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Evidence for Split Attentional Foci

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A partial report procedure was used to test the ability of observers to split attention over noncontiguous locations. Observers reported the identity of 2 targets that appeared within a 5 × 5 stimulus array, and cues (validity = 80%) informed them of the 2 most likely target locations. On invalid trials, 1 of the targets appeared directly in between the cued locations. Experiments 1, 1a, and 2 showed a strong accuracy advantage at cued locations compared with intervening ones. This effect was larger when the cues were arranged horizontally rather than vertically. Experiment 3 suggests that this effect of cue orientation reflects an advantage for processing targets that appear in different hemifields. Experiments 4 and 4a suggest that the primary mechanism supporting the flexible deployment of spatial attention is the suppression of interference from stimuli at unattended locations.

There is a substantial body of research showing that when observers direct attention to specific parts of the visual field, information processing is facilitated at attended locations relative to unattended locations. A basic question is how flexibly attention can be deployed over space. Most models of spatial attention have assumed that attention is allocated over contiguous regions of space (e.g., Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980), and various empirical tests have supported this claim (e.g., Eriksen & Yeh, 1985; Heinze, Luck, Muente, Goes, Mangun, & Hillyard, 1994; McCormick & Klein, 1990; Pan & Eriksen, 1993; Posner, Snyder, & Davidson, 1980). However, more recent evidence has suggested that allocation of attention to noncontiguous regions is possible. Kramer and Hahn (1995) and Hahn and Kramer (1998) studied the influence of distractor compatibility at locations directly in between two cued locations and found that under certain conditions performance was unaffected by the distractors. In particular, they noted that when the distractors were presented by removing selected parts of a premask (the nononset condition), observers were able to suppress their influence. However, when the intervening distractors were presented as sudden-onset stimuli, distractor compatibility effects emerged. The investigators concluded that observers could divide attention effectively between noncontiguous locations but that this split focus was disrupted when new perceptual objects appeared in the intervening locations. They used a very strict criterion for evidence of split attention, however—namely, that distractors have absolutely no effect on target processing. The fact that the nononset conditions fulfilled this criterion is a compelling demonstration of split attentional foci, but split attention may not be so restricted. In the present work, we defined *attentional foci* as regions where visual processing is better relative to unattended locations (e.g., see the gradient models proposed by Downing & Pinker, 1985; LaBerge & Brown, 1989) rather than as islands surrounded by a complete absence of stimulus processing. Given this definition, it could be that observers had achieved split attentional foci even during the onset condition of the Kramer and Hahn studies (though to a lesser degree than in the nononset condition). This possibility could not be tested in those experiments because processing quality was not directly assessed at the intervening locations. The present research attempted such a test.

Experiment 1

We explored the flexibility of attentional deployment using a partial report procedure. Observers viewed an array of 25 characters, containing 23 letters and two digits. Their task was to report the identity of the digits. Prior to the onset of the stimulus array, cues indicated two noncontiguous locations where the digits were likely to occur. Twenty percent of the time, one of the targets appeared in between the cued locations, allowing a direct comparison of processing quality at the cued and intervening locations. If observers can split the focus of attention between the cued locations, digit identification should be better at the cued locations than at the position directly in between them. In addition, because all stimuli appeared abruptly in these experiments, we had the opportunity to test whether multiple attentional foci could be achieved even when new objects appeared in the intervening locations.

Method

Observers. Thirteen college students with normal or corrected-to-normal vision participated in a single 45-min session for class credit.

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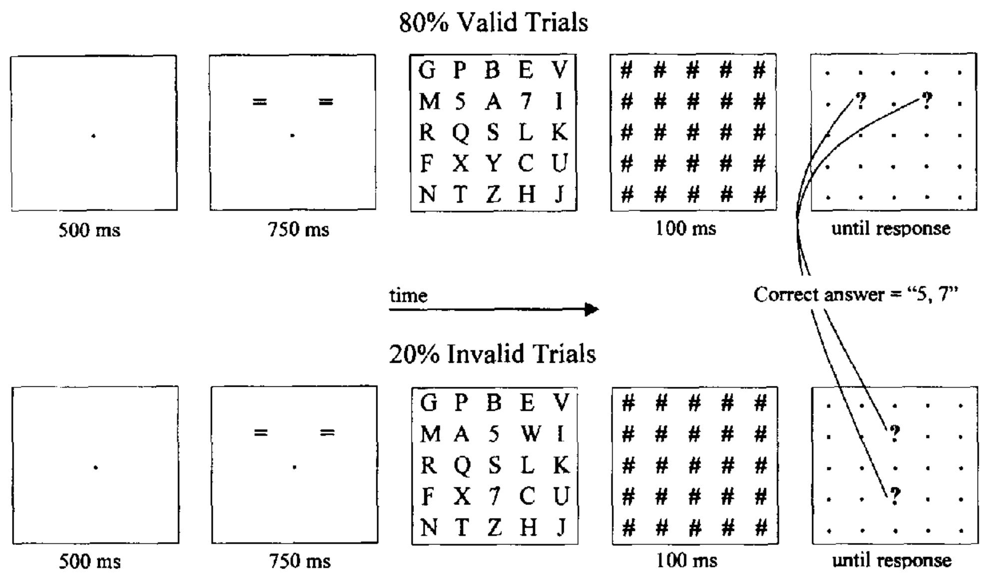

Figure 1. Sequence of events during the valid and invalid trials in Experiment 1. Observers fixated the central dot, and two cues denoted the most likely locations of the target digits. The target array appeared 100 ms after the offset of the cues; the exposure duration of the target array was adjusted within subjects. At the end of the trial, two postcues indicated where the target digits had appeared, and observers reported the target identities.

Apparatus and stimuli. Stimuli were presented on a 14" NEC color computer monitor driven by an IBM PC 486. Observers were seated approximately 45 cm from the display. All stimuli appeared within a centrally placed 5 × 5 array of evenly spaced positions, subtending approximately 6.3° on each side. Letters and digits appearing within these positions were approximately 1.0° tall and 0.4° wide. The horizontal spacing between characters was approximately 1.1°, and the vertical spacing was approximately 0.6°. During any particular trial, the stimulus array contained 23 uppercase letters and two target digits. A new letter set (all 26 letters were possible) and two target digits (from the digits 1–9) were randomly selected (without replacement) for each trial. All stimuli appeared as white objects on a black background.

Design and procedure. The sequence of events in a single trial (depicted in Figure 1) was as follows. (a) The appearance of a fixation dot in the central position of the array marked the beginning of each trial. (b) Five hundred milliseconds after the onset of the fixation point, two cues (the symbol "=") marked the likely locations of the target digits for 750 ms. The cues and target stimuli always appeared within the central 3 × 3 portion of the 5 × 5 array. The presence of the outer stimuli equated the number of characters surrounding each of the central nine stimuli; thus, lateral masking for each of these characters was also equated. There were four possible cue arrangements, depicted in Figure 2. As this figure illustrates, the cues were either horizontally or vertically aligned. The cues indicated the correct locations of the target digits on 80% of the trials. On invalid trials, one target digit always appeared directly in between the cued locations (the middle position), and the other appeared on the opposite side of the central 3 × 3 array (the far position). (c) One hundred milliseconds after the offset of the cues, the stimulus array was presented for a duration that was determined separately for each observer (see the *Timing procedure* section below). (d) Immediately after the offset of the stimulus array, a masking array (composed of 25 "#" symbols) occluded the entire 5 × 5 grid for 250 ms. (e) Finally, the masking array was replaced by a 5 × 5 array of 23 dots and two question marks (postcues) that indicated where the target digits had actually appeared. The postcues ensured that observers were accurately informed of target placement even during invalidly cued trials. The use of postcues and nondigit distractors was intended to minimize the likelihood that observers might report information mistakenly gleaned from nontarget locations.

Observers made an unspeeded report of the identity of both target digits by typing their responses into the computer. Targets were responded to in reading order (i.e., from left to right when they were horizontally arrayed, and from top to bottom when they were vertically arrayed), but observers were free to correct their responses if they accidentally pressed the wrong key. Observers indicated that they had completed their responses by pressing the carriage return key. After they had seen the correct answer, they initiated the next trial by pressing the carriage return key. Immediately after observers had entered their responses, the correct target identities were displayed as feedback. Observers performed 120 experimental trials each (96 validly cued trials, and 24 invalidly cued trials). Cue validity was randomized across all trials. Observers were instructed to maintain fixation whenever a trial was in progress[1] and to identify the digits as accurately as possible.

[1] The exposure durations during these experiments are generally too short to allow eye movements during target presentations. However, the 750-ms cue exposure durations could allow noncompliant observers to move their eyes before the targets appeared. Nevertheless, it is unclear how eye movements could stimulate the pattern of results that we observed. Saccades toward the middle locations would disrupt the large advantage observed at valid locations relative to middle locations. Eye movements toward either cued location would result in large performance decrements for the other cued location, inconsistent with the uniformly high accuracy we observed at valid locations during these experiments (e.g., 88% and 87% on the left and right, respectively, during horizontally cued trials in Experiment 1).

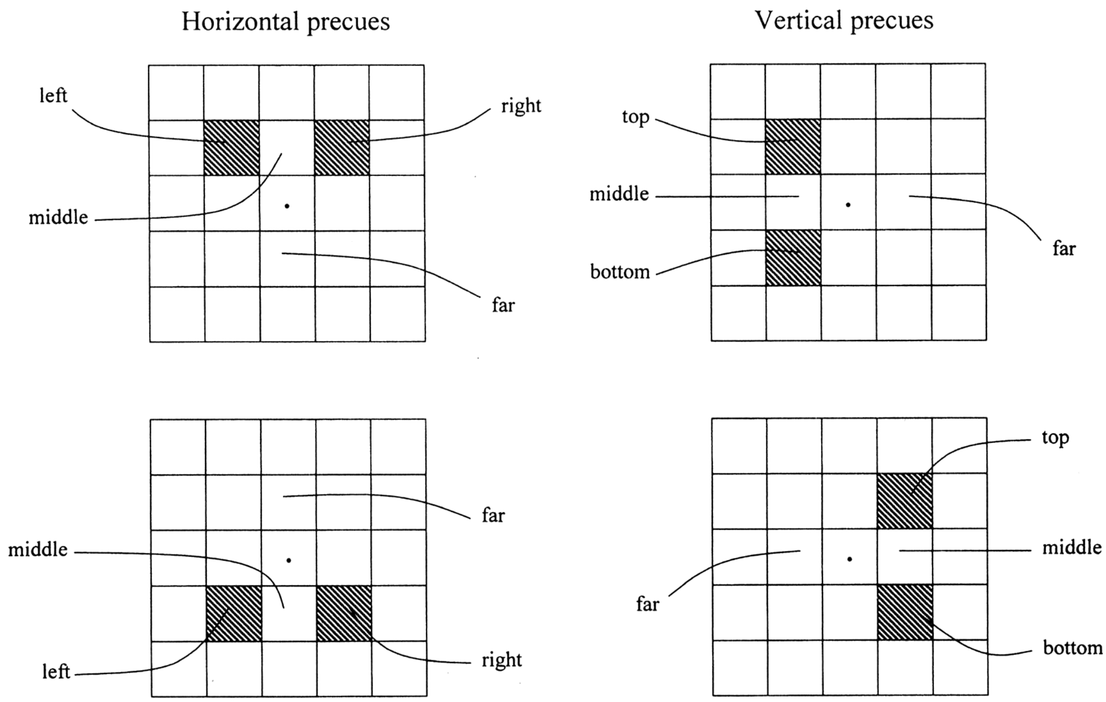

Figure 2. Four cue arrangements were used. The shaded areas indicate the cued locations. Cues were horizontally arrayed during half of the trials and vertically arrayed during the rest. After invalid cues, one target appeared directly in between the cued locations (middle), and the other target appeared on the opposite side of fixation (far).

Observers were made aware of the 80% contingency between the cues and the target positions and were instructed to attend to the cued locations.

Timing procedure. Observers varied significantly in the time needed to encode these target digits. In order to ensure an appropriate degree of difficulty for each observer, exposure duration was tailored to the abilities of each observer using a staircase timing procedure. Only validly cued trials were presented during this procedure. Observers began with the exposure duration set at 250 ms (an easy setting for all the observers we tested). Exposure duration was adjusted as follows. If both digits were reported correctly, exposure duration was lowered by 5 ms. If one digit was reported incorrectly, exposure duration was raised by 5 ms. If both digits were reported incorrectly, exposure duration was raised by 10 ms. Each observer completed 120 trials of this procedure, and the average exposure duration over the final 30 timing trials determined the duration used during the experimental trials.

Results and Discussion

The mean exposure duration determined by the timing procedure was 118 ms (SD = 39 ms). The mean accuracies within each condition of interest are presented in Figure 3A. There was a clear advantage for digits falling in the cued locations compared with those falling in the middle positions, and accuracy was lowest at the far locations. This cueing effect was confirmed by a two-way analysis of variance (ANOVA) with cue validity (valid, invalid–middle, invalid–far) and orientation (horizontal vs. vertical) as within-subject factors. A main effect was obtained for cue, $F(2, 12) = 125.3$, $p < .01$, and paired t tests showed that accuracy was higher at valid locations (78%) than at middle locations (33%), $t(12) = 9.3$, $p < .01$, and higher at middle locations than at far locations (13%), $t(12) = 4.3$, $p < .01$. Thus, despite the fact that sudden onsets occurred at intervening locations, it appears that observers were successful in maintaining a split attentional focus. Notice, however, that accuracy was not uniform across all uncued locations. Instead, there appears to be a gradient of processing quality that peaks at the attended locations, declines at the intervening location, and is lowest at the far location.

It is also apparent from Figure 3A that the cueing advantage was more robust when the cues were horizontally arrayed. This is reflected in a significant interaction of cue and orientation, $F(2, 24) = 8.7$, $p < .01$. Overall, performance during validly cued trials was lower when the cues were vertically rather than horizontally arrayed (69% vs. 88%), $t(12) = 6.6$, $p < .01$. Figure 3B shows the mean accuracies at the four corners where the horizontal and vertical cues appeared (i.e., during validly cued trials). This figure illustrates that a major source of the cue by orientation interaction was a drop in performance at the bottom position when the cues were vertically arrayed. Pairwise comparisons of performance during valid trials show that when the cues were horizontally arrayed, there was no difference between performance at the left (88.1%) and right (87.3%) positions, $t(12) = 0.32$, $p > .05$, or the top (88%) and bottom (87%) positions of the array, $t(12) = 0.38$, $p > .05$. However, when the cues were vertically arrayed, there was a

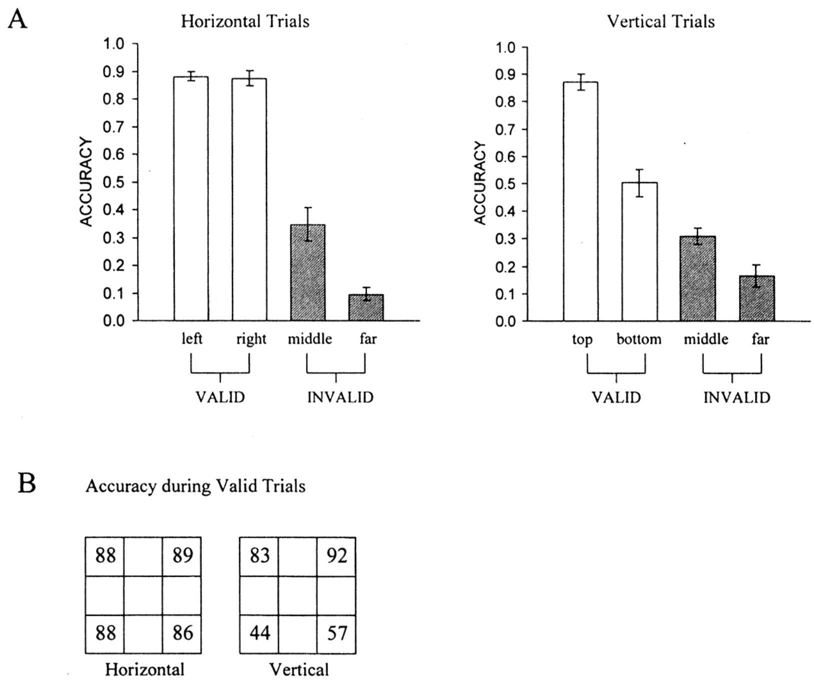

Figure 3. A: Experiment 1 mean accuracies ($\pm SE$) at valid and invalid positions after vertically and horizontally arrayed cues. B: Accuracy during valid trials at the corner positions after horizontally and vertically arrayed cues.

strong decline in performance at the bottom position (50.3%) versus the top position (87.1%), $t(12) = 6.1, p < .01$, as well as a smaller advantage for right positions (74%) over left positions (63%), $t(12) = 3.7, p < .01$. Performance with horizontal and vertical cues did not differ reliably at the middle, $t(12) = 0.63, p = .54$, or far positions, $t(12) = 1.8, p = .10$.

We considered an alternative explanation. Although these data are consistent with a split focus of attention, advantages at multiple cued locations could potentially be explained by a unitary focus of attention that is deployed differently from trial to trial (e.g., see Posner, Snyder, & Davidson, 1980). For instance, each of the cued locations could fall within a unitary focus of attention during half of the trials. In this case, the average accuracy at the cued locations would exceed that of the middle locations (where attention was never focused). However, the validity effects in the present experiment appear too strong to be accounted for by this model.

The essential idea of the single spotlight model is not that attention is confined, but rather that the distribution of attention over any linearly arranged positions (p1, p2, p3) on any trial is either monotonically decreasing or increasing (unless it reaches a maximum at p2, a possibility that is not relevant in this discussion). Assume that the accuracy achievable in any position is a monotonic function of capacity allocated to that position. Suppose that observers respond to cues at positions p1 and p3 by allocating attention as ($x1$, $x2$, $x3$) on some trials and ($x3$, $x2$, $x1$) on others, where $x1 \geq x2 \geq x3$. Now consider the data from the horizontal trials in Experiment 1, where the mean accuracy at p1, p2, and p3 was 88%, 35%, and 87%, respectively. If attention were allocated as ($x1$, $x2$, $x3$), then accuracy at p1, p2, and p3 could not exceed 100%, 35%, and 35%, respectively (given the accuracy observed at middle positions). Likewise, if attention were allocated as ($x3$, $x2$, $x1$), accuracy at p1, p2, and p3 could not exceed 35%, 35%, and 100%, respectively. Let $ax1$, $ax2$, and $ax3$ represent accuracy at p1, p2, and p3, respectively, when attention is allocated as ($x1$, $x2$, $x3$). According to the present mixture model, the mean accuracy at p1 and p3 cannot exceed $(ax1 + ax3)/2$. In Experiment 1, $(ax1 + ax3)/2 = (100\% + 35\%)/2 = 67.5\%$. Thus, the mean accuracy of 88% that we observed at valid positions (during horizontally cued trials) is sufficient to rule out this model. Although the cueing effects were weaker in the vertically cued trials, they were also too large to be explained by such a mixture model.[2]

[2] Another possibility is that observers deployed attention serially to each cued location during the presentation of the target array. In this way, benefits at valid relative to middle positions might be explained by a unitary focus of attention. However, the short exposure durations used in the present experiments were unlikely to allow for a serial identification strategy. For instance, Experiment 1a shows strong evidence of split attentional foci with an average exposure duration of only 69 ms. Previous estimates of the time to identify a stimulus at a cued location and switch attention to another location (e.g., Eriksen & Collins, 1969; Sperling & Reeves, 1980) have ranged from 100 ms to as much as 400 ms. Even if a much faster switching time of 50 ms were assumed, it is unlikely that observers would have time to identify the first target, execute this attentional shift, and identify the second target within 69 ms.

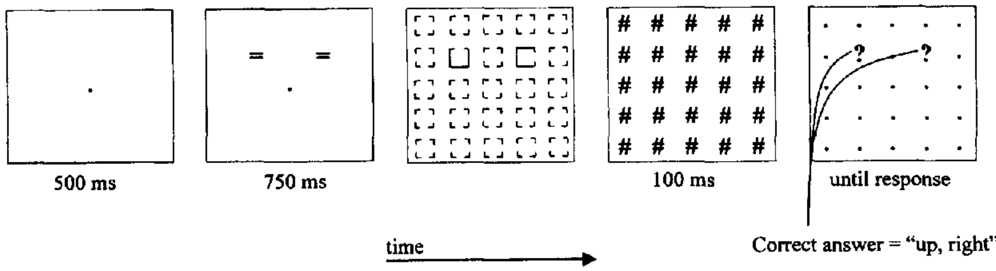

Figure 4. Sequence of events during a valid trial in Experiment 2. Observers reported the location of the gaps in the target stimuli.

Experiment 1a

The advantage at valid relative to middle locations cannot be explained by a mixture model, but another alternative explanation should be considered. Accuracy at the middle position may have been impaired solely by the requirement to report the far target. If attention were deployed equally over the cued locations and the middle location, then only the far location would fall in an unattended location. Then, if the report of an unattended target has a deleterious effect on the report of attended targets, the depressed performance at middle positions might not reflect split attentional foci. Experiment 1a was designed to assess this possibility. We replicated the design of Experiment 1, except that only a single target stimulus was presented during invalid trials. With this procedure we were able to assess visual processing at middle positions in the absence of the possible interference from the far stimulus.

Method

Observers. Twelve college students with normal or corrected-to-normal vision participated in a single 45-min session for class credit.

Apparatus, stimuli, design, and procedure. The apparatus, stimuli, design, and procedure were all identical to those in Experiment 1 with the following exceptions: During invalid trials, only a single target stimulus was presented, in either the middle or the far location. A single postcue marked the target location, and observers responded by entering a single digit. During both the timing procedure and the primary experimental blocks, only horizontal cues were presented.[3]

Results and Discussion

The mean exposure duration determined by the timing procedure was 69 ms (SD = 22 ms). Accuracy was superior at valid locations (73%) relative to middle locations (32%) and poorest at the far positions (12%). A one-way ANOVA with cue (valid, invalid–middle, invalid–far) as a within-subject factor confirmed these cueing effects. A main effect was obtained for cue, $F(1, 11) = 245$, $p < .01$, and paired t tests showed that accuracy was higher at valid locations than at middle locations, $t(11) = 6.6$, $p < .01$, and higher at middle locations than at far locations, $t(11) = 3.0$, $p < .01$. Performance during valid trials did not differ reliably between left positions (74%) and right positions (71%), $t(11) = 0.83$, $p = .42$, or between top positions (70%) and bottom positions (75%), $t(11) = 1.1$, $p = .28$. Just as in Experiment 1, the cueing advantage at valid positions was large enough to reject the mixture model proposed earlier. Most important, a 41% accuracy advantage remained at valid positions relative to middle positions, even when the middle targets were unaccompanied by far targets. It appears that the requirement to report the unattended far targets cannot account for the evidence suggesting split attentional foci.

Experiment 2

The source of the cue-by-orientation interaction observed in Experiments 1 and 1a is unclear. One possibility is that observers were more accurate in reporting horizontally arrayed targets because that is a typical orientation for alphanumeric stimuli. In Experiment 2, we sought to replicate the split attention effect with nonalphanumeric stimuli (a gap-detection task). In addition to reproducing the initial findings, this experiment provided the opportunity to observe whether the cue orientation effect is confined to the particular stimuli used in Experiment 1.

Method

Observers. Twelve college students with normal or corrected-to-normal vision participated in a single 45-min session for class credit.

Apparatus and stimuli. Figure 4 shows the sequence of events during a valid trial of Experiment 2. All trial events (including the relative positions of invalidly cued targets) were the same as in Experiment 1 with the following exceptions: Instead of digits, the

[3] The cues were restricted to horizontal orientations for two reasons. First, the interaction of cue and orientation is a robust feature of the data that will be corroborated by Experiments 2, 3, and 4. Observers are better at identifying targets that are arrayed horizontally rather than vertically. Given this difference, exposure durations could be more precisely estimated using only one cue orientation. Second, because horizontal cues provided the most robust evidence of split attention in these studies, it was important to rule out the proposed alternative in this context. That is, validity effects in the horizontal trials may have been magnified by the vertical orientation of the invalid cues. During Experiment 1a, invalid targets suffered no such disadvantage.

target stimuli were rectangles, approximately 0.8° tall and 0.5° wide, with a gap on one side of the stimulus. The gap was approximately 0.5° in size and was centered on one of the four sides of the rectangle. The distractor stimuli were the same shapes, but with gaps on all four sides. The placement of the gap was randomly determined for each target stimulus.

Design and procedure. These were the same as in Experiment 1, except that observers reported the orientation of the gaps in the target stimuli. They entered their unspeeded responses by pressing one of four keys for each of the two targets. Exposure durations were determined within each observer, using the timing procedure described earlier.

Results and Discussion

The mean exposure duration selected by the timing procedure was 117 ms ($SD = 27$). The mean accuracies within each condition of interest are presented in Figure 5A. In most respects, these data replicate those of Experiment 1. Again, accuracy was higher at validly cued locations (79%) than at middle locations (53%) and was the lowest at the far locations (43%). A two-way ANOVA with cue validity (valid, invalid–middle, invalid–far) and orientation (horizontal vs. vertical) as within-subject factors showed a main effect of cue, $F(2, 22) = 38.8$, $p < .01$. Paired t tests confirmed that performance was better at valid positions than at middle positions, $t(11) = 5.3$, $p < .01$, and better at middle positions than at far positions, $t(11) = 2.9$, $p < .01$. Thus, Experiment 2 provides further evidence of observers' ability to achieve split attentional foci. As Figure 5B shows, these data also replicate the difference in the effectiveness of horizontal and vertical cues; the interaction of cue and orientation was significant, $F(2, 22) = 16.9$, $p < .01$. Notice that although the validity effects observed during the horizontally cued trials are strong enough to reject the mixture model we have discussed, the results of the vertically cued trials cannot rule out this alternative.

Paired t tests of performance on valid trials showed that the source of the cue-by-orientation interaction is similar to the one observed in Experiment 1. Accuracy during the valid trials was higher after horizontal cues (88%) than after vertical cues (70%), $t(11) = 4.8$, $p < .01$. When the cues were horizontally arrayed, there were no significant differences in performance at left (88%) and right (87%) positions, $t(11) = 0.48$, $p > .05$, or between performance at the top (86%) and bottom (89%) positions, $t(11) = 1$, $p > .05$. However, when the cues were vertically arrayed, there were strong differences between performance at the top (81%) and bottom (58%) positions, $t(11) = 3.1$, $p < .01$, whereas performance did not differ at left (68%) and right (71%) positions, $t(11) = 0.87$, $p > .05$. One difference between these results and those of Experiment 1 is the effect of cue orientation on accuracy at the middle and far locations. Experiment 2 showed that when the cues were vertically oriented, accuracy was higher at both the middle, $t(11) = 2.1$, $p = .06$, and far locations, $t(11) = 2.8$, $p < .02$. Thus, two effects underlie the interaction of cue and orientation: (a) the asymmetric performance at top and bottom positions when valid cues were vertically oriented and (b) the higher accuracy at invalid locations when the cues were vertically arrayed. This replication of the cue-orientation effect suggests that it was not limited to the alphanumeric stimuli we used in Experiment 1.

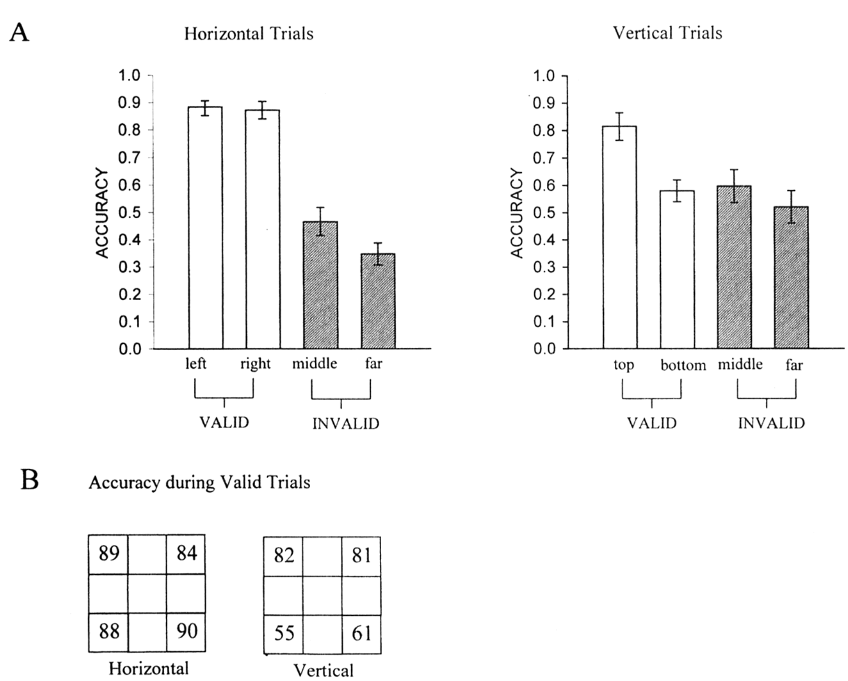

Figure 5. A: Experiment 2 mean accuracies (±*SE*) at valid and invalid positions after vertically and horizontally arrayed cues. B: Accuracy during valid trials at the corner positions after horizontally and vertically arrayed cues.

Experiment 3

Experiment 2 replicated the demonstration of split attentional foci and showed that the effects of cue orientation were not specific to a particular type of stimulus. What is the crucial difference between the horizontal and vertical cue arrangements? One possible factor is that the horizontal cues occupy different hemifields whereas the vertical cues share a hemifield. Previous research has demonstrated facilitated processing of multiple stimuli when they are presented in different hemifields (Davis & Schmit, 1971; Sereno & Kosslyn, 1991). Sereno and Kosslyn found that observers were faster at comparing stimuli that had initially been presented in opposite hemifields. They suggested that this different-hemifield advantage might result from hemisphere-specific processing of the initial stimulus information. In particular, they proposed that when multiple stimuli were initially processed within a single hemisphere, they might tax the resources of a common processing structure or stimulate some kind of intrahemispheric inhibition. Likewise, in the present studies, it is possible that processing of the target locations was hindered during vertically cued trials because the targets were initially processed within a single hemisphere. Moreover, recall from Figure 2 that the invalid locations were horizontally arrayed after vertical cues, but they were vertically arrayed after horizontal cues. Thus, the higher performance we have observed at invalid locations during vertically cued trials (relative to horizontally cued trials) may also reflect a different-hemifield advantage.[4]

Although the different-hemifield advantage might account for the effects of cue orientation, it is also possible that vertically arrayed targets are more difficult to process because they fall on opposite sides of the horizontal meridian. Some studies have suggested that both the horizontal and vertical meridian may be important boundaries in the allocation of spatial selective attention (e.g., Hughes & Zimba, 1987). Experiment 3 was designed to assess the putative advantage of different-hemifield presentations while controlling for the possible disadvantage of crossing the horizontal meridian. Observers were presented with diagonally arrayed cues. During half of the trials in the diagonal condition, the cues appeared in the bottom-left and top-right corners of the central 3 × 3 array; a mirror image of this arrangement was used during the remaining trials of this condition. Targets appearing at the diagonally arrayed locations should enjoy the potential benefits of occupying different hemifields, but they also share the potential disadvantages of crossing the horizontal meridian. Thus, if the advantage at horizontally cued locations is driven by a different-hemifield advantage, performance should remain relatively high during the diagonal trials. However, if the crossing of the horizontal meridian is the cause of the orientation effect, then accuracy should be relatively low during the diagonal trials.

Method

Observers. Eighteen college students with normal or corrected-to-normal vision participated in a single 45-min session for class credit.

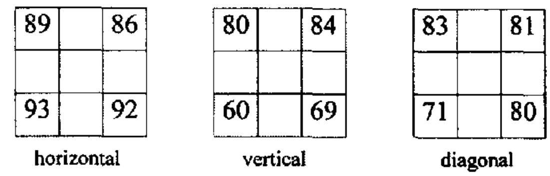

Figure 6. Accuracy at the corner positions in the horizontal, vertical, and diagonal conditions.

Apparatus, stimuli, design, and procedure. The apparatus, stimuli, design, and procedure were all identical to those in Experiment 1 with the following exceptions. Only validly cued trials were presented. In addition to the horizontal and vertical cue arrangements that were used in the previous studies, diagonal cue arrangements (described in the preceding section) were included. During diagonally cued trials, observers reported the top position first. Each cue orientation occurred 48 times, for a total of 144 trials. During the timing procedure, the three types of cue orientation occurred with equal probability. Cue orientation was randomized across all trials.

Results and Discussion

The mean exposure duration selected by the timing procedure was 100 ms (SD = 47 ms). The mean accuracies for each type of cue orientation are presented in Figure 6, broken down by the four positions where target stimuli occurred. A three-way ANOVA with observers, orientation (horizontal, vertical, diagonal), and position (top-left, top-right, bottom-left, bottom-right) as factors revealed a main effect of orientation, $F(2, 34) = 27.1$, $p < .01$. Pairwise comparisons confirmed that accuracy was higher in the horizontal condition (90%) than the diagonal one (79%), $t(17) = 4.3$, $p < .01$, and higher in the diagonal condition than in the vertical one (73%), $t(17) = 3.1$, $p < .01$. There was also a main effect of position, $F(3, 51) = 3.6$, $p < .02$, and a significant interaction of orientation and position, $F(6, 102) = 7.8$, $p < .01$. The main effect of position reflects a trend toward lower accuracy at the bottom positions (77%)

[4] The different-hemifield advantage raises the possibility that the superior accuracy we have observed at valid locations relative to middle locations may be driven in part by a baseline difference in the ease of encoding at the valid locations (that were always at the corners of the central 3 × 3 array, the corner positions) and the locations where invalid stimuli appeared (the central positions). In order to test this possibility, we assessed observers' encoding speed at these locations in a separate control experiment. Eight observers completed two blocks of the staircase timing procedure; one block tested encoding speed at the corner positions, whereas the other block tested encoding speed at the central positions (block order was counterbalanced across observers). All trials were validly cued. We compared the mean exposure durations during the last 30 trials at the corner and central positions. There was a trend toward faster encoding at the central locations (60 ms) than at the corner locations (83 ms), $t(7) = 2.0$, $p = .08$; accuracy was 74% in both conditions. It is likely that the advantage at central locations is due to the larger retinal eccentricity of the corner locations. In any case, the observed cuing effects cannot be accounted for by baseline differences in encoding difficulty.

than at the top positions (84%), $t(17) = 2.0$, $p = .06$. However, as the interaction of orientation and position suggests, the advantage at top positions is driven mainly by the vertical condition (82% vs. 64%), $t(17) = 3.5$, $p < .01$; this pattern replicates the results from Experiments 1 and 2, in which accuracy was consistently biased toward the top positions during the vertical trials. The diagonal trials did not show a reliable difference between accuracy at the top positions (82%) and the bottom positions (76%), $t(17) = 1.5$, $p = .14$, although lower accuracy at the bottom-left position contributed to a trend in this direction. The horizontal trials showed a small but reliable accuracy advantage at the bottom positions (92%) compared with the top positions (87%), $t(17) = 2.8$, $p < .01$. It is not completely clear why performance was lower in the diagonal condition than in the horizontal condition. It is possible that this effect reveals a disadvantage associated with crossing the horizontal meridian in the diagonal condition, but another salient difference between these conditions is the greater distance between the target stimuli in the diagonal condition.

Two aspects of the data from Experiment 3 support the idea of a different-hemifield advantage. First, performance is better in the diagonal condition than in the vertical condition, even though both conditions share the potential disadvantages of crossing the horizontal meridian. Second, all the data reported so far suggest that the disadvantage in the vertical condition reflects a drop in performance at the bottom positions, but this asymmetry is not reliable in the diagonal condition. Given that the clearest distinction between the diagonal and vertical conditions is the fact that the diagonally arrayed targets were in separate hemifields, these data seem best interpreted in terms of a different-hemifield advantage. At what stage of processing does this different-hemifield advantage emerge? One possibility is that this effect reveals a boundary condition in observers' ability to attend to noncontiguous locations. However, it is equally plausible that this different-hemifield advantage is a consequence of a baseline difference in the ease of encoding multiple items within and between hemifields (regardless of where spatial attention is oriented). The present data do not offer a firm resolution of this issue.

Experiment 4

Experiments 1 and 2 document a robust cueing effect at noncontiguous locations in the visual field, at least when the attended locations are horizontally arrayed. But what process drives this relative advantage at cued locations? At least two possibilities can be acknowledged. First, there may be enhanced processing of targets at the attended locations (e.g., Henderson, 1996; Mangun, Hillyard, & Luck, 1993). Second, attention may serve to suppress interference from the distractor stimuli (e.g., Eriksen & Spencer, 1969; Palmer, Ames, & Lindsey, 1993; Shiu & Pashler, 1994; Sperling & Dosher, 1986). In Experiment 4, we replicated the procedure of Experiment 1, but without distractor letters. The two possibilities outlined above are not mutually exclusive; both mechanisms may have contributed to the observed validity effects. However, the two hypotheses make divergent predictions regarding the elimination of the distractor letters. To the extent that Possibility 1 accounts for the effects we have observed, the cueing effects should be similar in Experiment 4. To the extent that these cueing effects result from the exclusion of interference from distractor stimuli, validity effects should be reduced.

Method

Observers. Twenty-two college students with normal or corrected-to-normal vision participated in a single 45-min session for class credit.

Apparatus, stimuli, design, and procedure. The apparatus, stimuli, design, and procedure were all identical to those in Experiment 1, except that targets were presented against an otherwise blank visual field. Figure 7 shows the sequence of events during a valid trial of Experiment 4.

Results and Discussion

The mean exposure duration from the timing procedure was 62 ms ($SD = 13$). The mean accuracies within each condition of interest are presented in Figure 8A. Although the cueing effects observed here are similar to those from Experiment 1, the present effects are far smaller. A two-way ANOVA with cue validity (valid, invalid–middle, invalid–far) and orientation (horizontal vs. vertical) as within-subject factors showed a reliable effect of cue, $F(2, 42) = 47.1$, $p < .01$. And paired t tests confirmed that accuracy was higher at valid positions (81%) than at middle positions (75%), $t(21) = 2.0$, $p < .05$, and higher at middle positions than far positions (42%), $t(21) = 8.6$, $p < .01$. In addition, the interaction of cue and orientation was replicated, $F(2,$

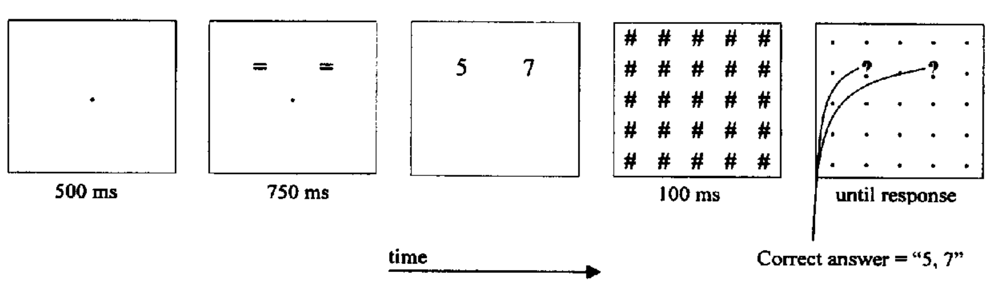

Figure 7. Sequence of events during a valid trial in Experiment 4. This procedure was identical to that of Experiment 1, except that no letter distractors were presented.

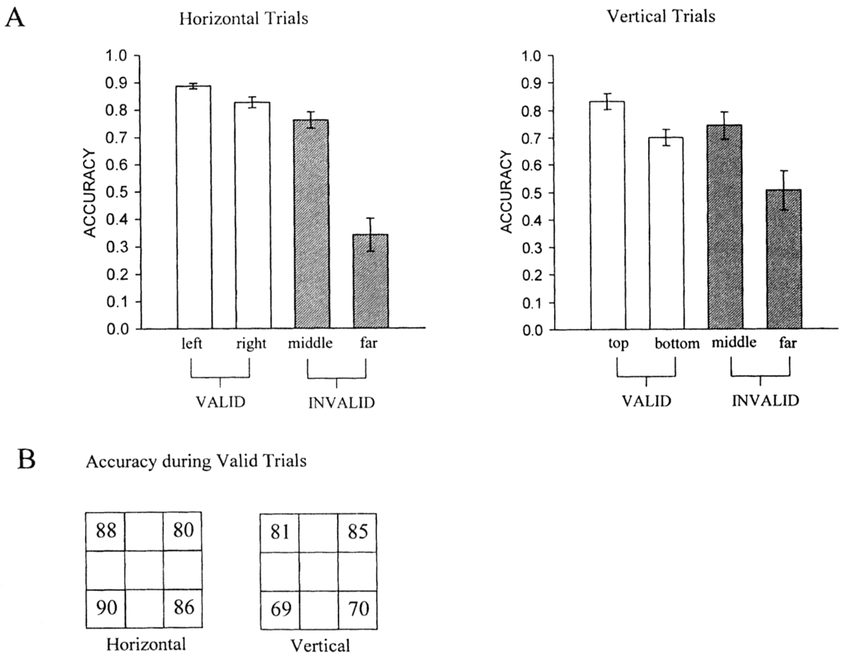

Figure 8. A: Experiment 4 mean accuracies ($\pm SE$) at valid and invalid positions after vertically and horizontally arrayed cues. B: Accuracy during valid trials at the corner positions after horizontally and vertically arrayed cues.

42) = 14.8, $p < .01$. Accuracy during valid trials was higher after horizontally arrayed cues (86%) than after vertically arrayed cues (76%), $t(21) = 4.0$, $p < .01$, and accuracy at the far locations was higher after vertically arrayed cues (50%) than after horizontally arrayed cues (34%), $t(21) = 3.7$, $p < .01$.

Accuracy at the four corners where the horizontal and vertical cues appeared (shown in Figure 8B) revealed biases similar to those observed in the previous experiments. On the vertically cued trials, there was a replication of the advantage at the top locations (83%) versus the bottom locations (70%), $t(21) = 3.1$, $p < .01$, and there was no difference observed between performance at the left (75%) and right (78%) positions, $t(21) = 1.2$, $p = .25$. However, during the horizontal trials, the data diverge slightly from the previous experiments; there was a trend toward lower performance at the top positions (84%) versus the bottom positions (88%), $t(21) = 1.9$, $p = .07$, and performance was significantly higher at left positions (89%) than at right positions (83%), $t(21) = 3.5$, $p < .01$. It is unclear why the left versus right difference emerged in the horizontal trials. It is possible that this effect is due to the fact that the leftward stimulus was almost always reported first in the horizontal trials (unless the observer took the opportunity to correct his or her responses). However, this hypothesis would have predicted a similar left–right difference in the first three experiments.

The result of primary interest is the diminution of the cueing effects after the elimination of the irrelevant letter stimuli. In order to quantify the apparent differences in the size of the cueing effects of Experiments 1 and 4, we carried out a three-way ANOVA with cue validity (valid, invalid–middle, invalid–far) and orientation (horizontal vs. vertical) as within-subject factors and distractor-presence (yes or no) as a between-subjects factor. This analysis revealed a main effect of cue, $F(2, 66) = 121.0$, $p < .01$, and distractor presence, $F(1, 33) = 40.5$, $p < .01$. The latter effect reflects observers' superior performance in Experiment 4, and unpaired t tests showed that the distractor-presence effect emerged during the invalidly cued trials. Performance was higher in Experiment 4 than in Experiment 1 at the middle positions (75% vs. 33%), $t(33) = 8.4$, $p < .01$, and at the far positions (42% vs. 13%), $t(33) = 3.9$, $p < .01$; and there was no reliable difference in accuracy at the valid positions during Experiment 4 (81%) and Experiment 1 (78%), $t(33) = 1.2$, $p = .23$. In addition, there was a significant interaction of cue and distractor presence, $F(2, 66) = 19.2$, $p < .01$. An unpaired t test confirmed that this interaction reflects a larger valid–invalid difference in Experiment 1 (55%) than in Experiment 4 (22%), $t(33) = 5.6$, $p < .01$. The dramatic reduction in cueing effects observed in Experiment 4 suggests that the primary effect of attention in these experiments is the exclusion of noise from distractor stimuli.

Experiment 4a

If attention merely suppresses distractor noise in these studies, why should there be any cueing effects at all in Experiment 4? That is, once the irrelevant letter distractors were eliminated, how can noise reduction drive accuracy differences at valid and invalid locations? One possibility is that the full-field mask used in Experiment 4 was a

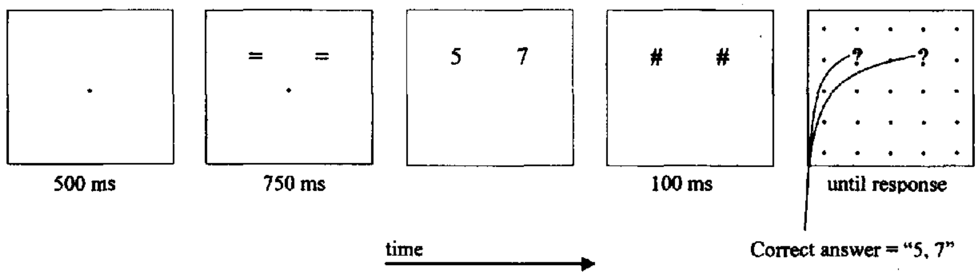

Figure 9. Sequence of events during a valid trial in Experiment 4a. This procedure was identical to that of Experiment 4, except that the masks appeared only over target positions.

significant source of noise at unattended locations. Using a digit identification task, Shiu and Pashler (1994) showed that when simultaneous multiple masks were presented, accuracy was higher with a valid cue than with an invalid cue; however, this difference was almost completely eliminated when only a single mask was presented over the target location. Cheal and Gregory (1997) also found larger cueing effects with multiple masks than with a single mask. Thus, evidence from past research confirms that masks may serve as a significant source of noise at unattended locations. To assess the extent to which the full-field mask was contributing to the cueing effects we had observed, we replicated Experiment 4 with masks that occluded only the locations of the target stimuli.

Method

Observers. Twenty-two college students with normal or corrected-to-normal vision participated in a single 45-min session for class credit.

Apparatus, stimuli, design, and procedure. The apparatus, stimuli, design, and procedure were all identical to those in Experiment 4, except that the masks appeared only directly over the locations where the target stimuli appeared on each trial. Figure 9 shows the sequence of events during a valid trial of Experiment 4a.

Results and Discussion

The mean exposure duration determined by the timing procedure was 59 ms ($SD = 14$). The mean accuracies within each condition of interest are presented in Figure 10. The cueing effects in Experiment 4a were even smaller than those observed in Experiment 4. A two-way ANOVA with cue validity (valid, invalid–middle, invalid–far) and orientation (horizontal vs. vertical) as within-subject factors shows a reliable effect of cue, $F(2, 42) = 12.9, p < .01$. Paired t tests showed that the cueing effect is entirely due to the difference between accuracy at the valid positions and the far positions (80% vs. 69%), $t(21) = 4.2, p < .01$. Accuracy was equal at valid and middle positions (80% vs. 81%), $t(21) = 0.3, p = .76$, suggesting that the split attentional focus that we have observed is driven by the suppression of information from the intervening locations rather than a direct enhancement of visual processing at the attended locations.[5,6] If visual processing were enhanced at valid locations relative to middle locations, there is no apparent reason why this advantage should disappear when the distractors were eliminated. However, if the valid–middle difference resulted from the suppression of noise from the intervening distractor, it is clear why the elimination of this noise source might preclude the need for attentional gating.

Experiment 4a was the first in which we did not observe a reliable interaction of cue and orientation. The first three studies documented better performance at the far positions (i.e., smaller validity effects) after vertical precues; however, Experiment 4a revealed no significant differences between the horizontally and vertically cued trials at valid, middle, or far positions. In Experiments 4 and 4a, horizontal cues resulted in 34% and 66% accuracy at far positions, $t(42) = 4.7, p < .01$; apparently, this rise in performance at far positions after horizontally arrayed cues eliminated the usual effect of cue orientation. Even so, the results of Experiment 4a do replicate the pattern of accuracy found at the validly cued positions during horizontal and vertical trials. That is, after vertically arrayed cues, accuracy was higher at the top positions (82%) than at the bottom positions (75%), $t(21) = 2.8, p < .01$, and accuracy was equal at left positions (79%) and right positions (79%), $t(21) = 0.03, p = .97$. In contrast, after horizontally arrayed cues, accuracy was equal at the top positions (80%) and the bottom positions (82%), $t(21) = 1.0, p = .38$, and accuracy was higher at the left positions (85%) than at the right positions (77%), $t(21) = 3.8, p < .01$. Just as in Experiment 4, these biases are unlikely to be explained by an order-of-report effect. Otherwise, we should have observed the same effects during Experiments 1 and 2. It is possible that this effect is tied to the absence of irrelevant distractors; this left–right asymmetry is absent

[5] This result also suggests a disconfirmation of the alternative explanation addressed by Experiment 1a. That is, even though observers in Experiment 4a reported middle and far locations simultaneously, there was no evidence of a difference between performance at valid and middle locations. Thus, the requirement to report targets at far locations is not sufficient to cause poor identification accuracy for middle targets.

[6] Although accuracy was equal at valid and middle locations, it is possible that a residual advantage at valid locations was obscured by the greater retinal eccentricity of the valid positions. Even so, the size of such an effect is likely to be negligible compared with the 45% advantage we observed at valid versus middle positions with distractor letters and a full-field mask (Experiment 1).

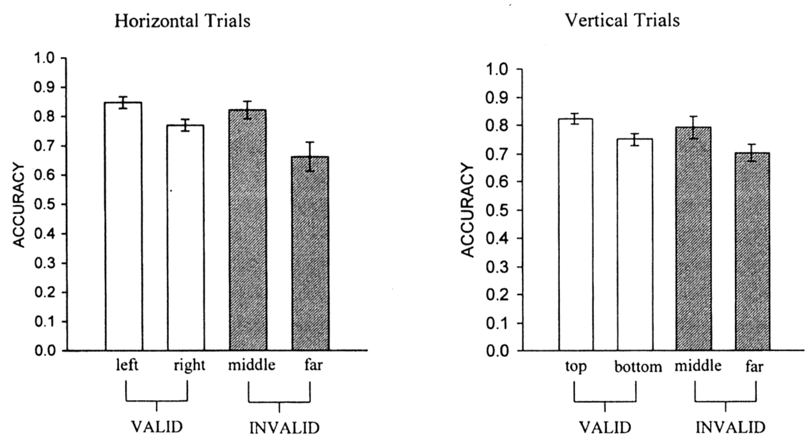

Figure 10. Experiment 4a mean accuracies ($\pm SE$) at valid and invalid positions after vertically and horizontally arrayed cues.

when irrelevant stimuli are presented (Experiments 1 and 2) and is present during the last two studies, in which the letter distractors were eliminated.

In order to quantify the different effects of the full and partial masks used in Experiments 4 and 4a, we carried out a three-way ANOVA with cue validity (valid, invalid–middle, invalid–far) and orientation (horizontal vs. vertical) as within-subject factors and mask type (full or partial; i.e., Experiment 4 or 4a) as a between-subjects factor. There is a robust effect of cue, $F(2, 84) = 59.1, p < .01$, and of mask type, $F(1, 42) = 7.5, p < .01$. The effect of mask type reflects higher accuracy during Experiment 4a than Experiment 4, particularly at far positions (68% vs. 42%), $t(86) = 5.0, p < .01$. The mean accuracy was also higher at middle positions during Experiment 4a (81% vs. 75%), but this effect did not reach significance, $t(86) = 1.5, p = .14$. Performance at the valid locations was equal during Experiment 4 and 4a, $t(86) = 0.78, p = .44$. There was a significant interaction of cue and mask type, $F(1, 42) = 15.4, p < .01$, and this effect also appears to have been driven by the difference in performance at far positions during the partial-mask and full-mask trials. That is, better performance at far positions resulted in smaller cueing effects during trials with partial masks. There was also a significant interaction of cue and orientation, $F(2, 84) = 13.2, p < .01$. As observed in the previous experiments, cueing effects were larger when the cues were horizontally rather than vertically arrayed; this effect can be traced directly to higher performance at far positions after vertically arrayed cues (60% vs. 50%), $t(43) = 3.0, p < .01$. Finally, we observed a significant three-way interaction of cue, orientation, and mask type, $F(2, 84) = 4.6, p < .01$. This interaction is apparently due to the fact that the higher accuracy at far positions (with partial masks relative to with full masks) is more pronounced when the cues are horizontally arrayed.

In summary, the change from a full to a partial mask resulted in a general rise in performance at invalid locations; as a result, the accuracy advantage at valid locations was eliminated relative to middle locations and markedly reduced relative to far positions (from 39% to 11%). The overall rise in accuracy caused by the use of partial masks in Experiment 4a confirms that the full-field mask is a significant source of noise at invalid locations (consistent with Cheal & Gregory, 1997; Palmer et al., 1993; Shiu & Pashler, 1994). Experiments 4 and 4a demonstrate that the majority of the cueing effects we have observed are dependent on the presence of extraneous visual noise; when the letter distractors and masking characters were eliminated from the nontarget locations, cueing effects were markedly reduced. Indeed, the difference between valid and far accuracy in Experiment 1 (65%) was almost six times greater than the 11% difference observed in Experiment 4a. Thus, the argument remains that the primary benefit of attention in these experiments is the reduction of interference from extraneous visual noise. Nevertheless, even with the partial masks, there was a reliable accuracy advantage at valid locations relative to far locations. Superior accuracy at valid locations has been observed with other procedures (Cheal & Gregory, 1997; Henderson, 1996; Luck, Hillyard, Mouloua, & Hawkins, 1996) that minimized irrelevant noise (i.e., distractor stimuli were excluded and masks were presented only at target locations). A pure noise-reduction account cannot easily explain these results. Pashler (1997) argued that cueing effects not attributable to noise reduction may take the form of cost rather than benefit and thus may not necessarily indicate enhancement. Because we did not include neutral conditions, our data do not speak to this rather thorny issue, and we do not pursue the question further here. We can conclude, however, that noise reduction doubtless explains some and may explain all of the evidence we have observed in support of split attentional foci. When partial masks were used, no advantage was observed for valid locations over the intervening locations.[7]

[7] An alternative account of these data (that does not invoke noise suppression) is that observers adopted a different orienting strategy in the absence of distractors. Under these conditions, observers may choose to expand their focus of attention to include intervening locations. This strategy may be viable precisely because of the absence of interfering visual information at the uncued locations. In

General Discussion

These studies provide clear evidence that it is possible for observers to achieve multiple foci of attention in the visual field. We observed a bimodal distribution of processing quality, in which accuracy was highest at two noncontiguous locations and markedly lower directly in between these locations. These data appear to disconfirm models that restrict the geometry of attentional deployment to a single gradient with a unitary peak in processing quality. This conclusion is consistent with some previous investigations (Bichot, Cave, & Pashler, 1999; Castiello & Umilta, 1992; Hahn & Kramer, 1998; Kramer & Hahn, 1995). However, several other studies have failed to find evidence for such flexible deployment of attention (e.g., Eriksen & Yeh, 1985; Heinze et al., 1994; McCormick & Klein, 1990; Pan & Eriksen, 1993; Posner et al., 1980). What are the key differences between these studies? Kramer and Hahn suggested that the appearance of new objects among the attended locations could disrupt the successful maintenance of split attentional foci; in line with this, their results showed that new objects appearing among the attended locations influenced the processing of the cued information (replicating the results of Pan & Eriksen, 1993), whereas the same distractors presented without sudden onsets did not affect target processing. However, the present studies show that when processing quality is directly assessed at the intervening locations, a clear advantage can still be observed at cued versus intervening locations, even when all stimuli are presented as sudden onsets. Thus, although new objects appearing between the attended locations may not be completely suppressed, they do not preclude noncontiguous peaks of processing quality.

Despite our results, the constraint offered by Kramer and Hahn (1995) may bear on why Heinze et al. (1994) failed to observe evidence of split attentional foci. In the Heinze et al. study, observers were cued to pay attention to two separate locations, and event-related potentials (ERPs) were recorded to behaviorally irrelevant probes that appeared at valid and invalid locations. The invalid locations included intervening locations (directly in between the cued locations) and adjacent locations (next to but not between the cued locations). Heinze et al. observed enhanced amplitude ERP signals at cued locations relative to adjacent locations, but the cued locations showed no such advantage over the intervening locations. The investigators concluded that observers were attending a unitary region that encompassed the cued and intervening locations. Hahn and Kramer (1998) suggested that the abrupt appearance of the irrelevant probes in between the cued locations may have disrupted the observers' focus of attention in this study. Heinze et al. observed reliable amplitude enhancements at cued versus adjacent locations; therefore, the explanation offered by Hahn and Kramer assumes that probes at adjacent locations were less disruptive than probes at intervening locations. Our data support this assumption. Accuracy was higher at the middle locations than at locations on the opposite side of the target array, consistent with the idea that filtering might be less effective at intervening locations than at other invalid locations. Although our experiments also involved the abrupt presentation of distractors at intervening locations, these stimuli occurred simultaneously with the relevant target data. The irrelevant singletons used by Heinze et al. may have been more likely to capture attention because they were not in competition with other sudden-onset events.

The predictive power of the cues that guide attentional allocation may be another relevant experimental factor. In the Kramer and Hahn (1995) paradigm, the relevant target information appeared at the cued locations during 100% of the trials. Similarly, in the present studies, each cued location was 80% likely to contain target stimuli. By contrast, in the McCormick and Klein (1990) study, the target probability at each of the cued locations was only .35. In the Posner et al. (1980) study, primary and secondary target locations were specified, with target probabilities of .65 and .25. In the Eriksen and Yeh (1985) study, two locations were most likely to contain the target, but the target probability was only .40 at each location. None of the last three studies had an average cue validity greater than 45%, and none of these studies observed evidence of split attentional foci. Even if multiple peaks of attention can be maintained, it is likely such flexible orienting is more difficult than orienting to contiguous locations. Thus, when the cues provide relatively unpredictive information regarding target locations, observers may revert to the easier strategy of attending a contiguous region in the visual field (e.g., the midlocation placement strategy suggested by McCormick & Klein, 1990).[8]

Finally, in the present studies, the majority (and perhaps all) of the evidence reported here in support of noncontiguous allocation of attention may reflect suppression of noise at invalid locations. That is, when distractor stimuli and masks at invalid locations were eliminated (Experiment 4a), accuracy was no higher at cued locations than at middle locations. If noise suppression explains the observed advantages at valid relative to middle locations, then the absence of irrelevant stimuli may help explain the negative results of Posner et al. (1980) and McCormick and Klein (1990).

We observed consistently larger cueing effects when the cues were horizontally rather than vertically arrayed. The results of Experiment 3 suggest that this advantage is at least partially due to the fact that the horizontally arrayed targets appear in different hemifields, whereas the vertically arrayed ones do not. Sereno and Kosslyn (1991) suggested that this different-hemifield advantage might result from competition between same-hemifield stimuli for the resources of a common processing structure. Thus, the effect of cue orientation may not necessarily reflect a difficulty in splitting

any case, it is clear that the present cueing advantages are dependent on the presence of distractors within the display. Further experiments would be required to determine whether these distractors are excluded by virtue of noise suppression or focused signal enhancement.

[8] This explanation does not apply to the studies of Bichot et al. (1999), because this study did not involve typical manipulations of cue validity.

attention within a single hemifield; rather, the disadvantage for vertically arrayed targets might result from a general difficulty in encoding visual stimuli that share a hemifield (i.e., a limitation associated with perception rather than attention). But as Sereno and Kosslyn (1991) pointed out, it is also possible that this effect indicates hemisphere-specific pools of attentional resources (e.g., Kinsbourne, 1987; LaBerge & Brown, 1989). In this case, one might predict that splitting attention between different hemifields would be easier, because both hemispheres could contribute resources. The present results cannot serve as a means of distinguishing between an explanation based on more efficient coding of horizontally arrayed targets and one suggesting that attentional deployment is less flexible within a hemifield. Regardless of which explanation is most appropriate, Hahn and Kramer (1998) observed reliable evidence of split attentional foci within a single hemifield, and Experiment 1 in the present investigation also showed robust evidence of noncontiguous attentional foci during the vertically cued trials. Thus, if it is easier to split attentional foci between hemifields, the difference appears to be relative rather than absolute.

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