

## Attention in Visual Search

as well as circle target locations in all three SOAs. Once again, there were no systematic attentional changes with distance from a target. Instead of there being an attentional gradient (e.g., LaBerge & Brown, 1989), only the location with the target feature received attentional facilitation.

## DISCUSSION

In Experiments 1 and 2, we measured spatial attention in visual search tasks using a probe technique. In conjunction search, the results suggest feature-driven selection, in which attention is allocated to locations containing either of the target features. Effects of attention were greatest for target locations, followed by distractor locations with the target color, and then by distractor locations with the target shape.

Feature search targets defined by shape also drew spatial attention to their locations. An additional feature search experiment with one, four, or seven items in each display produced search slopes of 0.25 ms/item for square targets and 3.98 ms/item for circle targets. These slopes are well below the 6 to 10 ms/item normally taken to indicate serial search (e.g., Duncan & Humphreys, 1989; Treisman & Souther, 1985; Wolfe & Pokorny, 1990). Thus, the probe results show that attention can be used in a very easy search that produces slopes generally considered to be parallel. Spatial selection must be more than just a facilitative mechanism for the most difficult searches, because it is used in at least some searches for clearly discriminable features. These results suggest that spatial selection is not limited to conjunction searches. Instead, a single spatial selection mechanism appears to work in conjunction and at least some feature searches.

These results also indicate a search asymmetry (Treisman & Gormican, 1988), with square targets requiring less attention for detection than circle targets. Perhaps the angles in the square targets served as a distinguishing feature. In fact, the RT probes showed no evidence of attention allocated to locations of square targets. There is a similar asymmetry in search slopes, with slopes for circle targets being significantly higher than those for square targets,  $F(1, 34) = 6.5, p < .05$ . However, probe letter accuracy clearly showed attentional allocation with both targets. Attention may have been more important to the primary task when letter probes were present. Because the letters were larger and appeared more frequently than the dot probes, they may have masked the primary stimuli more. Also, the letter identification task probably benefited more from attention than the dot detection task, which would explain the larger attentional effects in Experiment 2. Subjects may have been more likely to allocate attention for the primary task in Experiment 2 and then maintain it to help in identifying one of the target letters. This sustained attention may explain why the attentional pattern is so much more consistent across SOAs in Experiment 2 than in Experiment 1.

One might argue that attention is automatically allocated to every target after it is identified, and that the presence of spatial attention in feature search does not indicate a need for selection (e.g., Treisman, 1988). If that were true, however, then a spatial attention effect should have been found at the simple square target in Experiment 1 as well. The feature search slopes just described show that the square target is more easily detected

than the circle. If every target received attention automatically, its location would certainly be selected. Because the attentional allocation was stronger for circle targets than for squares in Experiment 1, attention must have been serving a useful role in processing. It is not just an automatic response to a target.

The results presented here cannot determine how many locations were activated simultaneously. Locations with potential target features may be selected serially, as in the guided search model (Cave & Wolfe, 1990; Wolfe, Cave, & Franzel, 1989), or may all be selected simultaneously. The results also do not show whether spatial attention is an obligatory processing step in every visual task.

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## Research Report

SPLITTING THE BEAM:  
Distribution of Attention Over Noncontiguous Regions of the Visual Field

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**Abstract**—In an effort to examine the flexibility with which attention can be allocated in visual space, we investigated whether subjects could selectively attend to multiple noncontiguous locations in the visual field. We examined this issue by pre-cueing two separate areas of the visual field and requiring subjects to decide whether the letters that appeared in these locations matched or mismatched while distractors that primed either the match or mismatch response were presented between the cued locations. If the distractors had no effect on performance, it would provide evidence that subjects can divide attention over noncontiguous areas of space. Subjects were able to ignore the distractors when the targets and distractors were presented as nononset stimuli (i.e., when pre-masks were changed into the targets and distractors). In contrast, when the targets and distractors were presented as sudden-onset stimuli, subjects were unable to ignore the distractors. These results begin to define the conditions under which attention can be flexibly deployed to multiple noncontiguous locations in the visual field.

A number of metaphors have been used to describe how organisms selectively process information in the visual field. Some researchers have suggested that attention operates like a spotlight (Broadbent, 1982; Posner, Snyder, & Davidson, 1980). Information that falls within the spotlight is actively processed while information outside the spotlight either passively decays or is actively inhibited. In general, the spotlight is assumed to be of a fixed diameter, so focusing attention on objects in different regions of the visual field requires a movement of the spotlight. Other theorists have proposed a somewhat more flexible model of visual attention. For example, it has been suggested that attention operates like a zoom lens on a camera (Eriksen & St. James, 1986; Jonides, 1983). The lens can be either tightly focused on a limited area of visual space or expanded to include a larger portion of the visual field. Within this framework, the rate of processing is inversely related to the size of the focus. Thus, it is assumed that attention is a limited resource and that processing rate is proportional to the number of resource units allocated per unit of visual space. Processing of information outside the focus involves either expanding the focus of the lens or reorienting a tightly focused beam. One important assumption shared by both the spotlight and the zoom-lens models is that there is a unitary attentional focus. Thus, within these theoretical frameworks, attention cannot be focused simultaneously in noncontiguous areas of the visual field.

There are, however, several models which do suggest that

attention can be focused on noncontiguous regions of the visual field. For example, LaBerge and Brown (1989) have suggested that multiple attentional gradients can be imposed upon different locations in visual space such that objects may be selectively processed within these areas but not in intervening portions of the visual field. A number of other researchers (Baylis & Driver, 1993; Duncan, 1984; Kahneman, Treisman, & Gibbs, 1992; Kramer & Jacobson, 1991) have suggested that attention is focused on objects or perceptual groups in the visual field. Within these object-based models of visual attention, it is possible to divide attention among noncontiguous regions of space in situations in which objects with similar characteristics are distributed across the visual field. For example, according to these models, it should be possible to selectively process traffic that is moving at a constant velocity and direction, and therefore forms a perceptual group, and ignore stationary objects such as route signs, which may be physically interspersed among the moving automobiles.

Empirical tests of the assumption of noncontiguous attentional selection have produced mixed results. Previous studies have varied the probability that a target will appear at one of several locations in the visual field and have found patterns of response times that have been interpreted as evidence that attention was divided on the basis of this probabilistic information (Shaw & Shaw, 1977). However, other researchers have suggested that this pattern of performance could be the result of shifting attention from location to location across trials rather than dividing attention among locations within a single trial (Posner et al., 1980). Other researchers have cued two locations, one in each hemifield, and have found an inverse relationship between the size of a box cue and response time to detect a luminance increment target (Castiello & Umiltà, 1992). Given the assumption that processing rate is inversely related to the size of the attended region, these findings suggest that attention can be divided among multiple locations, at least in situations in which only a single stimulus appears in the visual field.

However, several other studies have failed to find evidence for the division of attention among noncontiguous locations. For example, in studies in which multiple locations were pre-cued as potential target locations, processing time benefits were found either for only the most probable location (Posner et al., 1980) or for the second most probable location only when it was adjacent to the most probable target location (Eriksen & Yeh, 1985). Other studies have found that subjects are unable to selectively ignore distractor stimuli that are located between two cued target locations (Heinze et al., 1994; Pan & Eriksen, 1993).

These results leave unresolved the question of whether it is possible to divide attention among multiple noncontiguous re-

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Portions of the visual field. We believe that one important characteristic of the studies that have failed to find evidence consistent with the division of attention is that the targets and distractors presented in the center of the display. When subjects had fixation points, they pressed the space bar, which began the onset and nononset trials is presented in Figure 1. In the onset condition, two precue boxes appeared, in either the upper or the lower visual field, after subjects pressed the space bar. After 150 ms, two targets and two distractors were presented for 60 ms, at which point the boxes and letters were replaced with a pattern mask. In the nononset condition, pressing the space bar led to the presentation of the two precue boxes along with two figure-eight premasks, two in the target positions (i.e., in the boxes) and two in the distractor positions. After 150 ms, two targets and two distractors. The targets and distractors remained on the display for 60 ms and then were replaced with a pattern mask.

We also included onset and nononset control conditions in which the targets were presented in the absence of the distractors. These conditions were included to assess whether differences in reaction time (RT) or accuracy between onset and nononset conditions were due to the presence of the distractors.

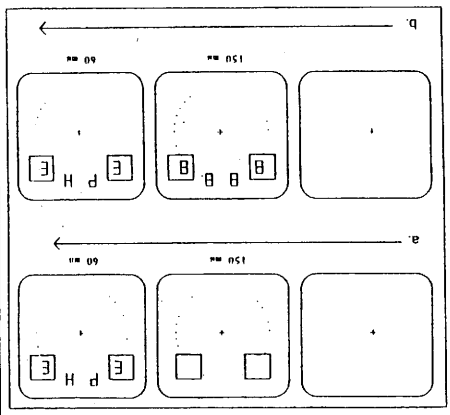


Fig. 1. Graphic illustration of the displays and temporal sequence of events within a trial in Experiment 1. The three panels in (a) represent the temporal sequence of the displays on the onset trials. The fixation cross was presented until the subjects depressed the space bar on the computer keyboard. Next, the two precue boxes were presented for 150 ms. Finally, the two targets and two distractors were presented for 60 ms. The three panels in (b) represent the temporal sequence of the displays on the nononset trials. The fixation cross was presented until the subjects depressed the space bar on the computer keyboard. Next, the two figure-eight premasks, targets, and distractors appeared as white stimuli on a black background.

**Subjects**  
Eight undergraduate students (age range: 19–26 years) were paid \$5.00 per hour to participate in the study. Four of the subjects were male. All of the subjects possessed corrected visual acuities (Snellen) of at least 20/20.

**Apparatus and Stimuli**  
Stimulus letters were displayed by a Dell 3165X computer with a VGA graphics adaptor and monitor. Uppercase E, H, P, B, and U served as the targets and distractors. In the onset condition, the target and distractors were presented simultaneously. In the nononset condition, the targets and distractors were presented by removing two of seven segments of a figure-eight premask. Each letter subtended a visual angle of 0.4° in width and 0.6° in height from a viewing distance of 60 cm. Viewing distance was controlled by using a chin rest. Each of the eight premasks, targets, and distractors appeared as white stimuli on a black background.

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**METHODS**

of distractors. For example, it is conceivable that onset stimuli, with their associated increase in inattention, might provide more effective temporal cues for the occurrence of the targets than the nononset trials. If this were indeed the case, we would expect onset trials to be faster and more accurate than nononset trials whether the distractors were present (experimental conditions) or absent (control conditions).

The subjects' task in both the onset and the nononset conditions was to decide whether the two target letters matched or mismatched. If the two targets matched, subjects depressed one of two keys on the IBM-style keyboard (either the / or the \ key); if the letters mismatched, subjects pressed the other key. Response key was counterbalanced across subjects. Subjects were instructed to respond as quickly as possible while maintaining their accuracy above 85%.

Subjects were also instructed to maintain fixation on the central cross throughout the trial because movement of their eyes to a target location would place the distractors closer to the fovea, thereby making the task more difficult. Subjects were presented with feedback on average speed and accuracy after each block of 60 trials.

Subjects performed two experimental sessions on subsequent days. In each session, subjects performed 15 blocks of 60 trials each. Half of the blocks were onset blocks and the other 50% of the blocks were nononset blocks. Response type (match or mismatch), distractor presence (present or absent), and distractor type (same or different) were within-block variables. In the same-distractor condition, the two distractors were identical. On a same-distractor/match-response trial, the two distractors were also the same as the two target letters. In the different-distractor condition, the two distractor letters were different from each other and also different from the target letters. Fifty percent of the trials were match-response trials, and 50% were mismatch-response trials. Each of the two distractor types occurred 50% of the time on the distractor-present trials. Each session lasted for approximately 1 hr, and subjects were encouraged to take breaks whenever they desired. The first onset and the first nononset trial block were considered practice and were not analyzed.

**RESULTS**

Four factors were manipulated in the study: display condition (onset or nononset), response type (match or mismatch), distractor presence (present or absent), and distractor type (same or different). Display condition was a blocking factor; distractor type, distractor presence, and response type were randomized within blocks.

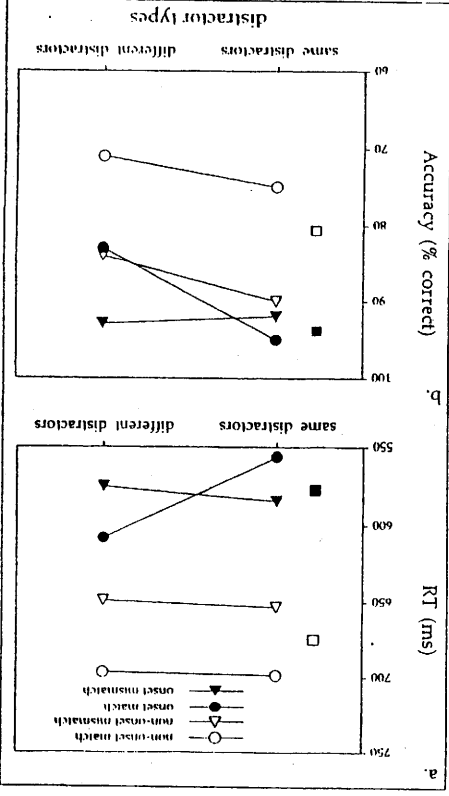


Fig. 2. Mean of the median reaction times (RTs) (a) and accuracy data (b) for the experimental conditions. Results for the control (i.e., nondistractor trials) conditions, averaged across match and mismatch responses, are indicated by solid (onset trials) and unfilled (nononset trials) squares.

The RTs and accuracies were submitted to three-way analyses of variance with display condition (onset vs. nononset), distractor type (same vs. different response), and response type (match vs. mismatch) as within-subjects factors. A main effect was obtained for display condition (RT:  $F(1, 7) = 17.2, p < .01$ ; accuracy:  $F(1, 7) = 10.1, p < .01$ ). Subjects were slower and less accurate responding in the nononset than in the onset conditions.

## Splitting the Beam

More important, however, with respect to the question of whether subjects are able to divide attention between noncontiguous spatial locations was the significant three-way interaction among display condition, response type, and distractor type (RT:  $F(1, 7) = 12.3, p < .01$ ; accuracy:  $F(1, 7) = 8.4, p < .01$ ). As can be seen in Figure 2, there was a significant interaction between response and distractor type for the onset but not for the nononset trials. Thus, the physically inserted distractors influenced task performance only when both the targets and the distractors were presented as onset stimuli. When the targets and distractors were formed from premasks (i.e., nononset stimuli), subjects' performance was uninfluenced by the nature of the distractor.

There is, however, one aspect of the data that might be interpreted as evidence that target processing was influenced by the distractors on the nononset trials. As can be seen in Figure 2, performance on nononset trials was slower and less accurate than performance on the onset trials. Thus, it might be suggested that these performance differences are consistent with the influence of distractors on target processing on the nononset trials. The data obtained in the control conditions, in which distractors were not present, discount this interpretation. If the distractors were responsible for the RT and accuracy differences between onset and nononset trials, we would not expect onset-versus-nononset performance differences on the control trials. However, if the main effects on RT and accuracy between onset and nononset trials were due to more effective temporal cuing for the appearance of the targets on the onset trials, then we would expect similar onset-nononset performance differences whether the distractors were present (experimental trials) or absent (control trials). The data are consistent with the latter interpretation. There were no significant differences between control and distractor-present trials for onset and nononset conditions for either RT or accuracy measures.

## DISCUSSION

The results obtained in our study clearly suggest that attention can be flexibly deployed and maintained on multiple locations in the visual field as long as new objects do not appear among the attended locations. These data are important in that they suggest that the great majority of models of visual attention, with the exception of the gradient model proposed by LaBerge and Brown (1989), require modification if they are to accommodate the flexibility of attentional control demonstrated by young adults. As described previously, space-based models of attention, such as the spotlight (Broadbent, 1982; Posner et al., 1980) and zoom-lens (Eriksen & St. James, 1986; Eriksen & Yeh, 1985) models, suggest that attention is distributed in a unitary area of the visual field. Object-based models of attention (Duncan, 1984; Kahneman et al., 1992) allow for more attentional flexibility because in these models attention can be distributed in noncontiguous locations as long as the information in these areas is perceptually grouped (e.g., a building that is partially occluded by a tree, aircraft flying in formation). However, in the present study, there is no obvious grouping of the target locations. Thus, it appears that attention can be di-

vided between noncontiguous locations even in the absence of some form of grouping between the items in these locations.<sup>1</sup>

The fact that sudden-onset distractors (new objects) do disrupt the goal-directed allocation of attention is probably fortunate: From an evolutionary perspective, such events (e.g., a predator, an automobile suddenly approaching a crosswalk) are often significant. It is of interest to note, however, that a number of researchers have found that attentional capture by sudden-onset objects can be overridden under some conditions. Yantis and Jonides (1990) found that if subjects are given a sufficient amount of time to focus their attention on a potential target location, sudden onsets that occur elsewhere in the visual field do not disrupt performance (see also Theeuwes, 1991; Koshino, Warner, & Juola, 1992). In fact, Yantis and Jonides (1990) found that a location precue-target stimulus onset asynchrony (SOA) of 200 ms was sufficient to override the influence of a sudden-onset distractor.

In our study, a precue-target SOA of 150 ms was ineffective in eliminating the influence of the sudden-onset distractors on the processing of the two targets. In an effort to determine whether additional preparatory time would enable subjects to effectively ignore the onset distractors, we conducted another study with equivalent experimental conditions and procedures except for a 600- rather than a 150-ms precue-target SOA. The results of this study with 6 subjects are presented in Figure 3. As in our previous experiment, subjects were unable to ignore the sudden-onset distractors. However, subjects were able to effectively ignore the distractors when they were presented as nononsets. Whether attentional capture by sudden-onset distractors can be overcome with longer precue-target SOAs or additional practice in situations in which subjects must focus on multiple display locations is an important topic for future research.

In our experiment, we used a brief precue-target SOA (150 ms) and a short display duration (60 ms) followed by a pattern mask in an effort to ensure that subjects neither had the time to move their eyes to the target locations nor had sufficient time to shift attention between these locations. Our choice of a 60-ms stimulus presentation duration was based on the results of previous researchers who estimated that it takes from 150 ms to

1. It might be argued that the two target locations in our task were grouped by virtue of the similarity of the precues (i.e., the two boxes). Although we view this as unlikely given the large separation between the two cued locations, we performed a control study in which both the targets and the distractors were precued with boxes. Eight subjects were instructed to compare the targets in the outermost boxes (i.e., the same locations that served as target locations in the main study reported here) and ignore the letters in the distractor (i.e., innermost) boxes. In all other respects, the control study was identical to the main study.

If subjects were grouping the target locations together on the basis of the similarity of the precues in the main study, we would expect that the four boxes used as precues in the control study would result in an interaction between distractor type and response type in both the onset and the nononset trials. If subjects were using the precues to orient attention to specific locations in the main study, we would expect distractor effects only on the onset trials. The data were consistent with this latter possibility. An interaction was obtained between response type and distractor type on the onset but not on the nononset trials in our control study.

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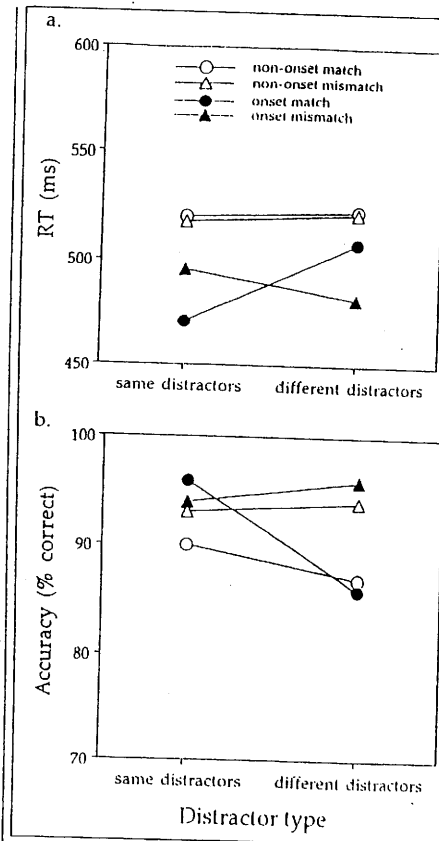


Fig. 3. Mean of the median reaction times (RTs) (a) and accuracy data (b) for each of the conditions when duration of the precue display was 600 ms.

250 ms to identify a stimulus at a precued location and switch attention to a second location (Eriksen & Yeh, 1985; Kruse & Julesz, 1989; Madden, 1992; Sperling, 1984). However, research performed in visual search paradigms has found search slopes of less than 30 ms per letter, suggesting that attention may be switched among locations in less than 30 ms, at least with extremely well practiced subjects (Czerwinski, Lightfoot, & Shiffrin, 1992). Although the visual search task appears to lend itself to faster shifts of attention than the matching task, given that in search the target is known in advance and is often

unchanged across many experimental trials, we decided to err on the side of caution and examine the attention-switching hypothesis more directly in an additional study.

To that end, we modified the matching task so that subjects would be required to identify a letter in one of two precued locations and then shift their attention to the second location. In this way, we could estimate directly the speed with which subjects could switch attention in our task. Subjects were instructed that if a particular letter (i.e., either E, H, P, S, or U) was presented in one of the two precued locations (the specific location in which this letter would appear was defined in the pretrial instructions to the subject), then they should shift their attention to the second precued location, where a second letter was presented, and decide whether the two letters matched or mismatched. If a different letter appeared in the predefined location, subjects were told not to make the match/mismatch response. For example, on a particular trial, a subject might be instructed to complete the matching task only if the letter E appeared in the precue box on the left side of the display. Thus, in essence, subjects were required to first identify the letter in one precued location (e.g., the left-most precue box) and then switch their attention to the second precued location (e.g., the right-most precue box).

A critical aspect of the study was the delay between the occurrence of the first target letter (i.e., created by removing segments of a figure-eight premask) and the occurrence of the second target letter. We reasoned that RT would begin to increase at delays that exceeded the amount of time required for subjects to identify the letter in the primary location and shift attention to the second location. Delays between the presentation of the first and second target letters were 0, 14, 28, 42, 56, 70, 84, and 98 ms. Six subjects participated in this study. A significant increase in RT, relative to the 0-ms delay (i.e., the simultaneous presentation of the target letters in the primary and secondary locations), was obtained for the 84- and 98-ms delays. Therefore, it appears reasonable to conclude that subjects did not have a sufficient amount of time to switch attention between locations in our study, but instead our results can be attributed to the division of attention between noncontiguous locations.

Although our results are intriguing in that they suggest a remarkable degree of attentional flexibility—that is, the ability to divide attention among noncontiguous locations in the visual field—there are a number of important unresolved questions. For example, how many locations can be attended simultaneously? Can attention be divided within as well as between hemifields? Is it possible to overcome the influence of sudden onsets on goal-directed attentional allocation? What are the neural mechanisms that underlie the ability to split the attentional beam? We are currently exploring these issues in our laboratory.

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Commentary

Helmholtz or Gibson?

Felice L. Bedford

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LOCALIZING THE SPATIAL LOCALIZATION SYSTEM:

McCluskey and a team of authors (1995) documented a fascinating deficit involving the localization of objects. When subject A.H. reaches for objects placed in different positions, she is often wrong about direction but not amount. An object located 30° to her left, say, might cause her to reach 30° to the right. The authors demonstrated that her motor abilities are flawless and that the errors are genuinely in vision. But precisely where in the visual localization process does the deficit occur?

I suggest that an analysis of how objects are normally localized may point to the source of error. I begin with a description of two separate visual localization systems, and then discuss how the nature of the deficit seems to implicate one of these systems over the other. Both localization systems can deal with the inherent ambiguity of a single retinal location. The ambiguity is easily appreciated by considering a simple example in which the image of an object is centered on the fovea. This retinal image can be caused by an object that is straight ahead of the person's nose, but only if the person is fixating the object. If the fixation is to the left, then the same retinal image will be produced by an object to the person's left. That is, one retinal image position could be produced by any position in the world, and one position in the world can produce an image anywhere on the retina.

The first proposed solution to this problem is one of Helmholtz's unconscious inference models (1866/1962). We owe the retinal ambiguity to the fact that we are movable observers; our eyes can move, our head can move, and so forth. Consequently, if we include information about the current state of the body in our visual calculations, we can uniquely recover the position of the object that produced the ambiguous retinal image. According to this model, then, the ambiguity is resolved by considering the extraretinal information about the position of the eyes in the head along with the retinal information. If head position is held constant, the simple cancellation method (eye position — retinal position) will reconstruct the correct position of the object in the world.

The second model is best known from the work of Gibson (1959). Gibson's general solution to ambiguity was to look over a wider area of the retina, rather than to address correspondence to Felice L. Bedford, Department of Psychology, University of Arizona, Tucson, AZ 85721; e-mail: bedford@cc.arizona.edu.

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calculate the state of the observer. As the eyes sweep across a scene, the retinal position of a single object changes, but the relationship between the retinal position of that object and the positions of other objects remains invariant. Thus, without ever referring to the position of the eyes in the head, information about the location of objects can be obtained through their relation to other fixed objects in the scene.

Can a breakdown in either one of these methods account for A.H.'s difficulties? In the first model, any incorrect value for retinal position or eye position would produce an incorrect calculation. For instance, if the retinal position is indeterminate, then the final location of the object would be indeterminate. If the eyes feel 5° further left than they actually are (e.g., as a consequence of artificial exposure to optical displacement—see Bedford, 1995—or because of natural syndromes such as past pointing), then the location percept would always be 5° off. A.H. has a different deficit: She is incorrect about left-right direction, yet correct about amount. Note that there is nothing about the Helmholtzian model which suggests that amount and left-right direction are naturally dissociable from one another. It is logically possible that the felt direction of the eyes is swapped left for right, but this substitution into the equation would produce a left-right reversal with amount preserved only in the special case when the value for the retinal position is 0. Amount and side are not obviously separate components in this method of determining location.

In the second model, the position of an object, B, is determined by its relation to other things, such as another object, A, or to an edge of the frame. The comparison provides information relevant to B's location in the world, such as "B is 4 feet from the wall." But is B to the left or to the right of A? This further judgment depends on the perspective one adopts when using the frame of reference. From where I am sitting, the lounge chair in my office is to the left of the door, but it is easy to appreciate that for someone facing me, the chair is to the right of the door. When using frames of reference, there is ambiguity about where to view the frame. The Helmholtzian model described earlier does not have this problem because that system calculates the position of an object with respect to the observer. Once the location judgment is detached from calculations of the state of the observer, as it is with the observer. In a frame of reference, then ambiguity about perspective arises. In a frame of reference, there