

Research Article

ATTENTIONAL ENHANCEMENT OPPOSITE A PERIPHERAL FLASH REVEALED USING CHANGE BLINDNESS

P.U. Tse,¹ D.L. Sheinberg,² and N.K. Logothetis³

¹Dartmouth College, ²Brown University, and ³Max Planck Institute for Biological Cybernetics, Tübingen, Germany

Abstract—We describe a new method for mapping spatial attention that reveals a pooling of attention in the hemifield opposite a peripheral flash. Our method exploits the fact that a brief full-field blank can interfere with the detection of changes in a scene that occur during the blank. Attending to the location of a change, however, can overcome this change blindness, so that changes are detected. The likelihood of detecting a new element in a scene therefore provides a measure of the occurrence of attention at that element's location. Using this measure, we mapped how attention changes in response to a task-irrelevant peripheral cue. Under conditions of visual fixation, change detection was above chance across the entire visual area tested. In addition, a "hot spot" of attention (corresponding to near-perfect change detection) elongated along the cue-fixation axis, such that performance improved not only at the cued location but also in the opposite hemifield.

Visual attention has been described as a "spotlight," "window," or "zoom lens" that moves either smoothly or discretely from an old to a new location (Eriksen & St. James, 1986; Posner, Snyder, & Davidson, 1980). Previous psychophysical mappings of attention have sampled only a few points in the visual field (but see Bennett & Pratt, 2001). This may in part account for the lack of consensus regarding how attention is spatially distributed and how that distribution changes over time. We introduce here a new method for mapping attention with high spatial and temporal resolution. The question we address using this method is the following: How does the distribution of visual attention change in response to a task-irrelevant cue¹ that flashes suddenly in the periphery?

We exploited a change-blindness paradigm to measure the accuracy of change detection at 149 points and at four latencies after a cue was flashed briefly in one of four locations around fixation. Change blindness can occur when there is a brief high-luminance full-field blank between two successive, overlapping images that differ (Rensink, O'Regan, & Clark, 1997). An observer might not notice a prominent change in the image during the global blank even when searching for the change, because the global transient introduced by the blank undermines detection of the local transients used by the visual system to locate sudden changes. Differences between the pre- and postblank images are detected at a given location only when attention is allocated to that location in both images, because only then can corresponding elements at that location be compared (Rensink, 2000b; Rensink et al., 1997; Simons, 1996; Simons & Levin, 1998). Attention permits comparison because observers are able to select a subset of all

the information in iconic memory for further operations, such as reporting (Sperling, 1960) or tracking (Pylyshyn & Storm, 1988). Without this selection, information in the iconic store is simply lost as incoming sensory input continually replaces existing information in the iconic buffer. Once selected, however, new information can be processed as a change in a monitored location or tracked figure (Kahneman, Treisman, & Gibbs, 1992).

Within this theoretical framework, attention can be defined as enhanced processing over a limited subset of sensory information that has been selected for monitoring or tracking. (Unattended information is either not monitored or suppressed.) Because the global blank undermines the visual system's normally automatic ability to detect changes on the basis of local transients, it can only detect changes using attentional monitoring. Our fundamental hypothesis, and the assumption behind our method, is that the probability of change detection at a given location indicates the degree of attention at that location. Our experimental design, shown schematically in Figure 1, exploits the hampered change detection that occurs in a flicker-induced change-blindness paradigm to create a map of how attention is redistributed in response to a peripherally flashed cue.

METHOD

Participants

Four participants (24–38 years of age) carried out the experiment. Three were paid observers who were naive regarding the purpose of the experiment, and 1 was the first author. The naive observers completed approximately 100 hr of training and testing over a 4-month period.

Apparatus

The visual stimulator was a dual-processor Pentium II workstation running Windows NT 4.0. The screen resolution was 1152 × 864 pixels, and the frame rate 85 Hz. Observers rested their chin in a chin rest. Fixation was ensured using an eyetracker (Sensomotoric Instruments, Berlin, Germany; Tse, Sheinberg, & Logothetis, 2002). Any time the subject's monitored eye was outside a fixation window with a 1.5° radius, the trial would be automatically aborted, and a new trial would be chosen at random from those remaining. If three trials were aborted in a row, the state system automatically reverted control to the eyetracker's calibration program. Once calibration was completed, the experiment resumed with a random trial.

Stimuli

The onset of a trial was indicated by the offset and immediate reonset of the fixation point against the black background. The fixation point was a yellow circle 0.15° in diameter. The circular background, shown in Figure 1b, was 30° in diameter and uniform black (<1 cd/m²). It spanned the

Address correspondence to P.U. Tse, Department of Psychological and Brain Sciences, Dartmouth College, Hanover, NH 03755.

1. The word *cue* is not intended to mean that the occurrence of a future event was cued. Rather, the sole purpose of the cue was to disturb the distribution of spatial attention.

Mapping Attention With Change Blindness

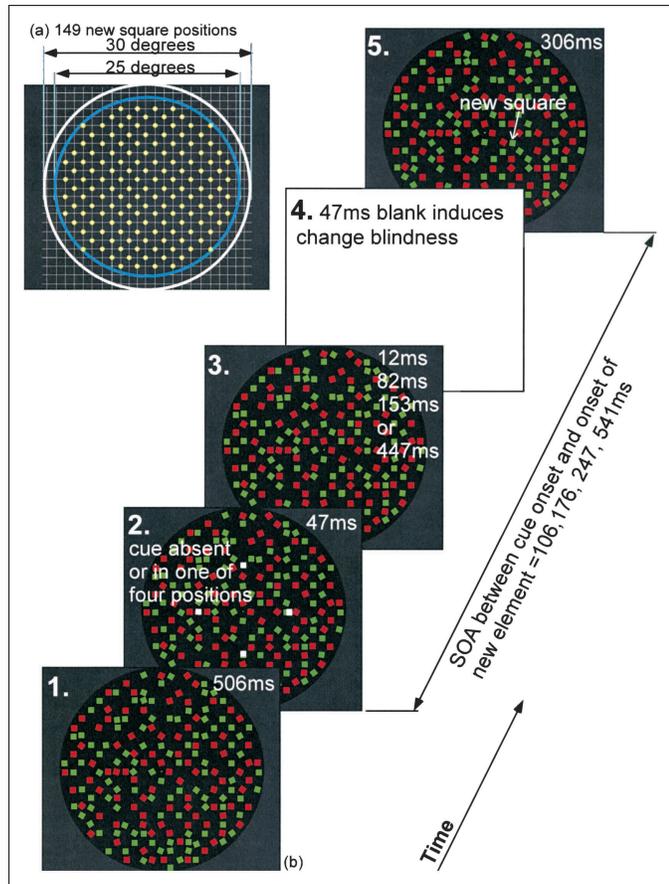


Fig. 1. Experimental design. The trial sequence is illustrated in (b). On cued trials, a cue appeared in Frame 2, as shown, and Frame 3 was presented for one of four durations. On noncued trials, there was no cue in Frame 2, and Frame 3 always lasted 12 ms. In the final frame of the sequence (labeled 5 here) on both cued and noncued trials, a new square was shown in one of 149 positions of the array (a); these positions represented a subset of the overall grid that fit within an imaginary 25° circle centered at fixation. The final frame always contained one and only one new element. The new square always appeared in a random position that had been unoccupied on previous frames within a given trial. The observers' task was to maintain fixation and report whether the new element was red or green. SOA = stimulus onset asynchrony.

height of the monitor at a viewing distance of 57 cm. The background outside this circular region was dark gray. A 23×23 array of square positions fit within a 30° by 30° square that circumscribed this circular "window." On a given trial, half of these positions were occupied by red and green squares ($0.69^\circ \times 0.69^\circ$); the shades of red and green used were equiluminant as measured by a photometer (Minolta CRT color analyzer CA-100). The probability that a square was red or green was 50%. Squares never overlapped. Their centers were at least 1.25° apart, and the orientation of each square was randomized on each trial. Squares at the edge of the window could be partly occluded.

In no-cue trials, the array was present for 565 ms, because the third frame (see Fig. 1) always lasted 12 ms. Frames 4 and 5 were the same as in trials in which a cue was present. In Frame 5 the array reappeared with a new square in one of 149 positions (indicated by yellow circles

in Fig. 1a); these positions represented a subset of the overall grid that fit within an imaginary 25° circle centered at fixation. The new square always appeared in a random position that had been unoccupied by a red or green square on previous frames within that trial. In cued trials, after 506 ms of the static array, two overlapping $1.00^\circ \times 1.00^\circ$ upright white squares were flashed in quick succession (24 ms at 6.25° from fixation, and then 24 ms at 6.87°) on the plus or minus *x*- or *y*-axis. The small outward apparent motion induced by this offset enhanced the salience of this cue. Cuing was followed by a return to the static array for 12, 82, 153, or 447 ms, and then a full-screen white blank that lasted 47 ms. After the blank, the array returned with a new square, as on no-cue trials.

The observers' task was to maintain fixation and to report whether the new element was red or green. Four temporal intervals between the onsets of the cue and new square were tested. Each trial could have either no cue or a cue at one of four positions and one of four temporal intervals, selected at random. This design resulted in a total of 25,330 test trials per observer: [1 (no cue) + 4 (cue positions) \times 4 (temporal intervals)] \times 149 (test positions) \times 10 (trials per position). The training phase included half that number of trials. Each of 10 blocks of 2,533 test trials was broken down into eight sessions of 316 or 321 trials. The intertrial interval was approximately 3 s in order to minimize possible effects of afterimages. A session typically lasted 35 to 45 min. Data were stored and later sorted and analyzed off-line.

Procedure

Observers were instructed to attend to the entire circular array of red and green squares and report the color of the new square in the final frame of each trial by pressing the appropriate button. There was no feedback on the correctness of responses. The instructions emphasized that the probability that this new square would appear at the cued location was the same as the probability that it would appear at any other tested location, and that therefore there was no advantage to attending to or ignoring the cues or their locations.

Practice Phase

The blank (white) fourth frame (see Fig. 1) was 12 ms in duration during the 12,665 practice trials for the 3 naive observers. This was the shortest duration permitted by the refresh rate of our monitor, and was chosen to make learning the task as easy as possible. All observers were initially unable to see the new element if it appeared further than approximately 3° away from fixation. With practice, however, 2 of the observers learned to see the new square even when it was as far away as 12.5° from fixation (see Fig. 2). The 3rd observer (shown in pink in Fig. 2) did not learn to "ignore" the global blank, and continued to perform at chance beyond approximately 3° from fixation. He was disqualified because he could not perform the task over the whole area of the visual field tested, and because it became apparent that he was not paying full attention to the task, at times performing at chance even near fixation. Instead, the first author served as the 3rd observer in the test phase of the experiment. He had received several thousand practice trials in the course of coding the experiment, but these practice data were not saved.

A blank of 47 ms was chosen for the test phase of the experiment because trained observers were neither perfect nor at chance at detecting the new square at this duration (Observer 1: 72.8% of 25,330 trials correct; Observer 2: 67.2% correct; Observer 3: 68.4% correct).

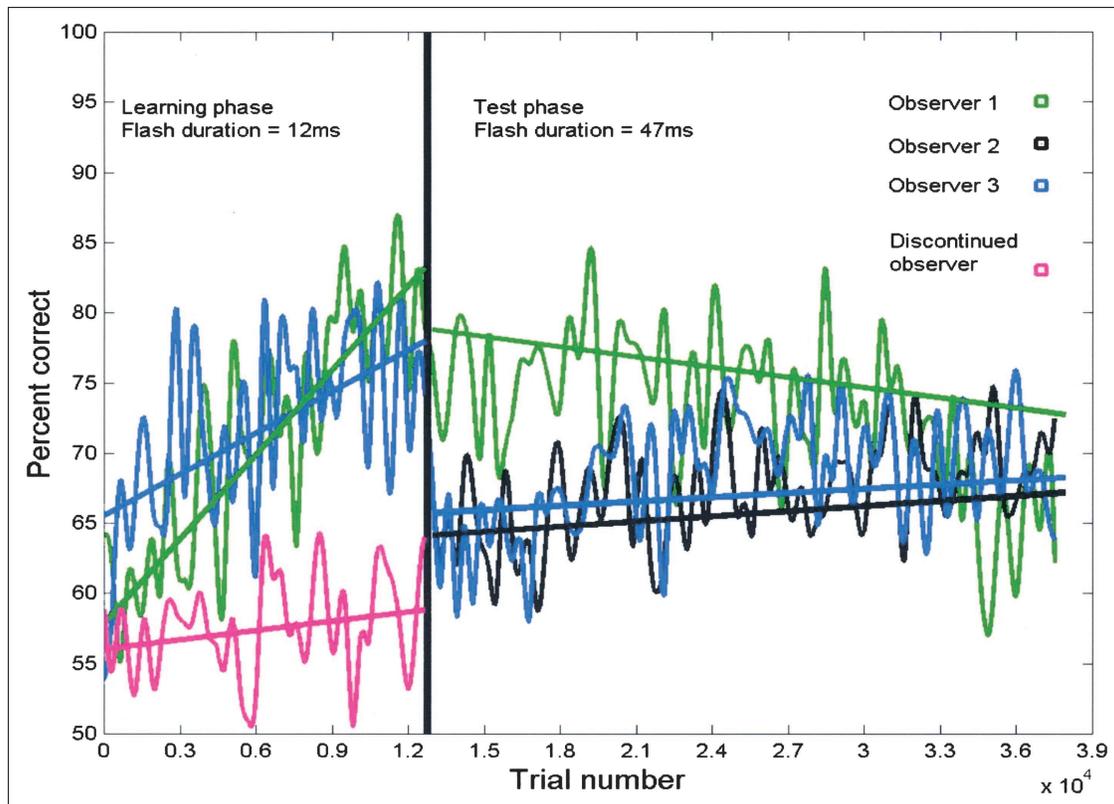


Fig. 2. Percentage correct during the learning and test phases. The graph shows both raw data (on successive blocks of 316 or 321 trials) and regression lines for each observer separately.

RESULTS

Figure 3 shows the pooled data for the 3 observers from the test phase of the experiment. Change detection was significantly above chance for almost the entire 25° circular area of the visual field tested, presumably because observers were instructed to attend to the whole array of squares. This corroborates the finding that outside the main focus of attention observers maintain a minimum degree of visual awareness, with which they can detect and discriminate pop-out classes of information at little or no cost to central attentional processing (Braun & Julesz, 1998). The attentional hot spot, corresponding to regions of near-perfect performance (yellow and white regions in Fig. 3), tended to change shape depending on the position of the cue, even though observers knew that the position of the cue was irrelevant to their task.

The no-cue case (Fig. 3, upper left) indicates the distribution of attention in the absence of a cue. This horizontal, elliptical hot spot can be thought of as the default shape of attention for this task. After the cue flashed, the hot spot elongated significantly (statistics described later in this section) along the cue-fixation axis away from its default shape for most conditions. This is consistent with the finding that an abrupt onset causes an automatic allocation of attention to the location of that onset (Jonides & Yantis, 1988; Yantis & Egeth, 1999), particularly when attention has been set (Everling & Munoz, 2000; Folk, Remington, & Johnston, 1992) to detect changes, as here.

Figure 4 reveals individual attentional differences in response to the flash. Compared with the other 2 observers, Observer 1 tended to

report more new elements correctly, and had a broader hot spot of attention. The distribution of attention for Observers 1 and 2 had a horizontal bias in the no-cue condition, whereas no such bias can be seen in the no-cue data of Observer 3. Nonetheless, there are also clear similarities among the observers. When the cue was to the left or right of fixation, the hot spot of attention tended to elongate along the horizontal axis, whereas when the cue was above or below fixation, the hot spot tended to elongate along the vertical axis. Also, for all observers, attention tended to pool not only at the cued location, but also at the corresponding location in the opposite hemifield.

Figure 5 allows a quantitative comparison of the individual and pooled data (see the appendix for details of the statistical analysis). As indicated by the numbers below the maps, at the stimulus onset asynchrony (SOA) of 106 ms, there was an initial expansion of the hot spot of attention along the cued axis. For some cue locations at this SOA, there was also a moderate expansion along the noncued axis. This overall expansion may indicate a general increase in the baseline level of attention after occurrence of the cue. Within 176 ms, there was clear expansion of the hot spot along the cue-fixation axis relative to the no-cue condition, and contraction along the orthogonal axis. The overall contraction of the hot spot at the 176-ms SOA relative to the 106-ms SOA may indicate that attention had become more focused, particularly along the cued axis. This focus presumably facilitated the detection of a new element at the cued location. Note that in most conditions, the hot spot spread out in the diametrically opposite direction from the flashed location along the cue-fixation axis, facilitating the detection of new elements up to 19° away from the cued location,

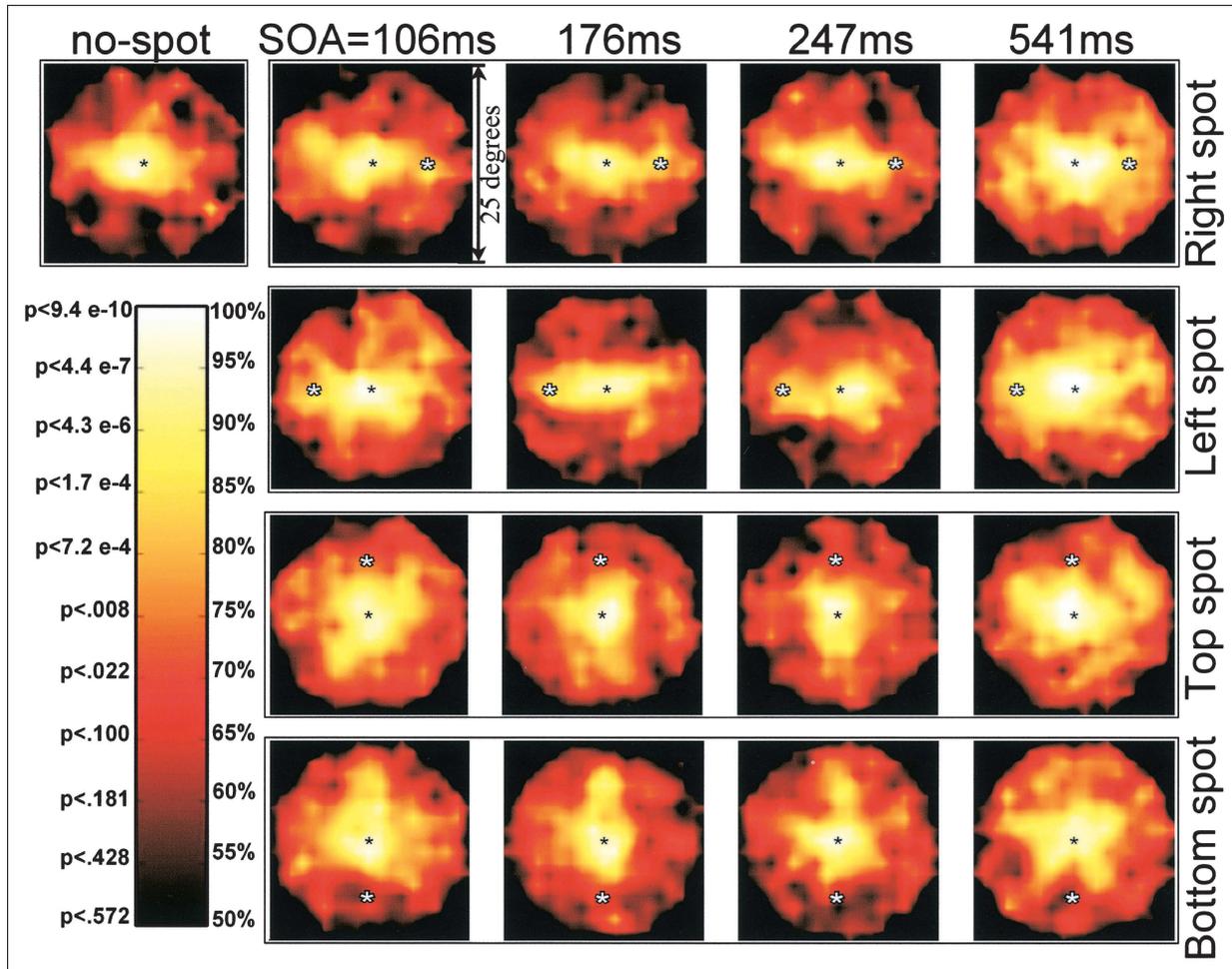


Fig. 3. Pooled percentage correct for no-cue trials and cued trials with each stimulus onset asynchrony (SOA) and each cued position (white stars). Each of the 149 tested locations shown in Figure 1a could have a maximum of 30 correct responses. Bilinear interpolation was used to obtain values for nontested positions, and results were smoothed using a rotationally symmetric 3×3 Gaussian low-pass filter with a standard deviation of 0.5 grid units. Values were then mapped to the $25^\circ \times 25^\circ$ color maps shown. The probability that observed values were obtained by chance is indicated by the p values to the left of the bar. These values were obtained using the binomial test, where $n = 30$ and $p = .5$. The test region was approximately an imaginary circle that touched the borders of these square maps. Black regions outside these circles were not tested. The fixation point is indicated at the center of each map.

relative to performance in the no-cue condition. The bilaterally elongated shape of the hot spot was most pronounced at 176 and 247 ms after cue onset, and diminished after that as the effects of cuing diminished.

DISCUSSION

We exploited the fact that change detection is hampered in a flicker-induced change-blindness paradigm to map how spatial attention changes in response to an irrelevant peripheral cue. The basis of our method is the assumption that the likelihood of detecting a change at a given location corresponds to the occurrence of attention at that location. On theoretical and experimental grounds (Rensink, 2000b; Rensink et al., 1997; Simons, 1996), we believe that the distribution of judgment accuracy correlates directly with the distribution of attention. In essence, change-detection accuracy affords an indirect mea-

sure of attentional occurrence because change-detection accuracy must increase and decrease with increases and decreases in the perceptual signal-to-noise ratio. If spatial attention is operationally defined as the mechanism that boosts this ratio (e.g., Lee, Itti, & Braun, 1999; Treue & Maunsell, 1999), then our method measures a correlate of attentional occurrence at each location. Change detection can thus be added to other indirect measures of attention, such as reaction time (RT) and sensitivity.

For most cue locations and SOAs, attention was enhanced (relative to the no-cue case) not only at the cued location, but also opposite the cued location. Because this result was unexpected, we took special care to ensure that data matrices were not inverted. Opposite pooling of attention was stronger along the horizontal than the vertical axis, but this may be because the hot spot of attention was already biased to extend along the horizontal axis in the no-cue condition. The differen-

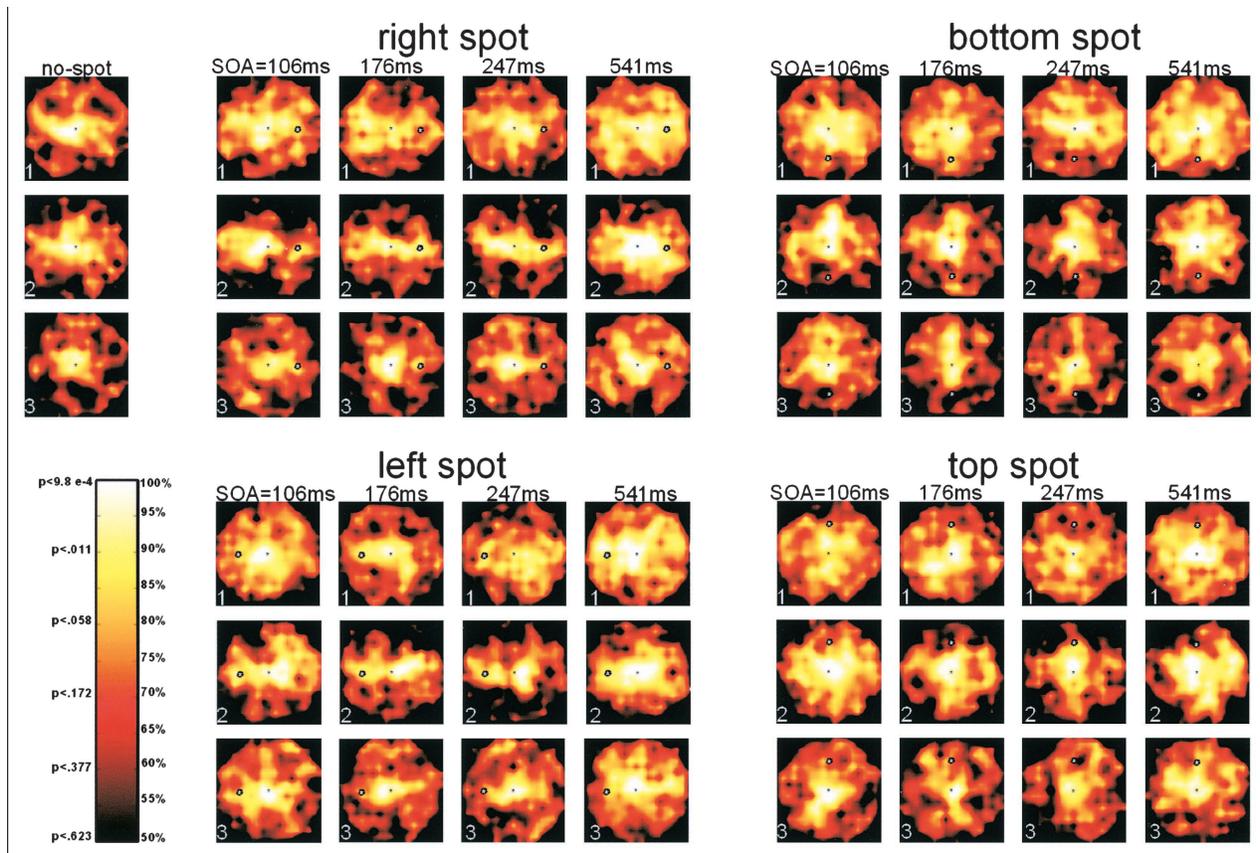


Fig. 4. Percentage correct for individual observers, for no-cue trials and cued trials with each stimulus onset asynchrony (SOA) and each cued position (white stars). The number in each map indicates observer number. Each of the 149 tested locations in each map could have a maximum of 10 correct responses. Bilinear interpolation was used to obtain values for nontested positions, and results were smoothed using a rotationally symmetric 3×3 Gaussian low-pass filter with a standard deviation of 0.5 grid units. Values were then mapped to the color maps shown. The probability that observed values were obtained by chance is indicated by the p values to the left of the bar. These values were obtained using the binomial test, where $n = 10$ and $p = .5$. The fixation point is indicated at the center of each map.

tial strength of the effect could also have arisen because callosal connections link regions that process the left and right hemifields but not the upper and lower hemifields. However, a purely callosal explanation is not sufficient to explain our data, because cuing the lower visual field led to pooling of attention in the upper visual field and vice versa. Another asymmetry between the horizontal and vertical axes is that accuracy at the cued location was lower for cues on the vertical than on the horizontal axis (see Fig. 3). Why this should be is unclear, but it may be that the cue can interfere with the detection of changes at its location more strongly at vertical-axis locations, where attention has relatively low resolution (cf. He, Cavanagh, & Intriligator, 1996).

The observed enhancement of performance opposite a cue may be related to inhibition of return (IOR). In IOR, RTs are initially faster to targets at cued locations than to targets at noncued locations, but after a brief delay, RTs to targets at cued locations are slowed. This is generally interpreted to mean that cued locations are inhibited from again receiving full attention starting approximately 300 ms after having been attended (Klein, 2000; Posner & Cohen, 1984). IOR is thought to enhance the efficiency of visual search by inhibiting attentional shifts to already searched locations and enhancing the likelihood of shifts to

new locations. In addition, recent evidence has shown that IOR involves a relative speeding of RTs opposite an attended location (Bennett & Pratt, 2001; Pratt, Spalek, & Bradshaw, 1999). Pratt et al. suggested that the opposite enhancement effect may be due to an “attentional momentum,” wherein attention returns to the fixation point from the cued location and then continues on toward the side opposite the cued location. Snyder, Schmidt, and Kingstone (2001) found only weak evidence supporting attentional momentum, and argued that attentional momentum and IOR are not caused by a common mechanism.

We also doubt that IOR underlies strengthening of attention opposite the cue, at least as measured within our paradigm. This strengthening of attention was apparent already at the shortest SOA we tested (106 ms), which is faster than the latency typically reported for IOR. Previous researchers have found enhancement of processing at a cued location up to approximately 150 ms after cue onset, followed by decrements in processing (IOR) 300 ms or more after cue onset, although increasing task difficulty can move this crossover point to beyond 600 ms (Klein, 2000). Future experiments within an IOR paradigm (cue, delay, target) should be able to determine whether RTs opposite the cued location speed up by approximately 100 ms, as predicted by our

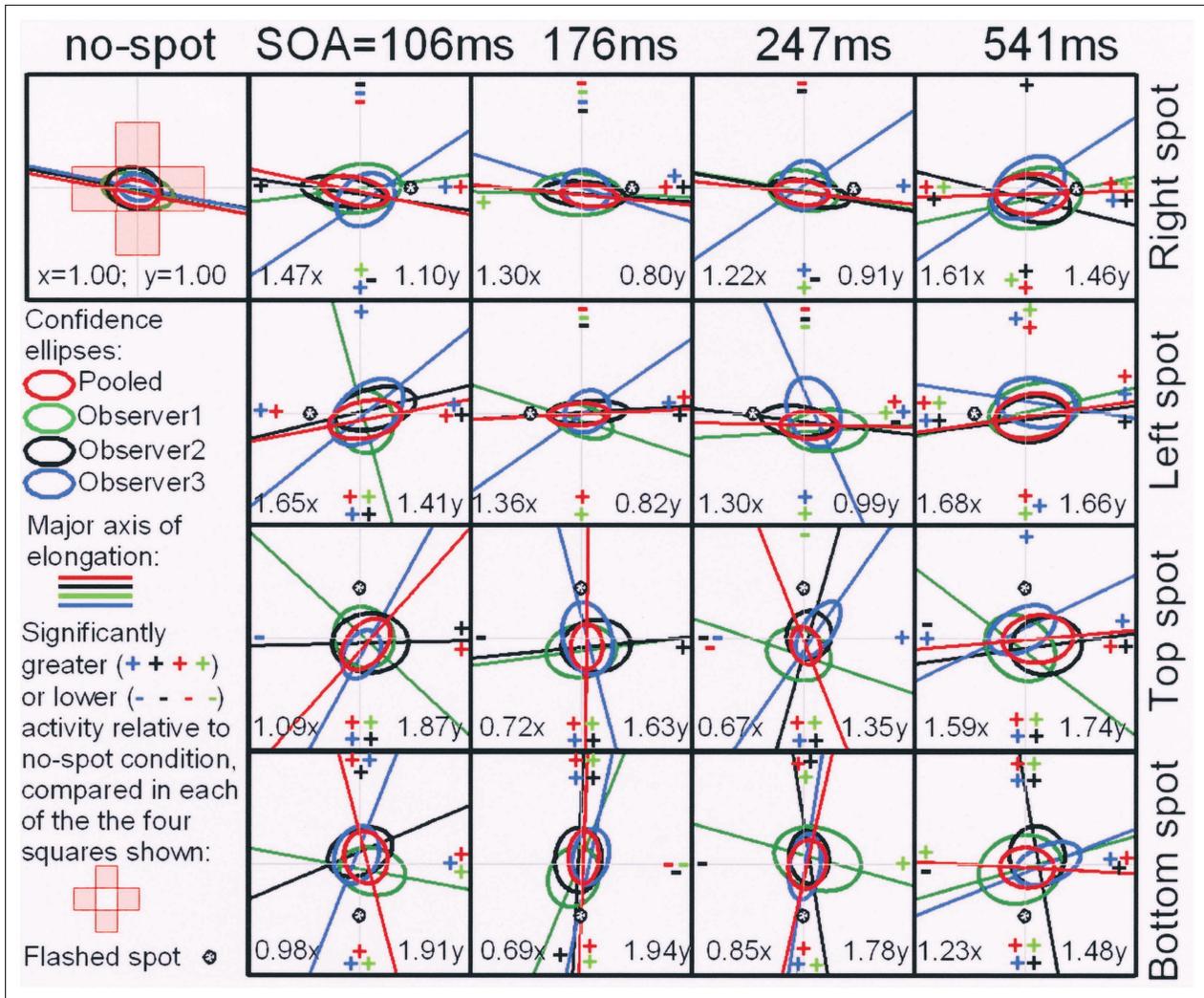


Fig. 5. Statistical analysis of pooled and individual data for no-cue trials and cued trials with each stimulus onset asynchrony (SOA) and each cued position (white stars). Each box shows confidence ellipses for the individual subjects, as well as the average data. The lengths of the major and minor axes of each ellipse indicate the standard deviation of the data projected onto those axes, which are the first and second principal components of the data. The major axis indicates the main axis of elongation of attention. The two numbers in each box indicate, for the pooled data, the degree of elongation along the *x*- and *y*-axes relative to the no-cue condition. The small colored plus or minus signs along the *x*- and *y*-axes indicate individual and average accuracy that was significantly greater or less ($p < .05$) than the corresponding no-cue accuracy within each of four $6.25^\circ \times 6.25^\circ$ squares (shown in pink in the no-cue condition) centered at the four cue locations. Plus signs indicate hot-spot elongation toward the plus sign's location, and minus signs indicate hot-spot contraction relative to the no-cue baseline. See the appendix for details concerning how the statistical analysis was conducted.

data. The visual system may orient to the cued and opposite locations along the cue-fixation axis in such a way that attention fades more rapidly at the cued location than at the opposite location. Note, however, that we did not see evidence of a more rapid decline in accuracy at the cued than the opposite location. It may be that our maximum tested duration (541 ms) was not long enough to demonstrate evidence of IOR in the RT data or evidence of attentional fading at the cued location.

We examined our 3 observers' RT data, summarized in Figure 6, but did not find a systematic correlation between the patterns of RTs and the patterns of correct responses (which we take to correlate with the distribution of attention), or between the patterns of RTs and the

positions of the cue. In particular, there was no systematic RT difference between cued and uncued locations, and thus no IOR as conventionally defined. Observers 1 and 3 were relatively faster at responding when the new square appeared within a few degrees of fixation than when it appeared peripherally, whereas the responses of Observer 2 were relatively faster when the new square appeared in the periphery rather than centrally. Overall, the individual RT data were more variable and less coherent than the accuracy data. If we had only measured RT, as is common in IOR research, we might have concluded that the cue did not cause a reflexive shift of attention or transient orienting, and that there was no enhancement of attention opposite the cued lo-

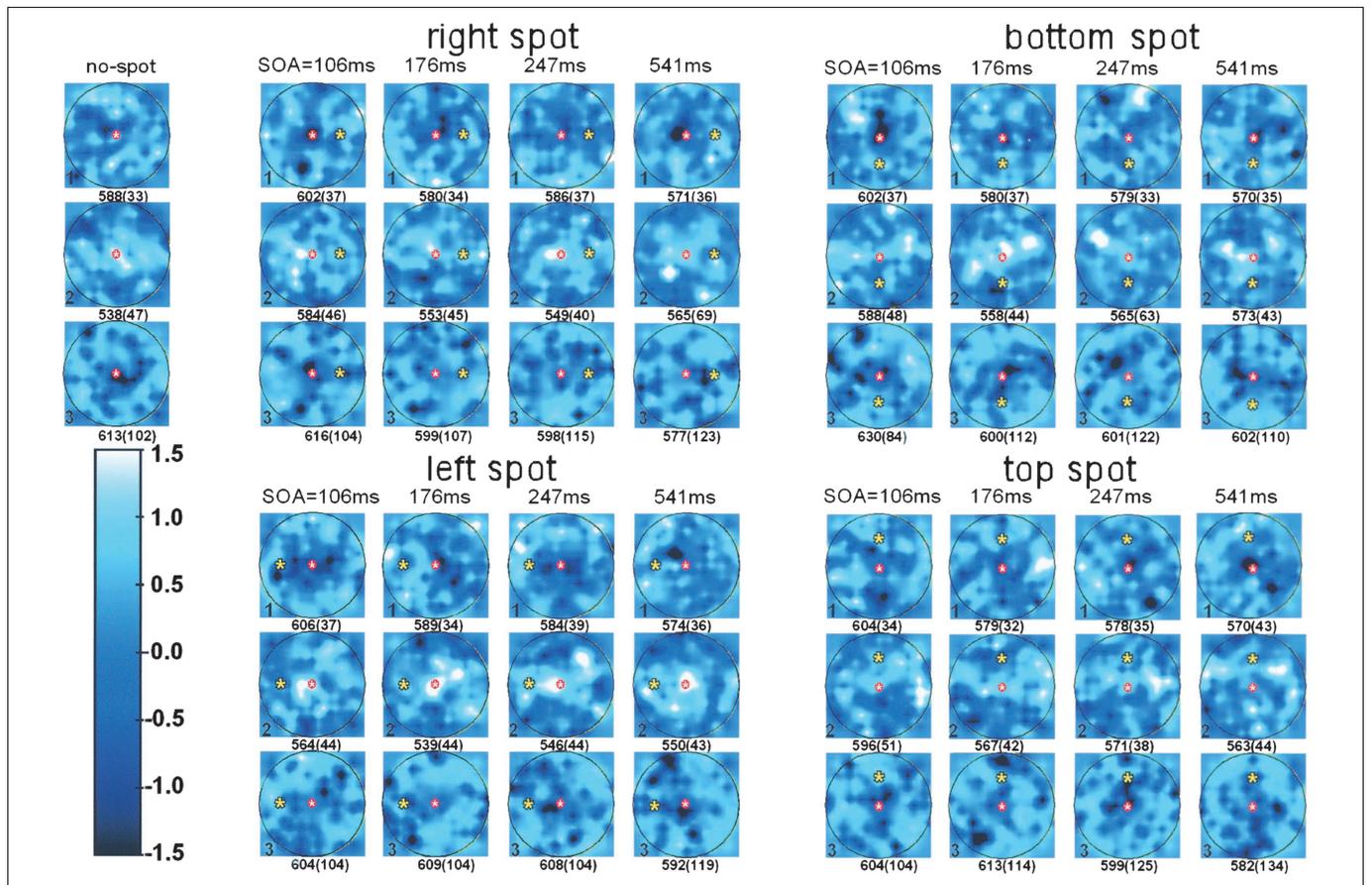


Fig. 6. Individual reaction times (RTs) for no-cue trials and cued trials with each stimulus onset asynchrony (SOA) and each cued position (yellow stars). The maps show z scores for average RTs, color-coded as shown in the bar. The number in the lower left corner of each map indicates observer number. The z scores were calculated for each condition independently and can be used to judge relative RTs for locations within a condition. Values more than $+1.5$ SD and less than -1.5 SD were mapped onto white and black, respectively. The large black circle in each map indicates the 25° circle containing the test points. Each point is the average of 9 RTs (the longest of the 10 RTs at each tested location was eliminated to eliminate possible outliers). The average RT in milliseconds is shown below each map (standard deviations are in parentheses). Bilinear interpolation was used to obtain values for nontested positions, and the results were smoothed using a rotationally symmetric 3×3 Gaussian low-pass filter with a standard deviation of 0.5 grid units. Smearing occurred outside the tested region (indicated by the black circles) because of low-pass filtering over tested points directly on the black circle. The red spot at the center of each map represents the fixation point.

ception, as indeed Snyder et al. (2001) reported. Our data show, however, that the cue had a rapid and probably reflexive influence on the spatial distribution of correct responses. We believe that accuracy may provide a more focused measure of the distribution of attention than RT. Accuracy also has an advantage over RT in that accuracy data have a baseline at chance. Because RT data do not have this baseline, it is not possible to use RT as a measure of, for example, the amount of attention remaining even at “unattended” locations. It may be that enhanced accuracy as measured in our paradigm and speeded RTs as measured within an IOR paradigm reflect a common underlying mechanism, such as attentional orienting. We may not have found evidence of IOR in our RT data because our paradigm was not designed to minimize RT variance or duration. In particular, we did not tell our observers to respond as quickly as possible.

Observers must receive extensive training in our paradigm before they are able to see changes away from fixation despite the “blinding”

blank (see Fig. 2). One concern is whether our highly trained observers allocated attention differently than untrained observers. We believe this is unlikely because the basic pattern of hot-spot elongation along the cue-fixation axis (with attention pooling at and opposite the cued location) was already apparent in the training phase for 2 naive subjects (Observers 1 and 3). Training is known to improve performance on attentionally demanding tasks. Training may function to lessen the difficulty of a task, by increasing its familiarity (Braun, 1998), reducing the amount of attention required to carry out the task (Norman & Bobrow, 1975), or increasing the efficiency or strength of attentional allocation (Cave & Zimmerman, 1997). But to our knowledge, there is no evidence that the spatial distribution of attention itself changes with practice in a cuing task. We believe our observers learned to ignore the blinding blank because in subsequent testing we found that they were able to transfer this ability to other change-detection tasks that involved a full-field blank. How observers learn to do this is not clear.

Mapping Attention With Change Blindness

Perhaps they learn to hold information in iconic memory (Sperling, 1960) for longer than untrained observers, or learn to stop the blank frame from fully flushing out that iconic buffer. As long as improvement in the task does not involve changes in the spatial allocation of attention, our results should also be informative about how untrained observers allocate attention in everyday circumstances.

Traditional metaphors that refer to attention as a moving spotlight or window fail to capture several properties of attention revealed by mapping the accuracy of change detection in a change-blindness paradigm. Our high-resolution maps reveal that spatial attention can be graded to cover virtually the entire visual field. Attention has a hot spot that deforms in response to a peripherally flashed cue, even when observers know that this cue is uninformative for the task at hand. This result is consistent with the finding that abrupt onsets invoke an automatic and mandatory capture of attention (Jonides & Yantis, 1988; Yantis & Egeth, 1999). The combination of a global-but-low-resolution distribution of attention with a local-but-high-resolution distribution of attention is consistent with models of attention (Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe & Gancarz, 1996) that allow for pop-out of targets that are highly distinguishable from distractors, but require serial search for targets that are not easily distinguishable without the high-resolution hot spot.

Unlike a moving spotlight, the hot spot of attention tends to remain centered at fixation (Wolfe, O'Neill, & Bennett, 1998). This is not surprising because visual acuity is highest in the fovea, and observers typically attend to that which they foveate. The hot spot also tends to be a single connected blob, as opposed to several disconnected blobs, at least when there is only one peripheral cue, as in the present study. This may account for results showing that attention is more easily allocated to compact regions than to multiple smaller regions of equivalent area (Podgorny & Shepard, 1983). Future experiments using two or more simultaneous cues can be carried out to determine how attention is split between two or more cues (cf. Bichot, Cave, & Pashler, 1999).

Because our data were averaged across trials, they cannot distinguish between two alternative accounts of how attention is spatially allocated: Either it is allocated in an "analog" manner to each location on each trial, albeit to varying degrees, or it is allocated "digitally" to a few objects or even one object (Rensink, 2000a) at a time. If the former is the case, changes were detected because attention was present at all locations, and different detection rates reflect different degrees of attending to different locations. The maps in Figure 4 would then indicate the probability of attentional strength at each location on each trial. If the latter is the case, changes may be represented implicitly (Thornton & Fernandez-Duque, 2000), and these implicit representations may be what then attracts attention (Smilek, Eastwood, & Merikle, 2000). The maps in Figure 4 would then indicate the likelihood of the all-or-none presence of attention on each trial.

We favor the analog account of attentional allocation because the hot spot was typically 15° to 20° across. In this hot spot, detection rates were more or less uniformly 100%. We take this as evidence that attention was globally distributed on each trial at least for this large hot spot. However, even outside the hot spot, detection rates were typically better than 60% over a wide area. If attention is allocated only in a spatially piecemeal or quantal fashion on any given trial, it would still have to be distributed over an average of 60% of the squares outside the hot spot on each trial to account for this result. Our data imply that a strong digital account, in which attention is necessarily allocated to one or very few objects or locations at a time, is implausible.

Our data are consistent with previous results indicating that attention grows in an analog manner away from fixation toward a peripher-

ally cued location (Shulman, Remington, & McLean, 1979; Tsai, 1983). However, our data do not rule out the possibility that there may also be nonanalog shifts of attention under some conditions (Remington & Pierce, 1984; Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995). Because the hot spot is aligned along the cue-fixation axis, it is possible that attention deforms in an analog manner along this axis, but need not traverse intermediate points between points that do not lie on this axis; this would be a compromise between temporally analog (Eriksen & St. James, 1986; Posner, Snyder, & Davidson, 1980) and quantal (Remington & Pierce, 1984; Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995) theories of attentional shifts.

It may be that the "unnatural" maintenance of fixation played a role in the tendency for attention to pool opposite the cued location. Future work should reveal whether opposite pooling occurs even when observers are permitted to saccade to the cue. These and other experiments will have to determine why attention pools opposite the cued location, and what role cuing and fixation play in triggering this pooling. Opposite pooling of attention should also be observable using other measures of attentional allocation and performance, such as detection thresholds.

The present experiment did not distinguish conscious change detection from mere unconscious but accurate guessing, because observers did not have to localize the change. In a future version of this task, we will ask observers to saccade to the location of a change. Also, unlike most natural scenes, our display was unstructured. Therefore, there may have been no recourse but to allocate attention in a purely spatial fashion. Several researchers have, however, provided evidence that attention tends to be allocated more to objects than to locations (e.g., Driver, Davis, Russell, Turatto, & Freeman, 2001; Duncan, 1984; Vecera & Farah, 1994). Using our method with objects may reveal a hot spot that adheres to a surface or a contour rather than being uniformly distributed across a large area. Finally, the psychophysical task we used required extensive training. Our results may therefore not reveal how attention would be allocated in natural circumstances by untrained observers. Future versions of this paradigm should involve less training, be less time-consuming, and more closely resemble real-world situations in which observers naturally allocate and shift attention.

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APPENDIX: STATISTICAL ANALYSIS OF DATA SHOWN IN FIGURE 5

To obtain the confidence ellipses shown in Figure 5, we converted the data matrix to a hot-spot-of-attention matrix, using a threshold procedure; elements above 80% correct were converted to 1, and all other elements were converted to 0. Clusters were favored by eliminating any 1s surrounded by 0s in the data matrix. For each data set (one average and three individual data sets) for each condition, principal components analysis yielded two eigenvectors, which were the major and minor axes of the ellipse. The major length was the square root of the larger eigenvalue, and the minor length was the square root of the smaller eigenvalue. The major or minor length corresponded to the standard deviation of the data projected onto the major or minor axis, respectively.

The numbers below each map in Figure 5 indicate the expansion or contraction of the confidence ellipse for the pooled data along the x - and y -axes, relative to the confidence ellipse in the no-cue condition; the minimum x and y values for an ellipse were subtracted from the corresponding maximum values to yield x - and y -axis projections, and these lengths were then divided by the corresponding lengths from the no-cue condition. A t test revealed significantly more expansion along the cue-fixation axis than the orthogonal axis for the first three SOAs (106 ms: $p = .003$; 176 ms: $p = .001$; 247 ms: $p = .004$; 541 ms: $p = .121$). An elongation *aspect ratio* was also calculated for each ellipse by dividing its x -axis projection length by its y -axis projection length, pooling over left- and right-cue data and over top- and bottom-cue data, respectively. A two-way analysis of variance of this SOA \times Cue Axis matrix (six aspect ratios per cell) revealed a significant main effect of cue axis, $F(1, 46) = 19.49$, $p < .0001$, but no main effect of SOA, and no SOA \times Cue Axis interaction. Subsequent t tests revealed a significant difference between the horizontal and vertical axes for the last three SOAs, but not for the shortest (106 ms: $p = .073$; 176 ms: $p = .010$; 247 ms: $p = .017$; 541 ms: $p = .013$).