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Automatic attraction of attention to former targets in visual displays of letters

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Shiffrin and Schneider (1977, Experiment 4d) reported that after consistent training in search for particular alphanumeric characters, presentation of one of these characters (former targets) as a distractor impeded detection of simultaneously presented current targets. Even if presented in an irrelevant display location, the former target appeared to attract attention. Here, we analyze weaknesses in the design of Experiment 4d and report four follow-up experiments ranging from a fairly close replication of the original multiframe experiment to a rather conventional single-frame search study. In each experiment, presentation of former targets consistently impeded detection of simultaneously presented current targets. The results suggest that automatic attention attraction to individual alphanumeric characters develops not only in the special experimental paradigm used by Shiffrin and Schneider, but also in standard visual search tasks. The fact that attention appeared to be attracted by shapes as complex as individual letters supports the assumption that simultaneously presented visual stimuli can be compared in parallel against memory representations of alphanumeric characters.

In a classical experiment, Shiffrin and Schneider (1977, Experiment 4d) investigated how prolonged and consistent training in visual search for particular alphanumeric characters (digits among letters) affected performance after a change in the search criterion. After training, the participants were told to search a particular diagonal of a 2 × 2 matrix of characters for particular members of the set of characters (letters) that had been used as distractors during the training. Characters on the other diagonal should be ignored. The results showed that when digits (former targets) appeared on the diagonal to be ignored, detection of simultaneous letter targets on the diagonal to be attended was impeded. Apparently, the former targets (*foils*) captured attention automatically, contrary to the will of the participants.

A theoretical account of the effects of training described by Shiffrin and Schneider (1977) was outlined by Shiffrin and Dumais (1981) and Shiffrin, Dumais, and Schneider (1981). In this account, attentional weights of targets and distractors diverge during training, because stimuli gain in weight when they are used as targets and lose in weight when used as distractors. Quantitative formulations were later developed by Bundesen (1990) and Shiffrin and Czerwinski (1988). In Bundesen's (1990, 1998) theory of visual attention (TVA), every stimulus is assigned an attentional weight, which determines the likelihood that the subject will attend the stimulus. The attentional weight, w_x, of stimulus x is defined as

$$w_x = \sum_{j \in R} \eta(x, j)\pi_j, \qquad (1)$$

where R is the set of all perceptual categories, $\eta(x,j)$ is the strength of the sensory evidence that x belongs to category j, and π_j is the *pertinence* (priority) value of category j. In the present context, the set of perceptual categories includes all types of alphanumeric characters, the sensory evidence could be the likelihood of a particular stimulus' being a particular letter or digit (e.g., that the stimulus is an H), and the pertinence values of digits would be higher than the pertinence values of letters if subjects were to look for digits while ignoring letters. The learning effect seen in Shiffrin and Schneider's experiments is explained by gradual increments and decrements of the pertinence values for types of stimuli used as targets and distractors, respectively. When the former target is presented as a distractor, subjects cannot eliminate the

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high pertinence value the item has acquired during the training. This results in the former target's being assigned a high attentional weight (see Equation 1), thus giving rise to the *breakthrough effect* found by Shiffrin and Schneider (also see Czerwinski, Lightfoot, & Shiffrin, 1992; W. Schneider, 1985; W. Schneider, Dumais, & Shiffrin, 1984; W. Schneider & Fisk, 1982; W. Schneider & Shiffrin, 1977).

The results found by Shiffrin and Schneider (1977) have had a strong impact on the development of general theories of attention (see, e.g., Bundesen, 1990, 1998; Duncan, 1980; Duncan & Humphreys, 1989; W. X. Schneider, 1995, 1999; van der Heijden, 1992). Proponents of late-selection theories of attention (e.g., Shiffrin & Schneider, 1977) have argued that if a particular type of stimuli automatically attracts attention, recognition of this type of stimuli must be possible preattentively and in parallel across the visual field. A weaker and safer claim is that if a particular type of stimuli automatically attracts attention, retrieval of evidence that stimuli belong to the type in question must be possible preattentively and in parallel across the visual field. Thus, the results of Shiffrin and Schneider suggest that simultaneously presented visual stimuli can be compared in parallel against memory representations of alphanumeric characters. In terms of Bundesen's (1990) TVA, the results support the assumption that parameters of the form $\eta(x, j)$ are computed preattentively and in parallel across objects (x) in the visual field for perceptual categories (j) such as types of letters and digits.

However, objections may be raised against the experimental method used by Shiffrin and Schneider (1977). First, Treisman and Gelade (1980) and Cheng (1985) conjectured that the target and distractor sets used by Shiffrin and Schneider may have been distinguished by differences in simple features, in addition to differences in character shapes (conjunctions of simple features). Thus, the search for digits among letters (or vice versa) in Experiment 4d might have been done by "using categorically distinguishing physical information directly, without first having to identify the individual items" (Cheng, 1985, p. 415). W. Schneider and Shiffrin (1985) called this conjecture *the visual feature hypothesis.* By the visual feature hypothesis, the results of Experiment 4d may have been caused by automatic attention attraction to particular simple features, rather than to particular character shapes. In Experiment 1 of this article, we attempted a replication of Experiment 4d with a stimulus material for which it seemed impossible to determine whether a stimulus character was a target or a distractor by testing for a particular simple feature or a particular disjunction of simple features.

Second, the representativeness of the results of Shiffrin and Schneider (1977) may be doubted because their training and test procedures were special and complex. Their experimental procedure was a rapid serial visual presentation (RSVP) paradigm with large target and memory sets of nine and four characters, respectively. During the 6,000 trials of training, stimuli and responses were related by a consistent mapping; if a stimulus was a target on one trial, it never appeared as a distractor. During the test phase, both the targets and the distractors that appeared in relevant display positions were drawn from the stimulus set that had been used as the distractor set during the training phase. In this phase, stimuli and responses were related by a mapping that was varied; stimuli that were targets on some trials appeared as distractors on other trials. In Experiments 2–4 of this article, we explored the generality of the findings of Shiffrin and Schneider by changing and simplifying the experimental paradigm in various ways.

Third, on closer analysis, there are subtle ways in which the procedure used by Shiffrin and Schneider (1977) may have encouraged subjects *not* to ignore the former targets when they appeared as distractors. In Experiment 4d, the appearance of a former target in a certain stimulus frame implied that if a current target was present on the same trial, it was located in the same frame as the former target or in a frame immediately before or after the frame of the former target. This aspect of the design may have induced participants to try to use the temporal location of a former target as a cue to the location of any current target. Furthermore, the probability that a current target was presented on a trial was higher when a former target was present than when former targets were absent (the probabilities were .75 and .50, respectively). Both aspects of the design of Experiment 4d may have counteracted incentives to ignore the former targets. In Experiment 1 of this article, we closely replicated the procedure of Shiffrin and Schneider, but in Experiments 2–4, we used procedures by which the participants had no incentives for attending to the former targets.

EXPERIMENT 1

The design of Experiment 1 was closely similar to that of Shiffrin and Schneider (1977, Experiment 4d). However, instead of using targets drawn from one alphanumeric category (letters vs. digits) and distractors drawn from the other one, we used two arbitrary stimulus sets (each consisting of nine consonants) as target and distractor sets during the training phase of the experiment. The letters in the two sets were chosen so that it seemed impossible to determine whether a stimulus character was a target or a distractor by testing whether the character had a particular simple feature or testing whether the character had at least one out of a particular set of simple features (i.e., testing for a disjunction of simple features).

Method

Participants. Four students (2 females and 2 males) from the Ludwig-Maximilians-University participated in the experiment. Each participant was paid DM 150 (US $95). The ages of the participants ranged between 21 and 41 years. All the participants had normal or corrected-to-normal visual acuity.

Stimuli. Two stimulus sets, each consisting of nine consonants, were used as target and distractor sets. Stimulus Set 1 consisted of *R, D, H, Z, N, T, B, G,* and *C*. Stimulus Set 2 consisted of *P, Q, F, L, X, M, S, K,* and *V*. There was no obvious way of discriminating members of Set 1 from members of Set 2 on the basis of simple physical features (see Figure 1). The letters were constructed by use of a small set of line segments, and a mask was formed by including all of the possible line segments in the same pattern.

Each stimulus frame contained four possible stimulus positions, one at each corner of an imaginary square centered at a small (3 × 3 mm) white (50.3 cd/m^2) fixation cross in the middle of the display screen. The distance from the fixation cross to each corner of the square was 106 mm (5.1°). The stimulus characters (letters and masks) were centered at the corners. The stimuli were white (50.3 cd/m^2) on a black (0.72 cd/m^2) background. The width and height of a stimulus character were 11 mm (0.5°) and 15 mm (0.7°), respectively.

General procedure. The experiments were run on a CRT controlled by an IBM-compatible PC. The participants were seated 1.2 m from the screen in a semidarkened room. Responses were recorded from the computer keyboard placed on a table in front of the participants. Two of the participants responded *present* by pressing a key with their right index finger and *absent* by pressing a key with their left index finger; the other two used the opposite response assignment.

Training. The mapping of stimuli to responses was perfectly consistent during the training phase. Participants 1 and 4 used Stimulus Set 1 as the target set and Stimulus Set 2 as the distractor set; Participants 2 and 3 used the opposite assignment.

Each trial began by presentation of a memory set consisting of four different letters drawn at random from the target set (see Figure 2). After having memorized the four letters, the participant triggered the stimulus presentation by pressing the space bar. With a latency of 1,000 msec after the barpress, the fixation cross appeared, and the cross remained on the screen during the rest of the trial. With a delay of 500 msec after the appearance of the fixation cross, the sequential presentation of 20 stimulus frames was begun. Each frame was exposed for 185 msec, and successive frames were separated by an interval of 15 msec, which yielded a stimulus onset asynchrony (SOA) of 200 msec. After the presentation of the 20 frames, the participant indicated whether any of the four target letters in the memory set had appeared in any of the 20 stimulus frames. The participant should respond either *present* or *absent* (forced choice), but no time pressure was imposed. If the response was in error, the participant was given a short tone as feedback.

For each trial, the 20 stimulus frames were constructed as follows. First, five different letters were drawn at random from the distractor set. Only these five letters were used as distractors in the trial. For each of the 20 frames, then, two randomly chosen positions among the four possible stimulus positions were filled with pattern masks. To fill the remaining two positions, two different letters were drawn at random from the set of five distractor letters, with the constraint that no letter could appear in the same position in two successive frames. Finally, in half the trials, a randomly chosen distractor within Frames 4–18 was replaced by a randomly chosen target letter from the memory set.

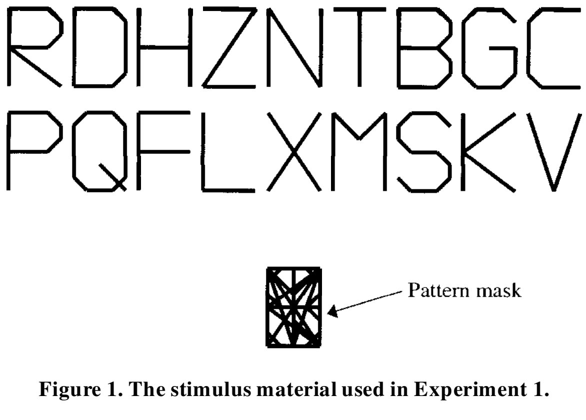

Figure 1. The stimulus material used in Experiment 1.

A block of trials consisted of 20 trials, half of which contained a target letter. The ordering of the trials was random. Each session consisted of 15 blocks (300 trials) and lasted about 1 h. Eight sessions were run during 4 successive days, two sessions per day, with a short break between the sessions. Thus, each participant received a total of 2,400 trials of training.

Test. The mapping of stimuli to responses varied from trial to trial during the test phase. On each trial, a memory set of two letters was selected at random from the stimulus set that had been used as distractor set during the training phase (the set of *former distractors*). Among the remaining seven former distractors, a subset of five was selected at random. Only these five letters were used as distractors in the trial. For each of the 20 stimulus frames in the trial, the four stimulus positions were filled with four different letters that were drawn at random from the subset of five distractor letters, with the constraint that no letter could appear in the same position in two successive frames.

The *relevant diagonal* in a frame was defined as the upper left and the lower right stimulus positions, and the *irrelevant diagonal* was defined as the upper right and the lower left positions. Now, with a probability of .67, a randomly chosen distractor on the relevant diagonal in one of Frames 5–17 was replaced by a randomly chosen target letter from the memory set. Furthermore, with a probability of .67, a randomly chosen distractor on the irrelevant diagonal in one of Frames 4–18 was replaced by a randomly chosen member of the stimulus set that had been used as target set during the training phase (the set of *former targets*). If a target letter from the memory set appeared in the same trial, the former target was placed, with equal probabilities, in the frame *before*, the *same* frame, or the frame *after* the frame containing the target letter. If no target letter from the memory set appeared in the trial, the former target was placed in a frame chosen at random among Frames 4–18. The six different types of trials that are listed in Table 1 were equally frequent.

A block of trials consisted of 60 trials, half of which contained a target letter. The ordering of the trials was random. Each session consisted of five blocks (300 trials) and took about 1 h. Two sessions were run during the 5th day following the 4 days of training.

Results

The error rates were analyzed by use of *signal-detection theory* (Green & Swets, 1966) to disentangle variations in sensitivity (measured by parameter d') from variations in response bias (measured by the natural logarithm of parameter β). Learning curves for each participant are shown with respect to both sensitivity (Figure 3A) and bias (Figure 3B). A linear regression analysis across the 4 participants showed a significant increase in sensitivity during the training period [$F(1,3) = 19.42, p < .05$]. The rate of increase in d' averaged 0.22 units per session. The linear trend in $\log\beta$ as a function of number of session also reached significance [$F(1,3) = 25.00, p < .05$].[1]

The effects of former targets on sensitivity and bias are illustrated in Figure 4. As can be seen in Figure 4A, sensitivity was lower when a former target was present than when former targets were absent. The effect of the former target was significant whether the former target was presented in the frame before the current target [$t(3) = 9.22, p < .005$], the same frame as the current target [$t(3) = 4.39, p < .05$], or the frame after the current target [$t(3) = 3.32, p < .05$). The decrements in d' for the three cases were 0.50, 0.43, and 0.34 units, respectively.

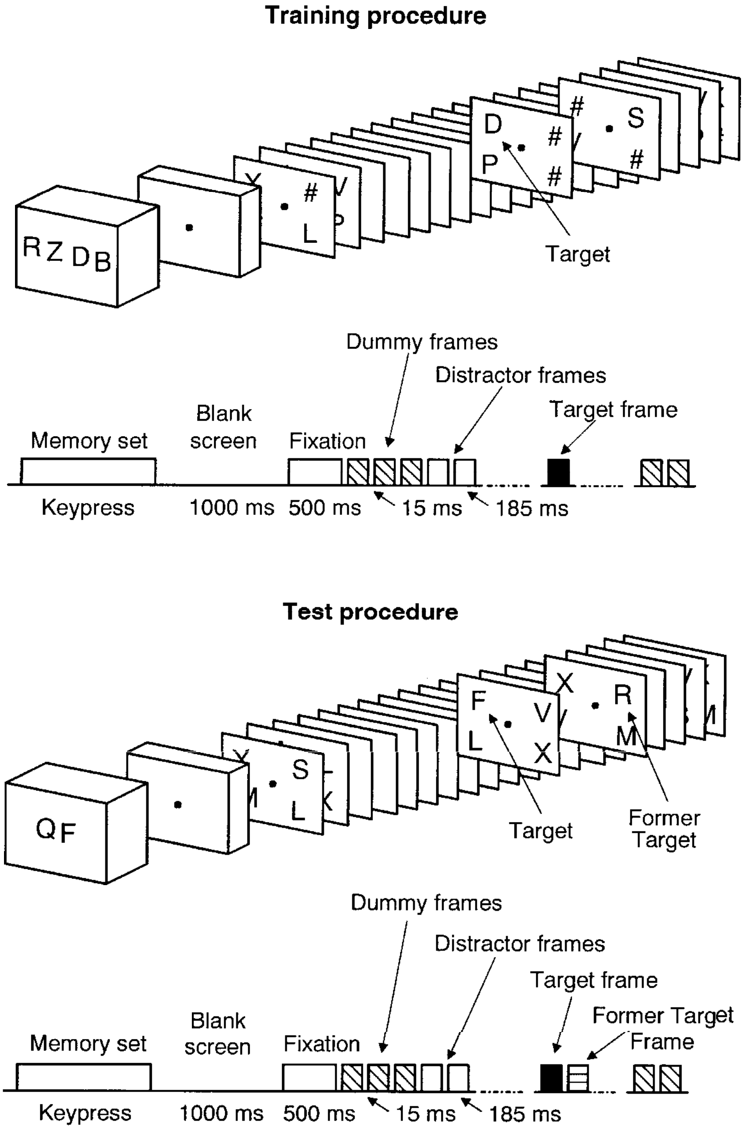

Figure 2. Training and test procedures in Experiment 1. For each procedure, the sequence of events during a typical trial is illustrated together with a time scale that indicates delays and exposure durations. Pattern masks are shown as hash marks (#).

Presentation of a former target had no consistent effect on response bias (see Figure 4B). The null effect was obtained whether the former target was presented in the frame before the current target [$t(3) = 0.54, p = .31$], the same frame as the current target [$t(3) = 0.54, p = .31$], or the frame after the current target [$t(3) = 0.60, p = .29$].

Discussion

The decrement in sensitivity caused by presentation of a former target replicated the breakthrough effect found by Shiffrin and Schneider (1977, Experiment 4d). The decrement we found in d' when a former target was presented in the frame before a current target (0.50) was greater than the corresponding decrement seen in the data of Shiffrin and Schneider (which was about 0.08). The decrements we found in d' when the former target appeared in the same frame (0.43) or in the frame after a current target (0.34) were comparable in magnitude with the corresponding decrements evidenced by Shiffrin and Schneider (about 0.69 and 0.26, respectively). The null effect on response bias also replicated the results of Shiffrin and Schneider.

Experiment 1 showed that the breakthrough effect of Shiffrin and Schneider (1977) can be obtained in conditions in which it seems impossible to determine whether a stimulus character is a target or a distractor by testing whether the character has a particular simple feature or testing whether the character has at least one out of a par-

Table 1
Different Types of Trials in Experiment 1

Type	Current Target	Former Target
1	present	absent
2	absent	absent
3	present	present in frame before
4	present	present in same frame
5	present	present in frame after
6	absent	present

ticular set of simple features (i.e., testing for a disjunction of simple features; see Treisman & Gelade, 1980). The results suggest that attention can be attracted by shapes as complex as individual alphanumeric characters.

EXPERIMENT 2

Experiment 2 was similar to Experiment 1, except that (1) the number of stimulus frames per trial was reduced from 20 to just 1 and (2) the probability that a current target appeared on a trial was independent of whether a former target appeared on the same trial. The experiment was conducted to investigate (1) whether the RSVP procedure used in Experiment 1 was critical for the breakthrough effect to occur and (2) whether the effect was due to aspects of the experimental design that could have induced participants *not* to ignore the former targets when they appeared as distractors—that is, the fact that the temporal location of a former target could be used as a cue to the location of any current target and the fact that the probability that a current target appeared on a trial was higher when a former target was present than when former targets were absent (see Table 1).

Method

Participants. Four students (2 females and 2 males) from the Ludwig-Maximilians-University participated in the experiment. None of the students had participated in Experiment 1. Each participant was paid DM 150. The ages of the participants ranged between 21 and 23 years. All the participants had normal or corrected-to-normal visual acuity.

Stimuli. The stimulus material and display conditions were the same as those in Experiment 1.

General procedure. On each trial, the procedure was the same as that in Experiment 1, except that the participant was presented with only one stimulus frame, which was followed by four pattern masks (see Figure 5). The SOA between the stimulus and the masking frame was 72 msec for Participants 1 and 2 in Sessions 1 and 2. In later sessions with Participants 1 and 2 and all sessions with Participants 3 and 4, the SOA was 43 msec.

Training. To specify a training trial, a memory set of four different letters was selected at random from the target set. Two randomly chosen positions among the four positions in the stimulus frame were filled with pattern masks. On half the trials, the remaining two positions were filled with two different letters drawn at random from the distractor set. On the remaining trials, one of the two positions was filled with a letter chosen at random from the set of distractors, and the other position was filled with a letter chosen at random from the memory set.

A training session consisted of 1,000 trials (50 blocks of 20 trials each) and took about 1 h. The ordering of the trials was random. As in Experiment 1, eight sessions were run during 4 successive days, two sessions per day.

Test. To specify a test trial, a memory set of two letters was selected at random from the set of former distractors (the stimulus set that had been used as distractor set during the training phase). Among the remaining seven former distractors, four different letters were chosen at random, one for each of the four positions in the stimulus frame. With a probability of .5, a randomly chosen distractor on the relevant diagonal was replaced by a randomly chosen target letter from the memory set. Independently, with a probability of .5, a randomly chosen distractor on the irrelevant diagonal was replaced by a randomly chosen former target (a member of the stimulus set that had been used as target set during the training phase). Two sessions of 1,000 (randomly ordered) test trials each were run on the 5th day of the experiment, after the 4 days of training.

Results

Figure 6 shows the learning curves for each of the 4 participants with respect to sensitivity (panel A) and bias (panel B). Effects of training on sensitivity were strong [$F(1,3) = 82.82, p < .005$]. The rate of increase in d' averaged 0.27 units per session. Effects of training on bias were not significant ($F < 1$).

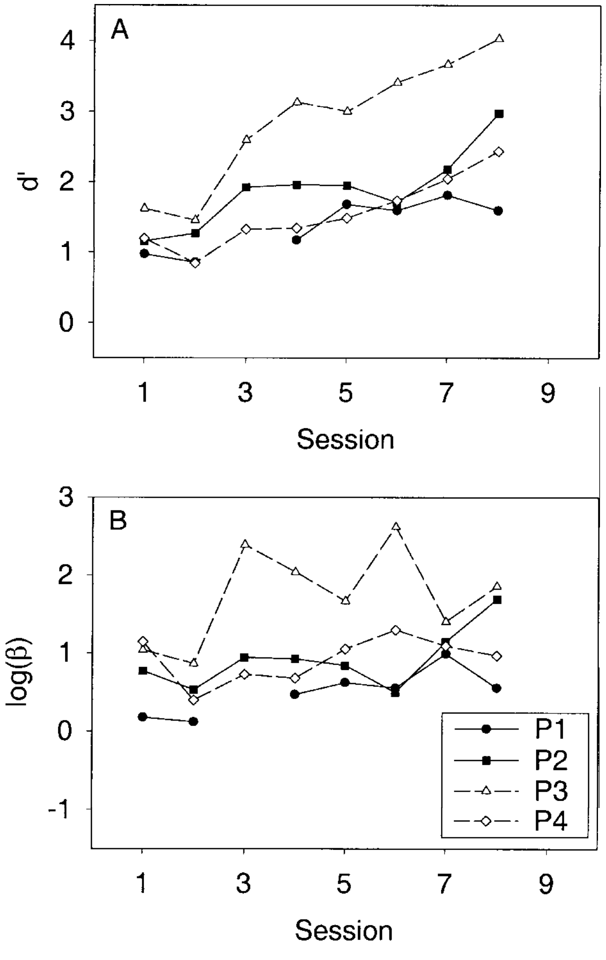

Figure 3. Results from the training phase of Experiment 1. Each graph depicts the data, session by session, for one participant. Panel A shows variations in sensitivity (d'), and panel B shows variations in bias (logβ). As can be seen from the graphs for Participant 1, the data from Session 3 were lost for this participant.

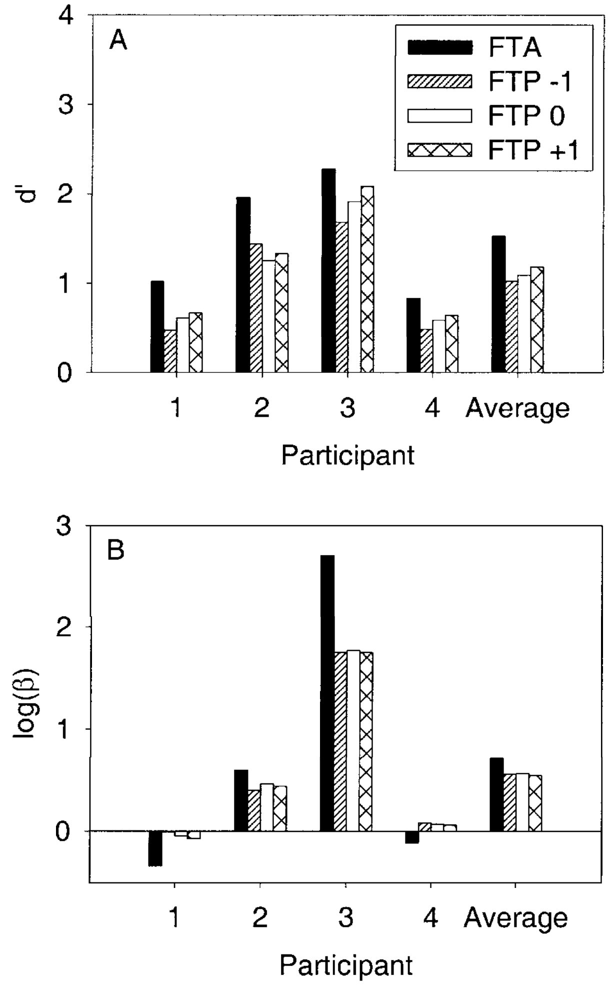

Figure 4. Results from the test phase of Experiment 1. The data are separately shown for trials in which former targets were absent (FTA) and trials in which a former target was presented in the frame before a current target (FTP −1), in the same frame as a current target (FTP 0), and in the frame following a current target (FTP +1). Results are shown both for each individual participant and averaged across participants. Panel A shows variations in sensitivity (*d*′), and panel B shows variations in bias (logβ).

The effects of former targets on sensitivity and bias are depicted in Figure 7. As is illustrated in panel A, sensitivity was lower when a former target was present than when former targets were absent [$t(3) = 3.65, p < .05$]. The decrement in *d*′ averaged 0.13 units. As is illustrated in panel B, the presentation of a former target had no consistent effect on response bias [$t(3) = 1.40, p = .13$].

Discussion

Experiment 2 showed that the breakthrough effect of Shiffrin and Schneider (1977, Experiment 4d) can be replicated not only in RSVP studies, but also in single-frame conditions. The experiment also showed that the effect can be seen in conditions in which presentation of current targets is statistically independent of presentation of former targets (i.e., conditions in which the presentation of a former target provides no more information about current targets than does the presentation of another distractor).

As in Experiment 1, the breakthrough effect appeared as a decrement in the sensitivity (*d*′) for current targets on trials in which a former target was presented. The decrement in *d*′ was smaller in the single-frame conditions used in Experiment 2 (0.13 units) than in the multiframe conditions used in Experiment 1 (0.43 units), but the decrement was significant in both experiments, and it was found in the data of each individual participant.

EXPERIMENT 3

The experimental procedures used for demonstrating the breakthrough effect in Experiments 1 and 2 were rather special. Experiment 3 was conducted to determine whether comparable effects of automatic attention attraction to a former target would be found in a conventional single-frame search paradigm. On each trial, the participant searched through a circular array of 12 letters. Both targets and distractors, including former targets, could appear at any of the 12 display locations.

Method

Participants. Four students (2 females and 2 males) from the University of Copenhagen participated in the experiment. Each participant was paid 700 DKK (US $105). The ages of the participants ranged between 26 and 35 years. All the participants had normal or corrected-to-normal visual acuity.

Stimuli. The target and distractor sets were the same as those in Experiments 1 and 2. Each stimulus frame showed a circular array of 12 letters (one at position 1 o'clock, one at 2 o'clock, . . . , and one at 12 o'clock) centered on fixation. The distance from the center of a letter to the small white fixation cross at the center of the screen was 105 mm (7.5°). The width and height of the letters were 21 mm (1.5°) and 32 mm (2.2°), respectively. All the stimuli were presented in white on a black background at a viewing distance of 0.8 m.

General procedure. Each trial began with the presentation of the memory set (see Figure 8). When the participant pressed a key, the memory set disappeared from view, and with a latency of 1,000 msec, the stimulus frame was exposed for 210 msec. The stimulus frame was immediately succeeded by a 500-msec exposure of a frame with 12 masks, 1 for each of the stimulus letters. The participant's task was to indicate whether any of the letters in the memory set appeared in the display. The response procedures were similar to the ones used in the prior experiments.

Training. During the training phase, each trial was generated as follows. A memory set of four different letters was selected from the target set of nine letters. Twelve distractor letters were drawn at random, with replacement, from the distractor set and distributed among the 12 possible positions. If the trial should contain a target letter, one of the distractors, chosen at random, was replaced by a randomly chosen letter from the memory set.

A block of trials consisted of 20 trials, half of which contained a target letter. The ordering of the trials was random. Each session consisted of 15 blocks (300 trials) and took about 1 h. Eight sessions were run during 4 successive days, again two sessions a day.

Test. The mapping of stimuli to responses varied from trial to trial during the test phase. On each trial, a memory set of two different letters was selected from the set of former distractors (the stimulus set that had been used as distractor set during the training phase). Then the 12 positions in the stimulus frame were filled by

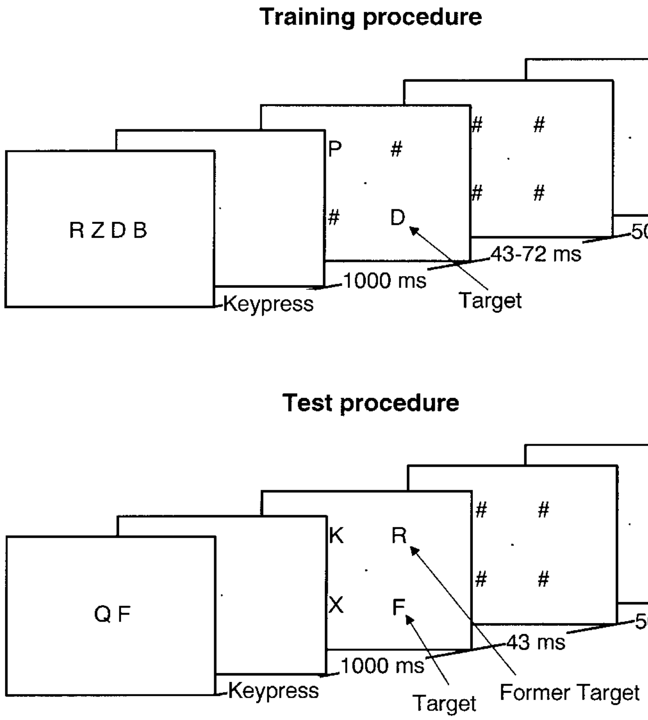

Figure 5. Procedure used in Experiment 2 during the training phase (top) and the test phase (bottom). Pattern masks are shown as hash marks (#).

drawing 12 times at random, with replacement, from the set of the seven remaining former distractors. In half of the trials, one of the distractors, chosen at random, was replaced by a randomly chosen letter from the memory set (a current target). Furthermore, in half of the trials with and half of the trials without a target letter, another randomly chosen distractor was replaced by a randomly chosen former target (a member of the stimulus set that had been used as target set during the training phase). The test phase comprised two sessions of 400 (randomly ordered) test trials each. The sessions were run on the 5th day of the experiment, after the 4 days of training.

Results

The effects of training failed to reach significance [for sensitivity, $F(1,3) = 2.77$, $p = .20$; for bias, $F(1,3) = 1.09, p = .37$; see Figure 9]. However, as in Experiments 1 and 2, presentation of a former target significantly impeded detection of current targets during the test phase [$t(3) = 2.98, p < .05$; see Figure 10A]. The decrement in d' averaged 0.21 units. Again, as in the previous experiments, the presentation of a former target had no consistent effect on response bias [$t(3) = 1.72, p = .09$; see Figure 10B].

Discussion

Experiment 3 was a conventional single-frame search paradigm in which targets and distractors (including former targets) could appear at any possible stimulus location in the display. As in Experiments 1 and 2, presentation of former targets impeded detection of simultaneously presented current targets. The decrement in d' (0.21 units) was slightly greater than the decrement found in Experiment 2 (0.13 units), but the decrements were the same in order of magnitude. Apparently, the effects of automatic attention attraction to former targets were comparable in Experiments 2 and 3.

EXPERIMENT 4

In Experiments 1–3, (1) the participants searched for multiple targets during both the training and the test phases, and (2) mappings of stimuli to responses were consistent during training phases but varied during test phases. Both constraints were lifted in Experiment 4. To reduce uncertainty concerning the identity of the search targets to a minimum, we used a simple single-frame search paradigm with one particular letter as the target throughout the training phase and another particular letter as the target throughout the test phase. As in Experiment 3, the target and distractors could appear at any of the possible stimulus locations in a display.

Method

Participants. Five students (3 females and 2 males) from the Ludwig-Maximilians-University and the University of Copenhagen participated in the experiment. None of the students had participated in any of the previous experiments. Each participant was paid DM 150 or 700 DKK. The ages of the participants ranged between 20 and 35 years. All the participants had normal or corrected-to-normal visual acuity.

Stimuli. Six letters (*H, L, N, T, X,* and *Z*) were used as stimuli. The stimulus letters were selected so that each type of line segment (horizontal, vertical, ascending oblique, and descending oblique) was used in at least two letters. Each stimulus frame contained eight

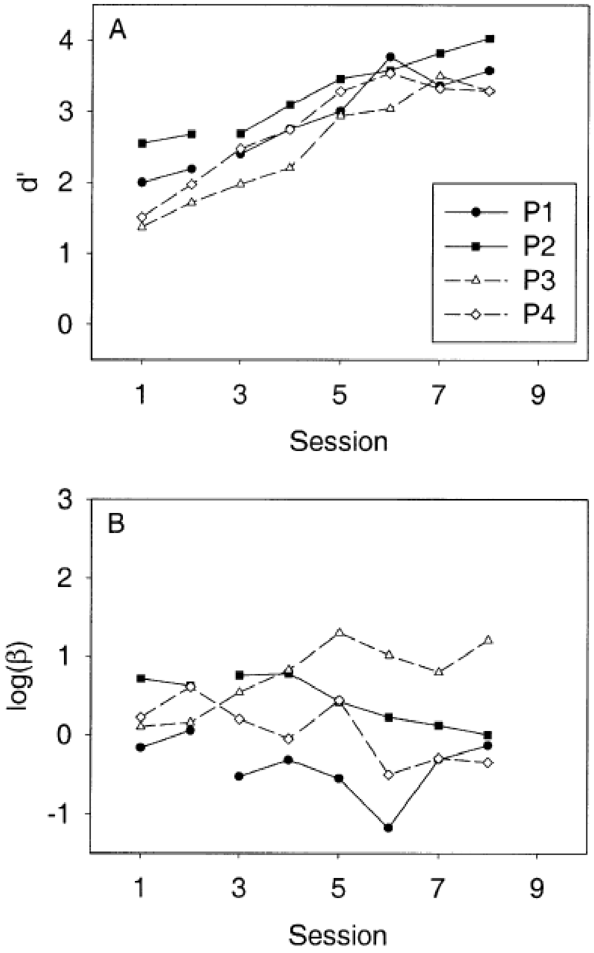

Figure 6. Results from the training phase of Experiment 2. Each graph depicts the data, session by session, for one participant. Panel A shows variations in sensitivity (*d′*), and panel B shows variations in bias (logβ). The breaks in the graphs for Participants 1 and 2 indicate a change in exposure duration from 72 to 43 msec between Sessions 2 and 3.

possible stimulus positions (N, NE, E, SE, S, SW, W, and NW) on the circumference of an imaginary circle centered on fixation. Three, five, or all of the eight positions were occupied by letters. The distance from the center of a letter to the small white fixation cross at the center of the screen was 46 mm (2.2°). The width and height of the letters were 11 mm (0.5°) and 15 mm (0.7°). All the stimuli were presented in white on a black background at a viewing distance of 1.2 m.

General procedure. Each trial was started by the participant's pressing a key, which released a brief exposure of the stimulus frame with a latency of 1,000 msec. The stimulus frame was immediately succeeded by a 430-msec exposure of a frame with eight masks, one at each of the eight possible stimulus positions (see Figure 11). The participant's task was to indicate whether a predesignated target appeared in the stimulus frame. The response procedures were similar to the ones used in the previous experiments.

The duration of the stimulus exposure was varied to prevent ceiling or floor effects. Participants 2, 4, and 5 ran all sessions at 43 msec. Participant 1 ran Sessions 1 and 2 at 43 msec and the remaining sessions at 57 msec. Participant 3 ran Sessions 1 and 2 at 43 msec and the remaining ones at 29 msec.

Training. For each participant, one of the six stimulus letters served as the target throughout the training phase, whereas the other five letters served as distractors. On each trial, the target appeared in the display with a probability of .5, regardless of the display set size (three, five, or eight letters).

One session consisted of 1,000 trials (50 blocks of 20 trials each) and took about 1 h. In the first 6 blocks of each session, the display set size (three, five, or eight letters) varied randomly from trial to trial, and the distractors were randomly drawn with replacement from the set of five distractor letters. Throughout the remaining 44 blocks, the display set size was kept constant at a value of three letters, and the distractors were randomly drawn without replacement from the set of five distractor letters. The spatial distribution of the display items across the eight possible stimulus positions was random. As in the previous experiments, eight training sessions were run during 4 successive days, two sessions per day.

Test. On the 5th day of the experiment, the target and distractor sets were redefined. One of the five letters that had been used as distractors during the training was selected to be the new target. The new distractor set consisted of the four remaining former distractors plus the former target. Two test sessions were run with the new tar-

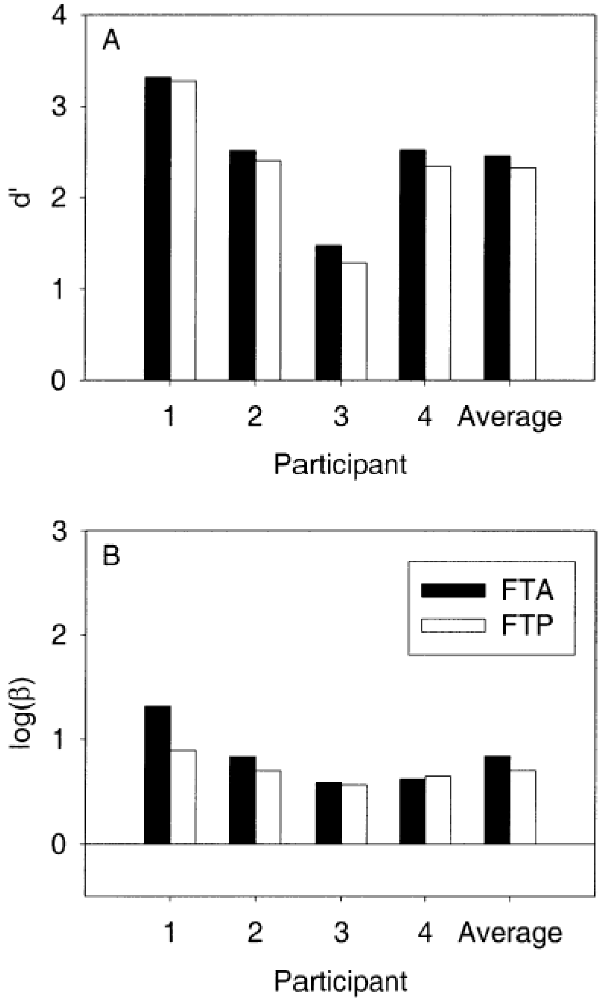

Figure 7. Results from the test phase of Experiment 2. The data are separately shown for trials in which former targets were absent (FTA) and trials in which a former target was present (FTP). Panel A shows variations in sensitivity (*d′*), and panel B shows variations in bias (logβ).

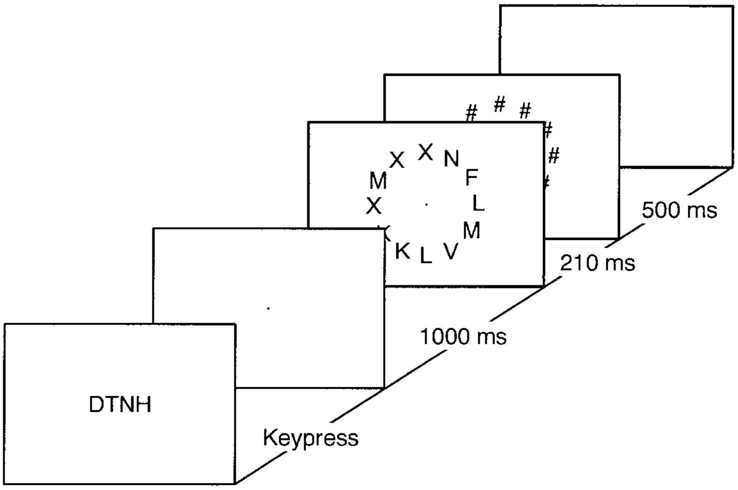

Figure 8. The procedure used during both the training and the test phases of Experiment 3. Note that the memory set contained four letters during the training phase but only two letters during the test phase. Pattern masks are shown as hash marks (#).

get and distractor sets. The former target appeared (once per display) in one half of the stimulus displays, regardless of display size. Except as noted, the procedure during the test phase was the same as that during the training. Thus, in those 44 blocks of each session in which display size was kept constant at a value of three letters, the probability that the former target appeared in a stimulus display was exactly the same as the probability that any other particular member of the new distractor set appeared in the display.

Results

The data from the six blocks of each session with varying display set size were subjected to a two-way (display set size × session) repeated measures analysis of variance. The analysis showed no significant effects of either display set size [$F(1,4) = 5.77, p = .07$] or training [$F(1,4) = 3.40, p = .14$] and no significant interaction between the two ($F < 1$).

The main analyses were based on those 44 blocks of each session in which the display set size was kept constant at a value of three letters. By linear regression, sensitivity measured by d' increased by 0.18 units per session (see Figure 12A). The effect was not significant by an F test [$F(1,4) = 2.41, p = .20$], but it was found in all of the 5 participants, which is significant by a sign test ($p = .03$). Similar analyses for effects of training on response bias (see Figure 12B) showed no significant effects [$F(1,4) = 5.57, p = .08$].

During the test phase, the presentation of a former target caused a decrement in d' averaging 0.15 units (see Figure 13A). The effect bordered on significance by a t test [$t(4) = 2.03, p = .056$] and reached significance at the .05 level by a sign test ($N = 5, x = 5$). Similar analyses for effects of former targets on response bias showed no significant effects [$t(4) = 1.25, p = .15$; see Figure 13B].

Discussion

In Experiment 4, uncertainty concerning the identity of the search targets was reduced to a minimum by using a simple single-frame search paradigm, with one particular letter as the target throughout the training phase and another particular letter as the target throughout the test phase. The target and distractors could appear at any of the possible stimulus locations in a display. As in the prior experiments, presentation of a former target impeded detection of a simultaneously presented current target. The decrement in d' (0.15 units) was smaller than the corresponding decrement found in the multiframe conditions used in Experiment 1 (0.43 units) but comparable in magnitude with the decrements found in the single-frame conditions used in Experiments 2 and 3 (0.13 and 0.21, respectively).

GENERAL DISCUSSION

Experiment 1 replicated the breakthrough effect of Shiffrin and Schneider (1977, Experiment 4d) with sets of stimulus letters that were constructed so that it seemed impossible to determine whether a letter was a target or a distractor by testing for a particular simple feature or a particular disjunction of simple features. The replication of the breakthrough effect in such conditions suggests that attention was attracted by shapes as complex as individual alphanumeric characters.

Experiment 2 showed that the breakthrough effect occurs not only in RSVP studies, but also in single-frame paradigms. The experiment also showed that the effect is found in conditions in which the presentation of a former target provides no more information about current targets than does the presentation of any other distractor. Thus, the experiment met the objection that the procedure used by Shiffrin and Schneider (1977) may have encouraged subjects *not* to ignore the former targets when they appeared as distractors.

Experiments 3 and 4 were conventional single-frame search paradigms in which targets and distractors (in-

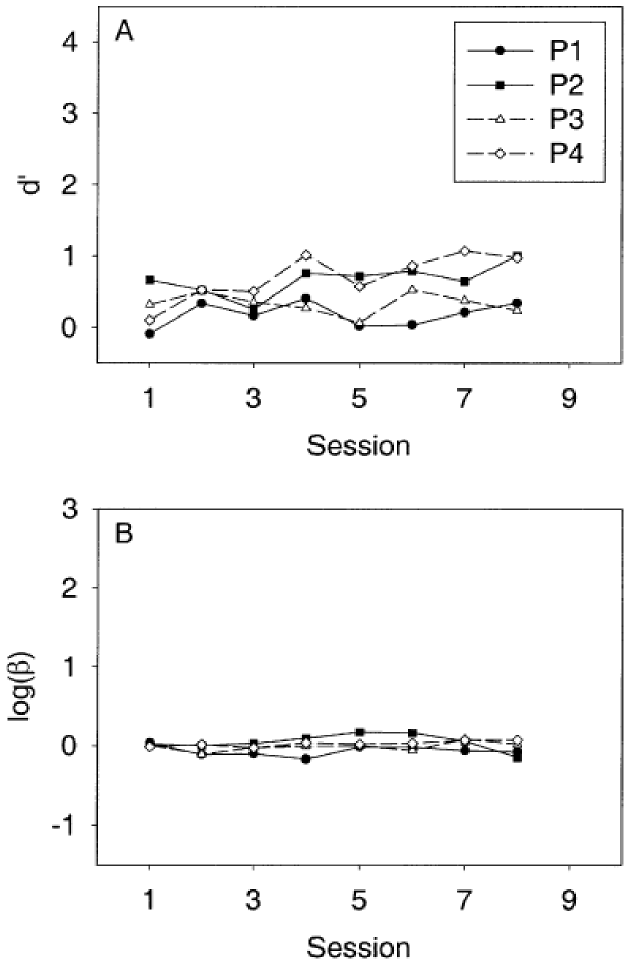

Figure 9. Results from the training phase of Experiment 3. Each graph depicts the data, session by session, for one participant. Panel A shows variations in sensitivity (*d*′), and panel B shows variations in bias (logβ).

cluding former targets) could appear at any possible stimulus location in the display. In Experiment 4, uncertainty concerning the identity of the search targets was reduced to a minimum by using just one particular letter as the target throughout the training phase and another particular letter as the target throughout the test phase. Measured by the resulting decrements in the value of *d*′ for detection of simultaneous current targets, the effects of presentation of former targets in Experiments 3 and 4 were comparable with the effects in Experiment 2.

Measured by the decrements in *d*′ for detection of simultaneous current targets, presentation of former targets had a stronger effect in the multiframe conditions that were used in Experiment 1 than in the single-frame conditions used in Experiments 2–4. It is possible that the stronger effect in Experiment 1 was due to the use of RSVP during the training phase, the use of RSVP during the test phase, or the use of RSVP during both the training and the test phases. It is also possible that the stronger effect in Experiment 1 was due to aspects of the design of the experiment that counteracted incentives to ignore the former targets: (1) the fact that the temporal location of a former target could be used as a cue to the location of any current target and (2) the fact that the probability that a current target was presented on a trial was higher when a former target was present than when former targets were absent.

Although the strength of the effect of presentation of former targets varied between experiments, the effect was highly reliable. For each participant in each of the four experiments, detection of current targets was impaired during presentation of former targets. The results confirm that automatic attention attraction develops not only in the special experimental paradigm used by Shiffrin and Schneider (1977), but also in standard visual search tasks.

Evidence for Parallel Processing

As was argued by Shiffrin and Schneider (1977), the breakthrough effect they found in their Experiment 4d

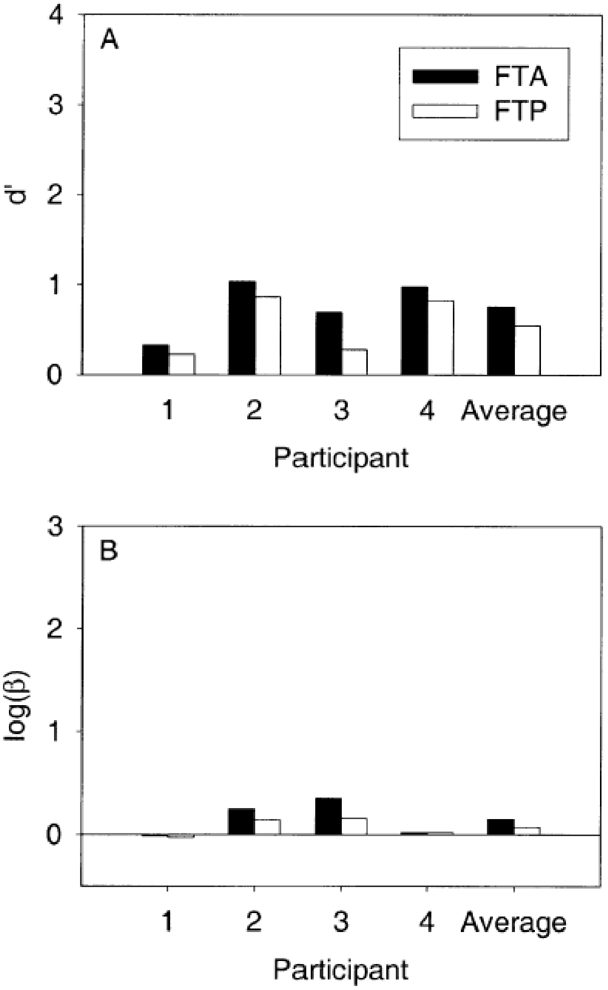

Figure 10. Results from the test phase of Experiment 3. The data are separately shown for trials in which former targets were absent (FTA) and trials in which a former target was present (FTP). Panel A shows variations in sensitivity (*d*′), and panel B shows variations in bias (logβ).

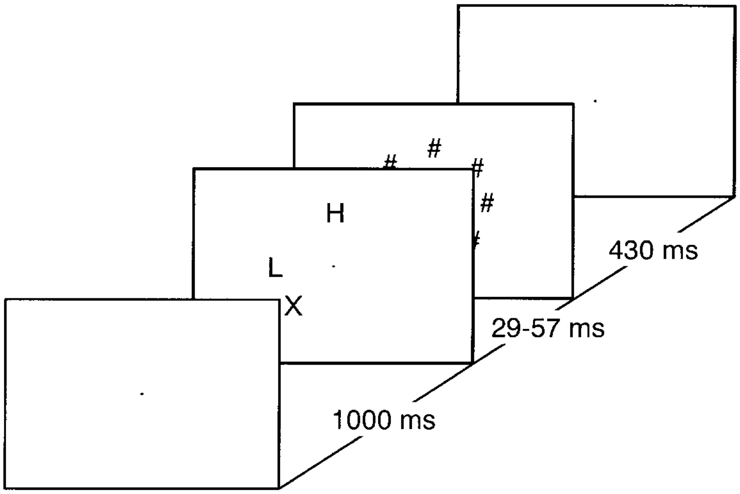

Figure 11. The procedure used during both the training and the test phases of Experiment 4. Pattern masks are shown as hash marks (#).

suggests that simultaneously presented visual stimuli were compared in parallel against memory representations of alphanumeric characters. Experiments 1 and 2 of the present article strengthened the evidence that participants were unable to prevent comparisons between visual stimuli in irrelevant display positions and memory representations of alphanumeric characters. In principle, this result might be explained by assuming a serial recognition mechanism directed to one letter at a time (see, e.g., Treisman, 1988, 1993; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) if the mechanism were assumed to be directed not only to letters in relevant display positions, but (with a certain probability) also to letters in irrelevant display positions. However, assuming automatic comparisons in parallel of simultaneously presented stimuli against memory representations of alphanumeric characters yields a more straightforward explanation for the results.

Separately considered, the results of Experiments 3 and 4 might be explained equally well by assuming serial recognition of stimulus letters, one by one in a random order, as by assuming parallel comparisons of stimulus letters against letter representations in memory. (Similar considerations apply to related studies in which former targets could appear at all the possible stimulus locations in the displays; see, e.g., W. Schneider & Fisk, 1982; see also Fisk, Lee, & Rogers, 1991; Fisk & Rogers, 1988.) However, the results of Experiments 1 and 2 suggest parallel, rather than serial, processing of the stimulus letters, and our finding that the order of magnitude of the effect of a former target (measured by decrement in d') was the same in Experiment 2 as in Experiments 3 and 4 lends further support to the assumption of parallel processing. Thus, if the interference from a former target were assumed to occur when the former target was sampled by a serial recognition mechanism, one would expect a much larger effect of former targets in Experiments 3 and 4 than in Experiment 2. In Experiments 3 and 4, former targets appeared in relevant display positions, so the probability that a former target would be scanned before the current target in a display containing both of them should be relatively high. In Experiment 2, former targets only appeared in irrelevant display positions, so the probability that a former target would be scanned before the current target in a display containing both of them should be quite low.

Related Findings

Attention attraction by salient features and abrupt onsets. During the past 15 years, research on attentional capture has blossomed (for reviews, see Theeuwes, 1996; Yantis, 1996, 1998). Most investigations have concerned the propensity of salient, preattentively processed feature discontinuities or abrupt onsets to attract attention. Theeuwes (1992, 1994, 1995) provided evidence that when the target of search is a featural singleton (e.g., a single red item among green ones), attention will be captured by the most salient singleton in the display, regardless of whether this singleton is relevant to the participant's task. Bacon and Egeth (1994) argued that when participants are looking for a featural singleton in a given dimension, they adopt a strategy (*singleton-detection mode*) of directing attention to the locations with the highest feature contrast, regardless of the dimension in which the contrast is found. Thus, attention should be guided by the output of a general feature-contrast detector.

Yantis has argued that when the participant's task does not require a deliberate attentional set for a featural singleton, an abruptly onset visual stimulus will capture attention (Jonides, 1981; Jonides & Yantis, 1988; Remington, Johnston, & Yantis, 1992; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984), but other types of stimuli will not (Hillstrom & Yantis, 1994; Jonides & Yantis, 1988). However, even capture by abrupt onsets seems not completely automatic. Yantis and Jonides (1990) reported

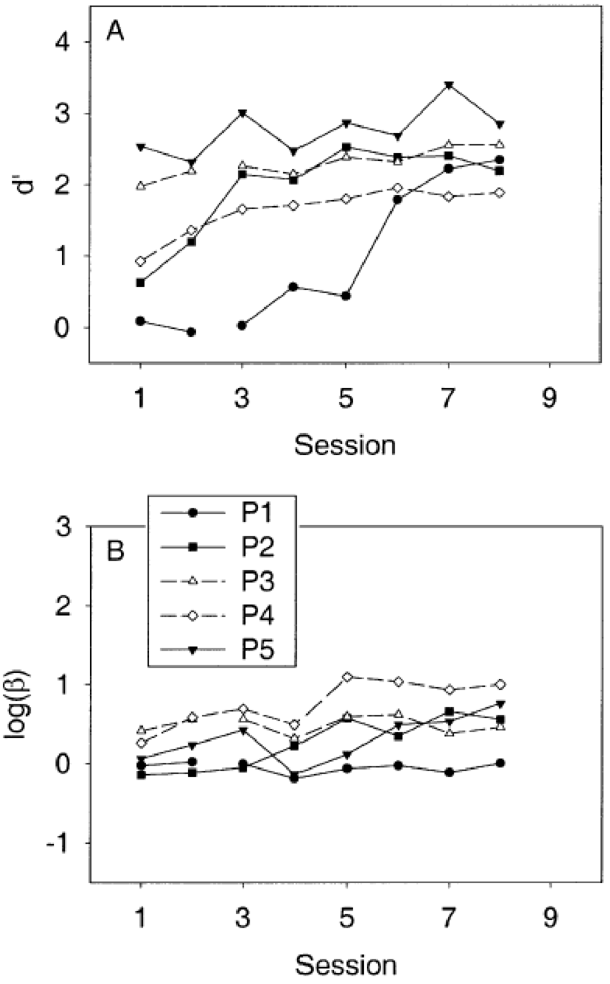

Figure 12. Results from the training phase of Experiment 4. Each graph depicts the data, session by session, for one participant. Panel A shows variations in sensitivity (*d′*), and panel B shows variations in bias (logβ). The breaks in the graphs for Participants 1 and 3 between Sessions 2 and 3 indicate a change in exposure duration from 43 to 57 msec for Participant 1 and a change from 43 to 29 msec for Participant 3.

that when participants had focused attention on a spatial location, no stimuli appearing elsewhere captured attention. Folk, Remington, and Johnston (1992) and Folk, Remington, and Wright (1994) argued that all cases of attentional capture are contingent on *attentional control settings*: Abrupt-onset stimuli may capture attention when participants are looking for abrupt-onset targets but not when looking for color targets, and vice versa (for further discussion, see Folk, Remington, & Johnston, 1993; Yantis, 1993; but see also Theeuwes, 1994).

In the theoretical framework of TVA, the development of automatic attention attraction to particular classes of stimuli in Experiments 1–4 should consist in learning perceptual priorities (π values; see Bundesen, 1990, pp. 540ff). As was noted by Folk et al. (1992, p. 1042), the attentional mechanisms of TVA may also be used for setting attentional controls for salient features and abrupt onsets. For example, if a general feature-contrast detector is available, attention can be guided by the output (η values) of the general feature-contrast detector by letting the perceptual priority (π value) of feature contrast be high and letting perceptual priorities of other properties be low. When TVA is configured in this mode (singleton-detection mode), the attentional weight of an item primarily depends on the feature contrast of the item. Similarly, if separate detectors are available for static versus dynamic discontinuities (see Folk et al., 1992; Folk et al., 1994), attention can be guided by the output (η values) of the detector for static discontinuities (e.g., color and shape singletons) by letting the perceptual priority (π value) of static discontinuity be high, and attention can be guided by the output (η values) of the detector for dynamic discontinuities (e.g., onset and motion singletons) by letting the perceptual priority (π value) of dynamic discontinuity be high.

Attention attraction by words? Experiments 1–4 suggest that visual attention can be attracted by shapes as

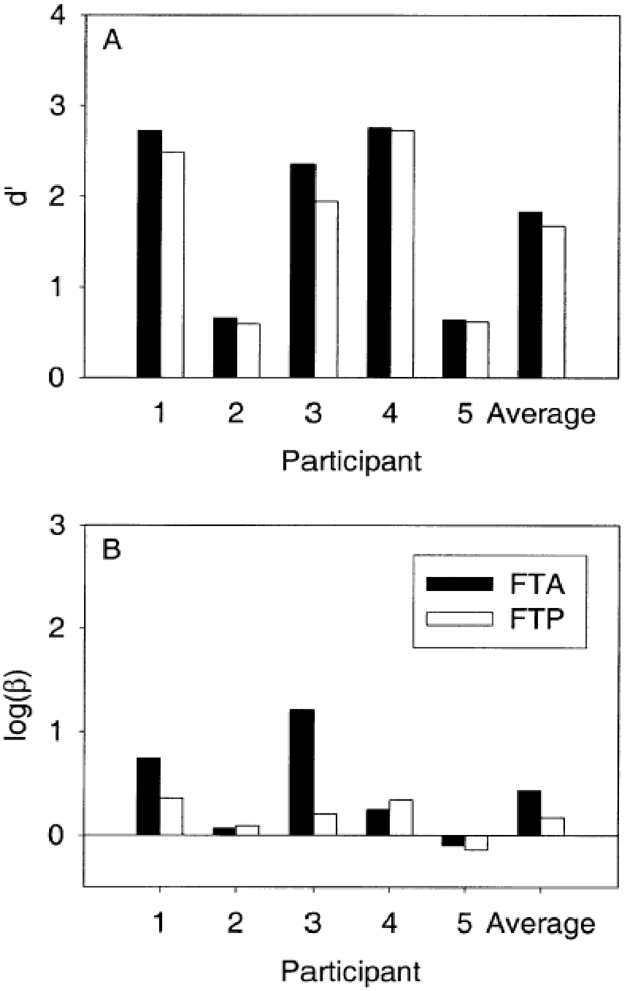

Figure 13. Results from the test phase of Experiment 4. The data are separately shown for trials in which former targets were absent (FTA) and trials in which a former target was present (FTP). Panel A shows variations in sensitivity (*d′*), and panel B shows variations in bias (logβ).

complex as individual alphanumeric characters. Other evidence seems to suggest that the initial allocation of attention to items in a visual display is insensitive to words. Bundesen, Kyllingsbæk, Houmann, and Jensen (1997) presented participants with briefly exposed visual displays of words, which were short, common first names. Each display consisted of four words: two names shown in red and two shown in white. The participants' task was to report the red names (targets) but ignore the white ones (distractors). On some trials, a participant's own name appeared as a display item (target or distractor). Presentation of the participant's own name as a distractor caused no more interference with report of targets than did presentation of other names as distractors. Apparently, visual attention was not automatically attracted by the participant's own name.

If priority learning could occur for visual words, so that a visual word could attract attention automatically, one would expect a participant's attention to be attracted automatically by his or her own name (see Moray, 1959). As was suggested by Bundesen et al. (1997), the contrast between findings with single letters and digits and findings with multiletter words may be explained by assuming that visual attention can be attracted by individual alphanumeric characters, but not by shapes as complex as multiletter words. This assumption could be tested by attempting a replication of Experiment 2, with visual words substituted for the letters.

REFERENCES

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, **55**, 485-496.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, **97**, 523-547.

Bundesen, C. (1998). A computational theory of visual attention. *Philosophical Transactions of the Royal Society of London: Series B*, **353**, 1271-1281.

Bundesen, C., Kyllingsbæk, S., Houmann, K. J., & Jensen, R. M. (1997). Is visual attention automatically attracted by one's own name? *Perception & Psychophysics*, **59**, 714-720.

Cheng, P. W. (1985). Restructuring versus automaticity: Alternative accounts of skill acquisition. *Psychological Review*, **92**, 414-423.

Czerwinski, M., Lightfoot, N., & Shiffrin, R. M. (1992). Automatization and training in visual search. *American Journal of Psychology*, **105**, 271-315.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, **87**, 272-300.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, **96**, 433-458.

Fisk, A. D., Lee, M. D., & Rogers, W. A. (1991). Recombination of automatic processing components: The effects of transfer, reversal, and conflict situations. *Human Factors*, **33**, 267-280.

Fisk, A. D., & Rogers, W. A. (1988). The role of situational context in the development of high-performance skills. *Human Factors*, **30**, 703-712.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception & Performance*, **18**, 1030-1044.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1993). Contingent attentional capture: A reply to Yantis (1993). *Journal of Experimental Psychology: Human Perception & Performance*, **19**, 682-685.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: Contingent attentional capture by apparent motion, abrupt onset, and color. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 317-329.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.

Hillstrom, A. P., & Yantis, S. (1994). Visual motion and attentional capture. *Perception & Psychophysics*, **55**, 399-411.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. [B.] Long & A. [D.] Baddeley (Eds.), *Attention and performance IX* (pp. 187-203). Hillsdale, NJ: Erlbaum.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, **43**, 346-354.

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, **11**, 56-60.

Remington, R. W., Johnston, J. C., & Yantis, S. (1992). Involuntary attentional capture by abrupt onsets. *Perception & Psychophysics*, **51**, 279-290.

Schneider, W. (1985). Toward a model of attention and the development of automatic processing. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 475-492). Hillsdale, NJ: Erlbaum.

Schneider, W., Dumais, S. T., & Shiffrin, R. M. (1984). Automatic and control processing and attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 1-27). New York: Academic Press.

Schneider, W., & Fisk, A. D. (1982). Degree of consistent training: Improvements in search performance and automatic process development. *Perception & Psychophysics*, **31**, 160-168.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, **84**, 1-66.

Schneider, W., & Shiffrin, R. (1985). Categorization (restructuring) and automatization: Two separable factors. *Psychological Review*, **92**, 424-428.

Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition, and space-based motor action. *Visual Cognition*, **2**, 331-375.

Schneider, W. X. (1999). Visual-spatial working memory, attention, and scene representation: A neuro-cognitive theory. *Psychological Research/Psychologische Forschung*, **62**, 220-236.

Shiffrin, R. M., & Czerwinski, M. P. (1988). A model of automatic attention attraction when mapping is partially consistent. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **14**, 562-569.

Shiffrin, R. M., & Dumais, S. T. (1981). The development of automatism. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 111-140). Hillsdale, NJ: Erlbaum.

Shiffrin, R. M., Dumais, S. T., & Schneider, W. (1981). Characteristics of automatism. In J. [B.] Long & A. [D.] Baddeley (Eds.), *Attention and performance IX* (pp. 223-238). Hillsdale, NJ: Erlbaum.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review*, **84**, 127-190.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, **51**, 599-606.

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: Selective search for color and visual abrupt onsets. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 799-806.

Theeuwes, J. (1995). Temporal and spatial characteristics of preattentive and attentive processing. *Visual Cognition*, **2**, 97-100.

Theeuwes, J. (1996). Perceptual selectivity for color and form: On the nature of the interference effect. In A. F. Kramer, M. G. H. Coles, & G. D. Logan (Eds.), *Converging operations in the study of visual selective attention* (pp. 297-314). Washington, DC: American Psychological Association.

Treisman, A. M. (1988). Features and objects: The fourteenth Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology*, **40A**, 201-237.

Treisman, A. M. (1993). The perception of features and objects. In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness and control* (pp. 5-35). Oxford: Oxford University Press.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.

van der Heijden, A. H. C. (1992). *Selective attention in vision*. London: Routledge.

Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 419-433.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception & Performance*, **19**, 676-681.

Yantis, S. (1996). Attention capture in vision. In A. F. Kramer, M. G. H. Coles, & G. D. Logan (Eds.), *Converging operations in the study of visual selective attention* (pp. 45-76). Washington, DC: American Psychological Association.

Yantis, S. (1998). Control of visual attention. In H. Pashler (Ed.), *Attention* (pp. 223-256). Hove, U.K.: Psychology Press.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 95-107.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 601-621.

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 121-134.

NOTE

1. All the reported statistics concerning response bias were calculated on the basis of logβ. Statistical tests based on values of β gave similar results.

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