Predicting future motion

Preeti Verghese
Smith Kettlewell Eye Research Institute, San Francisco, CA, USA

Suzanne P. McKee
Smith Kettlewell Eye Research Institute, San Francisco, CA, USA

Predicting the future course of a moving target is invaluable for planning actions. We used trajectory detection in noise to investigate this predictive capability. Using a contrast probe technique, we showed that in noise, contrast increments are more easily seen at the end of the trajectory than at the beginning. Analyses of the contrast data revealed that the improvement at the end of the trajectory was due to a substantial reduction in the number of detectors monitored, as well as to an increase in the gain of detectors responding to the increment. It appears that the first segment of the trajectory acts as an automatic cue that draws attention to subsequent segments of the trajectory, leading to enhanced detectability for predictable motion trajectories.

Keywords: signal detection theory, contrast discrimination, motion energy, cueing

Introduction

Objects in motion generally do not change direction abruptly. The human visual system takes advantage of this physical constraint to detect targets moving on predictable paths, presented in noisy surroundings (Ramachandran & Anstis, 1983; Nakayama & Silverman, 1984; van Doorn & Koenderink, 1984; Snowden & Braddick, 1989). Previous studies of trajectory detection in noise provide a striking demonstration of human sensitivity for predictable motion (Watamaniuk, McKee, & Grzywacz, 1995; Watamaniuk & McKee, 1995). These studies show that a single dot moving on a straight path in one of eight directions and presented at a random location in the midst of identical noise dots in random motion is easily detected. Although the standard motion energy model can account for the detectability of brief trajectories (100 ms) in dense motion noise, it does not explain human sensitivity for extended trajectories (Verghese, Watamaniuk, McKee, & Grzywacz, 1999). For example, a 200-ms trajectory is much more detectable than two 100-ms trajectories presented at independent locations; it is as detectable as six 100-ms trajectories scattered in the noise.

What makes an extended trajectory so much more detectable than the sum of its parts? Clearly, it is unlikely that a noise dot will continue in the same direction for the 6 steps that make up the 100-ms stimulus duration, and even less likely that it will for the 13 steps that make up the 200-ms duration. For instance, predictive filtering models suggest that 3 consecutive steps in the same direction are sufficient to signal the presence of a trajectory (Burgi, Yuille, & Grzywacz, 2000). But the spatial and temporal limitations of the early motion detectors in the visual system make such a short trajectory invisible in noise. How then does the visual system detect a behaviorally relevant trajectory that is unlikely to occur by chance? A hint comes from a study in which we manipulated the spatial and temporal arrangements of two 100-ms trajectory segments. Figure 1 plots the detectability (d') of two 100-ms segments presented in various configurations within a 200-ms window. In this experiment, observers were asked to detect which of two intervals contained a trajectory. We used five configurations that included a straight trajectory and a trajectory where the second segment changed direction by 45°. We also used a reversed sequence in which the second segment hopped backward to appear before the beginning of the first to investigate the effect of a pure orientation cue formed by the spatial alignment of the two segments. Finally, we used configurations in which the second segment was constrained to appear either within 2° of the first or was displaced by at least 2° from the first. The data averaged over three observers show that the two segments in noise were most detectable when they formed a straight trajectory. However, presenting any two segments in close spatiotemporal proximity enhanced their detectability somewhat relative to two 100-ms segments presented at widely separated locations. Note that two 100-ms motion segments presented at widely separated positions are no more detectable than a single 100-ms segment presented in a 100-ms noise interval (threshold for one segment shown by horizontal line). These results suggested that the first segment of the trajectory (i.e., the first 70 -100 ms) acts as a cue that alerts the visual system to subsequent motion segments, thereby increasing their visibility.

DOI 10:1167/2.5.5 Received May 2, 2002; published September 20, 2002 ISSN 1534-7362

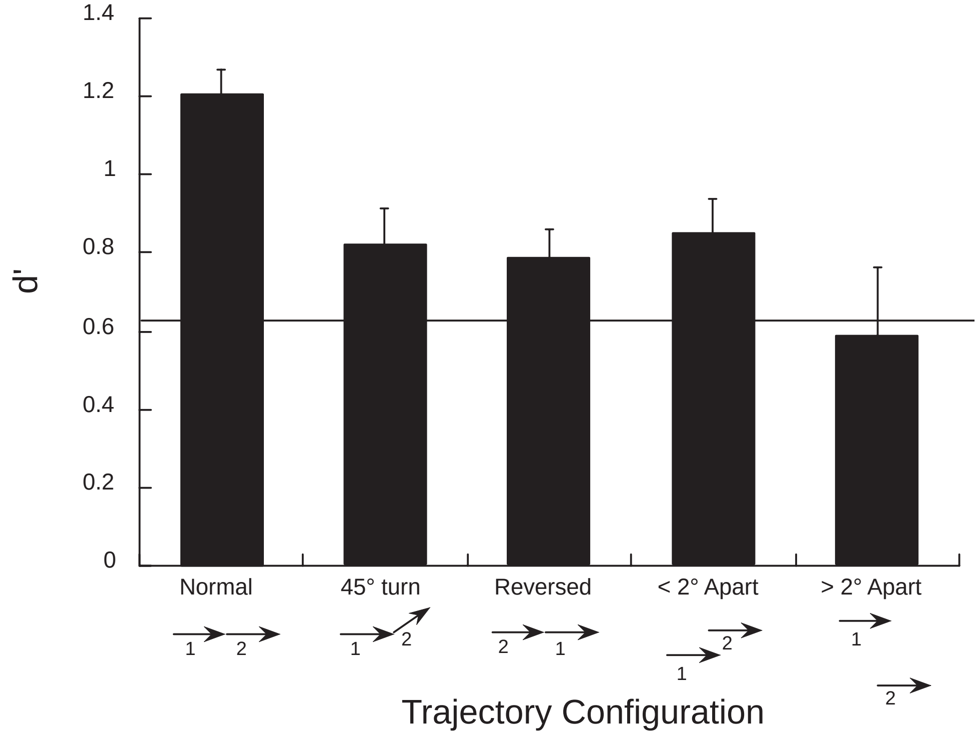

Figure 1. The detectability of various trajectory configurations as shown on the abscissa. Each arrow represents a 100-ms segment. The numbers 1 and 2 indicate the temporal order in which the two segments were presented. Observers had to choose which of two temporal intervals contained a trajectory signal. Each interval was 200 ms and contained 380 noise dots in Brownian motion. The horizontal line represents the detectability of a single 100-ms trajectory segment presented in 100 ms of noise.

A cue is used to manipulate attention and is thought to improve performance by increasing the sensitivity of the cued detector, or by reducing uncertainty about which detector contains the signal, or by some mixture of both operations (Shiu & Pashler, 1994; Lu & Dosher, 1998; Dosher & Lu, 2000a,b; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Verghese, 2001). In physiological terms, the change in sensitivity might be achieved by increasing the gain of the signal neurons (Treue & Maunsell, 1996), and the reduction in uncertainty could be accomplished by a competitive interaction that results in the weaker neuronal responses being suppressed (Reynolds, Chelazzi, & Desimone, 1999). In the case of trajectory detection, we are proposing that the first 100 ms of the motion acts as a cue to subsequent similar motion signals in the vicinity. To determine how this cue enhances trajectory visibility, we measured contrast increments either at the beginning (first 70 ms) or the end (last 70 ms) of a 200-ms trajectory in separate experimental blocks (Figures 2a and 2b, respectively). In effect, observers are doing a contrast-discrimination task.

Increasing gain and reducing uncertainty have different effects on the psychometric function associated with a contrast threshold. As shown diagrammatically in Figure 2c, increasing the gain shifts the location of the psychometric function to lower values (and lower thresholds), without changing its shape. On the other hand, a reduction in uncertainty changes the slope of the psychometric function. The curve is shallow when the observer monitors the single detector that contains the signal, and the curve is steep when the observer monitors many (32) detectors, only one of which contains the signal. Figure 2d shows a pair of curves associated with different numbers of monitored mechanisms; the curve associated with 32 mechanisms is far steeper than the curve associated with 1 mechanism, although both asymptote to the same location on the abscissa. Note that if contrast thresholds are specified as a criterion percentage correct (e.g., 82%) they will be lower when the observer is monitoring fewer mechanisms, even if there is no accompanying change in gain.

To determine what combination of gain enhancement and uncertainty reduction explained trajectory detection, we used signal detection theory (SDT) (Green & Swets, 1966; Pelli, 1985) to fit the curves relating proportion correct to our contrast increment measurements. The SDT model has two parameters. The sensitivity parameter k represents the scaling factor between the physical contrast and its internal representation. Changes in this parameter reflect changes in gain (Figure 2c). The other free parameter M is uncertainty, or the number of detectors monitored (Figure 2d). We used an iterative procedure to find the best-fitting values of k and M for a given set of data.

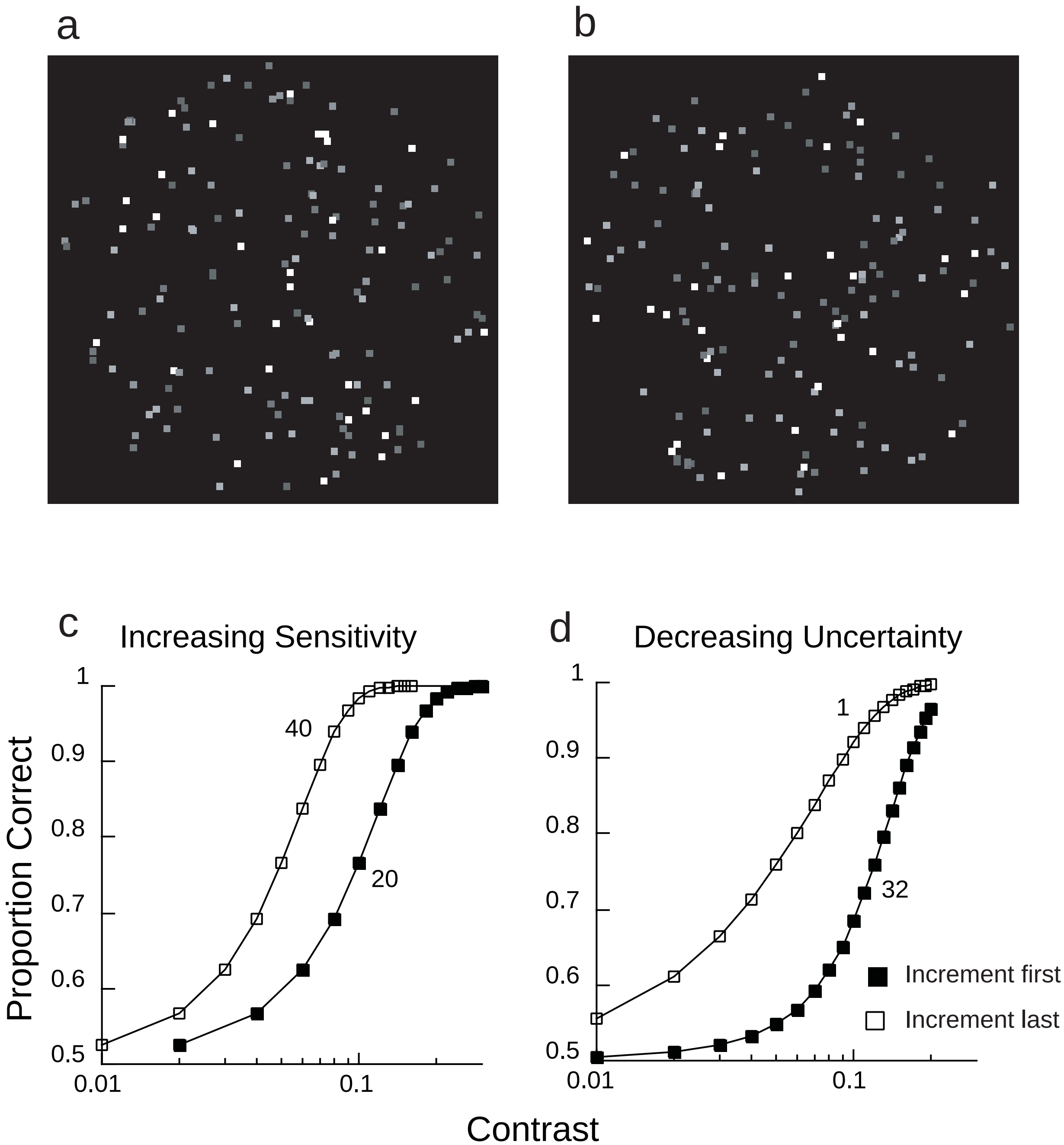

Figure 2. Stimulus configuration and predictions. Movies a and b show a 200-ms trajectory moving rightward with a contrast increment that occurs in the first 70 ms and last 70 ms, respectively (the movie is slowed by a factor of two relative to the actual stimulus). Each movie shows a trial made up of two intervals. Both intervals contain a trajectory that moves in 1 of 8 directions, but only one of the intervals has a contrast increment. The noise is Brownian motion with the same displacement as the trajectory on every frame, but a random direction. Each noise dot is randomly assigned one of 5 contrast levels centered on the mean contrast. The observer's task was to choose the interval with the increment. c and d show hypothetical psychometric functions predicted from the uncertainty model for increments at the beginning and end of the trajectory. c represents the case in which sensitivity *k* increases at the end of the trajectory, causing the curve to shift leftward without a change in slope. The values 20 and 40 refer to the sensitivity parameter *k*. d represents the case in which the uncertainty *M* decreases (observer monitors fewer detectors) at the end of the trajectory. A decrease in the number of detectors monitored (from 32 to 1) decreases the slope of the curve without changing the contrast at which performance asymptotes to being perfect.

Methods

The signal was a dot moving along a straight trajectory for 200 ms, which was displaced in a consistent direction by 0.17° on each frame. This corresponded to a velocity of 12°/s, given the 71-Hz frame rate of the display monitor. In the signal-known condition, the 200-ms trajectory was centered on fixation and moved in a single direction. We also added stimulus uncertainty in one or more of the following ways: by randomizing the location of the trajectory center to within ±1° of fixation, by having it move in one of 8 directions, and by adding Brownian noise. Each noise dot was displaced by the same amount as the signal on each frame, but its direction was randomly sampled from 360°. In the detection experiments (data of Figure 1 and Figure 7), observers were asked to choose which of two intervals contained the signal trajectory.

The luminance of the background was 13.5 cd/m^2. Each stimulus dot subtended 2 arc min at a viewing distance of 1 m. The signal dot had a contrast of 54%. In the contrast discrimination experiments, the contrast of the noise dots was one of 5 values centered about 54%, in steps of $2^{1/4}$ (0.075 log units). These 5 values corresponded to Michelson contrasts of 35.6, 44.9, 54.4, 66.9, and 82.7%. This range of noise values was used so that the contrast increment could not be identified as the brightest dot in the display. We were restricted in the range of contrast increments that could be added to our signal, which limited the highest proportion correct in the added noise conditions to values below 0.9. The display area was a circular region 12.6° in diameter. The number of dots in this area determined the dot density. For the noise experiments, the number of dots was either 190 or 380, corresponding to noise densities of 1.5 or 3 dots/deg^2, respectively.

We used a 2-alternative forced choice procedure with two temporal intervals. An auditory cue was presented 80 ms before the trajectory in both intervals to alert the observer to the upcoming stimulus. Both intervals contained the signal trajectory, but one of the intervals had a contrast increment on the trajectory. The increment occurred either in the first 70 ms or in the last 70 ms of the 200-ms trajectory. Increments at the beginning and the end of the trajectory were presented in separate blocks. Observers were asked to choose the interval with the contrast increment. Feedback was provided.

We generated a psychometric function by measuring proportion correct for 4 to 6 values of contrast increment. Data for each contrast increment were taken in a single block of 96 trials. The psychometric function was fit with the uncertainty model (see below) to obtain estimates of the fit parameters. We repeated the measurement of the entire psychometric function (at least once) to obtain error estimates of the fit parameters.

We used an iterative procedure to estimate the maximum likelihood fits of the two parameters of the uncertainty model outlined below to the psychometric functions (proportion correct vs. contrast or motion energy increment). The uncertainty model assumes that the observer monitors multiple detectors M in each interval. The detectors have a sensitivity *k*, and each detector produces a noisy response. The observer finds the largest of these responses in each interval and then chooses the interval with the larger response. Errors arise when the interval without the increment produces a larger response, and the probability of error increases with the number of detectors that the observer monitors. This formulation is based on Pelli's uncertainty model (Pelli, 1985). For our 2–interval forced choice task, the probability of choosing the interval with the contrast increment is given by

$$P_{correct}(c) = \int_{-\infty}^{\infty} \begin{bmatrix} f(x-k(c+\Delta c))F(x-kc)^{2M-1} \\ +(M-1)f(x-kc)F(x-kc)^{2M-2}F(x-k(c+\Delta c)) \end{bmatrix} dx$$

where

c is the contrast of the trajectory, Δc is the contrast increment

$f(x)$ is Gaussian probablity density function

$F(x)$ is the cumulative Gaussian $\int_{-\infty}^{x} f(x')dx'$

k is a sensitivity parameter

M is the uncertainty parameter.

We assume that the noisy responses are samples from a Gaussian distribution. When the detector is centered on the contrast increment, the response is a sample from a distribution with a mean at $c \pm \Delta c$, whereas the responses to non-increment contrasts are samples from a distribution centered at *c*. The variance of this distribution does not represent the variability in response to a single contrast value, but rather the pooled variance across all five noise contrasts. The observer monitors the output of M detectors in each interval and makes a correct choice when the largest response from the increment interval exceeds the largest response from the non-increment interval. There are two components to this correct choice. The first term on the right hand side is the probability that the largest response comes from the detector that sees the contrast increment. This is the probability that a sample from a distribution centered at $c \pm \Delta c$ is larger than 2*M*-1 samples from a distribution centered at *c*. As the observer monitors M detectors in each temporal interval, there is a total of 2*M*-1 detectors that see a contrast centered about *c*, *M*-1 from the interval with the increment, and M from the other interval. The second term is the probability that the largest response comes from the interval with the increment, but from a detector that does not see the increment. It is the probability that one of the non-increment detectors in the increment interval has the largest response.

We estimated the variability of the parameters *k* and M in two ways. The errors associated with the fit were obtained from the covariance matrix where the diagonal terms specify the variance of *k* and M. We also measured the standard deviation of the fits across repeated measurements of the psychometric function. Typically the errors estimated from repeated measurements are much smaller than the errors estimated from the fitting procedure. There is an overall tendency for the sensitivity term *k* to decrease with noise level, probably due to contrast normalization. Because the parameter M occurs as an exponent in the equation above, very small changes in the steepness of the psychometric function can produce dramatic changes in M. For values of M of the order of 10, the lower and upper bounds on M could be within a factor of 3 (M could range from 3.3 to 30). For values M of the order of 100, the lower and upper bounds could be within a factor of 7. Therefore, we are only interested in an order of magnitude for this parameter.

The experiments with static cues were performed in the standard 200-ms stimulus interval. The noise dots were visible during the entire stimulus interval whereas the oriented static dots appeared 84 ms into the interval, lasted 14 ms, and were immediately followed by a 100-ms trajectory segment. The single large dot was centered at the midpoint of an implicit 100-ms segment preceding the test trajectory. It appeared 42 ms into the stimulus interval, and also lasted 14 ms. The visibility of these static cues was manipulated by adjusting the number of dots in the oriented cue or the size of the single dot cue. All observers required 4 oriented dots in the static string and a single large 6-pixel dot to match the visibility of a 100-ms trajectory segment, for the noise levels that we considered. Observers were presented with two noise intervals, one of which had the trajectory and cue. Observers were asked to choose the interval with the trajectory, and detectability was measured as a function of the noise density.

The authors and three observers who were naïve about the outcome of the experiments participated in these studies. The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from the observers after explanation of the nature and possible consequences of the study. The research protocol and consent form were approved by the Institutional Review Board.

Results

Detecting Contrast Increments at the Beginning and End of the Trajectory

It is possible that the first segment of an extended trajectory always activates a network that facilitates activity in subsequent segments, whether or not there are competing motion signals (Hubbard & Marshall, 1994; Grzywacz, Watamaniuk, & McKee, 1995; Berry, Brivanlou, Jordan, & Meister, 1999). To test this possibility, we first measured contrast increments when the location and direction of the trajectory were known exactly and there were no noise dots on the screen. In Figure 3 the proportion correct has been plotted as a function of the contrast increment; solid symbols represent the data for increments in the beginning, and open symbols represent increments in the end.

The upper two graphs in Figure 3 show the results for a known trajectory presented in the absence of noise. For both observers, the data for increments at the beginning and the end of the trajectory are nearly identical. The lines are the best fits of the two-parameter SDT model to the data for each condition; the solid and dashed red lines are the fits to increment data at the beginning and end of the trajectory, respectively. Each fitted function is characterized by a sensitivity estimate and an uncertainty estimate. Both observers show small decreases in sensitivity and in uncertainty for increments at the end relative to increments at the beginning. However, these changes are within the error inherent in fitting these parameters to the data, as described in “Methods.” Overall, these data provide no compelling evidence for an obligatory facilitation that is propagated along the trajectory path.

We next compared these results to a situation that resembled the conditions of the original trajectory studies. The trajectory, moving in one of 8 directions, was presented in the midst of 380 dynamic noise dots for observer N.K., and 190 noise dots for observer A.J. The noise dots were randomly assigned one of five contrast values that spanned the range of the contrast increment. For observer N.K., the trajectory was presented at a fixed location on every trial, because randomizing the location of the trajectory at the higher noise level (380 noise dots) reduced her performance to chance. For observer A.J., the trajectory was randomly placed within a 2° region centered on fixation but at a lower noise level of 190 dots. The lower two graphs in Figure 3 show the contrast increment functions measured in noise (black symbols). Once again the solid symbols and line are associated with increments at the beginning and the open symbols and dashed line with increments at the end.

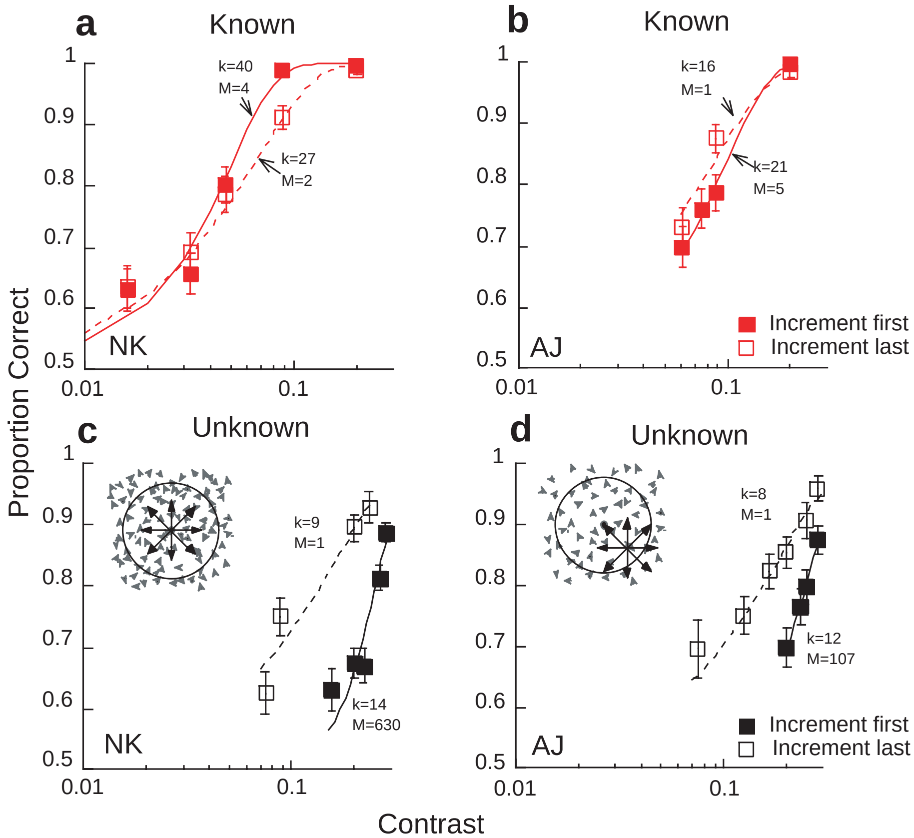

Figure 3. Psychometric functions for detecting increments on a trajectory in noise when the trajectory is known and when it is unknown. The solid and the open symbols represent contrast increments at the beginning and end of the trajectory, respectively. The red symbols in the upper two panels show data for a trajectory in a known location, moving leftward in the absence of noise, for two observers. The error bars represent the binomial standard error. The solid and dashed lines represent the maximum likelihood fit of the uncertainty model to the data for increments at the beginning and end. The sensitivity *k* and uncertainty *M* values associated with each fit are also listed. In this and other experiments, there is a tendency for the sensitivity parameter *k* to decrease with increasing noise level, probably due to contrast normalization (compare *k* values in the noise-absent data in the top panels to *k* values for the noise-present data in the bottom panels). Because the parameter *M* occurs as an exponent in the equation above, very small changes in the steepness of the psychometric function can produce dramatic changes in *M*. Therefore, we are only interested in changes of an order of magnitude for this parameter. The black symbols in the lower panels show data for detecting a trajectory in *noise*. For observer N.K., the trajectory was centered at fixation, and moved in one of 8 directions in the midst of 380 noise dots. For observer A.J., the trajectory location was randomized within a 2° box centered on fixation, moved in one of 8 directions and was presented in the midst of 190 noise dots.

By comparing the upper and lower graphs in Figure 3, we can see that noise has its greatest effect on the early part of the trajectory sequence. The observer is having trouble detecting the contrast increment at the beginning because she cannot *find* the trajectory. By design, the trajectory motion resembles the motion of the noise dots on a frame-by-frame basis; the only difference is that the trajectory moves in the same direction on every frame, whereas the noise dots change direction on every frame. During the initial 20 to 30 ms of the display, there is only a small difference between the responses generated in a motion mechanism by the trajectory dot and by the noise dots. The observer has no way of knowing which moving dot is the true trajectory, and so must monitor all directions and locations within the 2° region surrounding fixation. For observer N.K., the higher noise level appears to offset the benefit of a fixed trajectory location; even though only the direction of the trajectory is randomized, her uncertainty estimate for increments at the beginning of the trajectory indicates that she acts as if uncertain of the location of the trajectory. As the trajectory continues on its straight path, it generates a motion response that becomes increasingly larger than the responses generated by most of the noise dots (Verghese et al., 1999). The robust motion response generated by the first 100-ms segment is an effective cue to the location and direction of the subsequent parts of the trajectory, thereby producing the marked improvement in detecting contrast increments at the end of the trajectory.

When the trajectory is presented in noise, both observers can detect the increment at the end of the trajectory far more easily than the increment at the beginning of the trajectory. The calculated fits indicate that there are small changes in the sensitivity parameter *k*, perhaps amounting to about a factor of 1.5 for end increments relative to beginning increments. However, there is a huge change, by more than a factor of 100, in the uncertainty parameter M. Two other observers participated in these experiments (see Figure 4). They also found detection of contrast increments in noise to be easier at the end of the trajectory than at the beginning. While one of these observers showed the same large change in uncertainty with little change in sensitivity, the other observer showed a large change in sensitivity (factor of 3) with little change in the uncertainty parameter. Figure 4 provides a comparison of the gain and uncertainty values associated with increments at the beginning and at the end of the trajectory for all four observers. The error bars represent the standard deviation associated with two repetitions of the experiment. This experimental variability is typically smaller than the upper and lower bounds estimated from the fitting procedure (see "Methods").

Gain Versus Uncertainty

One of our observers (S.P.M.) shows an improvement at the end of the trajectory characterized by an increase in gain while the other three observers show an improvement characterized by a large reduction in uncertainty. Studies by Lu and Dosher (Lu & Dosher, 1998, 1999; Dosher & Lu, 2000a, 2000b) have shown that cueing can produce both effects: which effect dominates depends on noise level. Under conditions of low noise, cueing a stimulus location increased the gain of the filter responding to the stimulus. Under high noise conditions, cueing excluded the added noise in their display. In the context of our experiments, we would expect that in the presence of high noise the first segment would reduce uncertainty about the trajectory by excluding extraneous noise dots. To test this hypothesis observer S.P.M. repeated the experiment at a higher noise level of 380 noise dots.

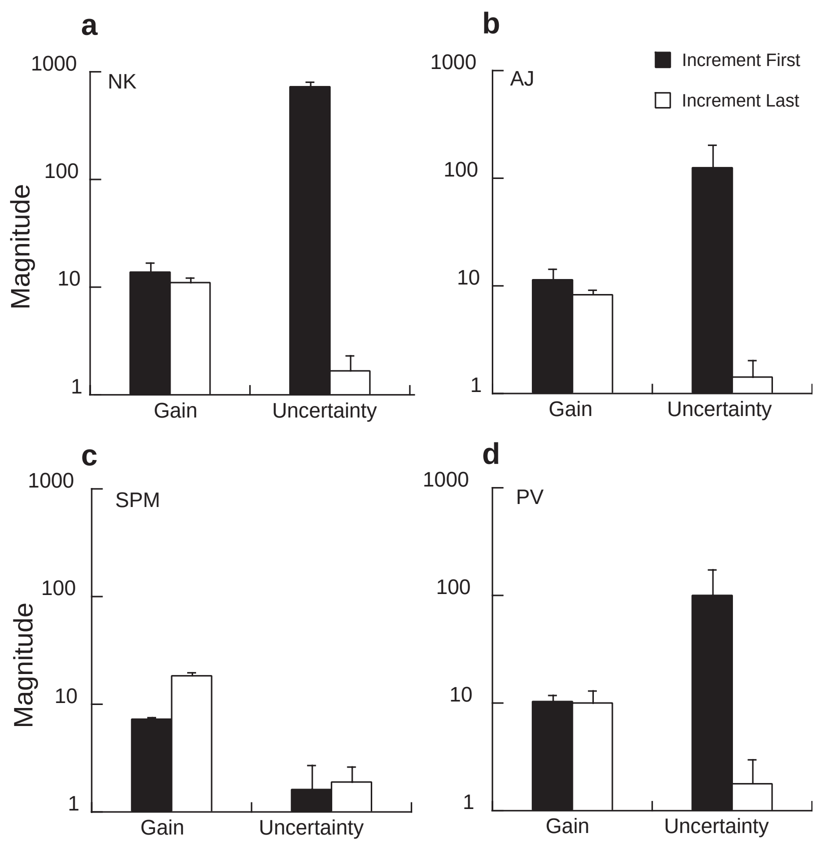

Figure 4. A summary of the gain and uncertainty values associated with increments at the beginning and at the end of a 200-ms trajectory in noise for all four observers. Note the logarithmic scale on the ordinate. Once again solid and open bars represent increments at the beginning and end of the trajectory. Panels a and b summarize the gain *k* and uncertainty *M* values for the data shown in Figure 2c and 2d, respectively. Panels c and d show the gain and uncertainty values for two other observers, S.P.M. and P.V., respectively. The 200-ms trajectory was presented among 190 noise dots for observer S.P.M. and among 380 noise dots for observer P.V. For these observers, the trajectory location was randomized within a 2° box centered on fixation and moved in one of 8 directions. The error bars represent the standard deviation of the parameters fitted to repeated measurements of the entire psychometric function. The variability across repeated measures is well within the errors estimated from the fitting procedure. The fit errors on the *k* term are about ± 2, and on the *M* term are a factor of 2 for *M* ~1 and about a factor of 7 for *M* > 100.

Figure 5 shows data for two noise levels for observer S.P.M. The gain and uncertainty numbers associated with 190 noise dots are plotted as in Figure 3. The improvement at the end of the trajectory at this low noise level is characterized almost completely by an increase in gain and a leftward shift of the psychometric function. Conversely, the improvement at the higher noise level (380 noise dots) appears to be due to an increase in uncertainty. These data support the hypothesis that cueing has a greater effect on uncertainty at higher noise levels.

The uncertainty about the location and direction of the trajectory adds another aspect to this hypothesis. In previous work, we have shown that the 100-ms segment in noise is highly visible *if* the observer knows where to look (Verghese et al., 1999). However, the first 100-ms segment, which is supposed to be cueing subsequent parts of the trajectory, is detected on only 55% to 65% of trials when it is presented in 380 noise dots at a randomly chosen location. Why is this strong local motion response so poorly detected when the observer is uncertain about its location and direction? Our simulations with motion energy detectors indicate that two things happen at higher noise levels that reduce the visibility of the first part of the trajectory: First, the motion response to the trajectory becomes more variable because the local motion detector now has many noise dots within its receptive field, and second, the number of effective noise competitors increases with noise level. Observers detect a 100-ms trajectory in dense noise in only about 60% of the trials because at least one noise competitor produces a larger response in the noise interval on the remaining trials. In short, some noise configurations may act as competing cues to other locations and motion directions. Nevertheless, the 100-ms trajectory can still act as an effective cue because only a few noise competitors at the end of 100 ms have a comparable motion response.

We did an experiment to explore the effect of deliberately creating competing cues. When a competing 200-ms trajectory (without a contrast increment) was added to the display, the ability to detect the contrast increment at the beginning of the test trajectory was almost the same as when there was only one (test) trajectory. This can be seen by comparing the filled gray and red symbols in Figure 6 for increments at the beginning of a single 200-ms trajectory and one of two 200-ms trajectories, respectively. However, the ability to detect the increment at the end of the test trajectory is significantly impaired by the addition of the competing trajectory (compare open gray and red symbols). This result supports the idea that the differential ability to detect increments at the beginning and end of the trajectory is due to different number of noise competitors at the beginning and end. At the beginning of the 200-ms trajectory, the competing trajectory is among the many contenders for strongest motion response. By the end of a 200-ms trajectory, the competing and test trajectories are probably the only two candidates; so the competing trajectory significantly affects the ability to detect the increment on the test trajectory.

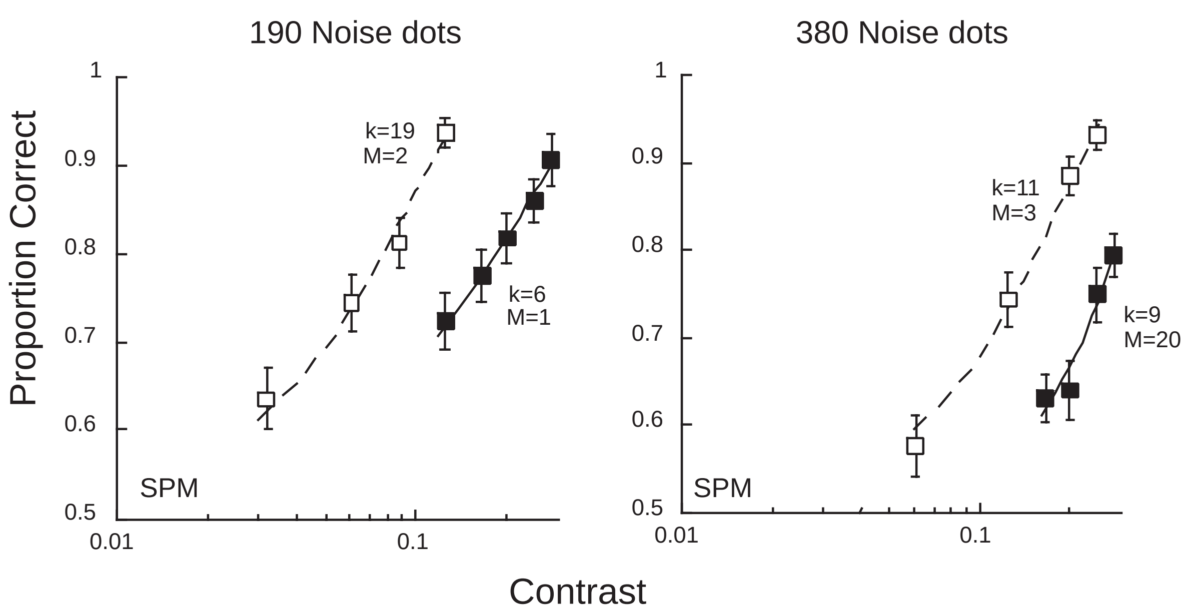

Figure 5. Plots of the psychometric functions for observer S.P.M. at two different noise levels. The data for 190 noise dots are summarized in Figure 4. The filled symbols represent measurements at the beginning of the trajectory, and the open symbols represent measurements at the end of the trajectory. The fit errors associated with the *k* parameter for increments at the beginning and end of a trajectory are 6±1 and 19±4 for 190 noise dots, and 9±1, and 11±2 for 380 noise dots. The fit errors associated with the *M* parameter for these data are all about a factor of 2 (one half to two times the best estimate of *M*).

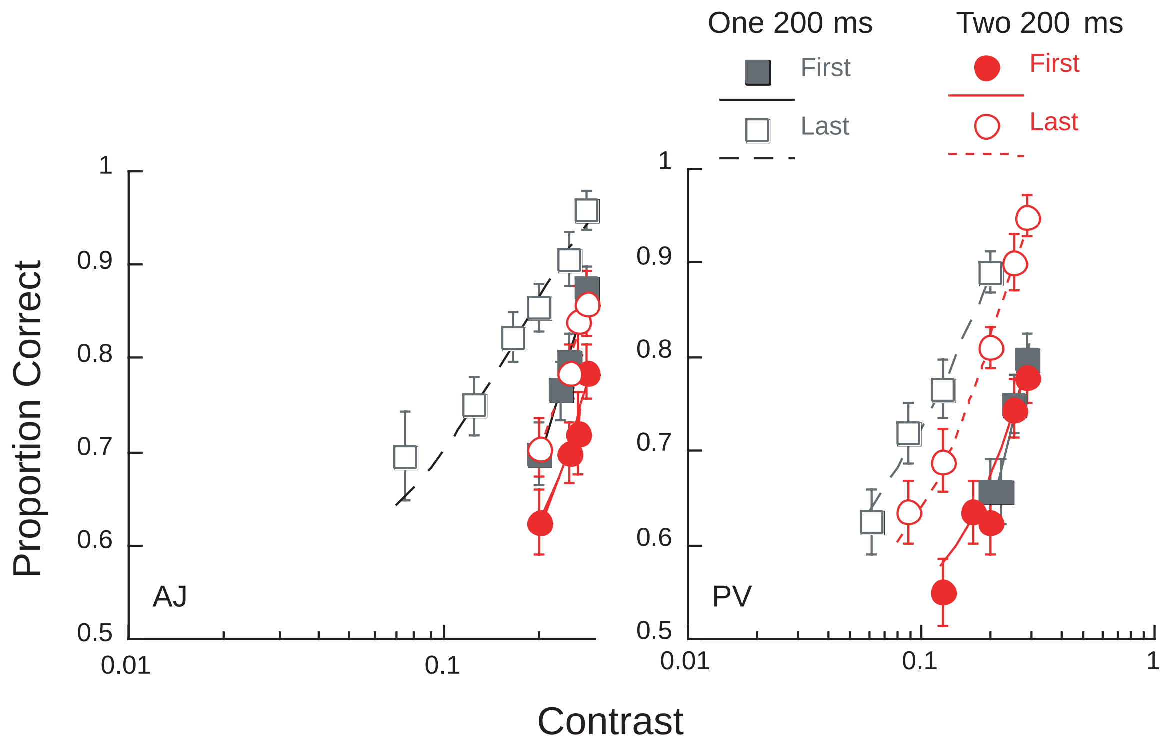

Figure 6. Psychometric functions for detecting contrast increments on a single trajectory in noise (gray symbols) and on one of two trajectories in noise (red symbols). The two trajectories were presented within ±1° from fixation. The trajectories were presented among 190 noise dots for observer A.J. and 380 noise dots for observer P.V. The data for the single trajectory (gray symbols) are replotted from Figure 3 for observer A.J. and are summarized in Figure 4 for observer P.V. The filled symbols represent measurements at the beginning of the trajectory and the open symbols represent measurements at the end of the trajectory. The two panels represent data for a naïve observer (left) and an author.

Static Cues to Motion

Static cues can also alert the motion system. The preceding experiments have measured the visibility of contrast increments on a trajectory. In this experiment we go back to measuring the detectability of a trajectory in various amounts of noise. To equate static and moving cues, we matched the detectability of the static cues to that of a 100-ms trajectory segment (see "Methods"). We then substituted the static cues for the first half of a 200-ms trajectory (see Figure 7). To obtain a measure of motion energy difference between signal and noise intervals, we calculated the motion energy response of a detector selective for a 100-ms segment moving with the speed and direction of the trajectory signal. This is equivalent to measuring the output of a motion detector centered over a 100-ms segment of the trajectory. Our earlier studies (Verghese et al., 1999) have shown that such a local motion energy measure predicts the detectability of short (100 ms) trajectories in noise. This detector was placed over the approximate location of the 100-ms trajectory presented alone or of the 100-ms segment preceded by either static or moving cues. To derive a motion contrast measure analogous to the increment contrast measure in the graphs above, the difference in response to the two intervals was divided by their sum and averaged over 1,000 simulated trials. This contrast measure is inversely related to noise density: as the number of noise dots increases, the mean response to both signal + noise and noise-only intervals increases. However, the proportion of the response due to the signal decreases with noise level, so motion contrast is low at high noise densities.

Four aligned static dots, presented with the same orientation as the trajectory path and flashed 14 ms before a 100-ms segment, greatly enhanced detectability relative to a 100-ms segment by itself, although this combination of a static cue and 100-ms motion segment was less detectable than a 200-ms moving trajectory. On the other hand, a less specific cue – a large bright dot flashed 50 ms before the segment – produced almost no improvement in the detection of the brief trajectory. Presumably, the close proximity in space and time and the informative orientation of the four-dot cue narrowed the range of potential locations and directions that the trajectory could take. Of course, the very best cue for a trajectory is the trajectory itself. Thus, straight or smoothly changing trajectories are most easily detected in noise.

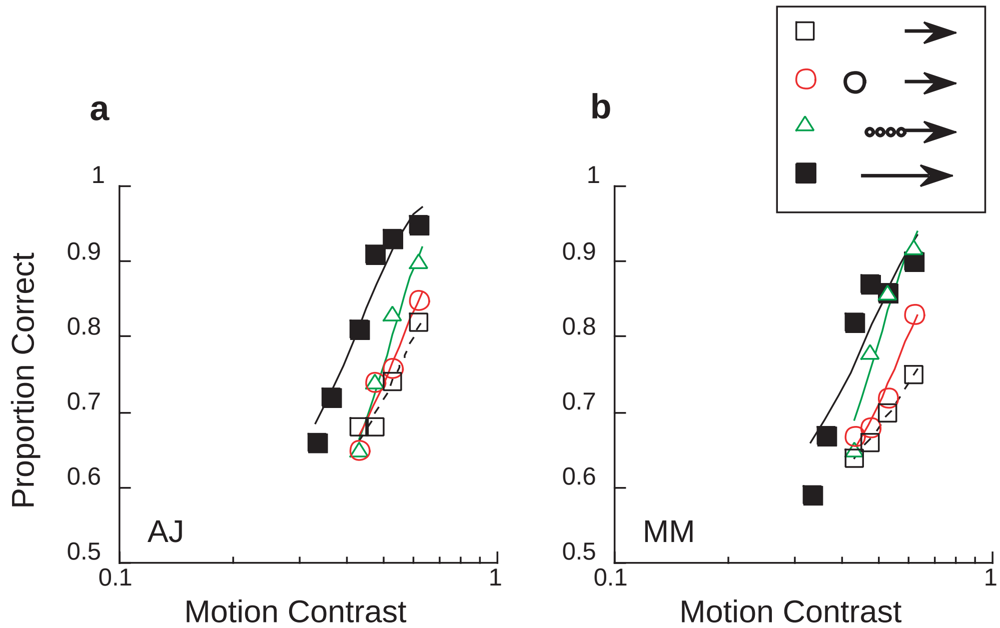

Figure 7. Effect of static cues. This experiment compared the effect of adding different cues on the detectability of a 100-ms trajectory (open black symbols) at different noise densities. The abscissa plots the average difference in the motion energy response over 1,000 simulated trials to the trajectory in noise and to noise alone, divided by the sum of these two responses. This measure of motion contrast between the two intervals in a trial is inversely related to noise density. Proportion correct is shown for a single 100-ms trajectory (open black squares) and for different cues that preceded the 100-ms segment: a single bright dot that occurred 50 ms before (red symbols), 4 static dots that appeared 14 ms before (green symbols), and a 200-ms motion trajectory (solid black symbols). At each noise density, the visibility of the static cues was matched to that of a 100-ms trajectory. The bright dot barely improves performance over the 100-ms trajectory by itself, but the 4 static dots enhance detectability presumably because they provide an orientation cue. Neither of these cues is as good as preceding the 100-ms segment by another 100-ms segment – a 200-ms trajectory.

Discussion

Our results show that the visual system can use consistent motion by itself as a cue to the most likely direction and future location of a moving feature. Self-cueing appears to be a simple and general-purpose method by which the visual system enhances the detectability of motion trajectories. It is general purpose because it does not require specialized motion architecture, such as filters extended in space and time matched exactly to all potential trajectories. It is simple because the cue is part of the signal itself. In typical cueing studies, the cue is explicit and clearly visible. In our study, the first part of the trajectory is barely detectable in noise, so it must act as an implicit cue. Ours is the first study that uses the rigorous signal detection theory approach (Pelli, 1985; Swensson & Judy, 1981; Burgess & Ghandeharian, 1984; Eckstein & Whiting, 1996) to show that an implicit cue reduces the number of detectors that the observer monitors.

Other studies have hinted at this spatiotemporal alerting. Welch, Macleod, and McKee (1997) showed that a dot flashed in the spatial and temporal vicinity of a pair of test dots undergoing apparent motion could bias the perceived direction of motion of the test dots. Because the bias is sensitive to the direction of the perturbing dot relative to the test pair, these findings are a motion-specific version of the general attentional effect described by Hikosaka and coworkers (Hikosaka, Miyauchi, & Shimojo, 1993). Our work emphasizes the specificity of this cue as well as the manner in which attention improves trajectory detection in noise.

Few studies have demonstrated changes in uncertainty of the magnitude shown here. We suspect that the high level of uncertainty at the beginning of the trajectory is due to the number of motion detectors activated by our motion noise. This large uncertainty would be true for any type of target presented in competing dense noise. In such circumstances, cueing, particularly self-cueing, can be extremely beneficial in narrowing potential target locations. As shown here, rigorous estimates of sensitivity and uncertainty are powerful tools for revealing the mechanics of cueing.

Acknowledgments

This work was made possible by National Eye Institute (NEI) grant RO1 EY12038 to P.V., by NEI grant R01 EY06644 to S.P.M., and by NEI core grant EY06883. Commercial Relationships: None.

References

Berry, M. J., Brivanlou, I. H., Jordan, T. A., & Meister, M. (1999). Anticipation of moving stimuli by the retina. *Nature, 398*, 334-338. [PubMed]

Burgess, A. E., & Ghandeharian, H. (1984). Visual signal detection. II. Signal location identification. *Journal of the Optical Society of America A, 1*, 1777-1787. (1984).

Burgi, P. -Y., Yuille, A. L., & Grzywacz, N. M. (2000). Probabilistic motion estimation based on temporal coherence. *Neural Computation*, *12*, 1839-1867. [PubMed]

Carrasco, M., Penpeci-Talgar, C., & Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity across the CSF: Support for signal enhancement. *Vision Research, 40*, 1203-1215. [PubMed]

Dosher, B. A., & Lu, Z. (2000a). Mechanisms of perceptual attention in precuing of location. *Vision Research, 40*, 1269-1292. [PubMed]

Dosher, B. A., & Lu, Z. L. (2000b). Noise exclusion in spatial attention. *Psychological Science, 11*, 139-146. [PubMed]

Eckstein, M. P., & Whiting, J. S. (1996). Visual signal detection in structured backgrounds. I. Effect of number of possible spatial locations and signal contrast. *Journal of the Optical Society of America A, 13*, 905-910. [PubMed]

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

Grzywacz, N. M., Watamaniuk, S. N. J., & McKee, S. P. (1995). Temporal coherence theory for the detection and measurement of visual motion. *Vision Research*, *35*, 3183-3203. [PubMed]

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33*, 1219-1240. [PubMed]

Hubbard, R. S., & Marshall, J. A. (1994). *Self-organizing neural network model of the visual inertia phenomenon in motion perception* (Technical Report No. 94-001). Chapel Hill, NC: Department of Computer Science, University of North Carolina at Chapel Hill.

Lu, Z. L., & Dosher, B. A. (1998). External noise distinguishes attention mechanisms. *Vision Research, 38*, 1183-1198. [PubMed]

Lu, Z. L., & Dosher, B. A. (1999). Characterizing human perceptual inefficiencies with equivalent internal noise. *Journal of the Optical Society of America A*, *16*, 764-778. [PubMed]

Nakayama, K., & Silverman, G. H. (1984). Temporal and spatial characteristics of the upper displacement limit for motion in random dots. *Vision Research*, *24*, 293-299. [PubMed]

Pelli, D. G. (1985). Uncertainty explains many aspects of visual contrast detection and discrimination. *Journal of the Optical Society of America A, 2*, 1508-1532. [PubMed]

Ramachandran, V. S., & Anstis, S. M. (1983). Extrapolation of motion path in human visual perception. *Vision Research*, *23*, 83-85. [PubMed]

Reynolds, J. H., Chelazzi, L., & Desimone, R. (1999). Competitive mechanisms subserve attention in macaque areas V2 and V4. *Journal of Neuroscience*, *19*, 1736-1753. [PubMed]

Shiu, L. -P., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 1037-1054.

Snowden, R. J., & Braddick, O. J. (1989). Extension of displacement limits in multiple-exposure sequences of apparent motion. *Vision Research*, *29*, 1777-1787. [PubMed]

Swensson, R. G., & Judy, P. F. (1981). Detection of noisy visual targets: Model for the effects of spatial uncertainty and signal to noise ratio. *Perception & Psychophysics, 29*, 521-534. [PubMed]

Treue, S., & Maunsell, J. H. R. (1996). Attentional modulation of visual motion processing in cortical areas MT and MST. *Nature, 382*, 539-541. [PubMed]

van Doorn, A. J., & Koenderink, J. J. (1984). Spatiotemporal integration in the detection of coherent motion. *Vision Research*, *24*, 47-53. [PubMed]

Verghese, P. (2001). Visual search and attention: A signal detection theory approach. *Neuron, 31*, 523-535. [PubMed]

Verghese, P., Watamaniuk, S. N. J., McKee, S. P., & Grzywacz, N. M. (1999). Local motion detectors cannot account for the detectability of an extended trajectory in noise. *Vision Research*, *39*, 19-31. [PubMed]

Watamaniuk, S. N. J, & McKee, S. P. (1995). Seeing motion behind occluders. *Nature, 377*, 729-730. [PubMed]

Watamaniuk, S. N. J., McKee, S. P., & Grzywacz, N. M. (1995). Detecting a trajectory embedded in random-direction motion noise. *Vision Research*, *35*, 65-77. [PubMed]

Welch, L., Macleod, D. I., McKee, S. P. (1997). Motion interference: Perturbing perceived direction. *Vision Research, 37*, 2725-2736. [PubMed]