the entire display. The results showed that participants performed inefficient visual searches until "persuaded", by extensive experience with the hidden stimuli, that they could rely on memory. Thus, it is possible to use memory in the presence of a visual stimulus, however, visual search seems to be the preferred mode. Oliva et al. (2004) argued that participants made a 'pragmatic choice' between vision and memory and suggested that they were biased to perform a visual search task over a memory one, even if visual search was less efficient than memory search.

Still, if memory search really was more efficient than visual search then why do participants chose initially to use the less efficient strategy? In fact, the repeated search task does not demand that observers chose between visually searching for the target or responding from memory alone. Common sense would seem to tell observers to remember where the target was and then to visually conform that memory. In Experiments 1-4, we solve this mystery by showing that memory search is actually *less* efficient than visual search. In the previous work of Wolfe et al. and Oliva et al., observers were making a choice but it was not a choice between two modes of search. The automatized memory search of Wolfe et al (2000) is not a search task as much as it is an efficient response-mapping task. Observers learn to associate one set of probe letters with one response key and another set with the other response (Schneider & Shiffrin, 1977). In the present experiments, we make the memory task more like the visual task by making both of them localization tasks. Participants had to point and click on an individual target location. This change has several benefits. Firstly, it makes both tasks a little more realistic. In the real world, search tasks are typically carried out in order to direct action toward the target. One does not generally search for the milk merely to confirm that it is still in the refrigerator. Secondly, the method ensured that each search stimulus required a different response. Please note that in all tasks the number of stimulus to response (S-R) mappings were equal. This is important as the Hick-Hyman law states that increasing the number of response alternatives increases the time taken to respond (Hick, 1952; Hyman, 1953). Finally, it makes it more likely that participants were performing similar tasks in the memory and visual search conditions. Using this method, Experiment 1 found that memory search was both inefficient and slow compared to a visual search task when there were six possible responses. Experiment 2 showed that memory search was inefficient and slow if there were up to six multiple response types compared to a 2AFC task. The primary conclusion of this paper is that participants do not use memory to guide inefficient visual search processes in the repeated search task because the memory that could do the guiding is even less efficient. Experiments 3 and 4 found that even after extensive training, of the sort used in Oliva et al (2004), memory search remained inefficient.

Turning to the second question posed above: Given that we can learn to restrict our attention to potential target locations in most real-world searches, why do we apparently fail to restrict our attention in the repeated search task? The answer lies in the structure of the tasks. As mentioned above, in the real world, when a scene becomes familiar, we reduce the effective set size. The number of plausible locations for an object declines and the number of potential target items may also decline. Initially the cat could be *anywhere*. Eventually, you learn that he has three favorite spots and you restrict your initial search to those locations. In the repeated search task, in contrast, the numbers of targets and their locations never change. If the observer is looking for these six letters in these six locations on trial 1, she is looking for the same six letters in the same six locations several hundred trials later. Every item in the display is at, one point or another, relevant and thus searched. This turns out to be critical. In Experiments 5 and 6, we modify the repeated search task to allow observers to learn that targets can appear in some locations but not others. Under these conditions, observers can use memory to restrict their attention to a subset of target locations and thus use this to guide their visual attention.

Experiment 1

Experiment 1 investigated whether memory search in a repeated search task would be more efficient than visual search when stimuli could not be consistently mapped to two response types (e.g. is the target present or absent). In this experiment, rather than making the usual 2AFC response, participants had to use the mouse to point to the location of the target item in both the repeated visual search and the memory search condition. This made sure that the mapping of test probe to response was the same in the visual and memory search versions of the task.

Method:

Participants:

Twelve individuals between the ages of 18 and 55 years served as participants. Each participant passed the Ishihara test for color blindness and had normal or corrected to normal vision. All participants gave informed consent and were paid for their time.

Apparatus and Stimuli:

The experiment was conducted on a Macintosh computer using MatLab Software with the PsychToolbox (Brainard, 1997; Pelli, 1997). The search stimuli consisted of 3 or 6, uppercase letters of the English alphabet. All letters were white and appeared on a black background. The dimensions of the letters ranged from 0.3°- 1° in width by 1°- 1.3° in height (depending on the letter) and each letter was positioned at a distance of 4° from the center. The target probe was a lowercase letter (0.1°- 0.6° in width, 0.5°- 1° in height) presented at the center of the screen within a circle of diameter 1.5°.

Procedure:

There were three conditions: (i) a repeated visual search task, (ii) an unrepeated visual search task and (iii) a memory search task. At the start of each trial a cursor appeared in the center of the circle. In all conditions participants were instructed to move the cursor and to click on the location of the uppercase target letter that corresponded to the lowercase cue. The lowercase cue appeared in the central circle and changed from trial to trial, however it was always a letter that was present in the outer display (i.e. there were no target absent trials). In the repeated search condition, the display did not change, and remained visible throughout the experiment. In the unrepeated search condition, the display letters changed from trial to trial. In the memory search condition, participants were instructed to memorize the positions and identities of the display letters prior to the task. During the search task, the letters were removed and replaced by white-framed black boxes. Participants were asked to click on the box corresponding to the now hidden target letter. In all conditions, participants were asked to respond as quickly and as accurately as possible. In order to be counted as a correct response, with all set sizes, participants had to make sure that they clicked within the outlined box (of dimensions 1.3° x 1.8°). Furthermore, they were encouraged to move the mouse cursor directly to the target. For each condition, each participant completed one block of trials with set size 3 and one with set size 6. Each block consisted of 20 practice trials and 500 experimental trials, which were divided into 10 epochs of 50 trials for analysis. The order of the blocks was randomized. Figure 1 shows example displays for each condition.

Results & Discussion

Figure 2a shows RT as a function of epoch for each combination of condition and set size while Figure 2b shows overall RT as a function of set size. At each epoch, search slope is computed from the average RTs for set sizes 3 and 6. Those slopes, the critical measures of search efficiency, are shown in Figure 3. The results are clear. Replicating the original repeated visual search results, search remains inefficient after 500 trials – just as inefficient as unrepeated search. Moreover, with this change in method, repeated memory search is markedly less efficient than visual search, even after 500 trials.

Figures 2 and 3 about here

Overall error rates were low (less than 1%). There was a main effect of condition: participants made more errors in the memory condition than in the repeated and unrepeated search conditions, $F(2, 22) = 4.2$, $p < 0.05$. However, none of the other main effects or interactions proved reliable. As the error rates suggest that there was no speed-accuracy trade-off, we do not discuss them further and instead concentrate on RT and slope analysis. RTs below 200 msec and above 4000 msec were removed from analysis. This led to the removal of less than 1% of the data. There are many main effects and interactions that could be reported in this experiment. For the sake of simplicity and brevity, we focus on those analyses that are relevant to the questions addressed in this paper.

There was no effect of epoch on any of the conditions. Overall RTs did not decrease with trial number in the repeated condition ($F(9, 99) = 0.7$, p = n.s. and $F(9, 99) = 1.5$, p = n.s., for set sizes 3 and 6 respectively), the unrepeated condition $F(9, 99) = 1.1$, p = n.s. and $F(9, 99) = 0.6$, p = n.s., for set sizes 3 and 6 respectively) or in the memory condition ($F(9, 99) = 0.7$, p = n.s. and $F(9, 99) = 1.7$, p = n.s., for set sizes 3 and 6 respectively).

There were significant RT differences between conditions. Comparing the repeated and unrepeated search conditions we see that RTs in the repeated condition were faster than those in the unrepeated condition, $F(1, 11) = 17.5$, $p < 0.01$. This occurred for both set size 3, (98 msec; $F(1, 11) = 7.4$, $p < 0.05$) and set size 6, (106 msec; $F(1, 11) = 20.2$, $p < 0.01$). This replicates the findings of both Wolfe et al. (2000) and Oliva et al. (2004). The overall slowing of response between repeated and unrepeated tasks could be due to a number of factors. Firstly, items in the repeated condition were consistently mapped to a response whereas items in the unrepeated condition were not. Inconsistent mapping tasks are known to be slower than consistent mapping tasks (Schneider & Shiffrin, 1977). Secondly, RTs in the unrepeated search condition might be slowed by a cost associated with front-end perceptual processing of a new visual display on each trial.

Overall, RTs in the memory search were slower than those in the repeated search task, $F(1, 11) = 7.1$, $p < 0.05$. As can be seen in Figure 2 and 3, this was driven by a large difference at set size 6, (148 msec; $F(1, 11) = 12.3$, $p < 0.01$). There was no reliable difference at set size 3, $F(1, 11) = 0.4$, p = n.s.. None of the condition x epoch interactions proved to be significant. This pattern of data was different from that found by Wolfe et al. (2000). In those experiments, using a 2AFC response task, RTs in the memory search task were faster than those in the repeated search task and the RTs in the memory task interacted with epoch. The present data show that when using a target localization task the pattern of results was reversed.

Turning to the slope data, slopes in the memory condition were substantially larger than those in the repeated search condition, $F(1, 11) = 7.5$, $p < 0.05$. Furthermore, search slopes in the memory condition did not become more efficient over time, $F(9, 99) = 0.4$, p = n.s.. This pattern was the direct opposite of that found in the 2AFC repeated search tasks, where performance on that memory task did improve over time and did become more efficient than the repeated search (Wolfe et al., 2000). The visual search data reported here are similar to those from the original 2AFC repeated search findings (Wolfe et al., 2000). Search efficiency did not improve over epoch in either the repeated search or unrepeated search condition ($F(9, 99) = 0.5$, p = n.s. and $F(9, 99) = 0.5$, p = n.s., respectively), and there was no overall difference between the search slopes of the repeated search condition and those of the unrepeated search task ($F(1, 11) = 0.0$, p = n.s.).

The results make a number of interesting points. Firstly, these data serve as a replication of the basic repeated visual search results reported by Wolfe et al. (2000). Search slopes in the repeated search task did not differ from those in the unrepeated search task and did not decrease over time. Participants were unable to perform an efficient letter search even after searching for the same letters in the same, unchanging display for hundreds of trials. Secondly, and more importantly, the data respond as to why participants chose not to use memory when faced with a repeated search display. The answer is that guidance by memory search did not occur because the memory search was less efficient than visual search.

Why did this experiment fail to show the improvement in efficiency in memory search that was found in Wolfe et al. (2000)? It is not simply that localization tasks cannot be efficient. For example, Logan, Taylor and Etherton (1999) found that location could be encoded during automatization. In their work they trained participants to respond to sets of visual stimuli so that RTs became faster with practice. In a test phase, if the location of the items changed Logan et al. (1999) found RTs to respond to each stimuli increased, suggesting that the consistent mapping of location to response could be encoded. Furthermore, in a baseline study, we ran a 2AFC repeated search localization task, where participants had to respond to whether the target was to the left or the right of the central fixation probe. The experiment included repeated search, unrepeated search and memory search conditions. The results showed that a 2AFC localization version of a memory search task was more efficient than a 2AFC localization version of a repeated visual search task ($F(1, 15) = 4.5$, $p = 0.05$). These memory results mimicked those of the 2AFC present/absent task found in the memory search conditions of Wolfe et al. (2000) and Oliva et al. (2004). Simply introducing a spatial element to the task did not cause the pattern of the results to change.

Instead, we propose that the earlier apparent advantage for memory search was actually a change in the task that the observers were performing. Wolfe et al. (2000) wanted observers to search either the visual stimulus or the memory set. Instead, the observers learned to efficiently use the response mappings of two different probe types (i.e., present or absent) to two different responses. In contrast our Experiment 1 forced observers to continue to search, by eliminating the 2AFC response option. Under these circumstances, we find that efficiency does not improve over the course of 500 trials.

Experiment 2

The analysis of Experiment 1 relies on the assumption that memory tasks with a small number of response alternatives can become automatic while tasks with a larger repertoire of possible responses do not. This hypothesis was tested in Experiment 2 by directly comparing a 2AFC and a localization version of a memory search task.

Method:

Participants:

Fourteen individuals between the ages of 18 and 55 years served as participants. Each participant passed the Ishihara test for color blindness and had normal or corrected to normal vision. All participants gave informed consent and were paid for their time.

Apparatus and Stimuli:

The apparatus and stimuli were similar to the memory search condition of Experiment 1, except that here the target probe appeared directly above the central circle so that it was not partially occluded by the initial cursor that appeared within the central circle. Please note that any occlusion in Experiment 1 was minimal and did not affect the pattern of results.

Procedure:

There were two conditions in this experiment (i) a localization condition where participants clicked on the remembered location of the target and (ii) a 2AFC condition where participants determined whether the target was present or absent. In both conditions participants were instructed to memorize the positions of the capital letters prior to a block of trials. During the memory search, the capital letters were removed and replaced by white-framed black boxes. The localization task was similar to the memory search condition of Experiment 1. The appearance of the display of the 2AFC present/absent task was similar to that of the localization task. However, the target probe only corresponded to one of the capital letters on approximately half of the trials. On the remaining trials, the target probe was selected from a group of *N* letters that were not present, where *N* equaled the set size. On each trial, participants pressed the letter 'l' if the target was present and the letter 'a' if the target was absent.

For each condition, participants completed 5 blocks of trials, one each for a set size of 2, 3, 4, 5, and 6. Each block consisted of 350 trials, which were divided into 7 epochs of 50 trials. The order of the blocks was randomized.

<u>Results & Discussion</u>

Figure 4 compares the slopes for the 2AFC and localization tasks. Curiously, the 2AFC memory task did not become particularly efficient. However it is clear that search was more efficient in the 2AFC version than in the localization version though the only difference between the tasks was the mode of response.

Overall error rates were low (5.8% in the 2AFC memory condition and 1.9% in the memory location condition). As the error rates suggest that there was no speed-accuracy trade-off, we do not discuss them further and instead concentrate on RT and slope analysis. RTs below 200 msec and above 4000 msec were eliminated. This led to the removal of 1% of the data.

Figure 4 about here

The RTs from the localization condition increase with set size, $F(4, 52) = 18.7$, $p < 0.01$. There was also an overall effect of epoch, In fact, in this case, RTs *increased* modestly with time, $F(6, 78) = 3.1$, $p < 0.01$. Though there appears to be an initial drop in slope in the localization conditions (Figure 4), there was no reliable set size x epoch interaction, $F(24, 312) = 1.1$, p = n.s., nor any reliable effect of epoch on search slopes, $F(6, 78) = 1.0$, p = n.s.. These data replicate those in Experiment 1[1].

[1] Overall, the memory slope for this experiment seems to be more efficient than that for Experiment 1. One potential reason for this may be that memory search was affected by the context of having a prior visual search task. In this case, any previous consistent mapping within the visual search tasks may add noise to the memory search task making it less efficient than when there were no other consistent mapping tasks. We leave this for future work to investigate.

Turning to the target present trials of the 2AFC condition, there was a main effect of set size, $F(4, 52) = 18.4$, $p < 0.01$ and epoch, $F(6, 78) = 7.8$, $p < 0.01$. In general, RTs *increased* with set size and *decreased* with epoch. This decrease in RTs across epoch was more pronounced at higher set sizes, as indicated by a reliable set size x epoch interaction, $F(24, 312) = 2.0$, $p < 0.01$. The same pattern occurred for absent trials. In contrast to the localization condition, search slopes became more efficient over time. This occurred both for target present trials, $F(6, 78) = 5.0$, $p < 0.01$ and target absent trials, $F(6, 78) = 3.3$, $p < 0.01$. Thus, the data from the 2AFC condition mirrors that of Wolfe et al. (2000), though the slopes for the present/absent condition asymptote at a surprisingly inefficient 25-30 msec/item.

Overall, the results are consistent with the hypothesis that 2AFC tasks become more efficient with extensive practice while localization tasks, requiring a mapping of more than two responses, do not become more efficient. This, in turn, supports the account of the memory search advantage in the Wolfe et al, (2000) data. The well-practiced 2AFC task became a response-mapping problem while the visual search task remained a search/localization task. In the panorama experiments of Oliva et al. (2004), we would suggest that visual search became more efficient with practice because observers learned to treat the repeated visual search task like a 2AFC memory task even when targets were intermittently visible. In Experiment 3, we examine the effects of similar training on the localization task.

Experiment 3

In Experiment 3, observers were trained on a mixed visual and memory search localization task in order to determine if observers could learn to perform an efficient repeated memory search with a localization response.

Method:

Participants:

Thirteen individuals between the ages of 18 and 55 years served as participants. Each participant passed the Ishihara test for color blindness and had normal or corrected to normal vision. All participants gave informed consent and were paid for their time.

Apparatus and Stimuli:

The apparatus and stimuli were identical to that of Experiment 2.

Procedure:

There were three conditions: a pure memory search control condition, and two training conditions: memory search with repeated visual search training and memory search with mixed visual and memory training (see Figure 5 for example displays of the latter condition). In all conditions participants were asked to click on the location of the target. For each condition, participants completed two blocks of trials, one each for a set size of

3 and 6. Each block consisted of 500 trials, which were divided into 10 epochs of 50 trials. The order of the blocks was randomized. The pure memory search condition was identical to the localization condition of Experiment 2. Participants memorized the display and proceeded to search through 3 or 6 hidden stimuli for 500 trials. In the visual training condition, the search stimuli were visible for the first 150 trials (the 'initial training phase'). After this they were removed and replaced by white-framed black boxes. Participants completed the remaining 350 trials from memory. In the mixed training condition participants were instructed to memorize a search display, prior to the task. During the 'initial training phase', for set size 6, three letters of the search display remained visible while the other three letters were replaced by black white-framed boxes, whereas in set size 3, one letter remained visible while the other two letters were replaced by black white-framed boxes. After 150 trials (the 'post-training phase'), all the letters were replaced by white-framed black boxes so that none of the stimuli were visible. As in the other conditions, participants had to respond from memory for the remaining 350 trials.

Figure 5 about here

Results & Discussion

Figures 6 and 7 show the RTs and search slopes, respectively, for all conditions in Experiment 3. The results were clear. There was no benefit from either training regime.

After training, all three versions of localization memory search were inefficient and did not improve over hundreds of trials.

Figures 6 and 7 about here

Overall error rates were low (less than 1.5%). There was a main effect of set size with observers making more errors at the larger set size, $F(1, 11) = 6.0$, $p < 0.05$, and a main effect of epoch, reflecting an increase in errors after training ended, $F(9, 99) = 2.9$, $p < 0.01$. There was also a reliable condition x epoch interaction, $F(18, 198) = 2.2$, $p < 0.01$ and a set size x epoch interaction, $F(9, 99) = 2.6$, $p < 0.01$. However, as the error rates suggest that there was no speed-accuracy trade-off we do not discuss errors further and instead concentrate on RT and slope analysis. RTs below 200 msec and above 4000 msec were eliminated. This led to the removal of 1% of the data.

For each condition the data were split up into the initial training phase (epochs 1-3) and the post-training phase (epochs 4 – 10) for analysis. During the initial training period, there were reliable differences between the conditions in RT, $F(2, 22) = 9.6$, $p < 0.01$, and slope, $F(2, 22) = 11.0$, $p < 0.01$. The training conditions, with some or all items visible, were faster and more efficient than the pure memory search condition. After training (epochs 4-10), there were no significant differences in RT, $F(2, 22) = 0.2$, p = n.s., or slope, $F(2, 22) = 0.4$, p = n.s.. Comparing the end of the training period to the beginning of the post-training period, RTs at set size 6 become slower in both the visual and mixed training conditions ($t(11) = 4.4$, $p < 0.01$ and $t(11) = 6.8$, $p < 0.01$, respectively). There was no change in RTs at set size 3. Slopes become steeper in both the visual and mixed training conditions ($t(11) = 4.2$, $p < 0.01$ and $t(11) = 4.7$, $p < 0.01$, respectively).

Hillstrom and Logan (1998) suggested that mechanisms in memory search were a subset of those in visual search. Therefore, training in visual search led to improved performance in memory. At first glance our work seems to contradict that of Hillstrom and Logan (1998). In our Experiment 3, memory search does not become more efficient over time, even after visual or partial visual training. The critical difference appears to be the use of the localization task. If the memory task cannot be reduced to a 2AFC task, it is highly inefficient even after 500 trials of search through the same memory set.

Perhaps memory search in the training condition of Experiment 3 did not become more efficient as participants were not trained hard enough? In the initial training phase, a given item was either visible or hidden. However, in the post-training phase all items were hidden. Therefore, a previously visible stimulus had never been responded to by memory prior to the post-training phase. Perhaps if we switch whether each item was responded to by memory or vision during the initial training phase, then search through memory may become more efficient. We investigated this in Experiment 4.

Experiment 4

Method:

Participants:

Twelve individuals between the ages of 18 and 55 years served as participants. Each participant passed the Ishihara test for color blindness and had normal or corrected to normal vision. All participants gave informed consent and were paid for their time.

Apparatus and Stimuli:

The apparatus and stimuli were identical to that of Experiment 2.

Procedure:

There were three conditions: a pure memory search control condition and two training conditions: repeated visual search and a ‘swap’ condition where a given search stimulus swapped from being hidden to visible, or vice-versa, during the initial training period. In all conditions participants were asked to click on the location of the target. For each condition, participants completed two blocks of trials, one each for a set size of 3 and 6. The pure memory search and repeated visual search training conditions were identical to the conditions of Experiment 3. In the swap condition, participants were instructed to memorize a search display, prior to the task. The search display was identical to that of the repeated visual search training condition, except that each letter was surrounded by a box, defined by its white outline. At the start of the trial a subset of the stimuli were removed or ‘hidden’. This occurred for three of the stimuli when the set size was 6 and two of the letters when the set size was 3. The remaining letters were visible and the display remained unchanged for 15 trials. After trial 15, the display changed so that the previously visible stimuli were removed and the previously ‘hidden’ stimuli were now visible. This remained unchanged for the next 15 trials at which point the visible stimuli became hidden and the hidden stimuli became visible (so that it resembled the first 15 displays). This process continued so that the visible/hidden status of each stimulus changed every 15 trials. After 150 trials (the initial training phase), all the letters were removed so that none of the stimuli were visible and participants had to respond solely from memory. Each block consisted of 500 trials, which were divided into 10 epochs of 50 trials. The order of the blocks was randomized.

Results & Discussion

Results of Experiment 4 mirror those of Experiment 3. Memory search, in the post-training phase was essentially the same with or without training.

Overall error rates were low (1%). There was a main effect of condition, $F(2, 22) = 5.4$, $p < 0.05$, where participants made more errors in the memory condition compared to the repeated search and swap condition and of set size, $F(1, 11) = 20.3$, $p < 0.01$, where participants made more errors in set size 6 than set size 3. There was also a reliable condition x epoch interaction, $F(18, 198) = 2.0$, $p < 0.05$, where error rates increased in the repeated search condition between the training and post-training phase, but did not change in the memory or swap condition. However, none of the other main effects or interactions proved reliable. As the error rates suggest that there was no speed-accuracy trade-off, we do not discuss them further and instead concentrate on RT and slope analysis. RTs below 200 msec and above 4000 msec were eliminated. This led to the removal of 1% of the data.

For each condition the data were split up into the initial training phase (epochs 1-3) and the post-training phase (epochs 4 – 10) for analysis purposes. The data for the swap condition, in the initial training phase, were also separated into whether the target on a given trial was visible or hidden.

During the initial training period, there were reliable differences between the conditions in RT, $F(3, 33) = 7.6$, $p < 0.01$. RTs were fastest in the visual training condition, slowest in the memory and hidden trials of the swap condition and intermediate for the visible trials of the swap condition. There was a similar difference in slopes, $F(3, 33) = 7.7$, $p < 0.01$. After training (epochs 4-10), there were no significant differences in RT, $F(2, 22) = 0.7$, p = n.s., or slope, $F(2, 22) = 0.8$, p = n.s..

Overall, the results in the post-training phase were similar to those of Experiment 3. Even in the swap condition, when all items were trained as both visual and memory search targets, there was no benefit, in the post-training phase.

To summarize Experiments 1-4, when memory search cannot be reduced to a 2AFC response-mapping problem, it remains inefficient after hundreds of trials. This is true, even if observers are given extended visual and/or mixed training prior the memory search. The failure of observers to use memory of target locations during repeated visual search (Wolfe et al., 2000) is no longer a mystery. Relying on memory (e.g., look at *this* location to find *that* letter) is less efficient than simply re-running the visual search, even if that visual search is inefficient.

As noted at the outset, at face value, the results of repeated search experiments fly in the face of our common experience. When faced with familiar real world scenes, we can often restrict our attention to the locations that we learn to be relevant for the task in hand. Experiment 5 addresses this issue, showing that, if only a subset of target locations are ever relevant in repeated search, then observers can use this information to restrict their search to this subset of potential targets and target locations.

Experiment 5

Experiment 5 investigates whether observers can restrict their search to a subset of repeated relevant locations. For example, if participants learn that within a display of N items only M of them are ever being queried, can they learn to restrict their visual search to the relevant subset of those M items?

Method:

Participants:

Thirteen naive observers between the ages of 18 and 55 served as participants. Each participant passed the Ishihara test for color blindness and had normal or corrected to normal vision. All participants gave informed consent and were paid for their time.

Apparatus and Stimuli:

The search stimuli were similar to that of Experiment 1. Here however, the search stimuli consisted of 2, 4, 6, 12 or 18 uppercase letters (omitting the letters 'I' and 'L'). All letters were white and appeared on a black background. Because visual acuity declines as a function of the distance from the fixation point, the size of the letters increased with eccentricity. Those closest to the center subtended a visual angle of 0.5° x 0.6°, whereas those further out subtended a visual angle of either 1.0° x 1.2° or 2.0° x 2.5°, depending on their eccentricity. All stimuli were viewed from a distance of 57.4 cm. The target probe was a lowercase letter presented at the center of the screen within a circle of diameter 1.5°.

Procedure:

There were two conditions: a repeated search task and an unrepeated search task (see Figure 8 for example displays). In all conditions, participants had to decide if the central target probe was present or absent from the display. Participants pressed a left key ("a") if it was present and a right key (“l”) if it was absent and were asked to respond as quickly but as accurately as possible. The target probe changed on every trial, as in Experiments 1-4.

Figures 8 about here

In the repeated search task the search array always remained on the screen. In each condition there were either 2, 4, 6, 12 or 18 items on the screen. For set sizes 2, 4 and 6 all the stimuli could serve as targets (there were also an equal number of letters used as target absent probes). This replicates Wolfe et al. (2000). For set sizes 12 and 18, only a subset of the letters in a display could serve as targets. Thus, although there were always 12 or 18 letters visible, only 2, 4 or 6 items were probed (again there were an equal number of letters used as target absent probes). For example, consider Figure 8a. The overall set size is 12 but participants might only be queried about the letters Q, S, T or X. In this probe set size of 4 condition, none of the other visible letters would ever be asked about. Four other letters (e.g. A, F, N, P) would be used as probes on target absent trials. The letters used as targets remained constant throughout a block of trials so that participants learned by experience that only a subset of the letters and a subset of locations were relevant in each block. Since the physical display did not change, the identity and locations of stimuli remained perfectly correlated for a block of trials. Thus by constantly being probed about the same set of letters participants could learn that they only needed to search a subset of locations.

The unrepeated search task was intended as a baseline condition to measure the rate of search through these stimuli under standard conditions. In this task, the search stimuli changed from trial to trial along with the target probe. The set size was varied from 12 or 18 items, any of which could be a target, and thus all locations were being searched with equal probability. Each condition consisted of 350 experimental trials, and participants completed a block of practice trials prior to the experiment proper. The order of blocks was randomized across participants.

Results & Discussion

Results for target-present trials are shown in Figures 9 and 10. The pattern of target-absent results was similar. The critical finding is that search varies with the probed set size and not the screen set size. For example, if only 4 items are probed, it does not matter if the physical set size is 4, 12 or 18. Observers can restrict search to just these 4 items. Observers will need to search inefficiently through those 4 but not through the other 8 or 14 irrelevant items.

Figures 9 and 10 about here

Overall error rates were quite low at 3%. There was a main effect of target presence with errors for target present trials higher than target absent, $F(1, 12) = 38.4$, $p < 0.01$. Errors for unrepeated trials were higher than the those in the memory and repeated conditions, $F(13, 156) = 9.9$, $p < 0.01$. However this was more pronounced in the target present trials than the target absent as shown by the Target present/absent x Condition interaction, $F(13, 156) = 19.7$, $p < 0.01$. As the error rates suggest that there was no speed-accuracy trade-off, we do not discuss them further and instead concentrate on RT and slope analysis. RTs below 200 msec and above 4000 msec were eliminated. This led to the removal of less than 1% of the data.

Figure 9 shows the RT data across epoch for the display with the overall physical set size of 12 (Figure 9a) and that for the overall physical set size of 18 (Figure 9b). In all conditions participants responded faster in the repeated search tasks, where they were only ever asked about a subset of probes and thus locations, than in the unrepeated search tasks where the target could appear at any location (all $Fs > 30.5$, $ps < 0.01$ and all $Fs > 75.7$, $ps < 0.01$, for physical set sizes of 12 and 18 respectively). RTs also decreased with epoch in the repeated conditions, suggesting that participants were learning where the relevant target locations would be over the first few epochs, ($F(6, 72) = 10.6$, $p < 0.01$ and $F(6, 72) = 15.1$, $p < 0.01$, for set size 12 and 18 respectively).

For present purposes, the critical question is whether observers learned to restrict search to the subset of locations that could contain a target. The clear answer was yes as can be seen in Figures 10a and 10b. To look at asymptotic performance, we averaged the last 150 trials in each 350 trial block. In Figure 10a, we plot average target present RTs as a function of the *physical* set size (12 or 18) for the three subset conditions (e.g. "probe 2", "probe 4" or "probe 6") along with RTs from repeated search through 12 or 18 items. The "probe all" condition replicates previous repeated search experiments with search remaining inefficient after hundreds of trials. When targets were restricted to subsets of 2, 4, and 6, however, the physical set size became irrelevant. Only the size of the relevant set mattered as can be seen in the increase in RT from subsets of 2 to 4 to 6 items. If observers had not learned to restrict search to the relevant subset, then all of the conditions plotted in Figure 10a should have been equivalent in efficiency (though the repeated search conditions might have been somewhat faster than the unrepeated control conditions). Clearly, this was not the case. The unrepeated "probe all" condition yields a slope of 28 ms/item that is highly different from 0 ms/item ($t(12) = 7.0$, $p < 0.01$. For searches through subsets, the search slopes do not differ from 0 ms/item (all t's < 1, p's > 0.6)[2]. Likewise RTs in the repeated search conditions were faster than those in the unrepeated (all F's > 49, p's < 0.01). In these repeated conditions, participants were only searching the relevant items and were ignoring the rest of the distractors.

In Figure 10b, we plot target present RTs as a function of the probed set size. When the physical set size was 2, 4 or 6, then the probed and physical set sizes are the same. When physical set size equaled 12 or 18, the probed subset is 2, 4, or 6 items. In 10b we see that the repeated search subset conditions were equivalent to the standard repeated search conditions with physical set sizes of 2, 4, and 6. The slopes of 30.4 ms/item (set size 2, 4 and 6) 35.8 ms/item (set size 12), and 34.7 ms/item (set size 18) did not differ significantly ($F < 0.2$).

[2] These null results were not due to a lack of power. Analyses on these slopes all show a power higher or equal to 0.9, when looking for a similar difference to the unrepeated condition.

The important conclusion to be drawn from Experiment 5 is that participants are perfectly capable of restricting search to a relevant subset of stimuli in a repeated search task. However, in agreement with prior work and Experiments 1-4, it is not possible to eliminate search through the set of relevant items. Whether the set of possible targets is the set of all items or a subset, observers search through that set with the same efficiency after 350 trials as they did before.

Experiment 6

Experiment 6 again investigated whether participants can learn to restrict their attention to a subset of relevant items. Here however, instead of using a present/absent 2AFC response task this experiment used a localization response task similar to that found in Experiments 1-4.

Method:

Participants:

Twelve naive observers between the ages of 18 and 55 served as participants. Each participant passed the Ishihara test for color blindness and had normal or corrected to normal vision. All participants gave informed consent and were paid for their time.

Apparatus and Stimuli:

The search stimuli were identical to those found in Experiment 5.

Procedure:

The procedure was similar to that of Experiment 5. However in this case, participants were asked to click on the target location if present (as in Experiment 1-4). In addition to this there were also trials where the target was absent. In this case, participants were asked to click on an orange square (4° x 4°) that was presented 15.7° to the right of the central circle. In this experiment the physical set size could be either 12 or 18 items. The probe set size (i.e., the number of items that were ever asked about) was fixed at either 3 or 6. An equal number of letters were used as target-absent probes. Two unrepeated conditions (with a set size of 12 and 18) were used as baselines where the search display changed from trial to trial. Here the target could be any item in the display and could thus appear in any position.

Results & Discussion

Data from one participant was not included in the analysis as her data file was corrupted. Results for target-present trials are shown in Figures 11 and 12. The pattern of target-absent results was similar. Even when the response task was changed from a present/absent 2AFC task to a localization task the results replicate those of Experiment

5. Search varies with the probed set size and not the screen set size and thus can be restricted to a subset of relevant items.

Figures 11 and 12 about here

Overall error rates were quite low at 3%. There was a main effect of condition, $F(1, 10) = 47.2$, $p < 0.01$, where there was a higher percentage of errors in the Unrepeated condition compared to the repeated condition. As the error rates suggest that there was no speed-accuracy trade-off, we do not discuss them further and instead concentrate on RT and slope analysis. RTs below 200 msec and above 4000 msec were eliminated. This led to the removal of less than 2% of the data.

Figure 11 shows the RT data across epoch for the display with the overall physical set size of 12 (Figure 11a) and that for the overall physical set size of 18 (Figure 11b). In all conditions participants responded faster in the repeated search tasks, where they were only asked about a subset of probes and thus locations, than in the unrepeated search tasks where the target could appear at any location (all $Fs > 22.1$, $ps < 0.01$ and all $Fs > 71.0$, $ps < 0.01$, for physical set sizes of 12 and 18 respectively). RTs also decreased with epoch in the repeated conditions, suggesting that participants were learning where the relevant target locations would be over the first few epochs, ($F(6, 60) = 3.6$, $p < 0.01$ and $F(6, 60) = 8.5$, $p < 0.01$, for set size 12 and 18 respectively).

As in Experiment 5 the data again show that observers learned to restrict search to the subset of locations that could contain a target. To look at asymptotic performance, we averaged the last 150 trials in each 350 trial block. In Figure 12, we plot average target present RTs as a function of the physical set size (12 or 18) for the two subset conditions (e.g. "probe 3" or "probe 6") along with RTs from the unrepeated search through 12 or 18 items. When targets were restricted to subsets of 3 and 6, in repeated search the physical set size became irrelevant. For repeated searches through subsets of both 3 items or 6, the search slopes do not differ from 0 ms/item ($t(10) = -0.4$, p = n.s. and $t(10) = 1.4$, p =n.s., respectively). This was not the case for the unrepeated search task where search slopes were inefficient at 33 ms/item and much higher than 0 ms/item ($t(10) = 6.8$, $p < 0.01$). Mirroring the results from Experiment 5, the data suggest that participants were only searching the relevant items and were ignoring the rest of the distractors.

The findings from Experiment 6 replicate and extend those of Experiment 5. Again the data show that participants are able to restrict their attention to a subset of relevant items within a repeated search task. Implications of this are discussed further in the General Discussion.

General Discussion

To briefly summarize, repeating a visual search does not change the nature of that search. If the search is inefficient, it remains inefficient. The work presented here answers two puzzles within the repeated search literature. Firstly, it explains why, even when participants can remember where the stimuli are placed, they chose to search the display as though it were new. Experiments 1-4 showed that repeated memory search is less efficient than repeated visual search when observers are prevented from turning the memory search into a 2AFC response-mapping task. Thus, given six possible targets in a repeated search task, observers do not use memory to instruct vision because the memory search is less efficient than simply re-running the visual search. Secondly, Experiments 5 and 6 show that observers can restrict their attention to a subset of items if they learn that only these locations are ever relevant for search. Although search within the relevant subset remains inefficient, search performance overall is improved as participants are learning to guide attention to specific locations and away from irrelevant stimuli. We conclude that the intuitively obvious improvement in search that occurs as a scene becomes familiar is due to this ability to restrict search to a subset of locations and not to a change in the nature of the underlying search.

It is possible that memory search might become efficient with enough repetition. Logan (1979) found that the consistent mapping of eight S-R alternatives could be automatized if participants were trained extensively (e.g. over six days). This might have implications for some very over-learned visual search tasks (e.g. typing). However, in a world where S-R mapping may not be perfectly consistent and where stimuli are not continuously and exactly repeated our data suggest that it will be more efficient to perform visual search than to rely on memory search.

This work is also important as it gives us insight into when context is important for search. Work in contextual cueing studies has found that when participants are shown a repeated display, RTs to find the target are faster than when the display has not been seen before (e.g., Chun 2000; Chun & Jiang, 1998). On the face of it, the results of repeated search and contextual cueing experiments might seem to be in conflict[3]. In repeated search tasks, repeating a display does not improve search, whereas in contextual cueing tasks RT, at least, improves. Research from our lab has shown that, although RTs decrease with the number of repeated display repetitions, search slopes in contextual cueing do not become more efficient (Kunar et al., 2006; 2007). Thus, although participants respond more quickly when viewing a familiar context, a substantial portion of this effect may have nothing to do with improving the efficiency of search. A good portion of the contextual cueing effect may be due to a facilitation of early or late processing components (such as response selection). Nevertheless, as our Experiments 5 and 6 show, there are circumstances in which the 'context' of a repeated display can improve search efficiency by restricting search to a subset of the presented items.

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[3] Please note that the repeated search paradigm and the contextual cueing paradigm share several differences, which may account in part for these apparently contradictory findings (see Kunar et al., 2005, for details).

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Figure Legends

Figure 1. Example of conditions in the repeated search experiments. The lower case letter in the center circle indicates the target letter to be searched on each trial. In the repeated search condition the search display does not change throughout the condition. This is compared to a standard search, which changes display from trial to trial. In the memory search task, participants memorize the display prior to the condition, after which the stimuli are removed or 'hidden' from the display.

Figure 2. 2a Mean RTs (msec) across epoch for each condition in Experiment 1. 2b Overall mean RT as a function of set size for each condition in Experiment 1

Figure 3. Mean search slopes (msec/item) across epoch for each condition in Experiment 1.

Figure 4: Mean search slopes (msec/item) for repeated memory search across epoch for each condition in Experiment 2.

Figure 5. Example displays of the mixed training condition in Experiment 3.

Figure 6: RT as a function of epoch for the three conditions in Experiment 3. Note that during memory search, all three conditions produce essentially identical results.

Figure 7: Slope as a function of epoch for the three conditions in Experiment 3. Note that during memory search, all three conditions produce essentially identical results.

Figure 8. Example displays for Experiment 5. For the repeated search condition the set size was blocked and could be 2, 4, 6, 12 or 18. Here the probe size equaled the set size when the set size was 2, 4 or 6. However, when the set size was 12 or 18, then only 2, 4, or 6 items were probed. The unrepeated search set size was blocked and could be either 12 or 18.

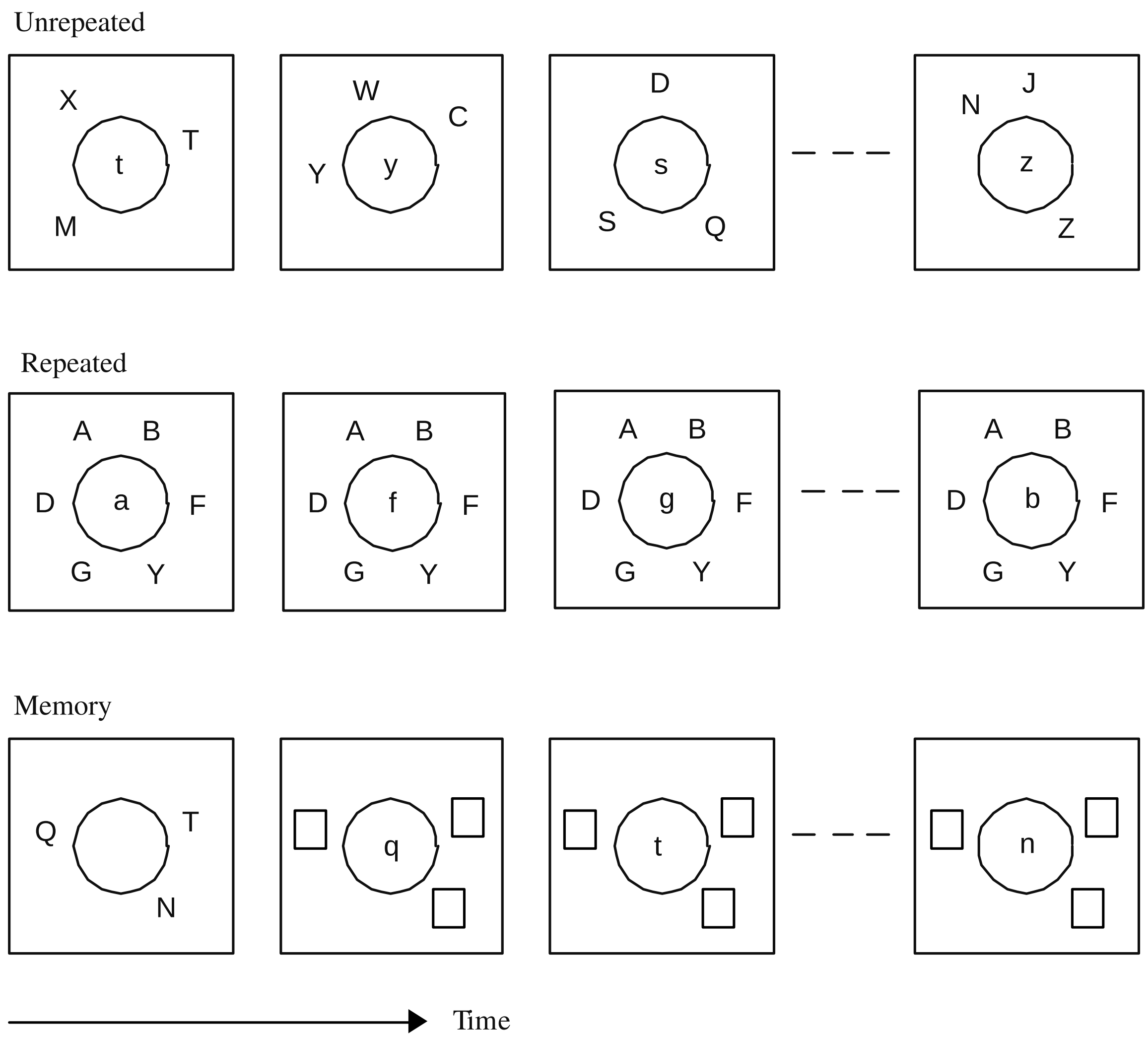
Figure 9: RTs over epoch for the Repeated ('Probe 2', 'Probe 4' and 'Probe 6') and Unrepeated conditions in Experiment 5. The probe numbers refer to the number of locations that have been searched in the repeated conditions. Figure 10a shows data when the overall physical set size was 12, while Figure 10b shows data when the overall physical set size was 18. RTs decreased over the first few epochs, in the repeated conditions, indicating that participants were learning to search only the relevant locations.

Figure 10: RTs for the last 150 trials of 350 trial blocks in Experiment 5. 8a shows RT as a function of physical set size. 8b shows RT as a function of the number of items probed in the display. Clearly it is probed set size that drives RT.

Figure 11: RTs over epoch for the Repeated ('Probe 3' and 'Probe 6') and Unrepeated conditions in Experiment 6. The probe numbers refer to the number of locations that have been searched in the repeated conditions. Figure 10a shows data when the overall

physical set size was 12, while Figure 10b shows data when the overall physical set size was 18. RTs decreased over the first few epochs in the repeated conditions indicating that participants were learning to search only the relevant locations.

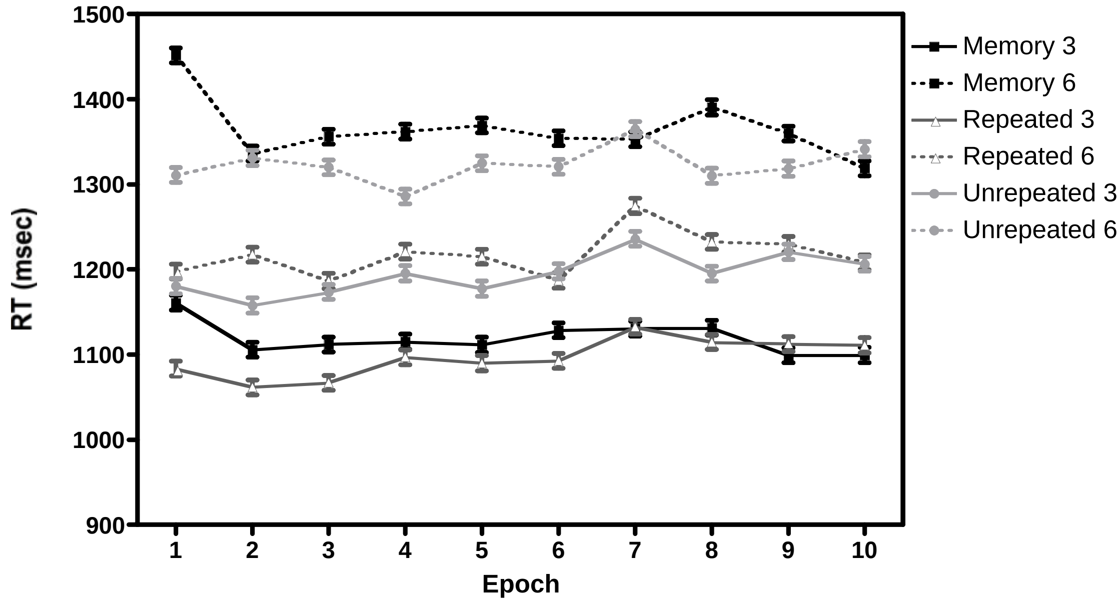
Figure 12: RTs for the last 150 trials of 350 trial blocks in Experiment 6 as a function of physical set size.



Unrepeated
X
T
t
M
W
C
Y
y
D
s
S
Q
J
N
z
Z
Repeated
A
B
D
a
F
G
Y
A
B
D
f
F
G
Y
A
B
D
g
F
G
Y
A
B
D
b
F
G
Y
Memory
Q
T
N
q
t
n
Time

Figure 1

a)


1500
1400
1300
1200
1100
1000
900
RT (msec)
1
2
3
4
5
6
7
8
9
10
Epoch
Memory 3
Memory 6
Repeated 3
Repeated 6
Unrepeated 3
Unrepeated 6

b)

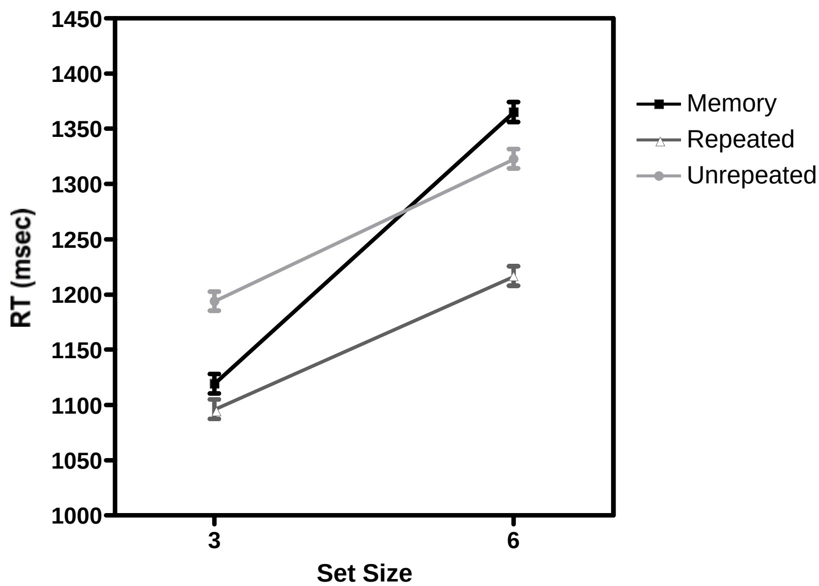

1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
RT (msec)
3
6
Set Size
Memory
Repeated
Unrepeated

Figure 2

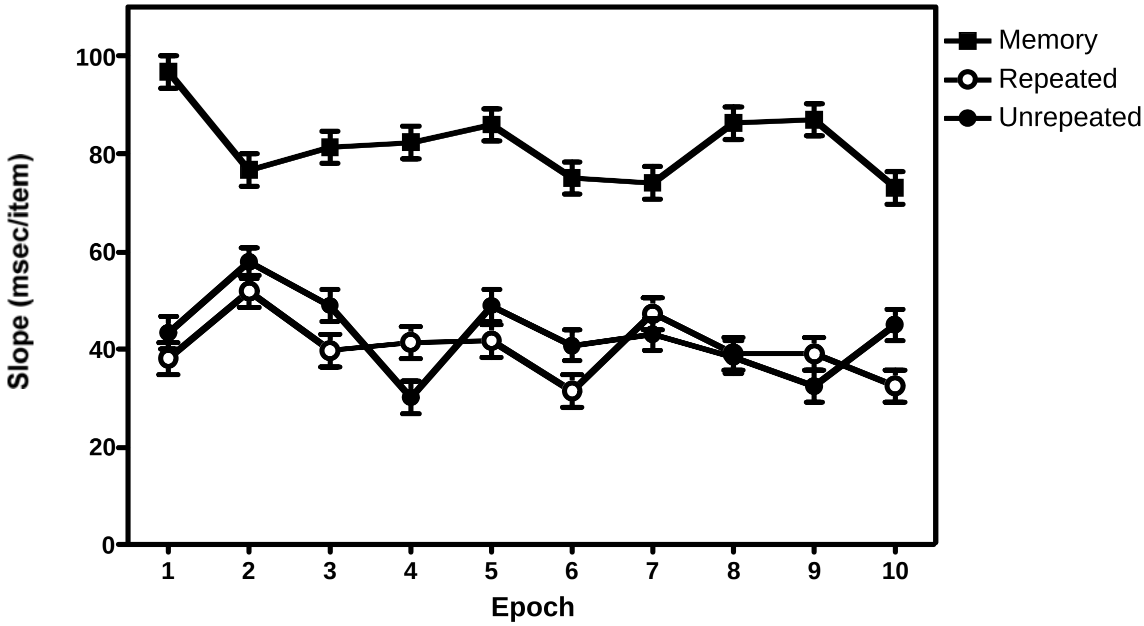
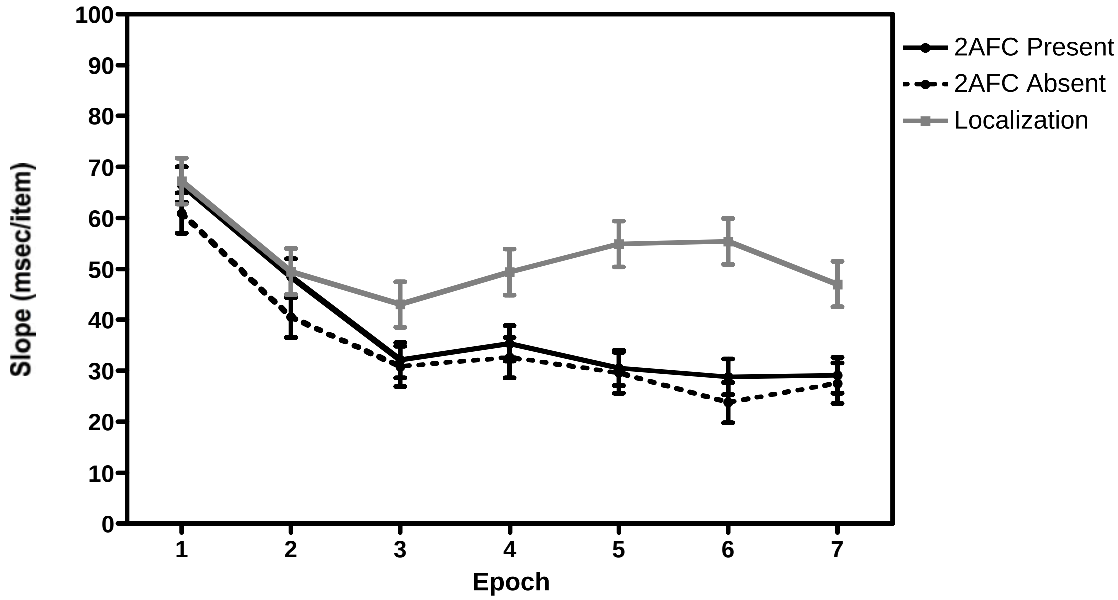
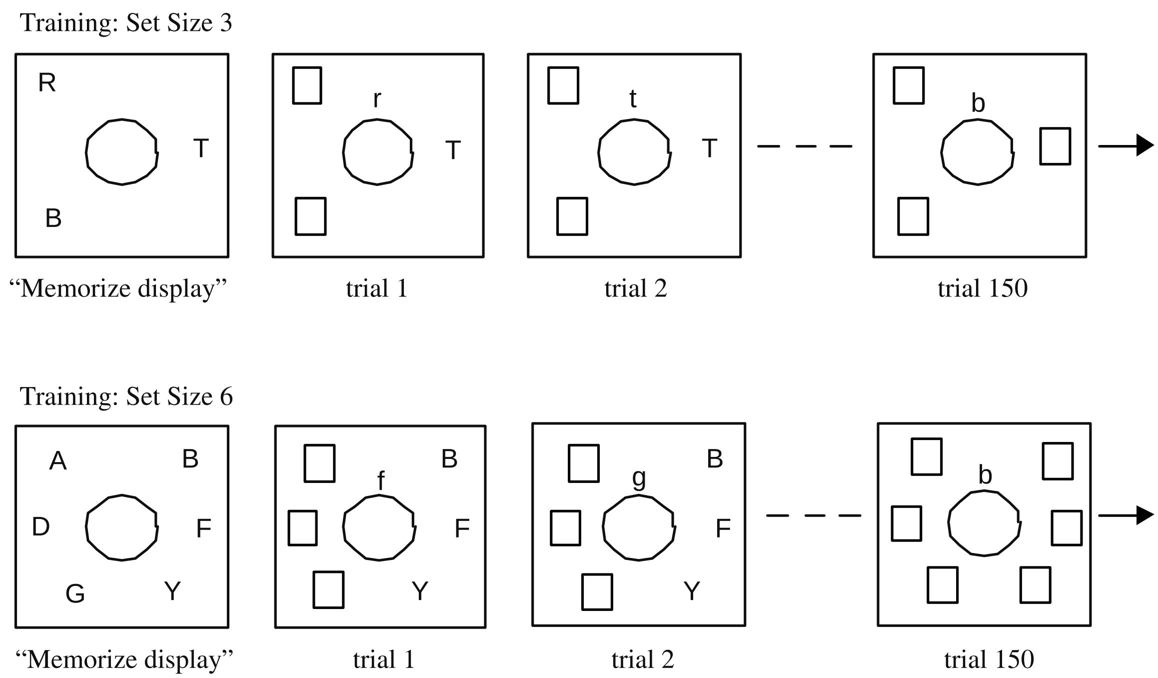

Memory
Repeated
Unrepeated
Slope (msec/item)
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
Epoch

Figure 3



100
90
80
70
60
50
40
30
20
10
0
Slope (msec/item)
1
2
3
4
5
6
7
Epoch
2AFC Present
2AFC Absent
Localization

Figure 4



Training: Set Size 3
R
T
B
"Memorize display"
r
T
trial 1
t
T
trial 2
b
trial 150
Training: Set Size 6
A
B
D
F
G
Y
"Memorize display"
f
B
F
Y
trial 1
g
B
F
Y
trial 2
b
trial 150

Figure 5

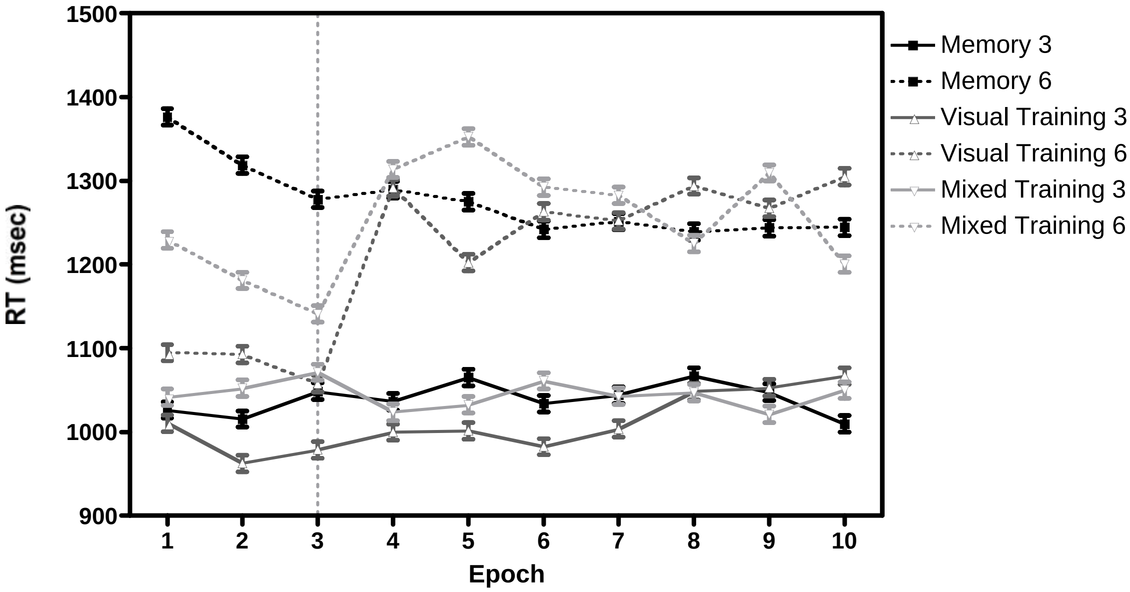

1500
1400
1300
1200
1100
1000
900
RT (msec)
1
2
3
4
5
6
7
8
9
10
Epoch
Memory 3
Memory 6
Visual Training 3
Visual Training 6
Mixed Training 3
Mixed Training 6

Figure 6

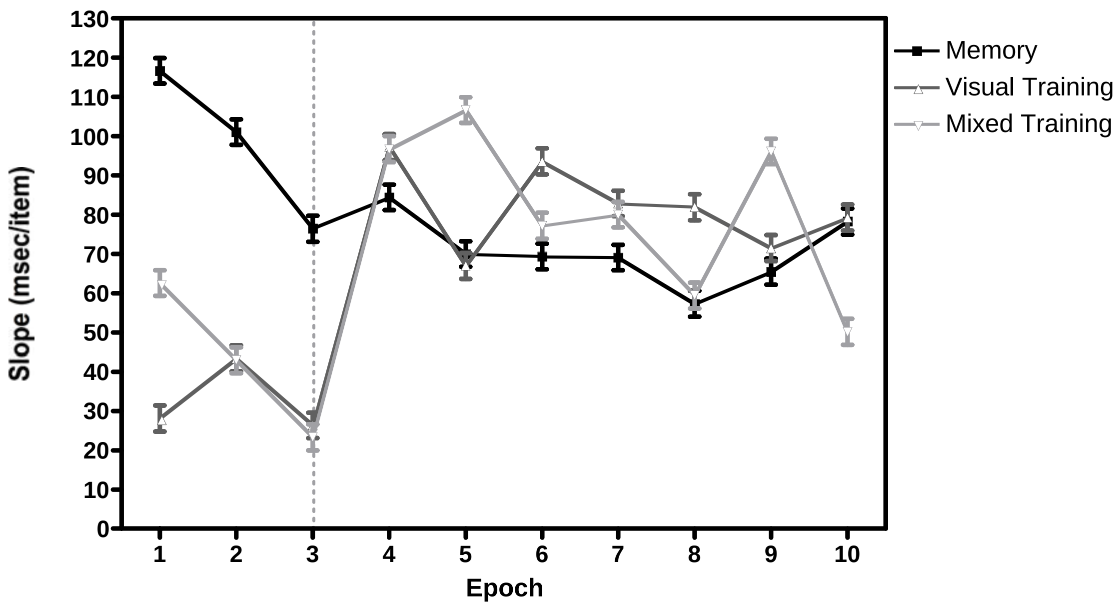
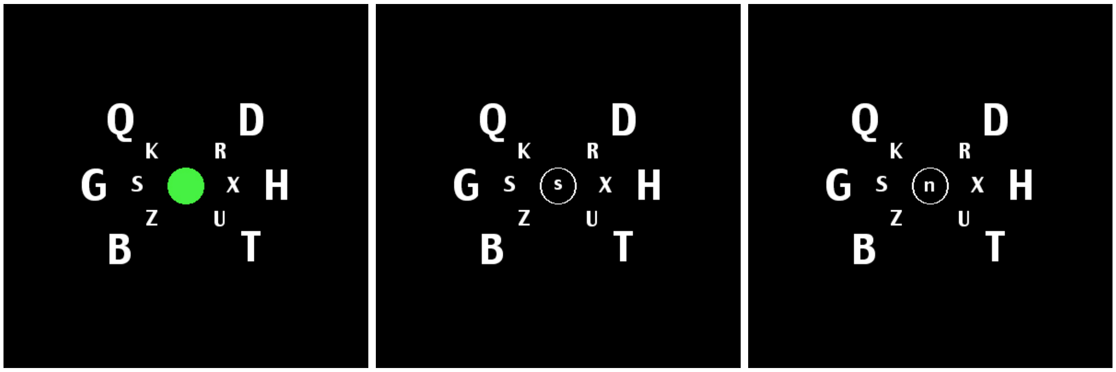

130
120
110
100
90
80
70
60
50
40
30
20
10
0
Slope (msec/item)
1
2
3
4
5
6
7
8
9
10
Epoch
Memory
Visual Training
Mixed Training

Figure 7

a) Repeated Set Size 12



b) Unrepeated Set Size 12

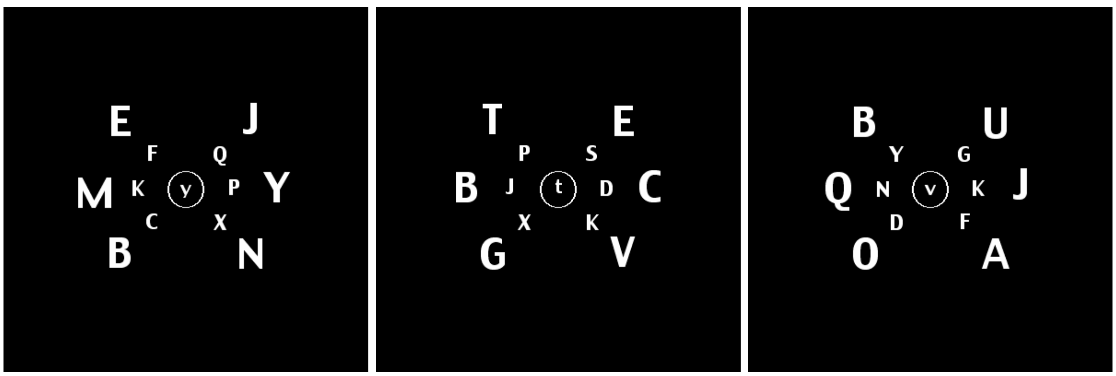
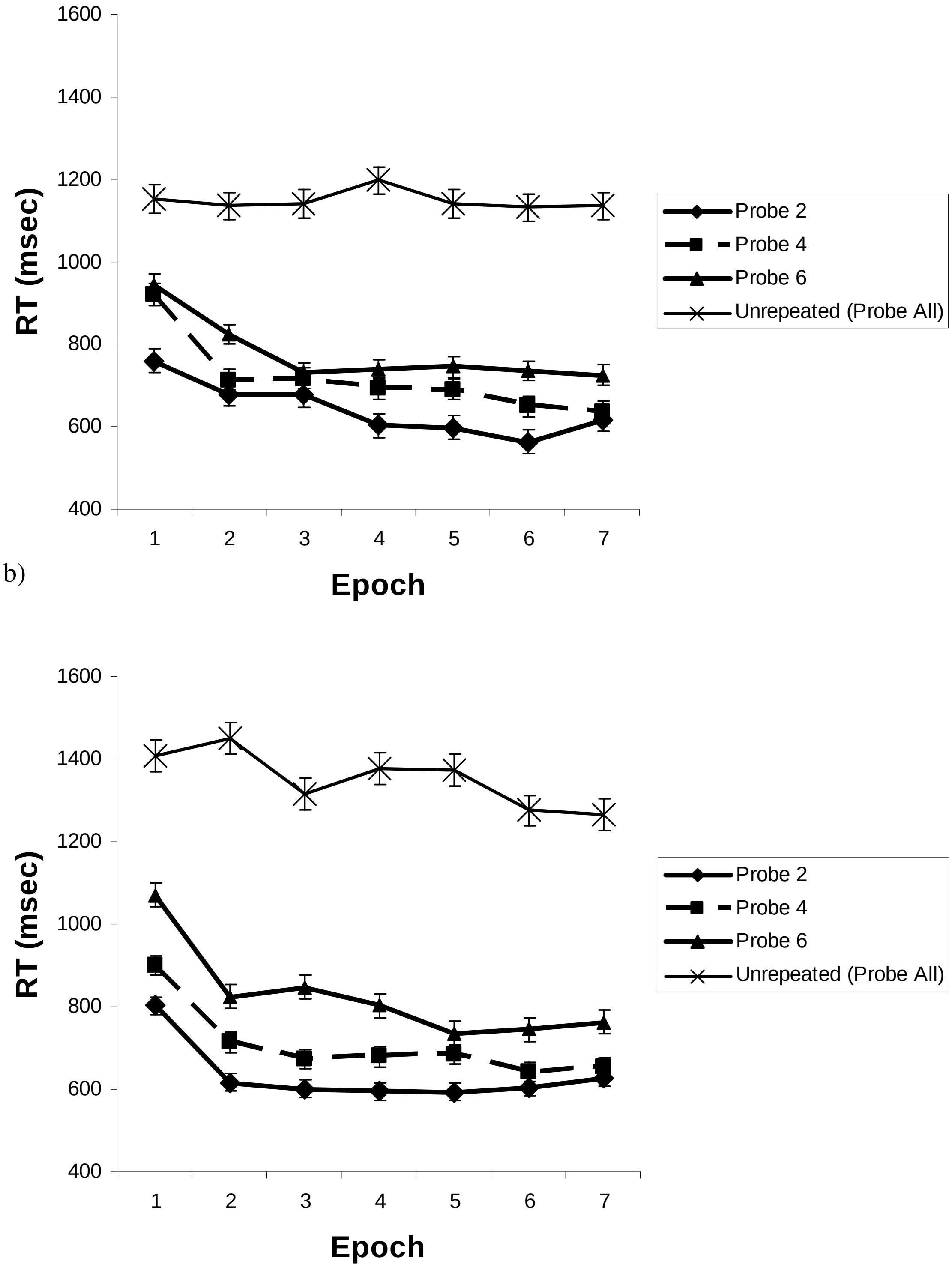


Figure 8

a)

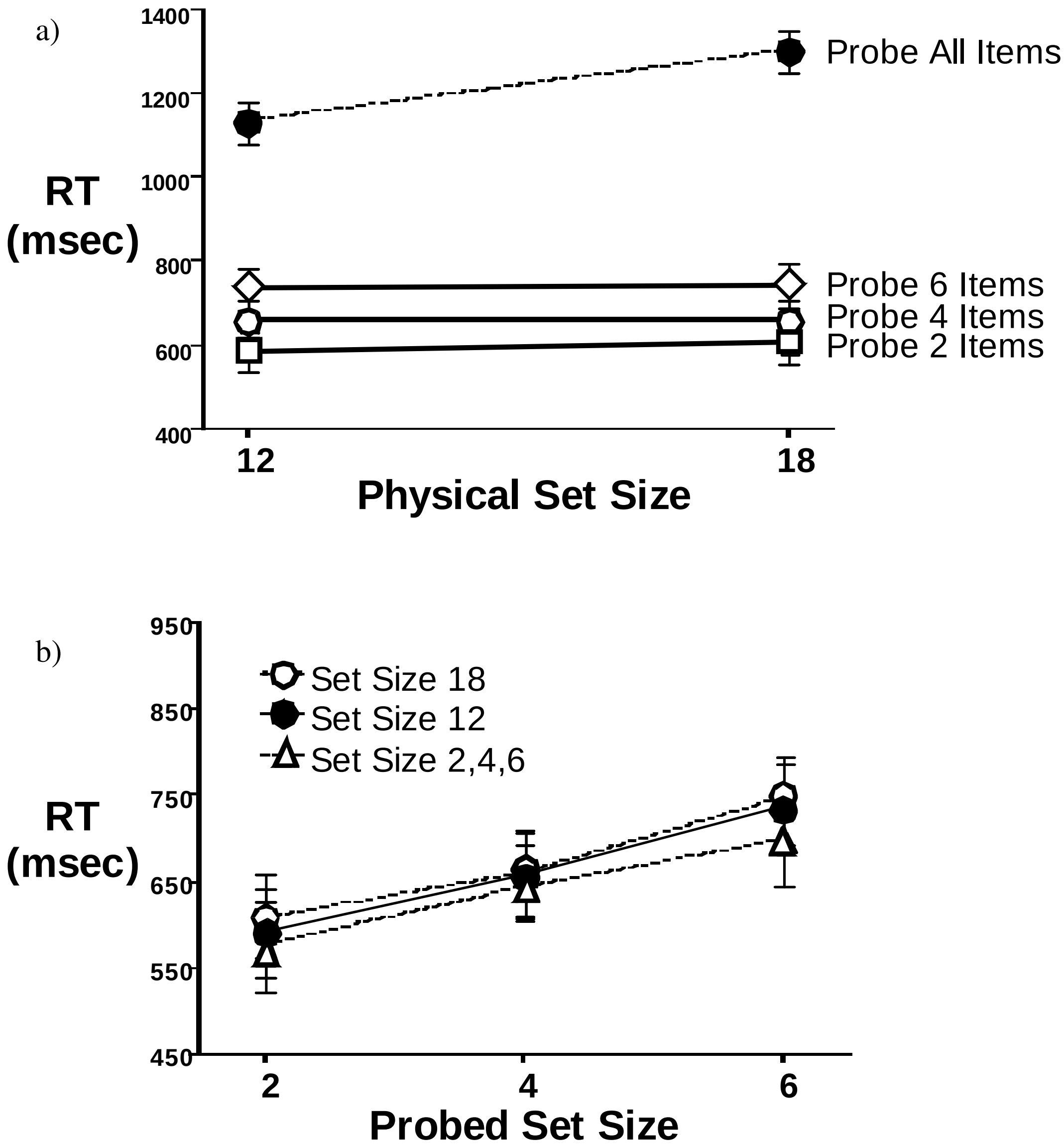


1600
1400
1200
1000
800
600
400
RT (msec)
1
2
3
4
5
6
7
Epoch
Probe 2
Probe 4
Probe 6
Unrepeated (Probe All)
1600
1400
1200
1000
800
600
400
RT (msec)
1
2
3
4
5
6
7
Epoch
Probe 2
Probe 4
Probe 6
Unrepeated (Probe All)

b)

Figure 9

a)


1400
1200
1000
800
600
400
RT
(msec)
Probe All Items
Probe 6 Items
Probe 4 Items
Probe 2 Items
12
18
Physical Set Size

b)

950
850
750
650
550
450
RT
(msec)
Set Size 18
Set Size 12
Set Size 2,4,6
2
4
6
Probed Set Size

Figure 10

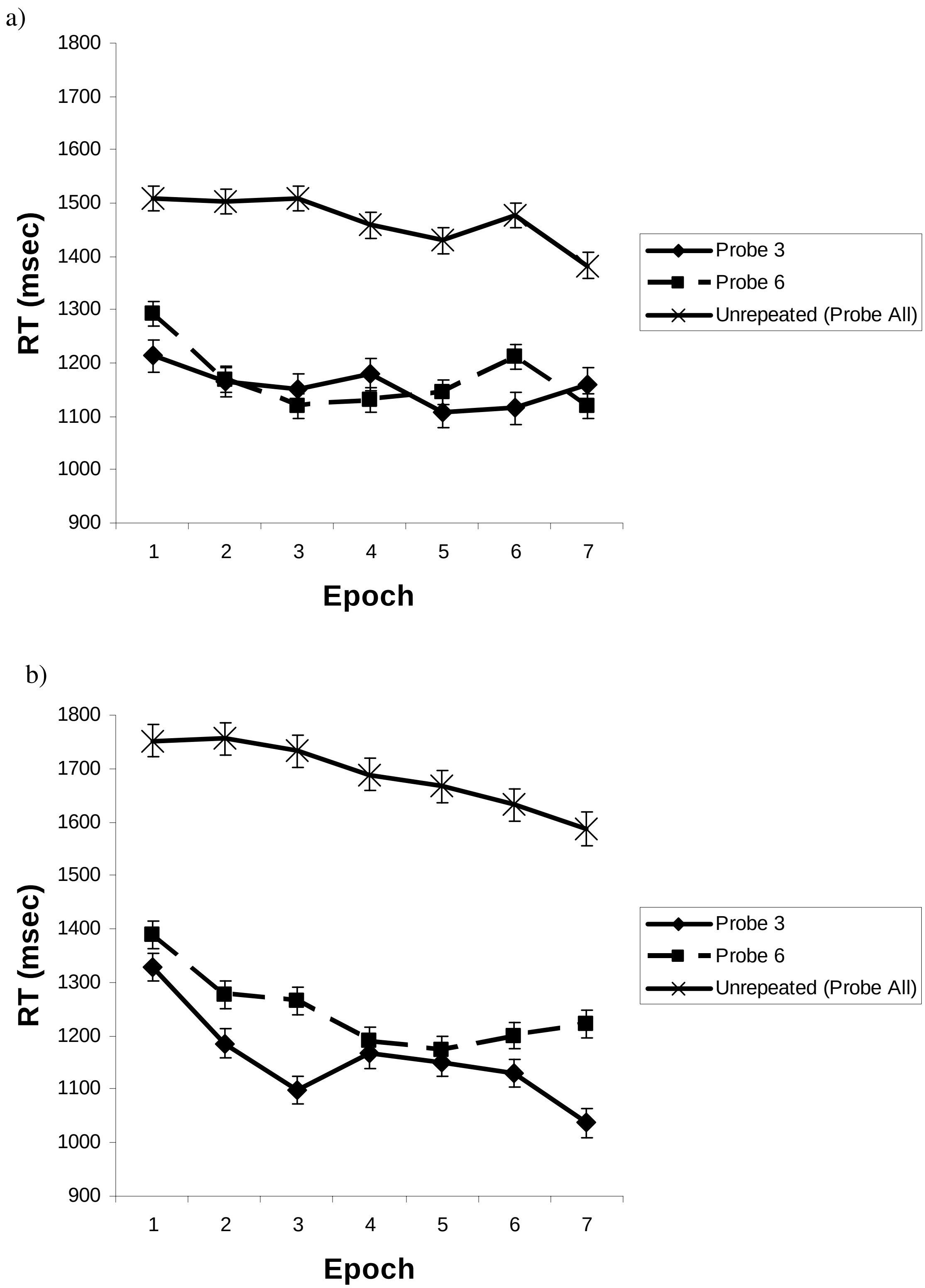

a)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
RT (msec)
1
2
3
4
5
6
7
Epoch
Probe 3
Probe 6
Unrepeated (Probe All)
b)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
RT (msec)
1
2
3
4
5
6
7
Epoch
Probe 3
Probe 6
Unrepeated (Probe All)

Figure 11

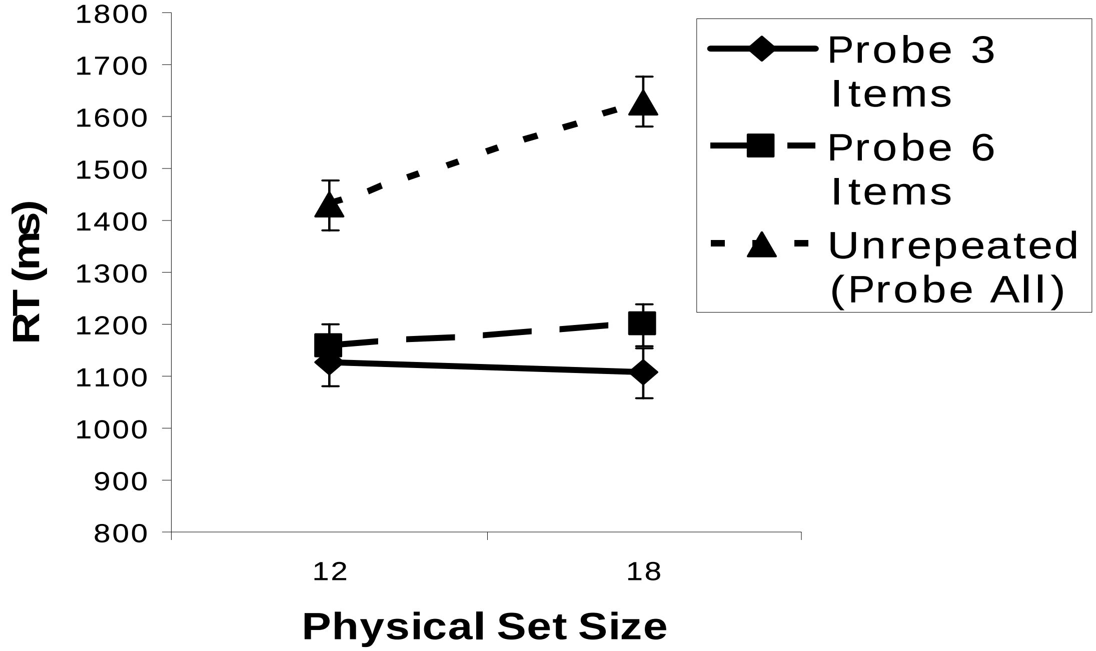

RT (ms)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
12
18
Physical Set Size
Probe 3 Items
Probe 6 Items
Unrepeated (Probe All)

Figure 12