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Perceptual learning of highly demanding visual search tasks

Ute Leonards [a,b], Regina Rettenbach [a], Gabriele Nase [a], Ruxandra Sireteanu [a,c,*]

[a] *Department of Neurophysiology, Max-Planck-Institute for Brain Research, Deutschordenstrasse 46, 60528 Frankfurt, Germany*
[b] *Neuroimaging Unit, Department of Psychiatry, University Hospital Geneva—Belle-Idée, Chemin du Petit-Bel-Air 2, 1225 Chêne-Bourg, Switzerland*
[c] *Department of Physiological Psychology/Biopsychology, Johann Wolfgang von Goethe University, Merton-Strasse 17, 60054 Frankfurt, Germany*

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Abstract

Inefficient visual search can become efficient with practice [Vision Research 35 (1995) 2037; 40 (2000) 2925]. In this study, we wondered whether this improvement depends on unique visual features associated with the target, on differences in item-specific brightness distribution between target and distractors, or only on a change in the allocation of attention and thus global search strategy. We found that both, unique visual features and differences in brightness distribution lead to parallelisation with practice of originally inefficient search. Prolonged practice of inefficient search tasks lacking both unique visual features and differences in brightness distribution (conjunctions) does not lead to improved performance, thus indicating that perceptual learning in visual search does not solely reflect an unspecific global improvement in search strategy. Changing the brightness polarity of the stimuli leads to instantaneous, complete transfer to the new task. There is no transfer but rather trade-off between the learning based on unique visual features or on differences in brightness distribution between target and distractors.

Keywords: Visual search; Perceptual learning; Visual feature; Local brightness distribution; Conjunctions

1. Introduction

In a visual search task, subjects look for a target item among a number of distracting items. If the time needed to complete the search is roughly independent of the number of distractors, with a processing time of <10 ms/item, the search is said to be efficient; if the search time increases linearly with the number of distractors, the search is said to be inefficient. The search time can vary dramatically according to which items play the role of targets or distractors. While, for example, a circle with a gap is easily found among a number of circles without gap, the search time increases with the number of distractors, if the circle without gap serves as target among circles with a gap as distractors (cf. Treisman & Gelade, 1980; Treisman & Souther, 1985).

Targets for which a search is efficient in subjects naïve to visual search experiments are considered to be elementary features of visual perception. Examples of features isolated by visual search are size, brightness or contrast, line orientation, colour, motion, etc. Search for targets containing features is thought to involve no or only few attentional resources. It was called pre-attentive in early publications on visual search (e.g. Treisman & Gelade, 1980; but see Joseph, Chun, & Nakayama, 1997). Targets for which a search is inefficient are thought to involve attentional resources (e.g. Bravo & Nakayama, 1992; Treisman & Gelade, 1980; Wolfe, 1998). One of the classical attention-demanding search tasks is conjunction search, in which the target cannot be distinguished from the distractors by visual features like shape, colour or orientation, but by a combination of features.

Theories focussing on mechanisms underlying visual search agree that a parallel processing mechanism underlies efficient search. For inefficient search, however, theories can be broadly divided into two big classes. First, so-called "serial" theories are based on the idea that, due to limited processing capacities, one part of a scene has to be processed after the other, serially. Such serial processing is accomplished by shifting attention like a "spotlight" from one item or group of items to the next (e.g. feature integration theory; Treisman & Gelade, 1980; guided search model; Wolfe, 1998; Wolfe, Cave, & Franzel, 1989). Second, so-called "parallel"

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[*] Corresponding author. Fax: +49-69-9676-9327/9433.
E-mail address: sireteanu@mpih-frankfurt.mpg.de (R. Sireteanu).

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theories propose parallel processing for both efficient and inefficient search. Increasing reaction times reflect nothing but increased competition of the growing set of information and thus prolonged processing as the number of distractors increases (e.g. biased competition model; Duncan & Humphreys, 1989), or changes in the internal–external signal to noise ratio (e.g. low threshold theories; Palmer, Verghese, & Pavel, 2000).

In several studies, efficient search is also called "parallel", "easy" or "effortless", while inefficient search is considered to be synonymous with "serial", "difficult" or "effortful" (e.g. Wolfe, 1998). In this manuscript, we use the terms "efficient" and "inefficient" to indicate that we make no assumptions on an underlying processing mode, e.g. the presence or absence of spatial shifts of attention (for reviews on this issue see Chelazzi, 1999; Townsend, 1990).

In previous work, we showed that some inefficient search tasks become efficient with practice (Sireteanu & Rettenbach, 1995, 2000). We refer to this process as parallelisation. Learning of visual search tasks is fast, enduring, but not specific: it transfers from a trained to an untrained task, from trained to untrained locations in the visual field, and also from the trained to the untrained eye of a subject, including the two eyes of stereoblind subjects (Sireteanu & Rettenbach, 1995, 2000). This lack of specificity of perceptual learning in visual search suggests that learning must take place on a different, probably higher cortical level than perceptual learning of other visual tasks, like the discrimination of complex gratings (Fiorentini & Berardi, 1980, 1981), orientation discrimination (Vogels & Orban, 1985), texture discrimination (Karni & Sagi, 1991), or vernier acuity (Fahle & Edelman, 1992; Poggio, Fahle, & Edelman, 1992). Surprisingly, conjunctions of colour and orientation do not become efficient even after extensive training (Sireteanu & Rettenbach, 2000), suggesting that perceptual learning in visual search, while implying a more efficient allocation of attention and thus a change in search strategy, occurs only under specific characteristics of target/distractor combinations. In other words, changes in search strategy depend on the stimulus material used and are thus not completely global.

One of the most striking findings in the previous studies (Sireteanu & Rettenbach, 1995, 2000) was the almost complete transfer of learning between a task containing only straight lines (the task "convergence", in which the target was a pair of converging lines among pairs of parallel line segments) and a task in which no straight lines were present (the task "gap", in which target and distractors were complete circles and circles with a 90° gap, respectively; see Fig. 1 left panels). Sireteanu and Rettenbach (1995) concluded that learning to allocate attention more efficiently mediates transfer from one task to another. We now wonder which are the stimulus characteristics that allow improvement in the allocation of attention, and where the limits are in such improvement.

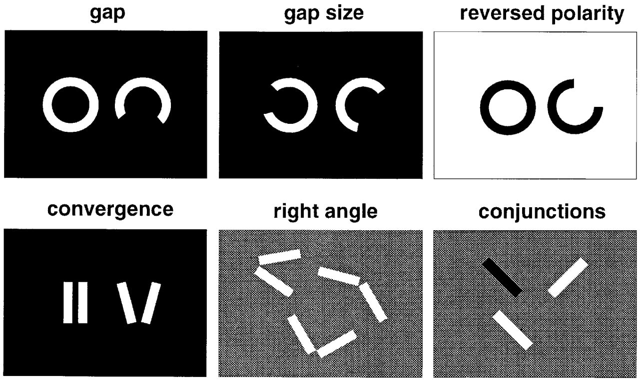

Fig. 1. Example of items used in the experiments: gap: white stimuli on blue background, gap size; reversed polarity; blue gap stimuli on white background, convergence; right angle; conjunction. For the tasks right angle and conjunction, distractors are shown in the upper row and targets in the lower row.

In those inefficient search tasks that became efficient with practice, targets were defined by a unique visual feature as well as a difference in brightness distribution. For instance, in the task gap, the target, a circle with a gap, differs from the distractors, closed circles, by the feature "line endings", as well as in its brightness distribution. In the study of Sireteanu and Rettenbach (1995, 2000), the subjects might have used the asymmetric luminance distribution within the target with the gap as a basis for learning. This could explain why learning transferred to the task convergence (a pair of converging lines among pairs of parallel lines); in this task, the target also differs from the distractors by showing an asymmetric luminance distribution.

In the present study, we attempted to find out whether the improvement in performance during learning of visual search tasks depends on the existence of a unique visual feature which is associated with the target but not with the distractors (e.g. the line endings in the task gap), or on differences in brightness distributions between target and distractors.

To answer these questions, we performed three learning experiments and two transfer experiments: In the first two experiments, we investigated the dynamics of learning in highly demanding search tasks, in which target and distractors differed either in the brightness distribution or in the presence of a unique visual feature. In a third long-term learning experiment, we attempted to induce learning of a task in which neither a unique visual feature, nor a difference in local brightness distribution were present (conjunctions). In the two transfer experiments, we aimed to identify by transfer experiments whether visual search of new tasks could benefit from prior learning of other search tasks. Subjects of all five experiments had given their written consent after the procedure was fully explained, and experiments were performed in accordance with the Declaration of Helsinki.

2. Learning experiments

2.1. Experiment 1: perceptual learning can be based on a difference in local brightness distribution (gap size)

In the first experiment, we asked whether learning can occur in a visual search task in which target and distractors are both circles with a gap, which differ in the size of their gap. In this task, the visual feature line endings (or the gap) was associated with both, the target and the distractors. Thus, a unique visual feature was not present. We called this task "gap size". If learning depends exclusively on the presence of a unique visual feature associated with the target (here line endings), there should be no learning in this task. Alternatively, parallelisation of this task would imply that learning can be based on a gap size difference, and thus either on the absolute length of the curved lines or on differences in brightness distribution between target and distractors.

2.1.1. Methods

This experiment was performed with two naïve (RaS and AS) and two experienced subjects (the authors UL and RS).

Stimuli were presented in four different variants: (a) a target circle with a gap of 45° among distractor circles with a gap of 135° (target with narrow gap), (b) a target circle with a gap of 135° among distractor circles with a gap of 45° (target with wide gap), (c) only distractor circles with a gap of 135° (homogeneous wide gaps), or (d) only distractor circles with a gap of 45° (homogeneous narrow gaps) (see Fig. 1 middle upper panel).

The stimuli were presented on a computer screen with a size of $19° \times 26°$. To preclude the need for foveal scrutiny (and hence for several fixations), the stimuli were so salient (mean diameter of an item was 3.5° visual angle) as to be easily discriminated in peripheral vision. Stimuli were white on a blue background (mean background luminance was 0.59 cd/m^2, luminance of the test items was 37.58 cd/m^2). The number of items in a set could be 1, 4, 8, or 16.

The subjects were seated at a distance of 57 cm from the screen, in an otherwise darkened room. The subjects' task was to indicate the presence or absence of a target by pressing a button of the computer mouse with the dominant hand as quickly and correctly as possible. As soon as the key was pressed, the stimuli disappeared from the screen. The subjects had to point to the location of the target if the trial had been positive, or raise the hand if negative. Reaction time and error rates were monitored. This procedure was used, instead of the more common one of pressing two different keys with the two hands, to ensure that decision time was not confounded with deciding which hand was appropriate. This procedure, which was used before by Sireteanu and Rettenbach (1995, 2000), drastically reduced the number of errors. For a set size of one item, the subjects were not required to distinguish between possible targets but to press the button as soon as the item appeared on the screen (simple detection task, "basic reaction time"). Reaction times for single items were identical for all targets, suggesting that, under our experimental conditions, all items had similar saliency. Each experimental session consisted of a block with 56 trials, in which all stimulus combinations were presented four times in different versions in a pseudorandom sequence. Subjects performed at least 16 sessions, grouped in two experimental sessions per day. Sessions were scheduled on consecutive days, including week-ends, whenever possible. There was no fixation point, but the subjects were asked to look at the center of the screen in between the trials. Feedback was provided.

For each experimental session, reaction times to all single items were averaged, thus yielding a measure of the basic reaction time. Also averaged were the reaction times (correct responses only) for all displays containing a target with a "narrow gap", a target with a "wide gap", homogeneous displays containing only items with narrow gap, and homogeneous displays containing only items with wide gaps. This way of processing the data was adopted from Sireteanu and Rettenbach (1995, 2000). Parts of the experimental data were included in Leonards, Rettenbach, and Sireteanu (1998).

2.1.2. Results and discussion

In the first sessions, the two naïve subjects (RaS, AS) showed a clear asymmetry in search slopes for targets with narrow or wide gaps (see search slopes for subject RaS in Fig. 1b of Leonards et al., 1998). Targets with narrow gaps were found faster than those with wide gaps (see Fig. 2, upper two panels, circles versus triangles).

The learning dynamics of the two naïve subjects over the entire training period are shown in the upper panel of Fig. 2: even though RaS showed clear learning effects, he did not reach an efficient search after 16 training sessions. For subject AS, parallelisation was achieved after 15–16 sessions. While search time improvement showed big interindividual differences, error rates were very low in both subjects right from the beginning, and were thus averaged over subjects (Fig. 2B).

The two experienced subjects (the authors UL and RS) both reached the stage of efficient search after prolonged practice (Fig. 4A, upper panels; see search slopes for subject UL in Fig. 1b of Leonards et al., 1998).

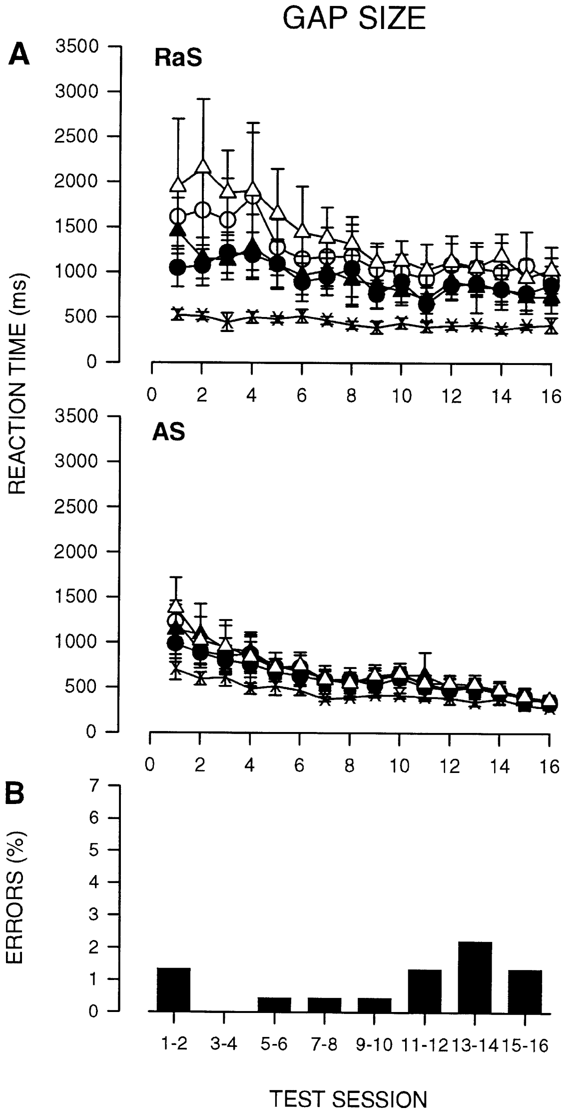

Fig. 2. (A) Individual learning curves, and (B) cumulated error rates of the task gap size for the two naïve subjects RaS and AS. The test sets could contain (a) a target with a narrow gap among distractors with wide gaps (filled circle), (b) a target with wide gap among distractors with narrow gaps (filled triangle), (c) only items with wide gaps (open circle), or (d) only items with narrow gaps (open triangles). Reaction time data contain correct responses only and were averaged for 4, 8, and 16 items. Single items were averaged over test sets, thus yielding a measure of the basic reaction time (×-symbols). Error bars refer to ±1 SEM. Error rates were averaged over the two subjects and over two consecutive sessions.

These results show that, albeit the dynamics of learning differ from subject to subject and depend on the amount of previous practice, visual search tasks in which no unique visual feature is present can become efficient with practice. This leaves the difference in brightness distribution (for instance, differences in line length) between target and distractor as a strong candidate for the process of learning of this task. In the following experiment, we asked whether learning can occur in a task in which target and distractors differ only by the presence of a visual cue associated with the target, but not with the distractors.

2.2. Experiment 2: perceptual learning can be based on a unique visual feature (right angle)

In this second experiment, we tested the dynamics of learning for a variant of the convergence task, which we called "right angle" task. In this task, subjects searched for a pair of lines with an including angle of 90° among distracting items consisting of pairs of lines with including angles of 40° and 140° (right angle, see lower middle panel in Fig. 1). In contrast to the first experiment, learning in this task could not be based on differences in line length, since all items had the same length. Targets differed from distractors only by their opening angle (90°).

2.2.1. Methods

This experiment was performed with one new naïve subject (RV) and one experienced subject (the author UL).

Subjects searched for a target element with an including angle of 90° within two types of distractor elements of 40° and 140°, respectively. The elements of the display were randomly oriented so that the search could not be based on orientation. This time, we used a two-alternative forced-choice condition. The subjects pressed a computer-controlled push-button with their non-dominant hand if the target (90° angle) was present, and another push-button with their dominant hand if the target was absent. Trials could consist of white or black elements on a grey background. The stimulus display subtended a visual angle of 13.5° × 13.5°, and single line elements measured 0.92° × 0.35°. Set size could be 1, 8, 16, or 24 items. Targets were present in 50% of the trials. An experimental session consisted of a block with 96 trials, in which every possible combination was presented six times in random order. Subjects performed four experimental sessions twice a day for at least 15 days. Reaction times for both target-present and target-absent trials and errors were monitored.

2.2.2. Results and discussion

In Fig. 3A (upper panels), learning curves are plotted for both the naïve (RV) and the experienced subject (UL). In the first training sessions, both subjects had high search slopes, indicating inefficient processing. In both subjects, extensive training led to parallelisation (e.g. search slopes for subject RV changed for target-present trials from 90 to 3.2 ms/item, and for target-absent trials from 100 to 8.4 ms/item). This result reinforces the findings of Experiment 1 that even highly demanding search tasks can become efficient with extended practice. This time, the unique visual cue appears to have been

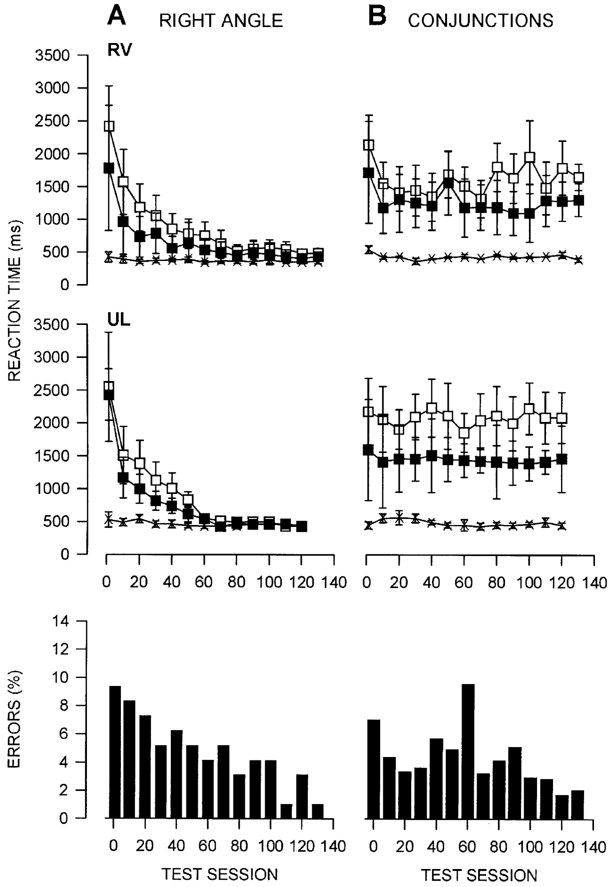

Fig. 3. Learning curves (upper panels) and cumulated error rates (lower panel) of the tasks (A) right angle (Experiment 2), and (B) conjunctions of contrast polarity and orientation (Experiment 3B) for the naïve subject RV and the experienced observer UL. For clarity reasons, only every tenth session is plotted. Data were averaged for 8, 16, and 24 items. Basic reaction time: ×-symbols; symbols: (■) target-present; (□) target-absent; error bars (mean of the two subjects for every tenth session only) refer to ±1 SEM.

sufficient for learning to occur, even in the absence of a difference in brightness distribution between target and distractors. In fact, one might suggest that the identification of the fixed angle of 90° as being associated with the target, but not with the distractors, could have served as a pre-cueing information, which might have helped the subjects to learn the task. Notice that parallelisation of this task could not have been based on a speed–accuracy "trade-off", since both reaction time and error rates decreased markedly during training.

2.3. Experiment 3: perceptual learning in visual search cannot be based on an improved global search strategy (conjunctions)

In the foregoing two experiments, we have shown that highly demanding, inefficient visual searches like gap size and right angle can be completely parallelised after extensive training. To exclude that this dramatic improvement might have been due to the emergence of a more efficient global search strategy instead of the postulated existence of a "marker" which distinguishes the target from the distractors (like the local brightness difference in the task gap size, or the unique visual cue of 90° in the task right angle), we turned to visual search tasks which were equally demanding: visual conjunctions. In these tasks, the target differs from the distractors neither by a local brightness distribution nor by a unique visual feature, but by a combination of features. We used two different conjunction tasks: (A) conjunctions of colour and orientation, and (B) conjunctions of contrast polarity and orientation. Previous studies from our laboratory indicated that a task devoid of both, brightness distribution and of unique visual features (for instance, a conjunction task of orientation and colour) cannot be learned, even with prolonged practice (Sireteanu & Rettenbach, 2000).

To exclude that the lack of improvement seen in these tasks was not due to a premature discontinuation of training, or to a specific inability of the subjects in the previous study to achieve parallelisation, this experiment was performed with subjects who had already achieved efficient status in other, unrelated, highly demanding tasks: in Experiment 3A, the task gap size; in Experiment 3B, the task right angle.

2.3.1. Methods

2.3.1.1. A: long-term practice of conjunctions of colour and orientation. Two highly experienced observers (the authors UL and RS) participated in this part of the study. Subject RS had participated previously in 22 sessions of conjunction search with similar stimulus configurations (Sireteanu & Rettenbach, 2000). The other subject (UL), while very experienced with different feature search tasks (e.g. see Experiment 1), was naïve to this task.

Targets were (a) red horizontal lines among green horizontal and red vertical lines, (b) red vertical lines among green vertical and red horizontal lines, (c) green vertical lines among red vertical and green horizontal lines, or (d) green horizontal among red horizontal and green vertical lines (see right lower panel in Fig. 1). Set size could be 1, 8, or 16 items. Stimulus presentation and the subjects' response were similar to those described for Experiment 1.

Each experimental session consisted of one block with 72 trials, in which all possible stimulus configurations were presented three times in random order. Each subject performed eight sessions, grouped in two sessions per day.

2.3.1.2. B: long-term practice of conjunctions of contrast polarity and orientation. Two experienced observers (author UL and subject RV) participated in this part of the study. Subject UL had participated previously in the sessions of conjunction search of colour and orientation (see Experiment 3A). The other subject (RV), while very experienced with the right angle search task (see Experiment 2), was naïve to conjunction search tasks.

Targets were (a) white lines of +45° among black lines of +45° and white lines of −45°, (b) white lines of −45° among black lines of −45° and white lines of +45°, (c) black lines of +45° among black lines of −45° and white lines of +45°, or (d) black lines of −45° among black lines of +45° and white lines of −45°. Set size could be 1, 8, 16, or 24 items. Stimulus presentation and the subjects' response were similar to those described for Experiment 2.

Each experimental session consisted of one block with 96 trials, in which all possible stimulus configurations were presented in three different variants in random order. Each subject performed four sessions twice a day for at least 15 consecutive days.

2.3.2. Results and discussion

2.3.2.1. Experiment 3A (conjunctions of colour and orientation). Results for the long-term practice of the conjunction search for colour and orientation for subjects RS and UL are shown in Fig. 4B. In spite of the fact that both subjects had reached the stage of efficient search with the task gap size (Fig. 4A upper panels), there was no improvement in performance with conjunction search of orientation and colour with extended practice in these two highly experienced observers (Fig. 4B upper panels). The results of the two subjects are remarkably similar, irrespective of the fact that one subject (RS) had been trained with conjunction search of orientation and colour before (Sireteanu & Rettenbach, 2000), while the second subject (UL) was naïve for the conjunction task. There was no benefit of previous practice on either feature or conjunction search tasks.

2.3.2.2. Experiment 3B (conjunctions of contrast polarity and orientation). Similar observations could be made for the long-term practice of conjunctions for contrast polarity and orientation for subjects UL and RV, as shown in the upper panels of Fig. 3B. Again, despite of the fact that both subjects had reached the stage of efficient search with the demanding task right angle, there was no improvement in performance with conjunction search of contrast polarity and orientation. (Note that both subjects passed more than 100 sessions each, which corresponds to more than 10,000 trials).

Thus, it seems that a task lacking both differences in local brightness distributions and unique visual features cannot be learned, in spite of extended practice. Previous practice with another highly demanding search task that led to parallelisation also does not seem to benefit conjunction search. Taken together, the first two experiments suggest that either a unique visual feature or a local brightness marker have to be present for learning to occur. In this third experiment, we ruled out that an improvement in global search strategy could lead to parallelisation. The question remains, whether learning based on unique visual features can transfer to a task containing only brightness differences, but no unique features, and vice versa. In the next two experiments, we attempt to disentangle the relative roles of visual features versus brightness distribution in perceptual learning of visual search by transfer experiments.

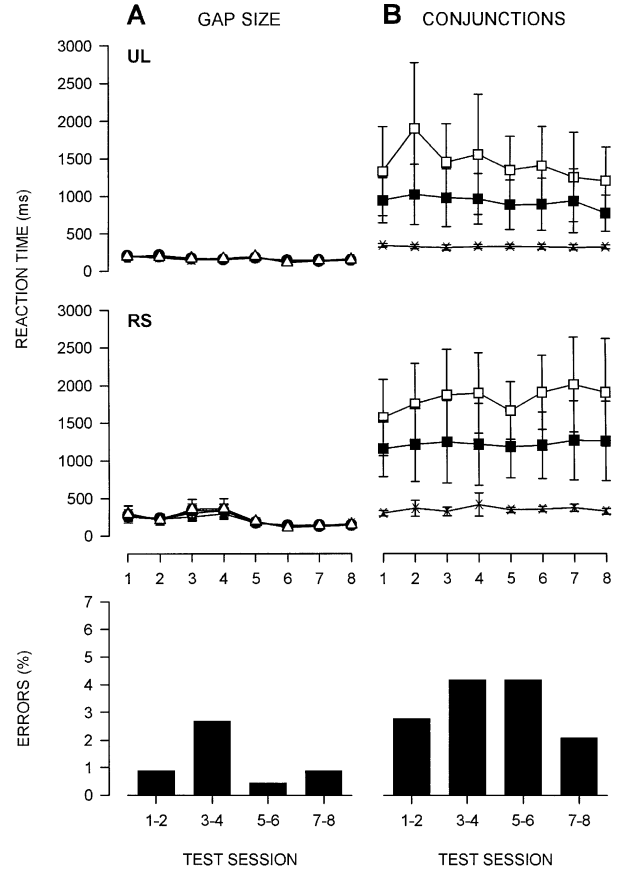

Fig. 4. Reaction times (upper panels) and cumulated error rates (lower panels) for the two highly experienced observers UL and RS. (A) Task gap size; analysis and symbols as in Fig. 2; (B) Conjunction search for orientation and colour. Data were averaged for 8 and 16 items; basic reaction time: ×-symbols; symbols: (■) target-present; (□) target-absent. Error bars refer to ±1 SEM.

3. Transfer experiments

3.1. Experiment 4: transfer of learning based on a unique visual feature (reversed polarity)

The previous experiments showed that highly demanding visual search tasks can become efficient with extensive practice, if the target differs from the distractors either by an intrinsic brightness distribution, or by a unique visual feature. In a fourth experiment, we tested whether learning of a task based on both a visual feature and a difference in brightness distribution between target and distractors (the task gap, see upper left panel in Fig. 1) transfers to a task in which the visual feature is kept constant, but the brightness polarity between stimuli and background is reversed ("reversed polarity", see upper right panel in Fig. 1). If learning of the task gap is based solely on the visual feature, there should be complete transfer to the new task. If contrast polarity is essential for learning, little or no transfer to the contrast-reversed task should take place.

3.1.1. Methods

Four new naïve subjects participated in this part of the study (LG, CS, SR, TS).

Two search tasks were used: white circles with a gap of 90° (gap) among circles without gap on a blue background (blue background) and blue circles with a gap of 90° (gap) among circles without gap on a white background (white background) (see Fig. 1 upper left and right panels). Set size could be 1, 4, 8, or 16 items. There were four different variants: (a) a target circle with a gap of 90° among distractor circles without gap (target with feature), (b) a target circle without gap among distractor circles with a gap of 90° (target without feature), (c) only distractor circles without a gap (homogeneous without feature), or (d) only distractor circles with a gap of 90° (homogeneous with feature). The methods were similar to those described in Experiments 1 and 3A. Two of the four subjects were trained on the task blue background for six consecutive sessions, after which they were tested on the task white background for another four consecutive sessions. Two other subjects were trained on the task white background and afterwards tested on the task blue background. Each subject thus performed 10 sessions, grouped in two sessions per day.

3.1.2. Results and discussion

Results are shown in Fig. 5. The upper four panels show that, in the first training session, the classical asymmetric search pattern for the task gap could be observed, irrespective of the colour of the background (target with a gap: −0.4 ms/item; target without gap: 16.9 ms/item; homogeneous displays without gaps: 16.2 ms/item; homogeneous displays with gaps: 18.9 ms/item). Performance improved with practice for the six training sessions, for both backgrounds. Switching to the new background led to a continuous further improvement in performance, resulting nearly in parallelisation in the last session (target with a gap: 1.8 ms/item; target without gap: 3.8 ms/item; homogeneous displays without gaps: 5.3 ms/item; homogeneous displays with gaps: 8.6 ms/item). Thus, there was complete transfer to the new task.

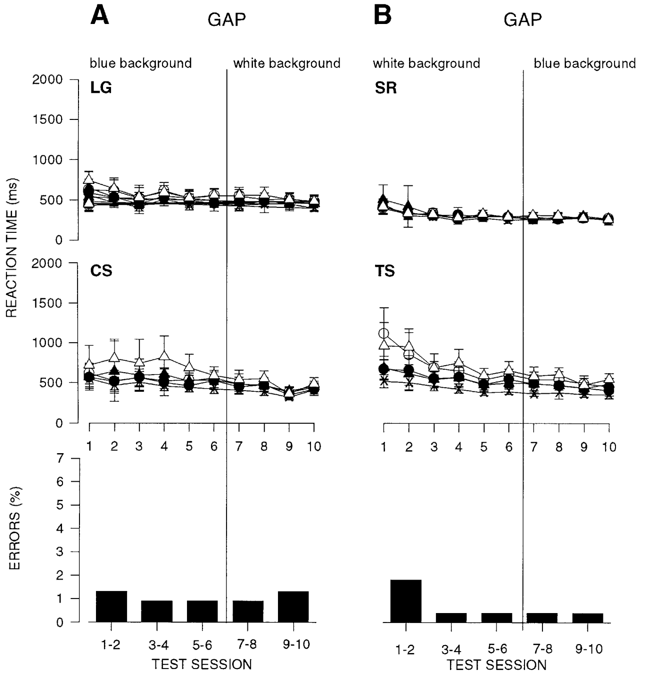

Fig. 5. Learning curves (upper panels) and cumulated error rates (lower panels) during transfer for the task gap to the task reversed polarity and vice versa. The number of items in a set could be 1, 4, 8, or 16. (A) mean reaction times of two subjects trained on the task blue background and transferred to white background, and (B) mean reaction times of two subjects trained on the task white background and transferred to blue background. The test sets could contain (a) a target with a gap among distractors without gaps (filled circle), (b) a target without gap among distractors with gaps (filled triangle), (c) only items without gaps (open circle), or (d) only items with gaps (open triangles); ×-symbols: basic reaction time. Error bars refer to ±1 SEM.

These results show that learning of visual search tasks transfers across brightness polarity, reinforcing the idea that learning can be based on the existence of a unique visual feature that differentiates target and distractors. Thus, as long as the feature of a visual search task remains stable, subjects benefit from previous search even after dramatic changes in the physical appearance of the stimuli.

3.2. Experiment 5: learning based on unique visual features does not transfer to a task based on local brightness differences (gap to gap size)

To investigate the relative importance of visual features for learning, we tested in a fifth experiment whether learning of a task in which target and distractors differ only by a local brightness distribution (gap size, see middle upper panel in Fig. 1) transfers to a task in which in addition a unique visual feature (gap, see left upper panel in Fig. 1) is present. In fact, the relative difference in brightness distribution between narrow and wide gaps in the task gap size was identical to the one between closed circles and circles with a gap in the task gap. We reasoned that there could be two outcomes: First, if learning in both tasks was based on the common difference in brightness distribution (gap width) between target and distractors, performance after task switch should benefit from prior training. (Thus, the task gap should be efficient after task switch.) Alternatively, if the two tasks were completely independent (one based on the feature line endings, the other on the differences in brightness distribution), performance after task switch should be identical to the performance of naïve subjects.

3.2.1. Methods

Six new naïve subjects participated in this part of the study.

Two search tasks were used: circles with a gap of 45° among circles with a gap of 135° (gap size), and circles with a gap of 90° among plain circles (gap) (see Fig. 1, first two upper panels). For each of the two tasks, four different variants of target and distractor combinations were presented and grouped according to their brightness distribution: (a) a target with narrow gap/target without line endings, (b) a target with wide gap/target with line endings, (c) homogeneous with wide gap/homogenous with line endings, or (d) homogeneous with narrow gap/homogenous without line endings. Stimuli, stimulus presentation and the subjects' response were similar to those described for Experiments 1 and 4.

Each experimental session consisted of a block with 56 trials. Three of the six subjects were trained on the task gap size for six consecutive sessions, after which they were tested on the task gap for another six consecutive sessions, and retested on the task gap size for yet another two consecutive sessions. Three other subjects were trained on the task gap afterwards tested on the task gap size, and then retested on the task gap. Each subject thus performed 14 sessions, grouped in two sessions per day, on consecutive days.

3.2.2. Results and discussion

Results are shown in Fig. 6. The upper panels show that performance for both tasks improved with practice. For the task gap size (sessions 1–6 in Fig. 6A), reaction times of the first group of three naïve subjects in the first three days of practice were much higher than they were for the task gap (sessions 1–6 in Fig. 6B) during the first three days of practice for the other three naïve subjects. Nevertheless, error rates were similar and very low for both tasks (see lower panels), indicating that, in spite of their different degree of difficulty, the initial decision criteria of the two groups of subjects for the two tasks were comparable.

As expected, the performance for the task gap became nearly efficient during the first few sessions, while for the task gap size, parallelisation was not yet achieved

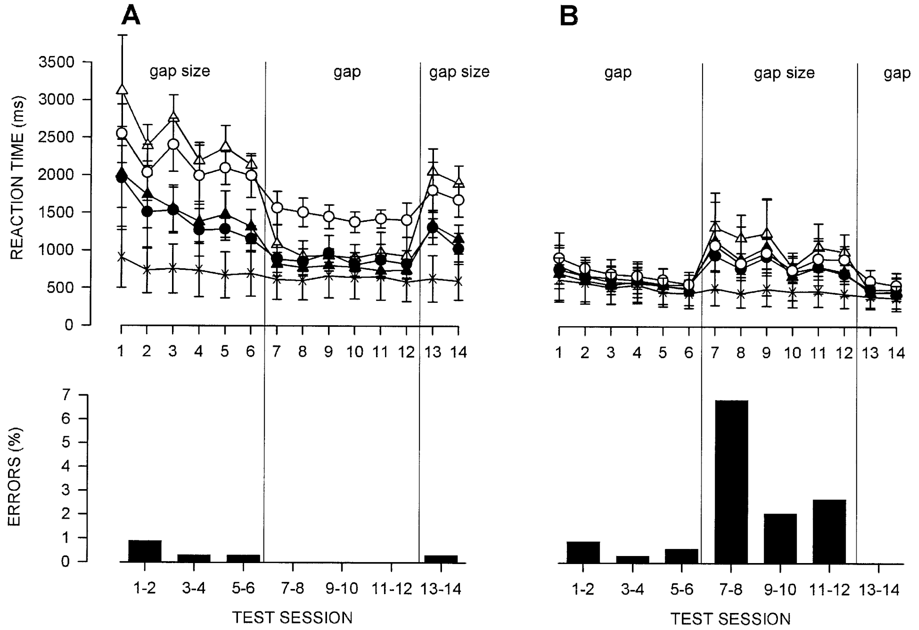

Fig. 6. Learning curves (upper panels) and cumulated error rates (lower panels) during transfer: (A) means of three subjects trained on the task gap size, tested on the task gap, and retested on the task gap size, (B) means of three other subjects trained on the task gap, tested on the task gap size, and retested on the task gap. According to their brightness distribution, the test sets could contain (a) a target with narrow gap/target without line endings (closed circles), (b) a target with wide gap/target with line endings (closed triangles), (c) homogeneous with wide gap/homogenous with line endings (open circles), or (d) homogeneous with narrow gap/homogenous without line endings (open triangles); ×-symbols: basic reaction time. Error bars refer to ±1 SEM. Note the reversal of open triangles and open circles after task switch, mirroring the change of the cue on which the search is based (feature line endings to brightness distribution, or vice versa).

during this period, in spite of clear improvement in performance.

Contrary to expectations, switching to the new task (sessions 7–12) led to four remarkable events: (a) for subjects trained with the task gap size (Fig. 6A), reaction times were much *longer* in the subsequently tested task gap than would be expected from naïve subjects (compare sessions 7–12, Fig. 6A, with sessions 1–6, Fig. 6B); (b) these subjects made no errors during the secondly tested task gap; (c) for subjects trained with the task gap (Fig. 6B), reaction times were much *shorter* on the subsequently tested task gap size than would be expected from naïve subjects (compare sessions 7–12, Fig. 6B, with sessions 1–6, Fig. 6A); (d) error rates in this group of subjects increased dramatically after switching from the easy (gap) to the difficult (gap size) task (from less than 1% to 6–7%).

In summary, initial training with the task gap induced a reduction of the reaction time for the subsequently tested task gap size, accompanied by an increase in error rates. Initial training with the task gap size induced a slowing-down of performance in the subsequently tested task gap, accompanied by an increase in accuracy.

As pointed out in the methods section of Experiment 1, the procedure used here yields an extremely low and stable error rate (about 1–2%). An error rate of 6–7%, as seen for the task gap size after task switch is highly indicative of a change in the decision criterion.

Furthermore, note that after task switch, the conditions provoking the longest reaction times are reversed (see open triangles versus open circles). Since similar symbols had been given to conditions with similar brightness distribution, such a reversal indicates that subjects based their search during the task gap size on brightness distribution as expected (the target narrow gap). During the task gap, however, they used the feature line endings which is associated with the reversed brightness distribution.

Retesting of the original task in the last two experimental sessions did not lead to any benefit in performance, as if there had been no interruption in the testing schedule. Neither reaction times nor error rates seemed to have benefited from the interleaved training sessions.

We therefore conclude that there is no transfer but rather a trade-off between the two tasks. The lack of transfer excludes angular differences in gap sizes between target and distractors as a basis for learning, since such angular differences were identical for the two tasks gap (0° versus 90°) and gap size (45° versus 135°). It thus seems that, while learning the difficult task gap size was certainly due to the differences in local brightness distribution, learning of the easy task gap was primarily based on the presence of a unique visual feature which distinguishes between target and distractors.

4. General discussion

4.1. Evaluation of the results

The main finding of the first two experiments is that prolonged practice can transform inefficient into efficient search, even for tasks in which no classical visual features are present. Indeed, neither the task gap size nor the task right angle do qualify for classical feature search, since none of the items involved can be detected efficiently by inexperienced naïve observers. Nevertheless, the search asymmetry for the task gap size before parallelisation suggests that the narrow gap item (the circle with the 45° gap) is more likely to be rapidly detected than the wide gap item (the circle with the 135° gap); the attribute narrow gap thus plays the role of a feature after training. This suggests that an item-specific brightness distribution alone, in the absence of a unique visual feature, can act as an attractor for visual attention on which perceptual learning can proceed in a visual search task, and this independently of whether being associated with the target or the distractors. In the task right angle, one might assume that the 90° angle might have acquired feature status by training.

Using two different response methods, a detection task with latter pointing to the discrepant item for the task gap size and a two-alternative forced-choice response for the task right angle, we could exclude that learning had been simply due to a shift in subjects' response strategy in the pointing condition, such as an internal search driven from short-term memory.

In Experiment 3, we confirmed that search for a target which does not contain a unique visual feature, and, at the same time, does not display a difference in local brightness distribution (conjunction tasks), does not become efficient even after extended practice. With conjunction tasks of colour and orientation as well as conjunction tasks of contrast polarity and orientation, extremely extended practice did not lead to efficient search. Since our observers had become efficient in the highly demanding search tasks gap size and right angle, these results exclude the possibility that learning in visual search might be exclusively explained by an improvement in global search strategy.

We conclude that tasks devoid of differences in local brightness distribution between target and distractors *and* of unique visual features might be difficult, if not impossible, to learn (as long as the identity of the target is not known to the subjects). Thus, a target in a visual search task needs a special marker—such as a visual feature or an asymmetry in brightness distribution—in order to attract attention and to mediate the learning process.

The results of the fourth experiment reinforce the importance of visual features for perceptual learning. Changing the brightness polarity of a task (from blue background to white background or vice versa) shows that the physical appearance of the stimulus is not important, as long as the specific attractors (e.g. the line endings in the circle with a gap), on which learning was based, are present.

The results of the fifth experiment extend this conclusion and show that learning can be based on each, local brightness differences *and* unique visual features, but that learning does *not* transfer between the two. Indeed, learning of a visual search task based on local brightness *without* visual feature (gap size) does not lead to an improvement in performance on a task in which the search is based mainly on the existence of a visual feature (gap). Conversely, improvement by practice in the task gap does not transfer to the task gap size. Albeit learning of one task does not benefit from practice on the other task, the two tasks gap and gap size are also not entirely independent. Indeed, performance on the difficult task (gap size) proceeds faster, but with more errors, after practice on the easy task (gap); performance on the easy task (gap) is slower, but more accurate, after practice on the difficult task (gap size). Thus, there is no transfer, but rather a speed–accuracy trade-off between the two tasks. The observed interference is not due to the "easiness" or "difficulty" of the tasks per se, but rather to the common elements shared by the two tasks: In both cases, the search involves circles with gaps; in both cases, the difference between target and distractors is a 90° gap. Apparently, subjects had learned to use a cue that was no longer valid after task switch and thus hindered optimal performance.

It appears that mastering a task defined by local brightness without a visual feature (e.g. gap size) requires more attentional resources than a task defined by a combination of local brightness differences and visual features (e.g. gap). Learning of the difficult task gap size, instead of benefiting the subsequently tested, easier task gap, interferes with this task and produces longer reaction times. Conversely, learning of the easy task gap produces shorter reaction times at the expense of accuracy in the difficult task gap size.

4.2. Relationship with previous studies

Our findings that conjunction search tasks of both colour and orientation or contrast polarity and orientation cannot be learned confirm and extend earlier observations of Treisman and Gelade (1980) and of our own group (Sireteanu & Rettenbach, 2000). However, Steinman (1987) reported that several conjunction searches can become efficient after several thousands of trials. We can exclude that this obvious discrepancy between Steinman's (1987) and our observations was due to the inability of our subjects for perceptual learning or an insufficient training time. All our subjects had become efficient in highly demanding search tasks, and subjects UL and RV performed more than 10,000 conjunction search trials without showing any sign of further improvement. The question arises whether the stimuli used in the Steinman study might have had slight brightness differences that could have been used by his subjects. Alternatively, the identity of the target might have been known to the subjects, thus acting as a "precueing" factor (as thoroughly investigated by Shiffrin & Schneider, 1977).

Ellison and Walsh (1998) reported that training of conjunction tasks benefits subsequent testing with feature search while training with feature tasks does not lead to improvement in a subsequently tested, unrelated conjunction search. Unfortunately, Ellison and Walsh did not use long-term training, and thus the observed effect might have been due to short-term improvements in global search strategy (cf. Ahissar & Hochstein, 1997). In addition, the identity of the target items in the conjunction search tasks of the Ellison and Walsh study was kept constant, thus acting as a "pre-cue".

4.3. Possible neural mechanisms

Our results suggest that inefficient search must be divided in two categories: searches that can become efficient with extensive training (e.g. gap size and right angle), and searches that cannot (e.g. conjunctions of colour and orientation, or of contrast polarity and orientation). This suggests that the two kinds of inefficient search might involve different cortical mechanisms.

From observations with neurological patients, brain imaging and transcranial magnetic stimulation (TMS) studies, it is known that inefficient visual search activates a complex cortical network, including frontal, parietal, and occipito-temporal regions (e.g. Arguin, Joanette, & Cavanagh, 1993; Corbetta, Shulman, Miezin, & Petersen, 1995; Eglin, Robertson, & Knight, 1991; Leonards, Sunaert, VanHecke, & Orban, 2000). Especially, these studies support the notion of a specific and critical involvement of posterior parietal cortex (particularly of the right hemisphere) in tasks requiring detection of a conjunction-defined target (for a recent review see Chelazzi, 1999). Using stimuli identical to those of Sireteanu, Dornburg, Kusch-Mielke, and Rettenbach (2000), Sireteanu and Rettenbach (2000) showed in a study involving 89 patients with focal brain damage, that lesions in the right parietal cortex led to impairments of both inefficient and efficient search, whereas lesions in frontal cortex only affected inefficient search.

In spite of the fact that all these studies indicate an involvement of parietal cortex in inefficient search, activity for conjunction search in this region is even stronger than for the highly demanding right angle task (Leonards et al., 2000). In contrast, this latter task produced higher activation than the former in occipito-temporal regions. In fact, activity in occipito-temporal regions correlated with subjects' search slopes, while activity in parietal regions did not. Thus, brain imaging data support the hypothesis of a functional dichotomy in inefficient search.

Since performance in a conjunction search task without a visual attractor is not improved, even after prolonged practice, one might predict that activity in the cortical network involved in such inefficient conjunction tasks should remain unaffected by extensive training. This prediction has not been tested empirically so far. Psychophysiological findings from our laboratory, in which skin conductance and muscle tonus were recorded while subjects were involved in long-term training with one of the tasks included in this study gap size, demonstrated that this highly demanding, initially inefficient search task remains an effortful task even after parallelisation (Leonards et al., 1998).

In conclusion, the present study has shown that even highly demanding inefficient search tasks can become efficient with training on the condition that some kind of attractor of visual attention is available. Possible attractors are unique visual features, differences in local brightness distributions, and, as remains to be confirmed, some kind of pre-cueing. Searches for targets lacking such attractors (e.g. conjunction search tasks in which the target item changes from trial to trial) remain inefficient, even after long periods of practice. This excludes an earlier interpretation that perceptual learning in visual search is simply due to an improvement of the allocation of attention and thus to a more efficient global search strategy. Moreover, given the obvious differences between non-improving conjunction search and clearly improving inefficient search tasks, we conclude that there exist two classes of inefficient search tasks relying on different underlying mechanisms. This will have a direct and important impact on the interpretation of patient data, in which the conjunction search task is often used to test subjects' capabilities to allocate attention. Further studies, including a combination of psychophysical, psychophysiological and brain imaging methods on the same subjects, might help shed more light on the fascinating process of learning-induced changes in the adult human brain.

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