



Perceptual Learning in Visual Search: Some Evidence of Specificities

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To test a recent suggestion that perceptual learning in visual search is non-specific, two groups of subjects were trained on visual search tasks and tested for transfer of learning to new tasks. One group was trained on parallel ("pop-out") tasks and transferred to serial, conjunction tasks and the other group trained on conjunction and transferred to pop-out. Some (not all) tasks which are initially serial, rapidly became parallel. Some transfer occurred between the different types of tasks. Under some conditions transfer was either absent or even negative. The specificities observed may reflect the roles of the brain regions involved in learning. © 1998 Elsevier Science Ltd. All rights reserved.

Visual search Perceptual learning Parietal cortex Plasticity

INTRODUCTION

The adult visual system retains a surprising degree of plasticity evident in the ability of subjects to improve substantially and rapidly on a wide range of visual tasks (see Ahissar & Hochstein, 1996) and in the adaptive responses which occur following changes in viewing conditions (Kapadia, Gilbert, & Westheimer, 1994). Most studies of visual perceptual learning have used simple visual stimuli in discrimination tasks and, correspondingly, the learning observed has been stimulus specific: orientation discrimination learning does not transfer to orthogonal orientations (Fiorentini & Berardi, 1981; Mayer, 1983; Poggio, Fahle, & Edelman, 1992; Fahle & Edelman, 1993) and learning can also be specific to spatial frequency (Fiorentini & Berardi, 1981), direction of stimulus motion (Ball & Sekuler, 1987), retinal location (Karni & Sagi, 1991), the trained eye (Fahle, 1994) or to local or global stimulus attributes (Ahissar & Hochstein, 1993). The majority of these data can be accounted for in terms of the tuning properties of neurons at the level of V1 (e.g. Saarinen & Levi, 1995) but there is increasing evidence that higher-level, cognitive processes are involved in perceptual learning. These cognitive effects are not limited to complex tasks such as visual search (Sireteanu & Rettenbach, 1995; Epelboim *et al.*, 1995) or attentional processing (Ahissar & Hochstein, 1993; Ahissar & Hochstein, 1997) but have also been observed in relatively simple tasks such as

vernier and resolution acuity (Beard, Levi, & Reich, 1995) and the detection of form-from-motion (Vidyasagar & Stuart, 1993). To understand the degree of plasticity at different levels of the visual system and assess the contribution of so-called top-down and bottom-up processes in learning, it is important to know which components of a task account for the improved performance that continues to accompany practice over hundreds—or for the psychophysically hardened observer, thousands—of trials.

Visual search, in particular, may prove to be a useful tool for investigating interactions between different levels of hierarchical processing or between systems which are usually considered to be functionally segregated. For example, search demands the spatial and attentional skills usually associated with the dorsal occipito-parietal visual system and also the stimulus recognition and identification skills usually associated with the ventral, occipito-temporal visual system (Ungerleider & Mishkin, 1982; Goodale & Milner, 1992; Walsh & Butler, 1996). Patients with damage either to parietal visual areas, temporal cortex or regions of frontal cortex all show deficits on visual search tasks (Eglin, Robertson, & Knight, 1991) and differences between these groups of patients reveal some of the possible roles of the cortical visual areas in visual search. Lesions to the occipito-parietal cortex, for example, can produce deficits on serial, conjunction search but not on parallel, "pop-out" searches (Arguin, Joanette, & Cavanagh, 1993). Conversely, interruption of the occipito-temporal processing stream can impair performance on some parallel search tasks but not on serial, conjunction searches (Humphreys, Riddoch, Quinlan, Price, & Donnelly, 1992).

In a recent *Vision Research* paper, Sireteanu and

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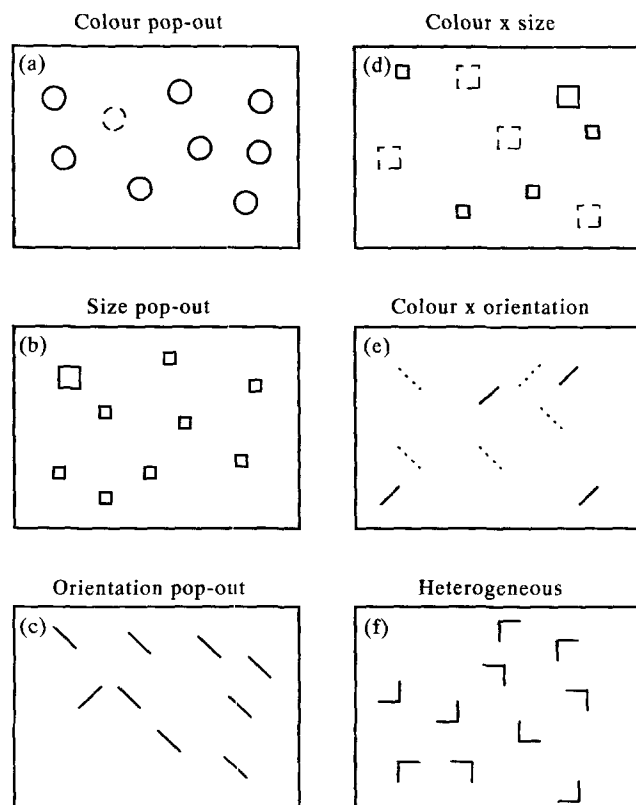


FIGURE 1. Examples of the arrays used to test visual search. (a), (b) And (c) represent targets that differed in only a fundamental feature from the distractors and were used in training subjects on pop-out tasks. (d) And (e) represent targets that differed from distractors in two attributes and (f) shows an array of heterogeneous distractors.

Rettenbach (1995) observed that perceptual learning in visual search was "fast, enduring but non-specific". Their data clearly demonstrated the first two of these claims—subjects improved rapidly over a single block of 56 trials (Figs 3 and 4 of Sireteanu & Rettenbach, 1995), and improvements were evident at intervals of up to 4.5 months. Using an extensive range of stimulus parameters and conditions, a different conclusion was reached by Ahissar and Hochstein (1993, 1997), who found that for a single, orientation pop-out task learning was stimulus specific and that learning did not transfer to elements of the same orientation but of smaller size. They also observed evidence of task specific learning (see discussion). Treisman (Treisman, 1992; Treisman, Vieira, & Hayes, 1992) has also suggested that perceptual learning in visual search may depend on "new and very specific associations between features, their locations, and the required responses" (Treisman *et al.*, 1992 p. 360).

There are two extreme possibilities, then: it remains possible that perceptual learning is truly non-specific, but it remains equally possible that learning occurs independently for each task. Between these poles lies the intermediate possibility that some transfer of learning did occur in the Sireteanu and Rettenbach experiment but that it was specific either to stimulus parameters or task demands. Given the richness of the mechanisms involved

in search (see, for example, Cheal & Lyon, 1992; Wolfe, 1994) and the known differences between spatial localization target detection and identification processes (Atkinson & Braddick, 1989; Saarinen, 1996) one might expect patterns of learning to reflect them.

One aspect of the Sireteanu and Rettenbach experiment which invites particular attention is that of their four display types three yielded serial search response patterns and one a parallel search pattern when subjects were exposed to them on the first day of training. One implication of this is that learning is non-specific for the different task demands imposed by parallel and serial search. This seems unlikely for two reasons. First, serial search is so presumably because it involves some extra element of processing not required to perform parallel search (Cheal & Lyon, 1992). It would be surprising if this extra processing requirement were not reflected in transfer of learning. Further, it is not clear that serial/parallel is the only dimension of interest, since the shape of the search function can be influenced by the uniqueness or conjunction of features (Treisman, 1985; Treisman & Gormican, 1988; Treisman & Souther, 1985), the presence/absence of targets (see Cheal & Lyon, 1992), the homo/heterogeneity of distractors (Duncan & Humphreys, 1989), the similarity of targets and distractors (Duncan & Humphreys, 1989) and even the extent to which the observer is familiar/unfamiliar with the stimuli being used (Wang, Cavanagh, & Green, 1994). Second, given the recent work on perceptual learning of low-level tasks which have demonstrated specificity of learning for retinotopic location (Karni & Sagi, 1991), trained eye (Fahle, 1994), orientation and a range of other factors, perhaps one should expect a responsive and plastic visual system to retain some specificity, even at higher level of perceptual processing—specificity perhaps for different components of complex tasks. It seemed to us that a task which contained the hallmarks of visuo-temporal, visuo-parietal and prefrontal cortex processing (shape identification, spatial analysis and decision making, respectively) would be subject to the differences in learning between these three regions. Atkinson and Braddick (1989) have shown the relative importance of spatial and object elements in search and their discussion anticipates some of the arguments developed in this paper. There is also good evidence from primate lesion studies that lesions to the posterior parietal cortex (Ockleford, Milner, Dewar, & Sneddon, 1977) or the inferotemporal cortex (Gross, Cowey, & Manning, 1971) have different effects on the transfer of perceptual learning.

To begin a programme of assessing the components of learning in visual search, we elected to investigate the specificity of perceptual learning by testing transfer of learning from tasks which produce parallel search functions to conjunction tasks, some of which produce serial search functions and vice versa. We report perceptual learning specific to stimulus elements, different demands between tasks and different demands made within tasks.

METHODS

Subjects

Six undergraduate subjects volunteered for the experiment. All were right-handed and had normal or corrected-to-normal vision. None of the subjects, with the exception of author A.E., was aware of the purpose of the experiment, nor had any of them any previous experience with visual search tasks.

Stimuli

Figure 1 shows examples of the different search arrays used. Stimuli were generated on a colour monitor which subtended 11.7×8.4 deg of visual angle and was divided into a virtual 8×6 array of 1.49×1.4 deg boxes. Stimulus sizes were as follows.

1. Colour pop-out [Fig. 1(a)]: The stimuli were open circles 0.9 deg in diameter with a line thickness of 0.09 deg. Red circles were targets and green circles were distractors.
2. Size pop-out [Fig. 1(b)]: The stimuli were open squares of side 0.9 deg (large) and 0.34 deg (small). The target was a large white square.
3. Orientation pop-out [Fig. 1(c)]: The stimuli were 0.93 deg long and 0.13 deg thick.
4. Size/colour conjunction [Fig. 1(d)]: The squares were of the same sizes used in the size pop-out task. The target was a large blue square and the distractors were small blue squares and large white squares.
5. Colour/orientation conjunction [Fig. 1(e)]: Dimensions were as for the orientation pop-out. A red slash was the target and green slashes and red backslashes the distractors.
6. Heterogeneous and homogeneous displays [Fig. 1(f)]: The stimuli were made up of line elements 0.42 deg long and 0.09 deg thick. In the heterogeneous condition the target was one of the L shapes against distractors of all three types shown in the figure. In the homogeneous condition (not shown) the target was one of the L shapes but against a background of distractors of only one of the three types shown in Fig. 1(f).

In all the displays the stimuli could be jittered within the full extent of the 1.49×1.4 deg boxes.

On 50% of trials the target to be detected was present and on 50% of trials it was absent. Five distractor set sizes were used and set size was randomized from trial to trial; the numbers of distractors used were 2, 4, 8, 16 and 32 on target present trials, on absent trials an extra distractor replaced the target to equate set sizes. On each trial the target (if present) and distractors appeared randomly in the 48 possible positions of the 8×6 array.

Pop-out training

Three of the stimulus arrays [Fig. 1(a, b, c)] were used for pop-out training. Pop-out trainees were presented with the colour pop-out, size pop-out and orientation pop-out arrays.

Conjunction training

Three arrays [Fig. 1(d, e, f)] were used for conjunction training. Conjunction trainees were presented with a colour/size conjunction task, a colour/orientation conjunction task and a heterogeneous distractors task which required the detection of a particular form conjunction in an array of conjunctions made from the same elements (Duncan & Humphreys, 1989).

Procedure

Subjects were seated 135 cm from the monitor and given a computer mouse with which to make their responses. All responses were made with the dominant hand and the mouse was placed such that responses were top (stimulus present) and bottom (stimulus absent). At the beginning of each trial subjects were presented with an alerting tone and a central fixation spot for 500 msec. This was followed by presentation of the search array, which remained on the screen until the subject responded. Speed and accuracy of the response were stressed and no feedback was given. In a single session the subjects were presented with six blocks of 150 trials. Each of their three training tasks was presented for two blocks per session and the order of presentation of the blocks was randomized. Thus, at the end of their 8 days of training each subject had been presented with 7200 trials made up of 2400 trials of each of their three training tasks.

Strategy

Subjects were divided into two groups. Three subjects were trained on the three pop-out tasks [Fig. 1(a–c)] and transferred to the three conjunction tasks [Fig. 1(d–f)] and also to the homogeneous distractors task. Three subjects were trained on the three conjunction tasks [Fig. 1(d–f)] and transferred to the three pop-out tasks and the homogeneous distractors task. Subjects carried out their training task for 8 consecutive days and were then transferred to the transfer tasks for 2 days. The homogeneous distractors task was chosen as another example of a parallel search task (Duncan & Humphreys, 1989).

Transfer testing

At the end of 8 days of training, subjects carried out transfer tasks for 2 days. The pop-out trainees were given the same tasks as the conjunction trainees plus the homogeneous distractors task and the conjunction trainees were given the three pop-out tasks plus the homogeneous distractors task. Trials were given in eight blocks of 125, and each of the four tasks was presented for two out of the eight blocks. The order of presentation was randomized.

RESULTS

Figures 2–5 show the mean performance levels (± 1 SE) of subjects on the first two and last two days of training and the two days of transfer. Reaction times for present responses are shown in Figs 2 and 3. Graphs on

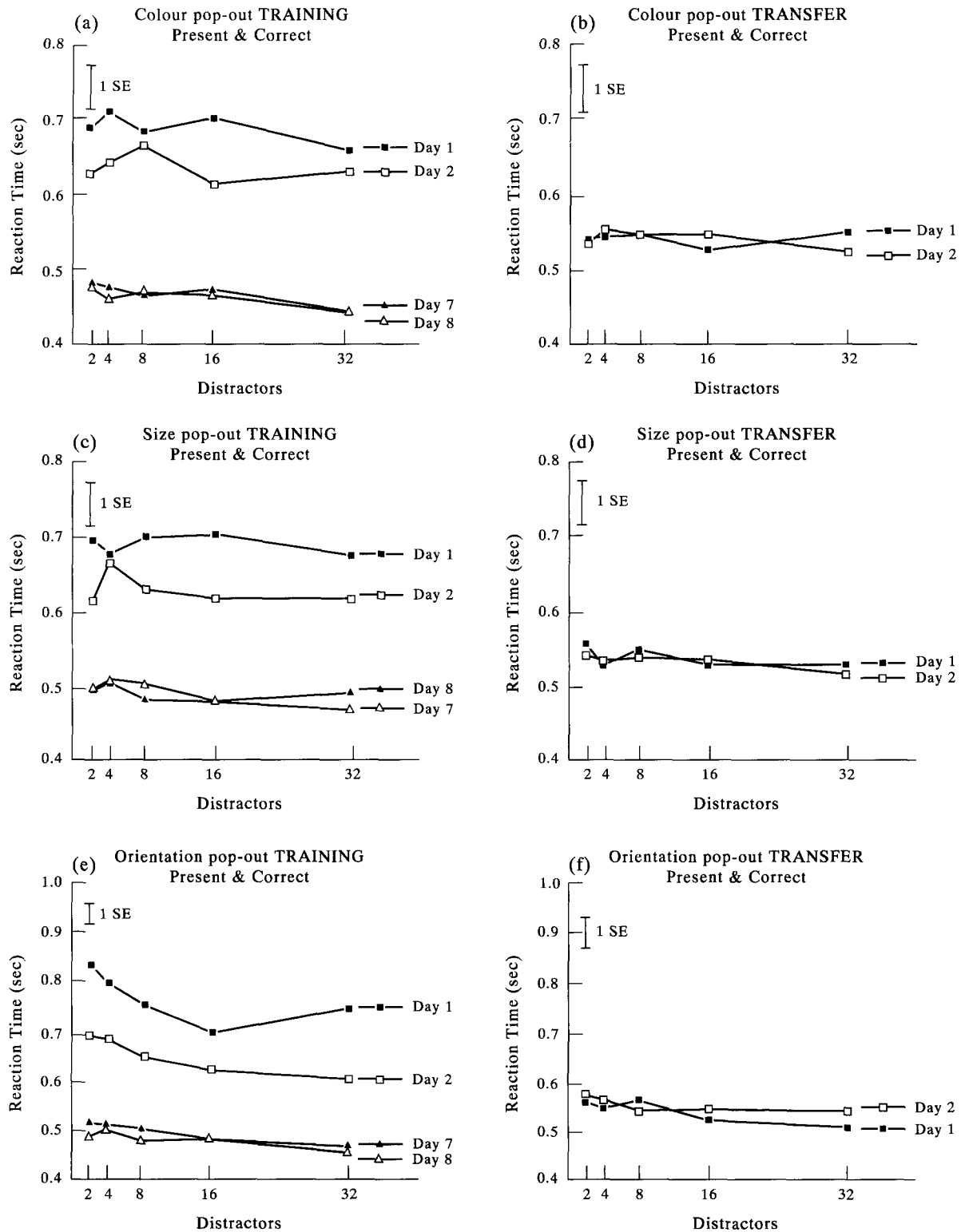


FIGURE 2. The left-hand column (a, c, e) shows the performance of the pop-out trainees on the first two and last two days of training. The right-hand column (b, d, f) shows the performance of the conjunction trainees when they transferred to the pop-out tasks. Note the large transfer of learning from conjunction to pop-out. Data shown are for present and correct responses.

the left of Fig. 2 (a, c, e) show the performance of pop-out trainees and graphs on the right side (b, d, f) show the performance of the conjunction trainees on the two days of transfer to the pop-out tasks. Graphs on the left of Fig. 3 (a, c, e) show the performance of conjunction trainees and graphs on the right side (b, d, f) show the

performance of the pop-out trainees on the two days of transfer to the three conjunction tasks.

Figures 4 and 5 show the data for absent responses corresponding to the data in Figs 2 and 3, respectively. Tables 1–3 shows the slopes of the search functions, before and after training, including transfer to the

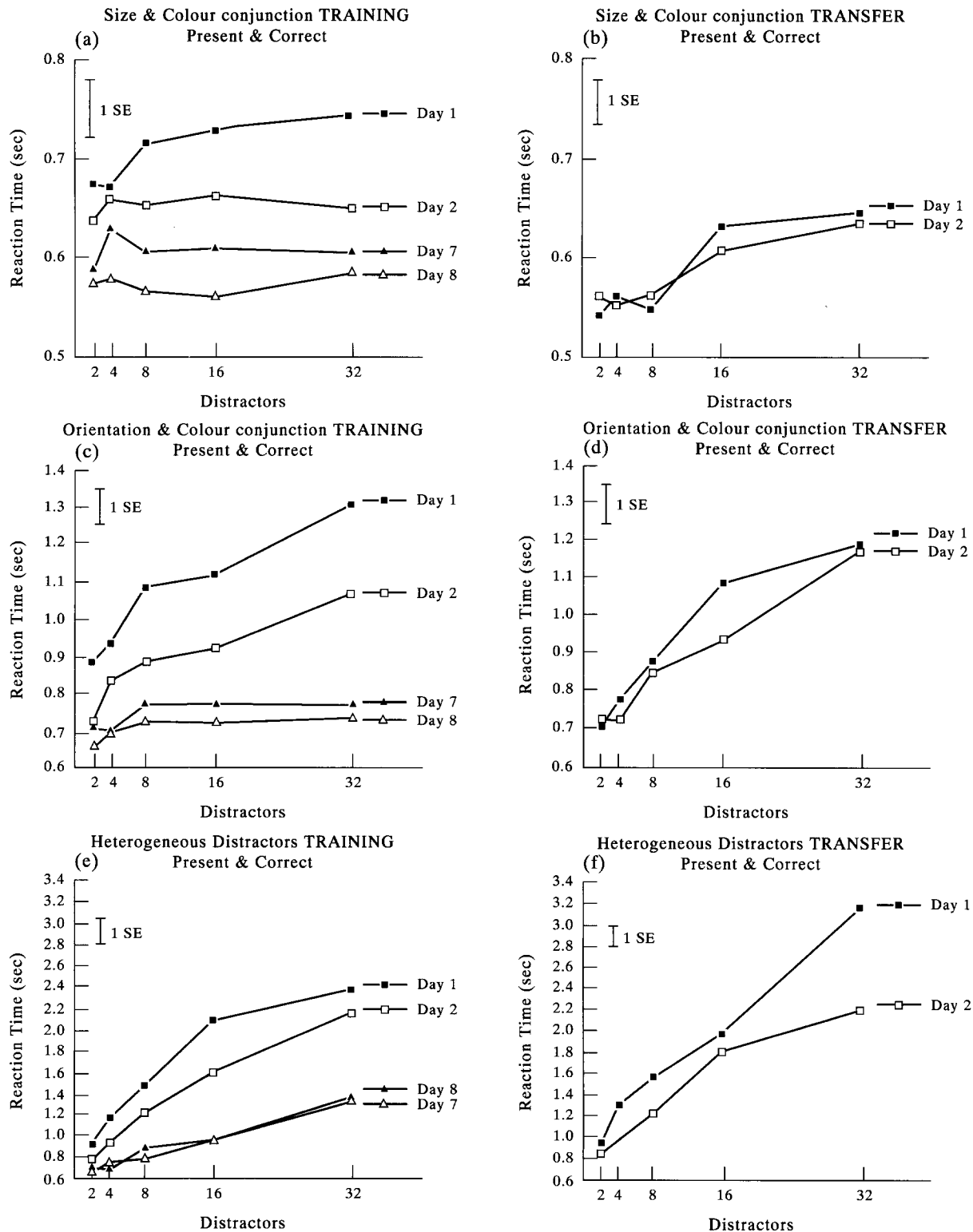


FIGURE 3. The left-hand column (a, c, e) shows the performance of the conjunction trainees on the first two and last two days of training. The right-hand column (b, d, f) shows the performance of pop-out trainees when they transferred to the conjunction tasks. Data shown are for present and correct responses.

homogeneous distractors task. Tables 4–6 summarize the improvements in the intercepts over training and transfer days. Pearson's r was calculated to assess the overall effects of training on slopes and intercepts, and comparisons between training and transfer were evaluated using Mann Whitney U.

Training

During training, all subjects showed improvements on all of the search tasks. Learning persisted throughout most of the training regime. The biggest gains were seen over the first three days of training and most subjects reached asymptotic levels of performance after 7 days.

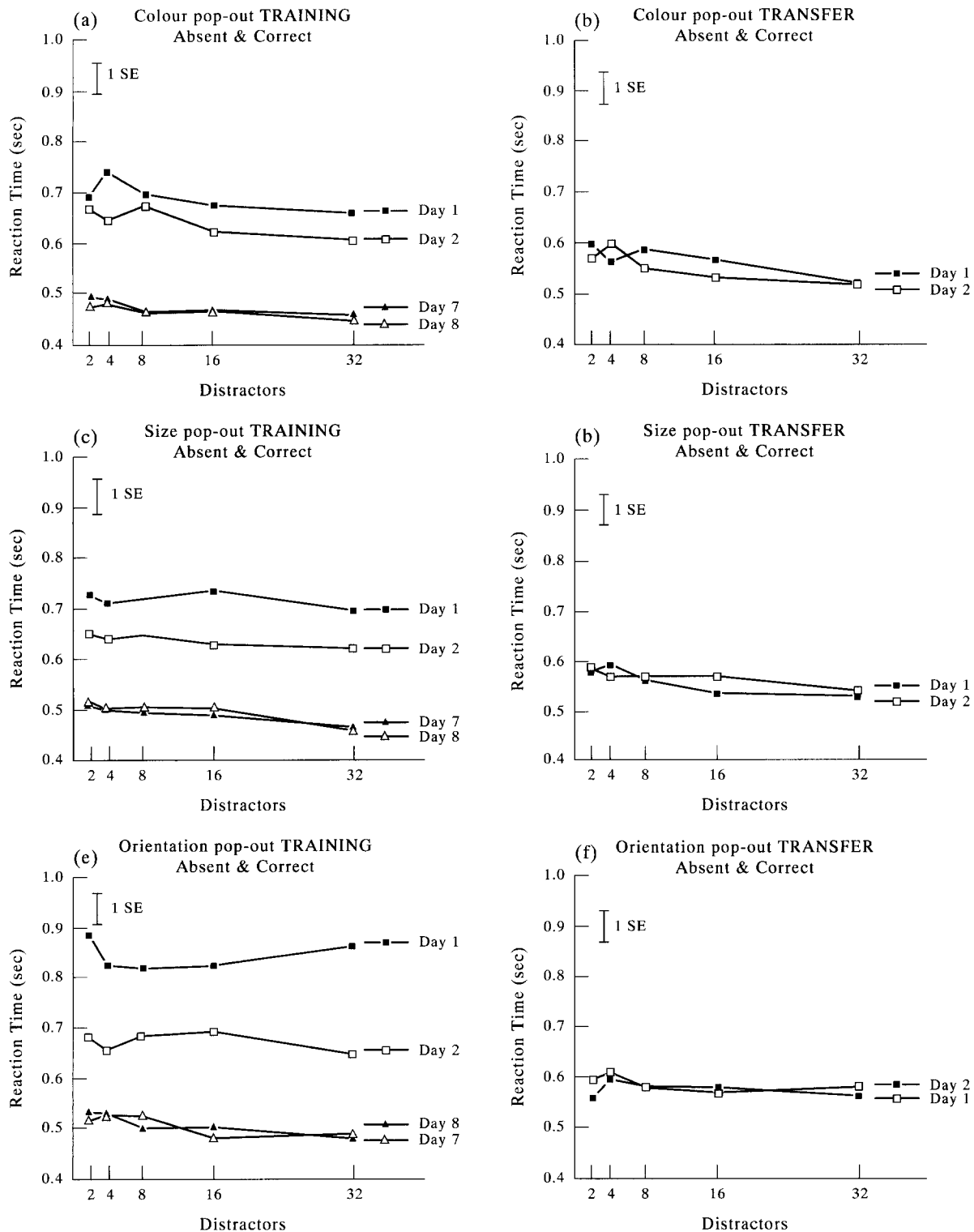


FIGURE 4. The left-hand column (a, c, e) shows the performance of the pop-out trainees on the first two and last two days of training. The right-hand column (b, d, f) shows the performance of the conjunction trainees when they transferred to the pop-out tasks. Note the large (but not total) transfer of learning from conjunction to pop-out. Data shown are for absent and correct responses.

For the pop-out trainees the patterns of learning were broadly similar for both target present and target absent conditions [Fig. 2(a, c, e) and Fig. 4(a, c, e)]. Intercepts improved significantly with training in all six conditions (colour: present $P < 0.01$, absent $P < 0.05$; size: present

$P < 0.01$, absent $P < 0.01$; orientation: present $P < 0.01$, absent $P < 0.05$). Significant changes in the slope of the search function were seen in the orientation pop-out task both for target present trials ($P < 0.05$) and target absent trials ($P < 0.01$), although of course qualitatively perfor-

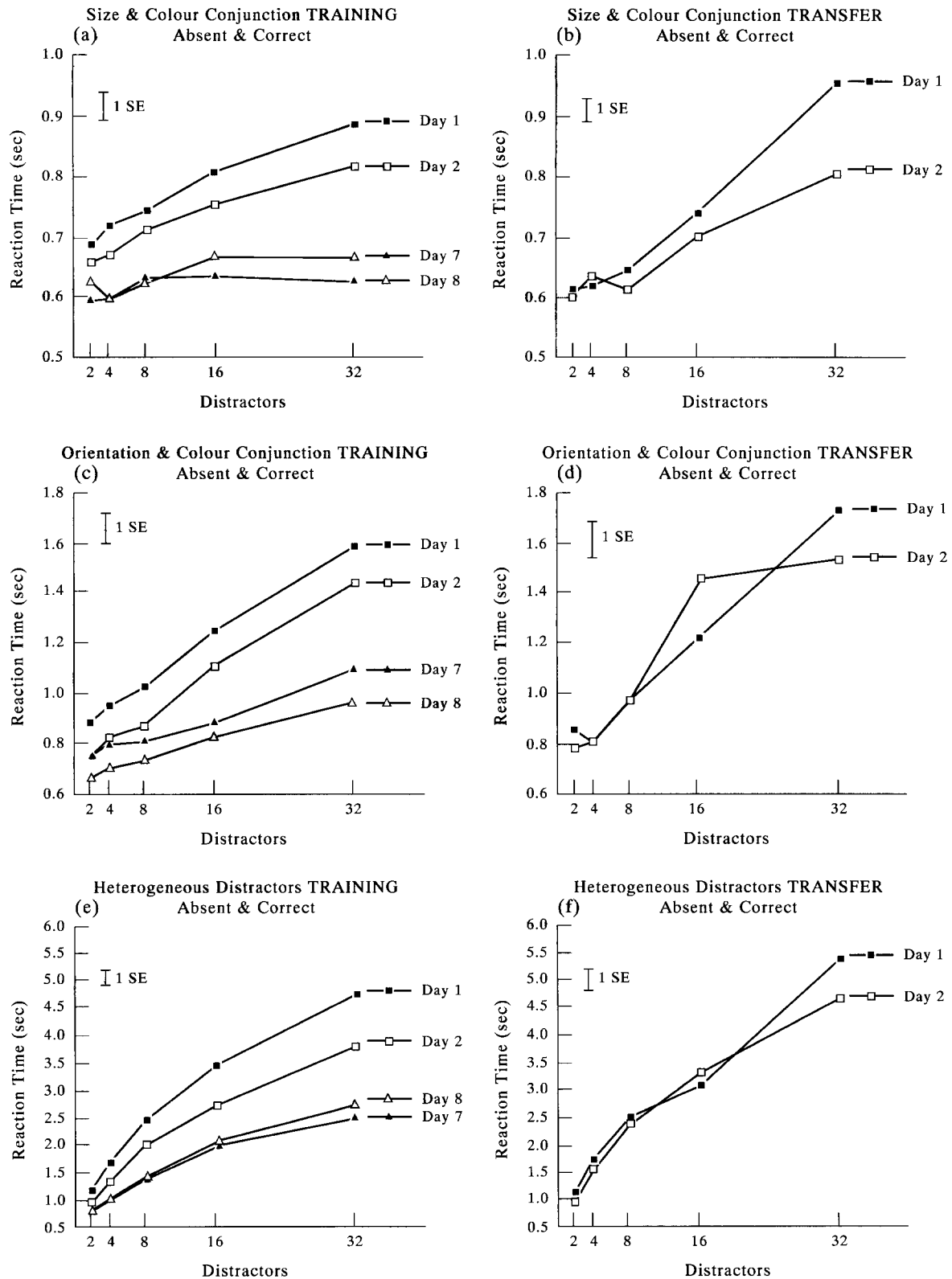


FIGURE 5. The left-hand column (a, c, e) shows the performance of the conjunction trainees on the first two and last two days of training. The right-hand column (b, d, f) shows the performance of pop-out trainees when they transferred to the conjunction tasks. Data shown are for absent and correct responses.

mance was always parallel. There were no other significant training effects on pop-out.

Conjunction training produced significant effects on the RT X Distractor slopes of the six training conditions (size/colour: present $P > 0.05$, absent $P < 0.05$; orienta-

tion/colour: present $P < 0.001$, absent $P < 0.001$; heterogeneous: present $P < 0.01$, absent $P < 0.01$). The size/colour conjunction was the exception here because it was performed as a parallel task from day 1 of training [see Table 1 and Fig. 3(a)]. All the intercepts improved

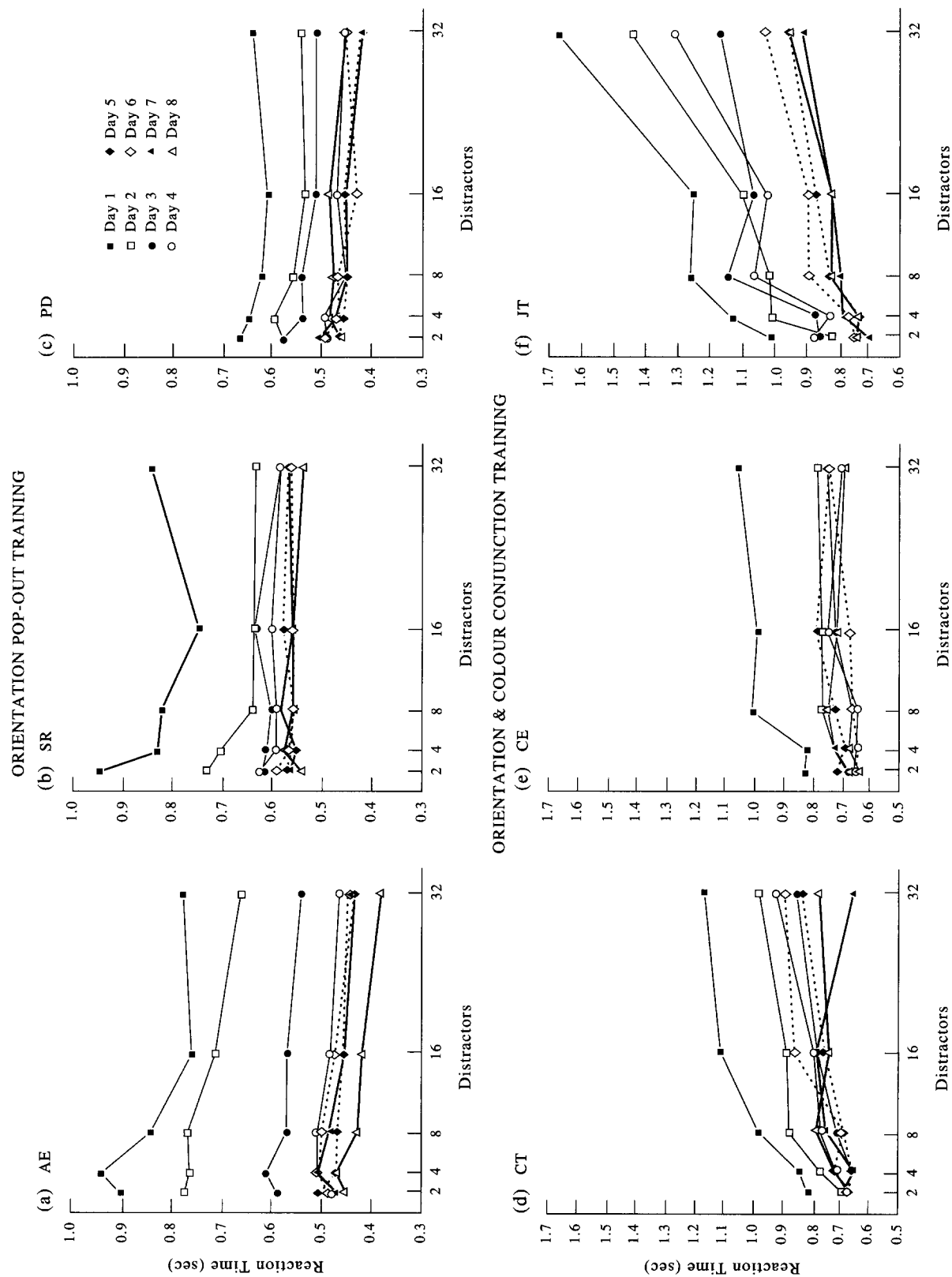


FIGURE 6. Examples of individual variability in reaction times (sec) in learning for present and correct responses. (a), (b), (c) Show learning of three subjects on pop-out training. (d), (e) And (f) show learning of three subjects on conjunction training.

TABLE 1. Training and transfer slopes for all days for colour, size and orientation pop-out tasks; present and absent responses

Day	Pop-out training slopes (msec per item)					
	Colour		Size		Orientation	
	Present	Absent	Present	Absent	Present	Absent
1	-1.1	-2.2	-0.4	-0.8	-2.6	0.1
2	-0.5	-2.2	-0.7	-1.0	-2.9	-0.8
3	-0.8	-1.3	-0.2	-1.1	-1.6	-1.5
4	-0.6	-1.3	-0.3	-1.2	-1.3	-1.5
5	-0.6	-0.9	-1.2	-2.1	-1.1	-1.8
6	-0.9	-1.7	-0.4	-0.6	-1.4	-1.5
7	-1.0	-1.2	-0.9	-1.5	-1.5	-1.7
8	-0.9	-1.2	-0.5	-1.8	-1.2	-1.4
Day	Pop-out transfer slopes (msec per item)					
	Colour		Size		Orientation	
	Present	Absent	Present	Absent	Present	Absent
1	0.1	-2.3	-0.8	-1.3	-2.0	-0.6
2	-0.7	-2.4	-1.0	-2.0	-1.1	-0.9

TABLE 2. Training and transfer slopes for all days for colour \times size, orientation \times colour and the heterogeneous distractors; present and absent responses

Day	Conjunction training slopes (msec per item)				Heterogeneous distrs	
	Size & colour		Orientation & colour		Present	Absent
	Present	Absent	Present	Absent	Present	Absent
1	2.2	6.5	12.7	23.5	47.0	115.5
2	0.1	5.3	9.4	23.4	44.0	93.1
3	0.7	4.1	6.6	21.2	42.2	93.6
4	0.1	2.7	5.6	16.3	26.3	82.6
5	-0.5	1.3	5.0	17.1	17.1	64.8
6	-0.4	0.9	5.5	17.4	18.9	61.5
7	-0.1	1.0	1.8	15.0	20.0	58.8
8	0.1	2.0	2.6	10.2	21.0	66.6
Day	Conjunction transfer slopes (msec per item)				Heterogeneous distrs	
	Size & colour		Orientation & colour		Present	Absent
	Present	Absent	Present	Absent	Present	Absent
1	3.6	11.8	15.7	30.9	68.0	135.0
2	2.7	6.8	14.9	27.2	45.0	120.0

TABLE 3. Transfer slopes of pop-out and conjunction trainees to the homogeneous distractors task

Day	Homogeneous distractors transfer			
	Conjunction trained		Pop-out trained	
	Present	Absent	Present	Absent
1	6.4	25.8	24.0	33.0
2	5.8	15.5	14.0	16

significantly over the eight days of training (size/colour: present $P < 0.01$, absent $P < 0.001$; orientation/colour: present $P < 0.05$, absent $P < 0.05$; heterogeneous: present $P < 0.05$, absent $P < 0.05$).

For absent responses on the size and colour conjunction task [Fig. 5(a)] search was serial for the first two days before becoming parallel (defined as a slope of less than 10 msec per item), whereas it was parallel from day 1 for present responses [Fig. 3(a)]. Similarly, orientation/colour conjunction search and the heterogeneous distractors condition both began as serial searches and the slopes became parallel [Fig. 3(c)] or very shallow [Fig. 3(e)] for the present responses but not for the absent

responses [Fig. 5(c, e)]. In other words, despite learning over 8 days and 7200 trials, absent responses still elicited serial search.

Transfer

Present responses. Overall, for present responses, there was a high level of transfer from conjunction to pop-out, but limited or even negative transfer from pop-out to conjunction.

Transfer from conjunction to pop-out equalled about 80% of the total learning acquired by the pop-out trainees [Fig. 2(b, d, f)] ($P < 0.01$).

Subjects trained on the pop-out tasks did show some

TABLE 4. Training and transfer intercepts for all days of training and transfer for colour, size and orientation pop-out tasks; present and absent responses

Day	Pop-out training intercepts					
	Colour		Size		Orientation	
	Present	Absent	Present	Absent	Present	Absent
1	701	730	695	730	803	842
2	642	683	638	683	690	683
3	562	581	556	596	588	602
4	499	491	513	518	536	530
5	481	498	512	531	516	533
6	494	518	513	517	519	542
7	481	530	499	511	515	530
8	473	524	503	524	498	524

Day	Pop-out training intercepts					
	Colour		Size		Orientation	
	Present	Absent	Present	Absent	Present	Absent
1	539	595	548	582	563	581
2	548	581	544	585	567	598

TABLE 5. Training and transfer intercepts for all days of training and transfer for colour \times size, orientation \times colour and the heterogeneous distractors; present and absent responses

Day	Conjunction training intercepts					
	Size & colour		Orientation & colour		Heterogeneous distrs	
	Present	Absent	Present	Absent	Present	Absent
1	678	689	902	847	1000	1520
2	650	657	766	707	779	1010
3	619	646	740	737	730	930
4	628	648	688	666	685	803
5	631	650	712	704	755	829
6	606	633	674	637	675	729
7	607	622	719	725	643	816
8	570	604	662	653	658	776

Day	Conjunction transfer intercepts					
	Size & colour		Orientation & colour		Heterogeneous distrs	
	Present	Absent	Present	Absent	Present	Absent
1	540	569	726	737	922	1124
2	550	588	680	776	837	1104

TABLE 6. (c) Transfer intercepts of pop-out and conjunction trainees to the homogeneous distractors task

Day	Homogeneous distractors transfer intercepts			
	Conjunction trained		Pop-out trained	
	Present	Absent	Present	Absent
1	687	759	717	912
2	622	729	672	833

transfer of learning to the colour/size conjunction task [Fig. 3(b)] which was initially performed as a parallel search by the conjunction trainees. On the transfer from pop-out to orientation/colour conjunctions the pop-out trainees performed as well as the conjunction trainees when there were only two distractors, but showed no evidence of transfer when there were more distractors, the overall curve being steeper than for the first day of learning of the conjunction trainees [Fig. 3(c, d)]. Pop-out trainees also showed negative transfer to the heterogeneous display and performed worse than the conjunction trainees on the homogeneous display to which both groups transferred (Table 1).

Absent responses. Transfer data for absent responses showed a positive transfer from conjunction to pop-out tasks which was equal to the extent of transfer on the present trials [Fig. 4(b, d, f)] ($P < 0.01$). The one exception here was the transfer to homogeneous, absent trials (Table 1), where the conjunction trainees' performance was equal to that of the pop-out trainees on present trials but was not quite as flat as their own performance on absent trials.

The pop-out trainees showed negative transfer to the conjunction tasks on absent trials [Fig. 5(a, c, e) and Table 1]. The greatest differences were on the transfer to homogeneous distractors and on the transfer to size/

colour conjunctions, on which the pop-out trainees showed good transfer on the present trials but not the absent trials on day 1. An effect of number of distractors is also seen in the absent responses [Fig. 5(b, d, f)], where the pop-out trainees appear to benefit when they transfer to trials with only two distractors. However, the slopes increase very rapidly (see Table 1).

Individual differences in learning and transfer

Figure 6 gives examples of the individual variability in learning and transfer. There were considerable differences between the subjects' baseline performances but learning appears to proceed in proportion with each subject's initial performance. On transfer, again performance is proportional to baseline. Full plots of all individual data are available from the authors.

DISCUSSION

The basis for this study was the claim that perceptual learning in visual search is non-specific for stimulus or task requirements (Sireteanu & Rettenbach, 1995). Our results clearly demonstrate this not to be the case and to that extent are in line with the suggestions of Treisman (1992) and Ahissar & Hochstein (1993) that perceptual learning can be specific for stimulus or task related elements of search.

Speed of learning

Sireteanu and Rettenbach demonstrated fast perceptual learning with feature arrays. Our data confirm this with feature arrays and extend it to conjunction arrays. However, some asymmetry can be observed even in the first two days of training. Over the first two days of training on the pop-out trials, absent responses improved more quickly than present responses [Fig. 2(a, c, e) and Fig. 4(a, c, e)], a feature which is reversed for the conjunction trainees [Fig. 3(a, c, e) and Fig. 5(a, c, e)], perhaps suggesting some differences in learning even at this early stage.

Learning to perform serial search as parallel

In agreement with other reports (e.g. Steinman, 1987; Sireteanu & Rettenbach, 1995) subjects' performances on initially serial tasks became parallel for present responses. However, this effect of practice did not extend to absent responses. This indicates that learning can be task specific when identical stimuli are used in two tasks (the tasks here being detection of a target for the present responses and the decision to terminate the search in the absent responses). This is a new demonstration of task specificity in visual search which shows that learning can be specific within a given task. Our result lends support to Treisman's and Ahissar and Hochstein's claims that perceptual learning can be task specific. However, Ahissar and Hochstein's experiment consisted of only two stimulus arrays and the task requirements were very different. In one task subjects had to attend to the individual elements of an array and report a target detection, and in the other task they had to ignore the

local elements and report a shape identification. The task thus differed in both attentional and response demands and it is not clear which dominated the learning process. Further, Ahissar and Hochstein state that "no substantial improvement was found for attributes that were not attentively processed" (p. 5718), but their Fig. 3(a) shows approximately 60% transfer from local to global discrimination tasks. This issue remains to be resolved.

Transfer of learning from pop-out to conjunction

The pop-out trainees showed complete transfer to only one of the conjunction arrays [size/colour, Fig. 3(b)]. It is notable that this conjunction task was performed as a parallel task from day 1 of training by the conjunction trainees. The question therefore arises of whether this transfer from pop-out to conjunction search is task or stimulus related. Experience with the stimuli may have aided transfer in this case. However, the positive stimulus in the conjunction task had not been presented to the pop-out trainees during training and the stimulus they had seen before (the large white square) was a target during training and a distractor during transfer. It does appear more likely than the alternative explanation of task (i.e. pop-out) specific transfer, however, because the pop-out trainees did not transfer learning to the homogeneous distractors task (Table 1), which can elicit parallel search from normal observers (Duncan & Humphreys, 1989) and also elicited parallel search from the conjunction trainees. One possible explanation is that the pop-out trainees learned about stimulus specificity. For example, the pop-out trainees trained on square stimuli in the size pop-out. The stimuli in the homogeneous distractors task therefore may have exacted a cost from the pop-out trainees because both the target and distractor elements of the homogeneous distractors task were components of a more complex stimulus that had previously been seen in the size pop-out. This could necessitate a strategy shift (to serial checking of the stimuli) to compensate for the confusion among the stimuli. A similar finding has been reported by Treisman (1992), who argues that "the benefits of extended practice appear to depend on very specific memory traces of the patterns in the context of the particular practiced task. Little or no generalized perceptual learning independent of the search task seems to take place..." (pp. 868–869).

Transfer of learning from conjunction to pop-out

We observed a high level of transfer from conjunction training to pop-out tasks for all stimuli and set sizes [Fig. 3(b, d, f)]. The transfer rate was around 80% of the total gains of the pop-out training [Fig. 2(a, c, e)]. From the asymmetry of transfer between pop-out to serial and serial to pop-out we infer that the mechanisms important for serial search contain all the elements of processing necessary for preattentive, pop-out search. This again agrees with Ahissar and Hochstein, who observed greater transfer from a task which required attention to and identification of the shape of an array (which they termed "global") to an orientation pop-out task (which they

termed "local") than vice versa. In terms of the debate addressed in this paper, this is another example of specificity of learning in visual search.

Individual differences

Previous studies of perceptual learning have emphasized individual differences in the course and extent of learning (Beard *et al.*, 1995; Fahle & Edelman, 1993; Fahle & Henke-Fahle, 1996; McKee & Westheimer, 1978; Saarinen & Levi, 1995). We too observed differences between individuals (Fig. 6). However, in agreement with the other studies, the trends of learning and transfer were similar across individuals.

Which brain regions mediate learning?

It is too soon to speculate on the roles of inferotemporal and frontal cortices in perceptual learning. However, a little more can be said with confidence about the parietal cortex.

The role of the parietal cortex in visual search seems to be to contribute to the spatial elements of the task which are often required for detecting targets in conjunction, but not feature arrays (Treisman, 1996). In support of this claim, a recent Transcranial Magnetic Stimulation (TMS) study showed that TMS over parietal cortex significantly impaired reaction times in a serial conjunction search but had no effect on the completion of a parallel, feature search (Ashbridge, Walsh, & Cowey, 1997). Subsequently we have demonstrated that TMS over the parietal cortex is only effective in disrupting novel, serial search and that training removes the effect of TMS. Further, the interaction between TMS and learning is stimulus specific (Walsh, Ashbridge, & Cowey, in press).

SUMMARY

The most important findings of this study are that:

1. Learning in visual search is specific.
2. There is substantial transfer from serial to pop-out searches but only limited transfer from pop-out to serial.
3. Learning and transfer is different for present and absent responses.
4. The differences between stimulus specificity and serial/parallel learning are consistent with the differences between the consequences of damage to temporal and parietal cortices, respectively.

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