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Decomposing Visual Search: Evidence of Multiple Item-Specific Skills

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Four experiments demonstrated that visual search can be decomposed into two components: one consisting of skills shared with memory search and the other consisting of skills not shared with memory search. A training–transfer paradigm was used to test for transfer from memory search to visual search and vice versa. When the same targets and distractors were used in training and transfer, visual search practice completely trained memory search, but memory search practice only partially trained visual search. Learning on both the shared and the private components of visual search benefited more from item-specific training than from nonspecific training. The relationship between the components and some theorized models of visual search are discussed, particularly in terms of prioritization learning.

Visual search performance changes with practice. Targets that were once difficult to detect often become quite easy to detect. Perhaps the most widely cited evidence of this change comes from studies that show that the impact of the number of elements displayed (*display size*) on response time diminishes with practice (Czerwinski, Lightfoot, & Shiffrin, 1992; Kristofferson, 1972; Lee & Fisk, 1993; Schneider, 1985; Shiffrin & Czerwinski, 1988; Sireteanu & Rettenbach, 1995) as long as the set of elements used as targets in various search displays does not overlap the set of elements used as distractors (a condition known as *consistent mapping;* Schneider & Shiffrin, 1977).

Over the years, visual search has come to be represented most often as a two- or three-stage process (e.g., Treisman & Sato, 1990; Wolfe, 1994). First, each element or cluster of elements is represented coarsely and in parallel and is assigned a priority according to how likely it is to be a target. Then, attentive processing is used to identify elements more precisely, either serially or in parallel, and the priorities from the first stage are used to ensure that high-priority elements are identified more rapidly than low-priority elements. Finally, a response is chosen and made. In such a model, practice effects are usually attributed to changes in the priorities assigned to preattentive representations of the elements. In essence, it is assumed that the coarse, preattentive, unidentified representations come to be easily tagged as potential targets or nontargets. Targets eventually attract attention automatically, and distractors eventually deflect attention (Rogers & Fisk, 1991; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1984).

Evidence suggests that training affects prioritization substantially (Czerwinski et al., 1992; Fisk, Lee, & Rogers, 1991; Graboi, 1971; Shiffrin & Schneider, 1977), but training very likely affects other parts of visual search as well (e.g., response selection), and it is unclear to what degree improvements in the other skills underlie some of the effects that have been attributed to improvements in prioritization. It would be useful to have a method for decomposing the learning of visual search into the learning of component skills, so that the learning of the component skills could be studied relatively independently. The research presented in this article explores one such decomposition.

We used a training–transfer paradigm to decompose the learning of visual search skills. Two tasks were used: a *hybrid* variant of *visual search,* in which participants decided whether one or none of a set of multiple targets was present in a display of multiple items, and *memory search,* in which participants decided whether or not a single displayed element was one of a set of multiple targets. This version of memory search is just like hybrid visual search except that displays are held to one element. Participants were either trained on visual search and transferred to memory search or trained on memory search and transferred to visual search.[1]

Memory search also becomes more efficient with practice. Previous research suggests that participants learn to more quickly compare the displayed item to each memory set member. One reason this might happen is if participants learn to "unitize" the memory set, which means making a single judgment about whether the display item belongs to the memory set rather than comparing the display item to each memory set member (Fisk, Cooper, Hertzog, Anderson-

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[1] We could have used a more typical visual search task and a less typical memory search task—namely, both visual search and memory search with memory sets containing only one element. We used the larger memory set sizes primarily in order to allow substantial learning effects in memory search. We predict the same relationship between visual search skills and memory search skills when single-element memory sets are used, and we are in the process of following up on this work.

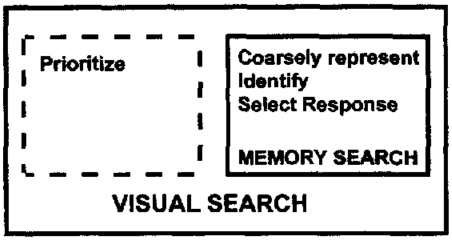

Figure 1. The hypothesized relationship between hybrid visual search and memory search.

Garlach, & Lee, 1995; Flach, 1986; Whaley & Fisk, 1993).[2] Or, participants might switch from serial comparisons with the memory set in short-term memory to parallel comparisons of the memory set in long-term memory (Logan & Stadler, 1991; Schneider, 1985). Regardless of what skills are involved in memory search, it seems apparent that because multiple targets are used in both tasks, memory search skills are required for both tasks. We expected that practice on visual search would train memory search skills as effectively as would practice on memory search itself.

We also expected that visual search would require skills not used in memory search, and so practice on memory search should train visual search skills less effectively than should practice on visual search itself. What skills are involved in visual search that are not involved in memory search? We believe visual search requires display-element prioritization.

We assumed that memory search skills are a subset of visual search skills and that visual search in addition uses a prioritization skill (for additional evidence of this relationship, see Atkinson, Holmgren, & Juola, 1969; Rogers & Fisk, 1991; Sternberg, 1969). Accordingly, the training–transfer paradigm isolates the prioritization component of visual search from the rest of visual search because prioritization is the only component that differentiates our hybrid version of visual search from our version of memory search (see Figure 1 for the hypothesized relationship between memory search skills and visual search skills). Memory search should improve with practice because of target-set unitization and because of improvements in object identification (Logan & Stadler, 1991), as should visual search. Visual search, though, should also have another reason for improving: changes in element prioritization.

It is possible, of course, that our hypothesized relationship between memory search and visual search is mistaken. At the very least, the present research explores the relationship between two tasks, visual search and memory search. Consider two possible alternative relationships. In the first, visual search and memory search involve all of the same skills. Both involve comparisons between displayed information and remembered information. Some past approaches to exploring this relationship have assumed that the number of comparisons made is the basis of response time regardless of whether the number of comparisons depends on variations in display size or variations in memory set size (e.g., Sternberg, 1967). If this assumption is true, training on memory search ought to train all skills involved in visual search, and training in visual search ought to train all skills involved in memory search, and the degree of transfer ought to depend on the amount of training, not on the skills involved. We would expect asymmetric transfer, as in the relationship we favor, but for a different reason. Visual search requires more display-element-to-memory-set-element comparisons per display than memory search does, and so visual search should train the comparison skill better than should an equivalent number of trials of memory search. What, then, distinguishes this alternative relationship from the hypothesized relationship? In the alternative relationship, identification of distractors would be better trained by practice on visual search than by practice on memory search because each distractor is seen more frequently in visual search than in memory search. Our hypothesized relationship does not make the same prediction.

Another possible relationship assumes that identification in single-element displays is a different skill than identification in multiple-element displays because of the lack of "visual noise" in the display (Duncan, 1979). In this case, memory search would use an identification skill that is not part of visual search, and visual search would use an identification skill that was not part of memory search. If such a relationship exists, the transfer results should show that training of neither task transfers well to the other. Transfer, or the lack thereof, should be symmetrical between tasks.

The training–transfer paradigm thus makes predictions that discriminate between some of the possible relationships between memory search and visual search. The transfer effects will provide some evidence about the feasibility of the assumed relationship.

The Present Experiments

In the current research, we used a training–transfer paradigm to functionally decompose visual search into one component that includes skills shared with memory search (the *shared* component) and another component that includes skills not used in memory search (the *private* component). We then explored the nature of learning for each component. The training–transfer paradigm we used involved training on either hybrid visual search or memory search and then transfer to the alternate task, with either the same target set used in both training and transfer or a different target set used in each.

Experiment 1

Participants trained for 5 days on either memory search or visual search for a set of targets and then transferred to the

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[2] Although several authors have claimed that practice in memory search unitizes the memory set, no one has provided a computational model of the unitization process or explained how a unitized memory set is easier to compare with a probe. Unitization of the memory set seems to be analogous to unitization of the letters that compose a word into a single object that can be compared with memory more easily (e.g., LaBerge & Samuels, 1974). However, it is not clear how unitizing a set of items can make it easier to compare a probe item with a single member of that set. In our view, unitization should make such comparisons harder.

alternate task for the same set of targets for 5 days. We predicted that visual search can be decomposed into a shared component and a private component. If this is so, practice in visual search should improve all the skills that practice in memory search improves. This would be evidenced by complete transfer from visual search to memory search: Memory search performance during the transfer phase (after training on visual search) should be completely predicted by memory search performance during the training phase (for the other set of participants). We also predicted that more skills are needed for visual search than for memory search. Thus, practice in memory search should not improve all the skills that practice in visual search improves. This would be evidenced by incomplete transfer: Visual search performance during the transfer phase (after training on memory search) should be slower than predicted by the other participants' visual search performance during the training phase.

An alternative relationship between memory search and visual search would be evidence either that this paradigm does not help in decomposing how training changes visual search or that such a decomposition is not possible. For example, finding that practice in visual search does not train memory search as effectively as does practice in memory search would be evidence that memory search uses skills that are not part of visual search. In this case, visual search could not be functionally decomposed into the proposed components.

Method

Participants. Eleven University of Illinois undergraduate or graduate students were each paid $50 to participate. One student was left-handed. Five were assigned randomly to the group trained in visual search and 6 to the group trained in memory search. An additional 3 students assigned to the visual search group and 1 assigned to the memory search group chose not to complete the experiment. One additional student assigned to the memory search group completed the experiment, but a computer failure during one of the transfer sessions rendered her level of practice inconsistent with that of other participants, so her data were not included in the analyses.

Apparatus. Displays in all experiments reported here were presented on a NEC MultiSync 3FGe monitor driven by a video graphics array (VGA) graphics card in a Gateway 2000 computer. Participants sat approximately 60 cm from the monitor. Responses were entered on a keyboard by pressing either the Z key with the left hand or the / key with the right hand. These keys were at opposite ends of the lowest row of keys on the keyboard used. Three participants trained on visual search and 3 participants trained on memory search pressed / to indicate a target was present in the display and Z to indicate no target was present, and the other 5 participants had the reverse response-key mapping. Response times were measured to the millisecond. Participants were tested individually in rooms containing from 1 to 3 participants. Standard, overhead, fluorescent office lighting was used.

Procedure. Before starting the training and transfer phases, participants were instructed about the task they would do in that phase. On Day 1, they were given a card listing their four targets and what buttons to press to indicate target present and target absent. The card was propped directly below the monitor for the 1st day and was not available during trials on Days 2–10. There were five training sessions and five transfer sessions, one session on each Monday through Friday of 2 consecutive weeks. On the rare occasions when a participant needed to miss a session, a replacement session was scheduled on Saturday or Sunday of the same week.

Each session consisted of 10 blocks of 72 trials, with a break of about 30 s after each block. Participants were encouraged to take a break lasting at least 2 min after the fifth block. The deadline for responding was 5,000 ms on the 1st day and 3,500 ms for the remaining 9 days. When participants responded incorrectly or did not respond by the deadline, "ERROR" was displayed in large letters for 500 ms. After a correct response was registered or an error message was presented, the screen was blank for 800 ms until the next display was presented.

Stimuli. Stimuli were consistently mapped. Participants were each assigned a set of targets and distractors. For each participant, two targets and two distractors were randomly chosen from the letters B, C, D, G, P, T, and V, and two targets and two distractors were randomly chosen from the letters F, H, J, K, L, M, N, R, and S. Participants were informed of their four target letters but were not told about the distractor set.

For memory search, the display to be processed on each trial consisted of a single gray letter presented in the middle of the monitor against a black background. At a viewing distance of 60 cm, the letter was 1.1° of visual angle tall and 0.8° wide. For half the trials in each block, the presented letter was one of the targets; for the remaining trials, it was one of the distractors. The targets were presented on equal numbers of trials. When a distractor was presented, it was chosen randomly.

For visual search, displays contained four, five, or six gray letters against a black background. The letters appeared in randomly chosen positions in a circular ring of six, evenly spaced, unmarked positions surrounding the unmarked center of the display. The letters were the same size as those used in memory search. The radius of the circle of elements was 2.1°. For half the trials in each block, a single target was among the letters presented. The four targets were presented on equal numbers of trials. The distractors in each display were chosen pseudorandomly: When a target was present, distractor positions were filled by cycling through a random ordering of the four distractors until all positions were filled. When no target was present, the same procedure was used to fill all positions but one; the remaining position was filled by choosing one of the distractors at random.

Results

Response times. Figure 2 presents mean target-present and target-absent response times for each group of participants in each session. Response times decreased over sessions during the training phase and during the visual search transfer phase. For participants trained in memory search and transferred to visual search, response times were much slower in Session 6 and beyond than in Session 5. More revealing is the fact that Session 6 visual search response times (for those trained in memory search) were much slower than Session 5 visual search response times (for those trained in visual search). There are clearly some skills in visual search that are not learned from practice in memory search. That those skills are subject to learning is evident from the improvement in visual search performance within the transfer phase, after the shared skills have been well learned. In contrast, for participants trained on visual

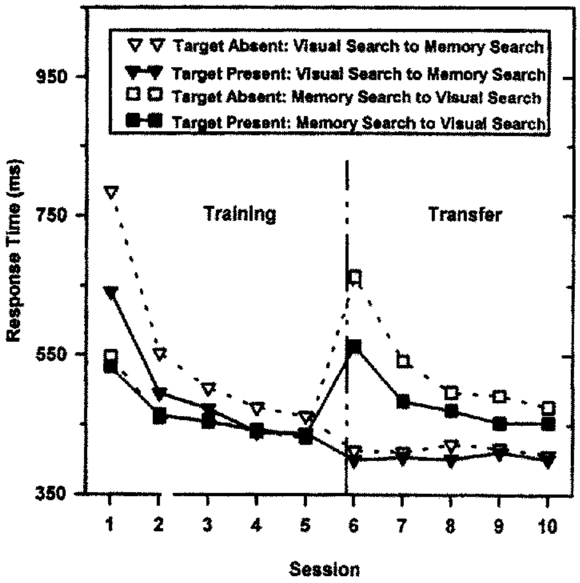

Figure 2. Mean response times for each group of participants in each session of Experiment 1. At transfer, each participant switched tasks but retained the same target set.

Table 1
Effect of Display Size (DS) on Response Times (in Milliseconds) in Experiment 1

	Target present				Target absent			
Session	DS 4	DS 5	DS 6	Slope	DS 4	DS 5	DS 6	Slope
Group 1: Visual search first								
1	620	645	659	20	750	770	832	41
2	486	497	502	8	532	552	575	22
3	463	479	477	7	487	505	517	15
4	431	445	443	6	466	475	484	9
5	429	441	443	7	456	461	471	8
Group 2: Memory search first								
6	547	560	583	18	615	647	726	56
7	471	487	496	13	519	534	572	27
8	466	465	481	8	478	499	514	18
9	449	451	460	6	478	487	512	17
10	443	454	463	10	465	467	497	16

search and transferred to memory search, memory search response times in Session 6 and beyond were at least as fast as memory search response times for the other participants in Session 5. The skills used in memory search were well trained by practice in visual search.

Figure 3 presents the same data for individual participants. Panels A and B present data for participants trained on memory search and transferred to visual search, and Panels

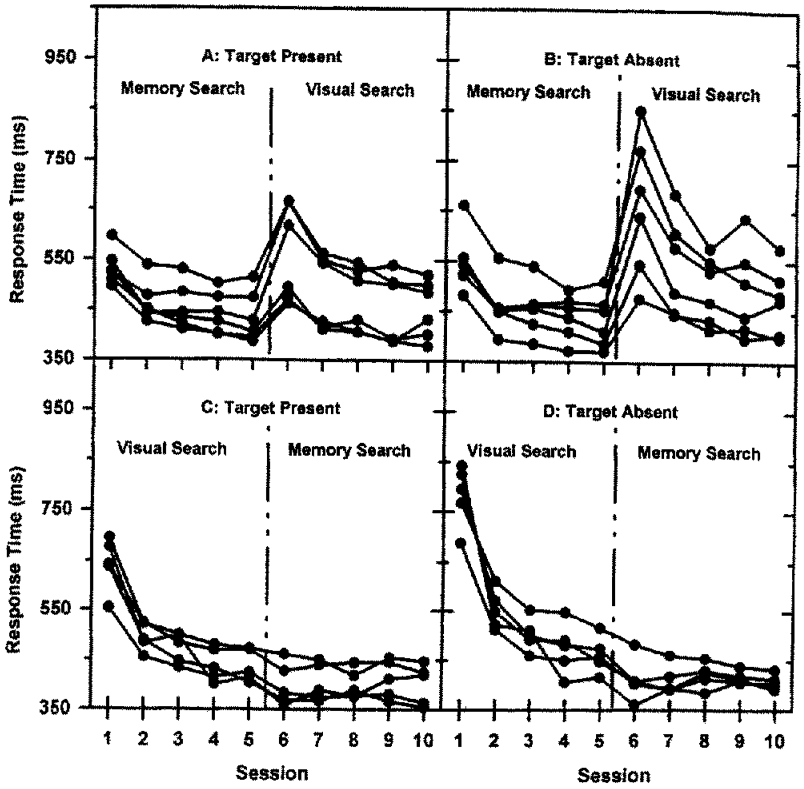

Figure 3. Response times for each participant in each session of Experiment 1. A: Target-present responses for participants trained on memory search. B: Target-absent responses for participants trained on memory search. C: Target-present responses for participants trained on visual search. D: Target-absent responses for participants trained on visual search.

C and D present data for participants trained on visual search and transferred to memory search. The pattern of data shown in Figure 2 was evident for all participants regardless of response mapping and regardless of response type.

Table 1 shows visual search response times as a function of display size, session, and response type. It also shows the slope of the display-size functions. Slopes were calculated for individual participants and then averaged; slopes were calculated by subtracting the mean response time for Display Size 4 from the mean response time for Display Size 6 and dividing by two. For both groups of participants, slopes decreased over sessions, which is in accord with previous research (e.g., Schneider & Shiffrin, 1977). A decrease in slope over time is typically interpreted as evidence that practice makes targets easier to find or that element prioritization improves with practice. The group that started with memory search and transferred to visual search had slopes comparable to those of the group that started with visual search. So any skills that transferred from memory search to visual search evidently did not affect element prioritization.

Error rates. Figure 4 shows error rates for target-present and target-absent responses for the two tasks in the two phases of the experiment. An analysis of variance (ANOVA) with one between-subjects factor, task order (memory search first vs. visual search first), and three within-subject factors, task, session in phase (1–5), and response (target absent vs. target present), was used to analyze the data. The results of the ANOVA are presented in Table 2. Order did not affect error rates, nor were any interactions involving order and task significant. Thus, any skill transfer that occurred affected response times but not accuracy. This means that the fast memory search response times and the slow visual search response times in the transfer phase are not due to simple speed–accuracy trade-offs. The only significant effects involved response: Target-absent responses were more accurate than target-present responses; the effect of response was larger for visual search than for memory search; and the effect of response diminished across blocks.

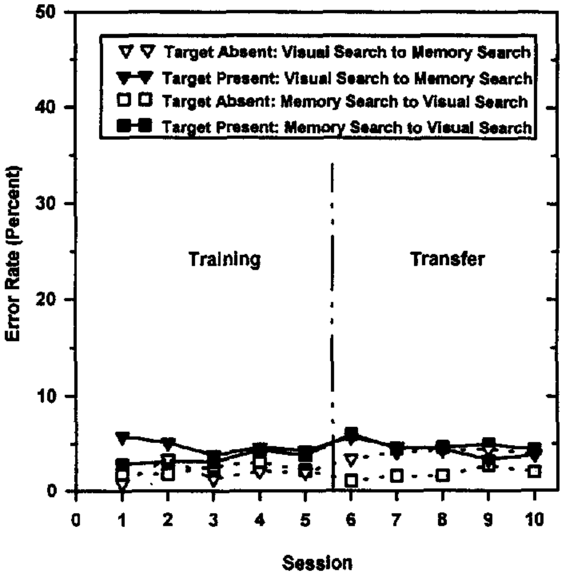

Figure 4. Mean error rates for each group of participants in each session of Experiment 1.

Table 2
Analysis of Variance for Error Rates in Experiment 1

Source	*df*	*MSE*	*F*
Order (O)	1, 9	26.6	<1
Task (T)	1, 9	9.7	<1
Session (S)	4, 36	3.3	<1
Response (R)	1, 9	10.1	18.5**
O × T	1, 9	9.7	2.6
O × S	4, 36	3.3	1.4
O × R	1, 9	10.1	<1
T × S	4, 36	2.9	<1
T × R	1, 9	2.6	25.0***
S × R	4, 36	2.0	3.7*
O × T × S	4, 36	2.9	<1
O × T × R	1, 9	2.6	<1
O × S × R	4, 36	2.0	<1
T × S × R	4, 36	1.1	1.5
O × T × S × R	4, 36	1.1	1.5

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Discussion

The visual search performance at the beginning of the transfer phase was far slower than the visual search performance of other participants at the end of training, so practice in memory search did not train all the skills that practice in visual search did. We conclude that visual search requires skills that are not required for memory search. The memory search performance at the beginning of the transfer phase was no slower than the memory search performance of other participants at the end of training, so practice in visual search did train all the skills that practice in memory search trained. In both the training and the transfer phases, display-size slopes decreased with practice. There was no noticeable difference in display-size slopes between phases, which leads to the conclusion that the shared skills do not contribute to the prioritization of elements. Thus, the results are consistent with the relationship we assumed between memory search and visual search: Memory search skills are a subset of visual search skills, and visual search includes at least one other skill as well, prioritization.

The results are not consistent with the possibility that memory search uses some skills (a different kind of identification, for example) that are not part of visual search: Practice on visual search trained memory search skills at least as well as did practice on memory search. And even though in this experiment we did not set out to test the possibility that memory search and visual search share all the same skills and that they were simply practiced in different amounts in the different tasks, the results are also inconsistent with this amount-of-practice explanation. If memory search and visual search are driven only by comparisons between memory items and display items, participants would have had far more practice at identifying distractors than targets when trained on visual search. So after visual search practice, performance on target-absent trials in memory search should have been better than performance on target-present trials. This result did not obtain (see Figure 2). We conclude that an amount-of-practice explanation is insufficient for explaining the results.

Experiment 2

Our goal in Experiment 2 was to provide more evidence to rule out an amount-of-practice explanation for the results of Experiment 1. To do so, we used a more prototypical version of visual search in which participants searched for only one target in each display, so that memory search and visual search would be equally difficult tasks. Participants engaged in either visual search for a single target in displays of five elements or memory search for a five-member target set in displays of single elements. The targets sought in individual trials of visual search were drawn from the five-member set used on each trial in memory search. Roughly the same numbers of display-to-memory comparisons are required in each task, but the assumed relationship between memory search and visual search skills is changed. If the results of Experiment 1 can be attributed merely to a larger number of display-to-memory comparisons being made in Experiment 1's visual search task, then in Experiment 2, the two task orders ought to show equivalent transfer. If, however, the results of Experiment 1 are due to the decomposition of visual search we proposed, then in Experiment 2, neither task should fully train the other task. Whereas in Experiment 1 both tasks required manipulation of multiple targets in the target set, in Experiment 2 that skill is only a part of memory search. Visual search, too, used a skill not used in memory search: element prioritization. So at the start of transfer, both groups of participants should exhibit performance that is not predicted by performance at the end of training for the other group.

Method

Participants. Sixteen right-handed University of Illinois undergraduate or graduate students were each paid $10 to participate. Eight were assigned randomly to the group trained in visual search and 8 to the group trained in memory search. An additional 2 students assigned to the visual-search-first group chose not to complete the experiment, and 1 more assigned to the memory-search-first group was replaced because of unusually high error rates (greater than 20% in some blocks).

Stimuli. Except where noted below, the same stimuli were used in this experiment as were used in Experiment 1. Five targets and five distractors were assigned to each participant. For each participant, two targets and three distractors were randomly chosen from the letters B, C, D, G, P, T, and V, and three targets and two distractors were randomly chosen from the letters F, H, J, K, L, M, N, R, and S.

Procedure. The procedure was the same as in Experiment 1 except as noted here. The card given to each participant on the 1st day showed only the response-key mapping, not the target set. Half the participants trained on each task pressed / to indicate a target was present in the display and Z to indicate no target was present, and the other half had the reverse response-key mapping.

There were two sessions separated by no more than 1 day without a session. The first session and half of the second session were devoted to training; the second half of the second session was devoted to transfer. Each session consisted of 10 blocks of 80 trials, with breaks given as in Experiment 1.

For memory search, all five targets were displayed for 750 ms before the search display was presented. Participants searched for all targets on every trial. The search display was presented as in Experiment 1.

For visual search, a single target was displayed for 750 ms, and then the search display was presented, with participants responding as to whether that single target was present or absent. Displays contained five letters against a black background, presented as in Experiment 1.

The targets used in visual search trials were all from the memory set that was used for memory search. Each of the targets was sought on one fifth of the visual search trials. For half the trials in each block the target was present, and for the remainder the target was absent.

Results

Response times. Figure 5 presents mean target-present (Panel A) and target-absent (Panel B) response times for each group of participants in each block. Response times

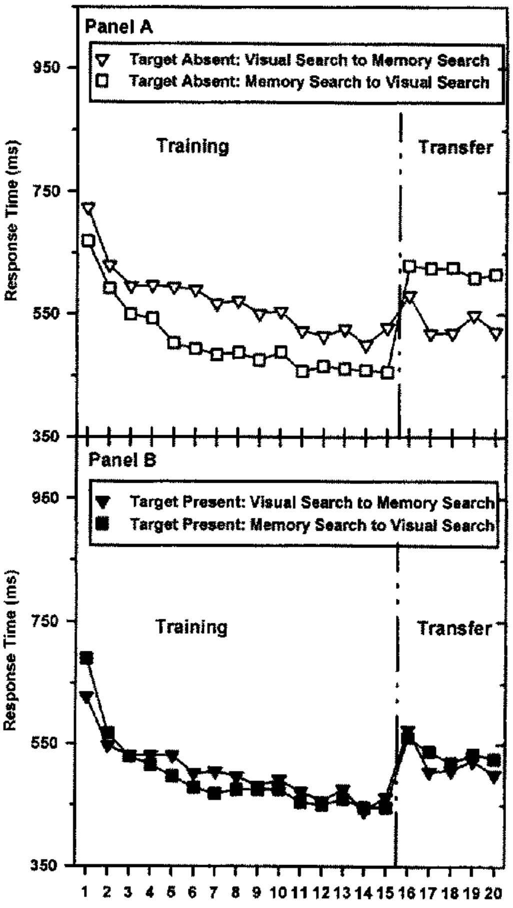

Figure 5. Mean response times for memory and visual search in each block of Experiment 2. At transfer, each participant switched tasks but retained the same target set.

decreased over blocks during the training phase and during the transfer phase. For both groups of participants, response times were much slower in Block 16 and beyond than in Block 15. To see if the slowing was reliable, for each task, we submitted response times from the last two blocks of the training phase and the first two blocks of the transfer phase to an ANOVA with one between-subjects factor, phase (training or transfer), and two within-subject factors, block (two within each phase) and response (target present or absent). The complete results are presented in Table 3. The reliability of the slowing is evidenced by significant effects of phase for both tasks.

Error rates. Figure 6 shows error rates for target-present and target-absent responses for each group of participants in each block. Overall, more errors were made on target-present trials than on target-absent trials, and more errors were made on visual search than on memory search. If transfer affected errors, it increased them only minimally. For each task, errors around the point of transfer were analyzed with an ANOVA with one between-subjects factor, phase (training or transfer), and two within-subject factors, block (two per phase) and response (target present or absent). The complete results are presented in Table 4. Phase did not reliably affect error rates for visual search but did so for memory search.

Discussion

The visual search performance at the beginning of the transfer phase was slower than the visual search performance of other participants at the end of training. Likewise, the memory search performance at the beginning of the transfer phase was slower than the memory search performance of other participants at the end of training. The results are consistent with the component-skill training predictions. Practice in memory search did not train all the skills that practice in visual search did. We conclude that this version of visual search requires a skill that is not required for this version of memory search: prioritization of display elements. Likewise, practice in visual search did not train all the skills that practice in memory search trained. We conclude that this version of memory search requires a skill that is not required for this version of visual search: handling of multiple elements.

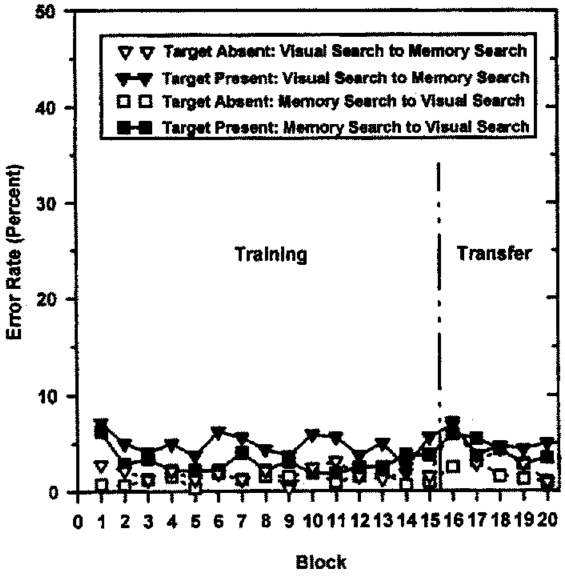

Figure 6. Mean error rates for memory and visual search in each block of Experiment 2.

Performance was not entirely consistent with a strict amount-of-practice explanation. As in Experiment 1, participants trained in visual search and transferred to memory search ought to have had more practice with distractors than with targets and so should have exhibited faster responses in memory search for target-absent trials than for target-present trials. This result did not obtain. In the transfer blocks, the average response time to target-absent trials was 538 ms, and the average response time to target-present trials was 522 ms. In addition, because the tasks were equated for the number of comparisons needed between visual elements and elements held in memory, the same amount of transfer was predicted from visual search to memory search as from memory search to visual search. Target-present responses seemed to show that pattern (see Figure 5A), but target-absent responses did not (Figure 5B). Because this experiment was conducted in two sessions rather than 10, some might wonder whether the reduction in practice caused the

Table 3
Analysis of Variance for Response Times in Experiment 2

		Visual search		Memory search	
Source	*df*	*MSE*	*F*	*MSE*	*F*
Phase (P)	1, 14	24,276.7	7.4*	10,676.9	13.0**
Block (B)	1, 14	1,689.0	<1	1,095.3	16.6**
Response (R)	1, 14	1,586.9	49.9***	428.0	4.3
P × B	1, 14	1,689.0	3.6	1,095.3	14.9**
P × R	1, 14	1,586.9	<1	428.0	<1
B × R	1, 14	521.5	1.1	1,218.9	<1
P × B × R	1, 14	521.5	<1	1,218.9	<1

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Table 4
Analysis of Variance for Error Rates in Experiment 2

		Visual search		Memory search	
Source	*df*	*MSE*	*F*	*MSE*	*F*
Phase (P)	1, 14	12.9	2.1	12.9	10.4**
Block (B)	1, 14	5.9	1.3	8.1	6.4*
Response (R)	1, 14	6.5	16.3**	15.6	2.8
P × B	1, 14	5.9	1.3	8.1	7.5*
P × R	1, 14	6.5	<1	15.6	1.8
B × R	1, 14	4.7	1.0	7.5	<1
P × B × R	1, 14	4.7	4.7*	7.5	<1

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

difference in results. We expected not, because previous research has demonstrated the same qualitative effects of automatization at high and low levels of practice (Logan & Etherton, 1994; Logan & Klapp, 1991).

Experiment 3

The skill in visual search that was not trained by practice on memory search could be either general or item specific. If it is general, then adding nonspecific practice in visual search to the item-specific practice in memory search that participants in Experiment 1 received ought to render training as efficient as training consisting of item-specific visual search practice. In Experiment 3, each participant received practice on both memory search and hybrid visual search but for different sets of targets and distractors. At transfer, the targets and distractors were switched between tasks. No matter which task is focused on in the transfer phase, this design can be thought of as providing nonspecific practice in that task and item-specific practice in the alternate task during the training phase. On the basis of Experiment 1, we expected a smooth transition at transfer for memory search, because the item-specific visual search practice should train all skills needed for memory search. Adding nonspecific memory search practice should be superfluous. The question of interest is whether adding nonspecific visual search practice to item-specific memory search practice during the training phase will render training as efficient as item-specific visual search practice. If it does, then visual search performance at the beginning of the transfer phase (on one target set) should be as efficient as visual search performance at the end of the training phase (on the other target set).

Method

Participants. Sixteen University of Illinois undergraduate and graduate students participated for $10 each. They were divided equally and randomly between eight combinations of between-subjects conditions: two orders of visual and memory search in training, two orders of visual and memory search in transfer, and two response-key mappings. One person did not return for the 2nd day of the experiment, another was tested in an incorrect task during one block of training, and 2 more had particularly low accuracy (errors on more than 10% of trials in more than one two-block run of visual search trials). These 4 participants were replaced by 4 others. Two of the final set of participants were left-handed.

Procedure. Participants alternated tasks every second block. Half started with visual search in training, and half started with memory search. Half of each of those groups started with visual search in transfer, and half started with memory search in transfer. There were 16 training blocks and 4 transfer blocks. Ten of the training blocks were run on the 1st day; the remaining training blocks and all transfer blocks were run on the next calendar day. Each block consisted of 72 trials. The deadline for responding was 5,000 ms for the first two blocks and 3,500 ms thereafter. Because a fair amount of time was used to restart the program every second block, no long break was enforced during each session. A card listing the target set for the current task was propped against the monitor for reference during all blocks of trials. In all other respects, the procedure was identical to that used in Experiment 1.

Stimuli. Stimuli were consistently mapped. Two sets of four targets and two sets of four distractors were assigned to each participant, one set of each for each training-phase task. Two letters of each target set, two letters of the memory search distractor set, and one letter of the visual search distractor set were from the following letters: B, C, D, G, P, T, and V. The remaining letters in each set were from the following letters: F, H, J, K, L, M, N, R, and S. There was no overlap of letters in the sets. The target set and distractor set used for visual search in the training phase were used for memory search in the transfer phase; the target and distractor set used for memory search in the training phase were used for visual search in the transfer phase. Displays were constructed the same way as in Experiment 1.

Results

Response times. Figure 7 shows mean target-present and target-absent response times in each block for memory search and visual search, collapsed across task order. Visual search responses were consistently slower than memory search responses, and both became faster over the course of training. When the stimuli were transferred between tasks, visual search responses slowed considerably compared with those in the most recent preceding block of visual search for all four groups of participants. Target-present responses were 157 ms faster in the last block of training than in the first block of transfer, on average. Memory search responses, on the other hand, did not slow appreciably. Target-present responses were 19 ms faster in the last block of training than in the first block of transfer, on average.

To determine whether the slowing at transfer was significant, for each of the tasks we compared mean response times in the last training block with those in the first transfer block using an ANOVA. Each ANOVA used two within-subject factors: phase (training vs. transfer) and response (target

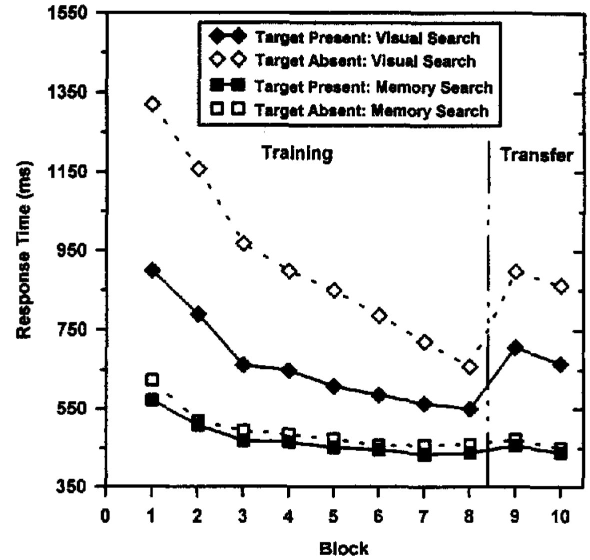

Figure 7. Mean response times for memory and visual search in each block of Experiment 3. In training, different target sets were used for each task. At transfer, the target sets used were switched between tasks.

absent vs. target present). For visual search, both phase and response significantly affected response time, $Fs(1, 15) = 28.1$ and 21.5, respectively, $ps < .001$. The interaction of the two was not significant, $F(1, 15) = 3.3$, $p > .05$. For memory search, response significantly affected response time, $F(1, 15) = 9.7$, $p < .01$, but neither phase nor the interaction of phase with response were significant: $F(1, 15) = 2.4$, $p > .05$, and $F(1, 15) < 1$, $p > .05$, respectively.

If the combined visual and memory search practice trained all skills needed for memory search, then the first block of memory search in the transfer phase should have acted like a continuation of the training phase, and so performance should have been somewhat improved from the last block of memory search in the training phase block. In contrast, the ANOVA described above tested whether actual performance could be discriminated from performance that had flattened out at the level of the last block of training. In an attempt to provide a more stringent test of our predictions, we fit each participant's memory search performance during training with a power function learning curve, and we used that power function to predict performance in the first block at which memory search occurred in transfer. This was done for target-present and target-absent responses separately. Eight points were fit for each participant, one for each block of memory search in training, and the points were spaced according to the spacing of memory search blocks during training (i.e., Blocks 1, 2, 5, 6, 9, 10, 13, and 14 for some participants and Blocks 3, 4, 7, 8, 11, 12, 15, and 16 for other participants). This spacing was used because we assumed that memory search skills were trained during the visual search blocks, although we could not use the response times for visual search in the curve fitting because they also reflected other skills. We fit power functions to the data using the STEPIT program (Chandler, 1965).

We performed an ANOVA like the preceding one (for memory search only), replacing actual data for the last block of training with predicted data for the first memory search block in transfer. Thus, the ANOVA compared actual transfer performance with predicted transfer performance. It turned out that predicted transfer performance ($M = 448$ ms) was not systematically faster than actual end-of-training performance ($M = 449$ ms), probably because the curve fits varied widely (median $R^2 = .81$; mean $R^2 = .79$; R^2 ranged from .26 to .97) and did not systematically underestimate or overestimate the tail of the curve and because the learning curves were close to asymptote by the end of training. According to the new ANOVA, neither phase nor the interaction of phase with response significantly affected response time: $F(1, 15) = 3.7$, $p > .05$, and $F(1, 15) < 1$, $p > .05$, respectively. Response did have a significant effect, $F(1, 15) = 14.5$, $p < .01$.

Table 5
Effect of Display Size (DS) on Response Time (in Milliseconds) in Experiment 3

	Target present				Target absent			
Block	DS 4	DS 5	DS 6	Slope	DS 4	DS 5	DS 6	Slope
				Training				
1	827	932	937	55	1,246	1,282	1,429	92
2	731	787	845	57	1,052	1,135	1,286	117
3	642	664	681	20	870	960	1,074	102
4	647	633	666	10	814	895	992	89
5	597	591	639	21	751	836	964	107
6	597	575	603	12	708	782	869	81
7	545	568	579	17	670	706	792	61
8	533	550	569	18	605	662	711	53
				Transfer				
9	657	720	742	43	789	859	1,046	129
10	633	674	693	30	780	856	955	88

Display-size effects for visual search are presented in Table 5. Slopes decreased during training and then more than doubled when the stimuli were transferred between tasks. We tested the change in display-size effect for significance by comparing the display-size effect in the last training block with the display-size effect in the first transfer block using an ANOVA with three within-subject factors: phase, display size, and response type. Responses slowed significantly as display size increased, $F(2, 30) = 19.9$, $p < .001$, and more important, the effect of display size was greater in the first transfer block than in the last training block, $F(2, 30) = 5.1$, $p < .05$. The Display Size × Phase × Response interaction was also significant, $F(2, 30) = 3.9$, $p < .05$, reflecting a greater impact of transfer on target-absent display-size slopes than on target-present display-size slopes. The significant increase in the effect of display size at transfer is evidence that the nonspecific practice in visual search together with the item-specific practice in memory search did not provide all the skills needed to find transfer targets efficiently. This, together with the results of Experiment 1, suggests that the attenuation of the display-size effect is due to an item-specific skill that is not used in memory search.

Error rates. Error rates for each task are shown in Figure 8, broken down by block and response. Participants made more errors on target-present responses than on target-absent responses, particularly in visual search. In the training phase, practice decreased error rates only for target-present responses for visual search. At transfer, visual search error rates increased sharply, at least for target-present trials (0.9% for target-absent and 0.7% for target-present responses in the last block of training; 4.1% for target-absent and 10.4% for target-present responses in the first block of transfer). Memory search error rates stayed relatively constant (1.9% for target-absent and 1.2% for target-present responses in the last block of training; 2.8% for target-absent and 2.6% for target-present responses in the first block of transfer). We tested these apparent trends at transfer using two ANOVAs, one for each task, that compared the error rates in the last block of training with the error rates in the first block of transfer. Each ANOVA used two within-subject factors: phase (training vs. transfer) and response (target absent vs. target present). For visual search, phase, response, and the interaction between them all significantly affected response time: $F(1, 15) = 12.5$, $p < .01$, $F(1, 15) = 27.3$, $p < .001$, and $F(1, 15) = 13.5$, $p < .01$,

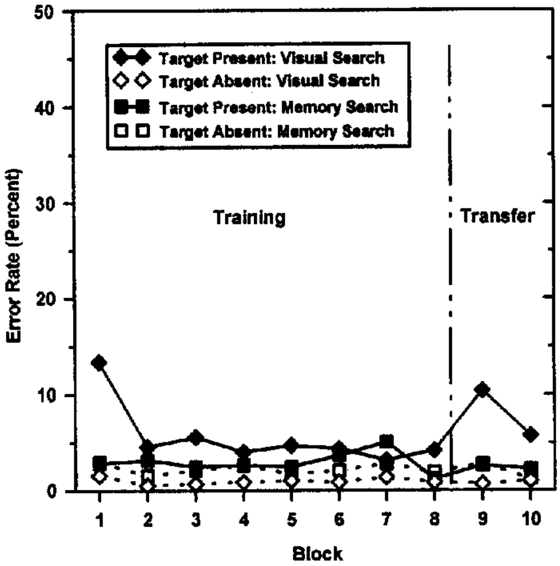

Figure 8. Mean error rates for memory and visual search in each block of Experiment 3.

respectively. For memory search, the small increase in error rate at transfer was significant, $F(1, 15) = 4.7, p < .05$, but neither response nor the interaction of phase with response were significant, $Fs(1, 15) < 1, ps > .05$.

The pattern of responses can be summarized as follows: For visual search, responses became slower and less accurate at transfer and so cannot be a result of a simple speed–accuracy tradeoff. For memory search, however, response times did not slow at transfer, but error rates did.

Discussion

Item-specific visual search training and nonspecific memory search training resulted in transfer performance for memory search that was almost what would have been predicted on the basis of item-specific memory search training. In order to claim that all skills that are inherent in memory search are also inherent in visual search, we would have had to show that both speed and accuracy improved or remained the same at transfer. We are skeptical that the observed decrease in accuracy is anything but an artifact, given that error rates in the last block of training look as if they are low because of random variance.

Item-specific memory search training and nonspecific visual search training resulted in visual search transfer performance that was slower than would have been predicted on the basis of item-specific visual search training. Display-size effects were higher at the beginning of transfer than at the end of training. Thus, within the limits of the precision of measurement of the experiment, the skills in visual search that are not part of memory search are, at least in part, item specific.

Experiment 4

Having determined that the skills used in visual search that are not used in memory search are subject to item-specific learning, in Experiment 4 we asked the same question about the skills that are common to visual search and memory search. Participants were trained to do memory search for one set of targets and were then transferred to doing visual search for both that set of targets and a new set. If the common skills are subject to item-specific learning, then visual search performance should be better for practiced stimuli than for new stimuli, although visual search performance for all stimuli will be slower than memory search performance. If the common skills generalize beyond stimuli used in training, then visual search for new targets should benefit as much from memory search practice as should visual search for old targets.

Method

Participants. Sixteen University of Illinois undergraduate and graduate students participated in the experiment for $10 each. They were divided equally and randomly between four combinations of between-subjects conditions: two orders of new versus old targets in the transfer phase and two response-key mappings. All but 1 were right-handed.

Procedure. There were 16 training blocks and 6 transfer blocks, each consisting of 96 trials. Ten blocks were run on the 1st day and 12 on the following day. In the training phase, participants performed memory search using one set of targets and distractors. In the transfer session, participants performed visual search using the same stimuli on half the blocks and new stimuli on the remaining blocks. Stimuli alternated between new and old from block to block. Half of the participants began the transfer session with a block of new stimuli, and half started with old stimuli. In all other respects the procedures were the same as those in Experiment 3.

Stimuli. Participants were assigned two sets of four targets and two sets of four distractors, set up as described for Experiment 3. One set of each was used for memory search during training and as the old stimuli for visual search during transfer, and the other sets were used as the new stimuli for visual search during transfer. Displays were constructed as in Experiments 1 and 3.

Results

Response times. Figure 9 shows target-present and target-absent response times in each block of trials.[3] Data are

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[3] After testing most of the participants, we discovered that the computer program controlling the experiment potentially allowed participants to miss receiving the instruction to flip the card listing search targets for the block. This could have led them to search for old targets in the first block in which they were supposed to be searching for new targets. But because participants were instructed at the start of the experiment that targets would alternate between old and new during the transfer phase, we believe they probably corrected their responses quite quickly. There was no way to determine which participants had seen the list of targets and which participants had not, but when we inspected the data files, it was apparent that participants responded to the correct targets quite early in the first two blocks of visual search trials. So instead of discarding the data for all participants tested so far, we discarded trials in Blocks 17 and 18 that preceded the first target-present response to a present target; once participants made this kind of response we could be reasonably confident that they were searching for the correct set of targets. This procedure led to the discarding of from 0 to 10 trials in a block (median number discarded was 1).

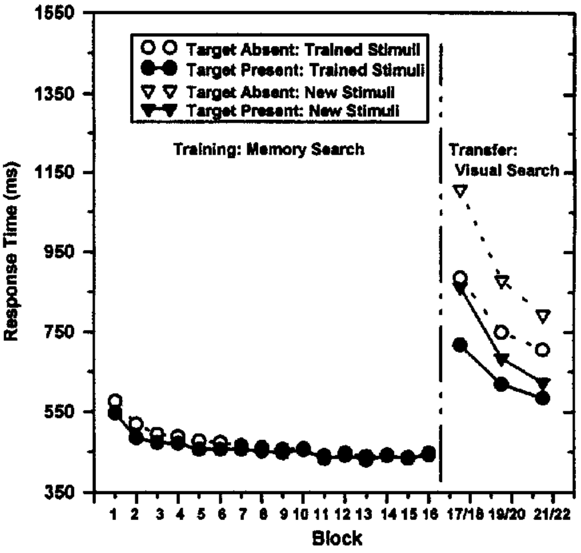

Figure 9. Mean response times for old and new stimuli in each block of trials of Experiment 4. At transfer, all targets were switched from memory search to visual search.

Table 6
Analysis of Variance of Response Times in Experiment 3

Source	*df*	*MSE*	*F*
Stimulus type (S)	1, 14	55,096.8	11.5**
Pair of blocks (P)	2, 28	9,469.8	85.8***
Response (R)	1, 14	28,258.1	49.8***
Order (O)	1, 14	198,852.3	2.4
S × P	2, 28	6,618.9	9.3**
S × R	1, 14	4,147.8	11.6**
S × O	1, 14	55,096.8	<1
P × R	2, 28	2,749.9	5.4*
P × O	2, 28	9,469.8	15.5***
R × O	1, 14	28,258.1	<1
S × P × R	2, 28	1,583.7	<1
S × P × O	2, 28	6,618.9	1.5
S × R × O	1, 14	4,147.8	1.5
P × R × O	2, 28	2,749.9	2.7
S × P × R × O	2, 28	1,583.7	<1

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

presented separately for old and new stimuli in the transfer phase. A moderate amount of learning occurred for memory search, and memory search performance was quite similar for target-present and target-absent responses. Visual search performance was much slower and showed more learning than memory search performance as well as an advantage for target-present responses. Old stimuli (shown by circles in Figure 9) were responded to faster than new stimuli (shown by triangles), which supports the contention that skills common to both tasks are subject to item-specific learning.

To test for the significance of the effects, we used a mixed-design ANOVA to analyze visual search response time data. One factor was between subjects, order of stimuli in the transfer phase (new first vs. old first); three factors were within subject, block pair in transfer (Blocks 17 and 18 were in Pair 1, Blocks 19 and 20 were in Pair 2, and Blocks 21 and 22 were in Pair 3), stimulus type for the block (old vs. new), and response (target present vs. target absent). The results are presented in Table 6. Old stimuli (710 ms) were responded to faster than new stimuli (825 ms), which again supports the contention that skills common to memory search and visual search are subject to item-specific learning. This effect was stronger in target-absent responses than in target-present responses. Stimulus type did not interact with stimulus order, nor was the interaction between those two and any other factor(s) significant. Thus, there was no evidence that the advantage for old stimuli over new stimuli was affected by which was encountered first in the transfer phase. All other main effects were significant. Target-present responses (682 ms) were faster than target-absent responses (853 ms); and responses in later pairs of blocks were faster than responses in early pairs of blocks (893, 732, and 676 ms in Block Pairs 1, 2, and 3, respectively). Pair can be thought of as reflecting learning during the transfer phase.

The significant interaction between pair and order thus appears to reflect greater learning when new stimuli were presented first than when old stimuli were presented first. The significant interaction between pair and stimulus type appears to reflect greater learning for new stimuli than for old stimuli. And finally, the significant interaction between pair and response appears to reflect greater learning for target-absent responses than for target-present responses.

Display-size effects for visual search are presented in Table 7. The effect of display size attenuated over blocks, both for old stimuli and new stimuli. It appears that old stimuli might be less affected by display size than new stimuli. An ANOVA with four within-subject factors, block pair, stimulus type, display size, and response type, was used to test the significance of that pattern. The results are presented in Table 8. Display size significantly influenced response times, and the attenuation over blocks was significant. However, no interactions involving display size and stimulus type were significant, so there is no basis for using these data to conclude that practice at identifying targets in memory search affected participants' ability to find those same targets amid distractors. Thus, common skills, whether

Table 7
Effect of Display Size (DS) on Response Times (in Milliseconds) in Experiment 4

	Target present				Target absent			
Block	DS 4	DS 5	DS 6	Slope	DS 4	DS 5	DS 6	Slope
				New stimuli				
1	832	885	877	27	1,008	1,078	1,238	115
2	666	688	698	16	815	859	959	72
3	602	609	656	27	767	753	861	47
				Old stimuli				
1	686	725	739	27	793	862	997	102
2	605	628	624	10	704	729	811	54
3	570	573	606	18	673	683	760	44

Table 8
Analysis of Variance of Display Size Effects for Visual Search in Experiment 4

Source	*df*	*MSE*	*F*
Display size (DS)	2, 30	8,947.3	47.9***
Pair of blocks (P)	2, 30	55,148.0	43.9***
Stimulus type (S)	1, 15	155,682.7	12.3**
Response (R)	1, 15	84,625.9	50.2***
DS × P	4, 60	4,402.7	5.8***
DS × S	2, 30	2,709.5	1.5
DS × R	2, 30	8,335.3	18.9***
P × S	2, 30	20,174.9	9.3**
P × R	2, 30	9,244.3	5.1*
S × R	1, 15	13,003.3	11.4**
DS × P × S	4, 60	4,320.4	<1
DS × P × R	4, 60	5,636.7	2.8*
DS × S × R	2, 30	5,009.2	<1
P × S × R	2, 30	4,627.0	<1
DS × P × S × R	4, 60	3,083.5	<1

*$p < .05$. **$p < .01$. ***$p < .001$.

item-specific or nonspecific training is given, do not contribute to attenuation of display size.

Error rates. We analyzed errors using an ANOVA with one between-subjects factor, order, and three within-subject factors, stimulus type, pair, and response. The results of that ANOVA are presented in Table 9, and mean error rates collapsed across orders are presented in Table 10. The most influential factor was response type: Far more errors were made on target-absent trials (7.0%) than on target-present trials (1.1%). This may reflect a bias to respond quickly before finding the target. Block pair and stimulus type also had significant effects, and the interactions among these three factors were all significant. Apparently, these effects are all due to the trends of more errors for new stimuli and fewer errors in later blocks. These trends are most evident in the target-present responses. Because both response times and errors are larger for new stimuli than for old, the effect of stimulus type on response time must not be due to a simple speed–accuracy tradeoff.

Table 9
Analysis of Variance of Visual Search Error Rates in Experiment 4

Source	*df*	*MSE*	*F*
Stimulus type (S)	1, 14	11.3	5.5*
Pair of blocks (P)	2, 28	11.1	6.6**
Response (R)	1, 14	12.6	132.3***
Order (O)	1, 14	22.0	1.3
S × P	2, 28	5.6	3.4*
S × R	1, 14	7.8	7.0*
S × O	1, 14	11.3	1.3
P × R	2, 28	8.6	8.3**
P × O	2, 28	11.1	<1
R × O	1, 14	12.6	<1
S × P × R	2, 28	6.3	4.5*
S × P × O	2, 28	5.6	<1
S × R × O	1, 14	7.8	<1
P × R × O	2, 28	8.6	<1
S × P × R × O	2, 28	6.3	<1

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 10
Mean Visual Search Error Rates (% of Trials) for Experiment 4

Block pair	Target absent	Target present
	Old stimuli	
1	7.1	1.4
2	5.5	0.9
3	5.2	1.1
	New stimuli	
1	11.3	1.1
2	8.5	1.2
3	4.7	1.3

Discussion

Item-specific transfer from memory search obtained. Thus, when visual search is decomposed into a component of skills shared with memory search and another component of private skills, training on the shared component is dependent, at least in part, on the items used during training.

General Discussion

Evidence of Separable Components of Visual Search

Practice on memory search did not completely train visual search for the same targets and distractors (Experiment 1) even if training was supplemented by practice on visual search that used different targets and distractors than were tested in transfer (Experiment 3). Practice on visual search did completely train memory search for the same targets and distractors (Experiment 1) unless participants received training on memory search for different targets while they were receiving item-specific visual search practice (Experiment 3). Except for the last result, these patterns are all consistent with the claim that visual search can be functionally decomposed into a component of skills shared with memory search and another component of private skills. The slight decrease in accuracy for memory search in Experiment 3 after item-specific training on visual search was small enough that we are skeptical that it represents a real threat to our claim. It may be merely the cost of switching from one stimulus–response set for memory search in training to another stimulus–response set for memory search in transfer (Allport, Styles, & Hsieh, 1994; Jersild, 1927).

The private component of visual search is, at least in part, an item-specific skill. Training on visual search for one set of targets did not transfer well to visual search for another set of targets, even when participants received item-specific memory search training concurrent with the nonspecific visual search training (Experiment 3). In Experiment 3, there appeared to be some benefit for visual search at the start of transfer compared with visual search at the start of training, but whether that was due to the nonspecific visual search training or the item-specific memory search training was not clear.

The private component of memory search also seems to be item specific, at least in part. When participants trained on memory search for a set of targets, transferring to visual search resulted in better performance when searching for the same set of targets than when searching for new ones (Experiment 4).

Generalization to Other Types of Visual Search

The version of visual search used in most of these experiments was what has often been called a hybrid visual search task, because participants were searching for any of a set of possible targets. This version of visual search was used because the relationship between it and a standard memory search task is relatively obvious: Both tasks require a set of potential targets to be remembered and used in the response decision. We would have predicted the same relationship between visual search for one target and a version of memory search that required participants to decide whether a single presented element was the same as a single remembered target. But such a simplified memory search task would have been so easy that we expected it might not produce measurable learning effects, so we opted for a more complex version of visual search.

In Experiment 2 we looked at transfer from visual search for single targets and memory search for multiple targets. In this case, we expected that memory search skills would not be a subset of visual search skills, because memory search required handling of multiple targets, whereas visual search required handling of single targets. Likewise, because visual search required element prioritization and memory search did not, we expected that visual search skills would not be a subset of memory search skills. As expected, training on visual search did not transfer well to memory search, and training on memory search did not transfer well to visual search.

Evidence That Prioritization Changes With Practice

Visual search can be functionally decomposed into two components, both of which are subject to learning. One involves skills used in memory search. We propose that these skills include element identification, response selection, and response production. Practice on this component ought to result in memory set unitization (Fisk et al., 1995; Flach, 1986; Whaley & Fisk, 1993) or faster identification because short-term memory is bypassed (Logan & Stadler, 1991). We also propose that the other component, comprising skills not shared with memory search, involves attentional prioritization. In all of our experiments, as in earlier research (e.g., Shiffrin & Schneider, 1977), the display-size effect became smaller as visual search was practiced. It has long been thought that training in visual search attenuates the display-size effect because it increases the differential between priorities assigned to targets and distractors (Czerwinski et al., 1992; Fisk et al., 1991; Graboi, 1971; Shiffrin & Schneider, 1977). In our experiments, display-size effects attenuated with practice on the private skills but not with practice on the common skills of visual search. Thus, our decomposition of visual search skills resulted in prioritization's being part of the private component of visual search.

Could the private component have other skills in it besides prioritization? Possibly. The visual search task presented stimuli away from the fovea, which implicates the involvement of eye movements, attentional shifts, and other means of dealing with nonfoveal stimuli in processing. The visual search task also requires identification of elements in the presence of distractors, implicating the involvement of selection during identification. To the degree that these skills can be learned, they are also part of the private component found by decomposing visual search learning.

Conclusions

Previous claims that practice at visual search changes the attentional prioritization of individual elements were supported. Three experiments showed that visual search can be functionally decomposed into element prioritization and identification processes. Both processes are subject to learning, and learning in both cases is to some degree item specific.

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