Perception & Psychophysics
1997, 59 (4), 567–579

Detection of spatial discontinuities in first-order optical flow fields

SUSAN F. TE PAS, ASTRID M. L. KAPPERS, and JAN J. KOENDERINK
Helmholtz Instituut, Universiteit Utrecht, Utrecht, The Netherlands

We investigated the extent to which the human visual system can detect discontinuities in first-order optical flow fields. We constructed two types of spatial discontinuities: a circular split field with a straight edge and a disk with annular surround. We used two different first-order optical flow components: an expansion and a rotation. We found an intriguing difference in the detection thresholds for straight and circular discontinuities. Whereas straight discontinuities yielded thresholds of 10%–50% difference in expansion or rotation, circular discontinuities could, at first, only be detected at extreme differences (≫100%). After a learning period, thresholds for such stimuli decreased, but they remained significantly higher than thresholds for the straight edge. Thresholds rose for stimuli that formed a gradual transition between a circular and a straight edge, and they decreased with increasing eccentricity of the circular discontinuity. Results suggest that symmetry in the stimulus, defined by the coincidence of the center of expansion or rotation and the center of the circular discontinuity, was responsible for the difference in thresholds for circular and straight discontinuities.

When we move around in the world, the optical flow field provides much information about the world around us and our movement relative to it (Gibson, 1950). In everyday life, we often come across spatial discontinuities in this optical flow. These discontinuities are caused by objects that move separate from their background or by movement relative to transitions between noncoplanar surfaces (such as between a wall and the floor).

Mathematically, one can extract information about the slant and tilt of objects and about the movement of the observer relative to these objects from the first-order structure of the flow field (Koenderink & van Doorn, 1975; Longuet-Higgins & Prazdny, 1980). Information can also be extracted about the difference between first-order optical flow components in two different planes (e.g., a floor and a wall; Koenderink & van Doorn, 1976) or at two different times. Of course, this does not mean that the human visual system uses all the information that can be extracted mathematically from the first-order flow field. To investigate whether the visual system is able to detect discontinuities in first-order flow fields, we constructed 2-D first-order optical flow stimuli with discontinuities that were step functions in the spatial domain.

To investigate spatial discontinuities, we implemented two different stimuli: one with a circular discontinuity and one with a straight discontinuity. The stimulus with a straight discontinuity consisted of a split field with the division along a diameter of the circular aperture. The stimulus with a circular discontinuity was a split field consisting of a circular center with an annular surround. As a first-order flow field, we chose either an expanding field or a rotating field. The center of expansion or rotation was always located in the center of the stimulus. The discontinuous straight line or the center of the discontinuous circle was located in the center of the stimulus.

With such stimuli, the dots that are close to the straight discontinuity move parallel to it in the case of expansion, whereas dots move parallel to the circular discontinuity in the case of rotation. We did not find different results for rotation and expansion in previous experiments (te Pas, Kappers, & Koenderink, 1996) in which subjects had to indicate the sign of the expansion or rotation in the presence of another flow component. However, because the movement relative to the discontinuity is different for expansion and rotation, we might find differences in thresholds in this study. Experiments investigating the effect of movement relative to the discontinuity in zero-order flow fields have had mixed results. When van Doorn and Koenderink (1982b, 1983) investigated the detectability of movement gradients in zero-order flow fields, they found no effect of the orientation of the discontinuity relative to the direction of motion. However, Nakayama, Silverman, MacLeod, and Mulligan (1985) reported that thresholds for shearing motion rise much faster with spatial frequency than do thresholds for compressive motion. Their results suggest that spatial integration is greatest in a direction orthogonal to the direction of motion. Thus, the effect of movement relative to the discontinuity probably depends on stimulus and paradigm, which made it difficult to make predictions for the present study.

Although there has not been extensive research in the area of discontinuities in first-order flow fields, a number of experiments have been conducted to investigate discontinuities in zero-order flow fields. Nakayama (1981) used straight spatial discontinuities in zero-order moving Julesz patterns to obtain thresholds for motion detection. He found Weber fractions of about 5%. Although the stimuli and the paradigm that we use are different, it would

Correspondence should be addressed to S. F. te Pas, Helmholtz Instituut, Universiteit Utrecht, Princetonplein 5, 3584 Utrecht, The Netherlands (e-mail: s.f.tepas@fys.ruu.nl).

be interesting to compare thresholds for first-order discontinuities with those for zero-order discontinuities. More recently, Sachtler and Zaidi (1995) measured thresholds for various different zero-order flow discontinuities and gradients. They found that sensitivity is greater for square-wave velocity profiles than for sine-wave velocity profiles. From this, we might also expect detection thresholds for discontinuities in first-order flow fields to depend on the type of discontinuity.

In this paper, we investigate to what extent the visual system can detect spatial discontinuities in expanding and rotating flow fields. We determine in what way the detection thresholds depend on the magnitude of the divergence and the curl and try to compare the thresholds that we find with the thresholds reported for zero-order motion. We also investigate whether the type of spatial discontinuity (circular or straight) has an effect on thresholds.

GENERAL METHOD

Apparatus

Our stimuli were generated on an Atari MegaST4 computer and shown on an Atari SM125 high-resolution 70-Hz white-phosphor P4 monochrome monitor. The monitor dimensions were 13.6 × 21.7 cm (400 × 640 pixels). The subject rested his/her head in a chinrest 34 cm from the screen. Thus, the screen area was 22.6° × 35.4° of visual angle, and pixel separation was 3.2 minutes of arc. Dot size was 3 × 3 pixels to ensure visibility. Experiments were performed monocularly with a natural pupil; the subjects used only the right eye. The subject was asked to fixate in the middle of the screen, where a fixation cross appeared immediately before and after the presentation of each stimulus. Experiments were conducted in a dark room so that the subject would not be distracted by elements outside the stimulus. The only light came from the computer screen.

Stimuli

Our stimuli were similar to those used by Kappers, van Doorn, and Koenderink (1994) and te Pas et al. (1996), although their stimuli did not contain discontinuities. However, the subject's task and the objectives of the experiments were different. We used pseudorandom-dot patterns, consisting of dark dots on a light background. The dots were situated on a perturbated hexagonal point raster to prevent the subject from recognizing local features arising from (random) clustering. The stimulus window was circular, with a diameter of 20° of visual angle. Moving patterns were generated by presenting sequences of frames stroboscopically. Between two consecutive frames, all dots "moved with the flow." The stimulus movement could be a divergence (either expansion or contraction) or a curl (either clockwise or counterclockwise rotation). In the rest of the paper, we will refer to those movements as *div* and *curl*. One should bear in mind that when we refer to "the curl" or "the div," we actually mean "the curl or the div of the (instantaneous) velocity field." The center of rotation or expansion was located at the center of the stimulus (unless otherwise indicated).

For clarity, we explain here what is meant by the standard mathematical phrases "the curl is 2 rad/sec" and "the div is 2/sec." The curl is defined as twice the angular rotation per second. Thus, a curl of 2 rad/sec means that an angle of one radian will be traversed in 1 sec. By div, we mean the relative area expansion (or contraction) per second. A div of 2/sec means that an area of size X will have expanded in 1 sec by twice its own size to become $3X$.

Subjects

Six subjects (1 of the authors, S. F. te Pas [henceforth referred to as Subject S.P.] and 5 others, A.M., F.K., G.K., M.A., and T.P.) participated in the experiments. Subjects A.M., F.K., G.K., M.A., and T.P. were paid for their efforts and were unaware of the purpose of the experiments. All subjects had normal or corrected-to-normal vision.

EXPERIMENT 1
Spatial Discontinuities

Method

Stimuli. Our stimuli contained a discontinuity in the first-order flow component. Discontinuities can be brought about in various ways, but we decided to start with a simple step function in the spatial domain. In polar coordinates, we can define a circular discontinuity centered on the center of the stimulus this way; in Cartesian coordinates, the discontinuity will be a straight line through the center of the stimulus. Because we use sparse random-dot patterns, these lines and circles are not well defined in the actual stimuli. We randomly varied the orientation of the straight edge (0°, 45°, 90°, or 135°) and the radius of the circular edge (60%, 65%, 70%, or 75% of the stimulus radius). In this way, the subject did not know in advance exactly where the discontinuity would be located. We kept the total presentation time constant at 16 frames (228 msec). We also kept the number of dots constant at 50 dots per frame. Figure 1 shows four examples of the stimulus. Here, the 16 consecutive frames are superimposed in order to create a static image of our (dynamic) stimuli.

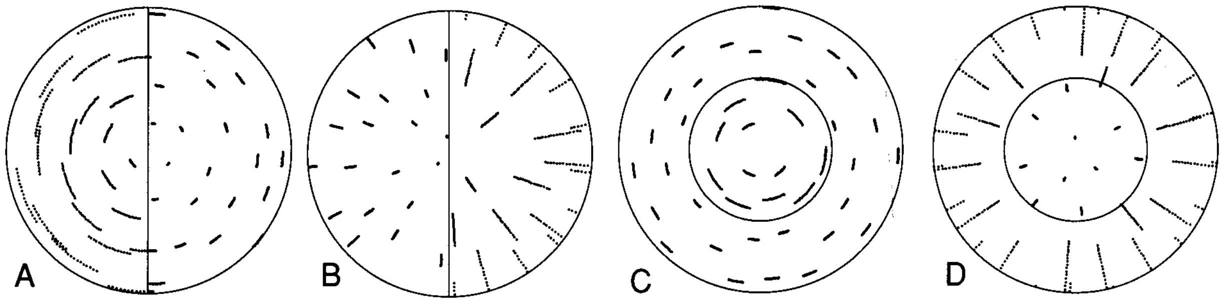

Figure 1. Four static examples of our dynamic stimuli (all 16 consecutive frames superimposed). For clarity, we have drawn lines to indicate the discontinuity and the stimulus window. These lines were not present in the actual stimulus. (A) A straight discontinuity in a rotating stimulus. The values of the curl are 1 rad/sec on the left and 4 rad/sec on the right side of the discontinuity. (B) A straight discontinuity in an expanding stimulus. On the left, the div has a value of 1/sec; on the right, the value of the div is 4/sec. (C) A circular discontinuity with a curl of 4 rad/sec on the inside and a curl of 1 rad/sec on the outside. (D) A circular discontinuity with a div of 1/sec on the inside and a div of 4/sec on the outside.

From Figure 1, a difference between div and curl can be observed. In the stimuli with a straight discontinuity (Figures 1A and 1B), the dots that were close to the discontinuity moved parallel to the discontinuity in the case of the div and moved perpendicular to the discontinuity in the case of the curl. In the stimuli containing a circular discontinuity (Figures 1C and 1D), the opposite occurred. Here, the dots moved parallel to the discontinuity in the case of the curl and perpendicular to the discontinuity in the case of the div. When the dots moved at right angles to the discontinuity, some of the dots actually crossed the discontinuity line (they suddenly moved at different speeds). This created a local cue that was not present in the case of parallel movement. With parallel movement, however, one could compare the movements of two dots that were close to the discontinuity on either side directly over all frames; in the case of perpendicular movement, this was impossible. Thus, differences could occur in the subjects' performance for div and for curl.

Procedure. Four subjects participated in this experiment (F.K., G.K., S.P., and T.P.). One experimental session took about 15 min to measure. In such an experimental session, we varied the step height (i.e., the discontinuity in div and curl). All other parameters were fixed. We measured thresholds for div and curl as well as thresholds for circular and straight edges in separate sessions. Thus, a typical session resulted in a threshold for one display type (e.g., a circular edge at a reference curl of 2 rad/sec).

In each trial, the subjects were shown two stimuli successively in random order: a test stimulus with discontinuity and a reference stimulus without discontinuity. The subjects' task was to decide in which of the two stimuli the discontinuity was present (a two-alternative forced choice paradigm). The value of the div or the curl in the reference stimulus was the average value of the two values presented in the test stimulus. Thus, the overall average speed was about the same in both stimuli. We chose reference values that ranged between 0.5 rad/sec and 8 rad/sec for curl and between 0.5/sec and 8/sec for div.

During one experimental session, we presented eight values for the step height, each 20 times, in random order. These eight points were spaced evenly around the reference value, with the spacing dependent on the subjects' performance (typically between 0.05 rad/sec and 0.2 rad/sec for a reference curl of 1 rad/sec). We determined the optimal spacing for each subject in a pilot session. We ran two experimental sessions for every reference value. Thus, each step height was presented 40 times. We fitted a psychometric curve (cumulative Gauss distribution) to these data points. A psychometric curve can be characterized by a μ (the mean, a measure of position) and a σ (the standard deviation of the underlying Gauss distribution, a measure of the slope). Here, μ describes the shift of the answers relative to the reference value. In our experiment, the various values for the step height were spaced evenly around the reference value. Thus, μ should not deviate too much from the reference value if thresholds are the same on the high side and the low side of the reference value. The most interesting parameter is the threshold σ. It describes how high the step in div or curl must be to enable the subjects to detect the discontinuity in 84% of the presentations (Macmillan & Creelman, 1991).

Results

During Experiment 1, we came across an unexpected phenomenon. Whereas we had absolutely no trouble obtaining thresholds for the straight discontinuity, we could not determine thresholds for the circular discontinuity at all, because our subjects could not detect these discontinuities, even at the highest differences. We could not solve this problem by using a larger measuring interval; only for extremely large differences (about 600%) could the subjects actually see the circular discontinuity. We could not measure the value of these thresholds without totally changing the paradigm, but their order of magnitude is obviously different from the thresholds for the straight discontinuities. If expressed in overall percentages correct for two sessions, the subjects scored 50% correct for the circular edge even for the largest possible measuring intervals (test values between 10% and 190% of the reference value). For straight edge discontinuities, the subjects' scores rose from 50% for small measuring intervals to 100% for the largest measuring intervals. Of course, we were curious as to the nature of this phenomenon. In the following experiments, we investigated the validity of a number of possible explanations. First, however, we give the results of the experiments with straight discontinuities.

The difference between μ and the reference value as a function of div and curl for 1 subject (S.P.) is depicted in Figure 2.

As we expected, this difference was close to zero over a large range. However, when we increased the value of the first-order flow component (div or curl), at a certain point, the difference between μ and the reference value started to increase as well. If we look at the psychometric curves, we observe the following: Above a certain speed, the subjects were unable to discriminate between two values of the div or curl. Thus, the curve became somewhat lopsided, and a psychometric curve no longer describes the data accurately. Scores were worse on the high side of the reference value than on the low side of the reference value. This means that the characterization by μ and σ became meaningless above a reference value of about 4 rad/sec for curl and 4/sec for div (depending on the subject). Therefore, the other subjects did not run sessions for reference values above 4 rad/sec for curl and 4/sec for div. In the analysis of our data, we checked whether the difference between μ and the reference value was larger than two times the spacing between two successive step heights. This occurred only at reference values of 4 rad/sec or 4/sec and higher, and we left those points

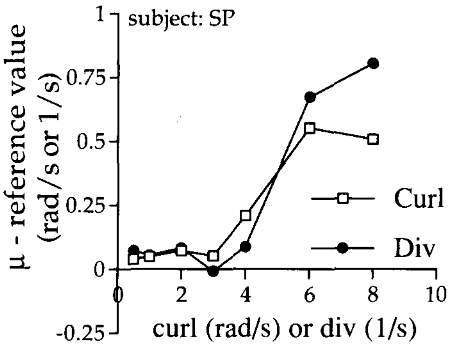

Figure 2. Results for the difference between μ and the reference value as a function of the value of div and curl. If a psychometric curve is an adequate descriptor, μ − reference value should be close to zero. From this graph, it is obvious that, above a reference curl of about 4 rad/sec and a reference div of about 4/sec, a psychometric curve does not present a good description of the data.

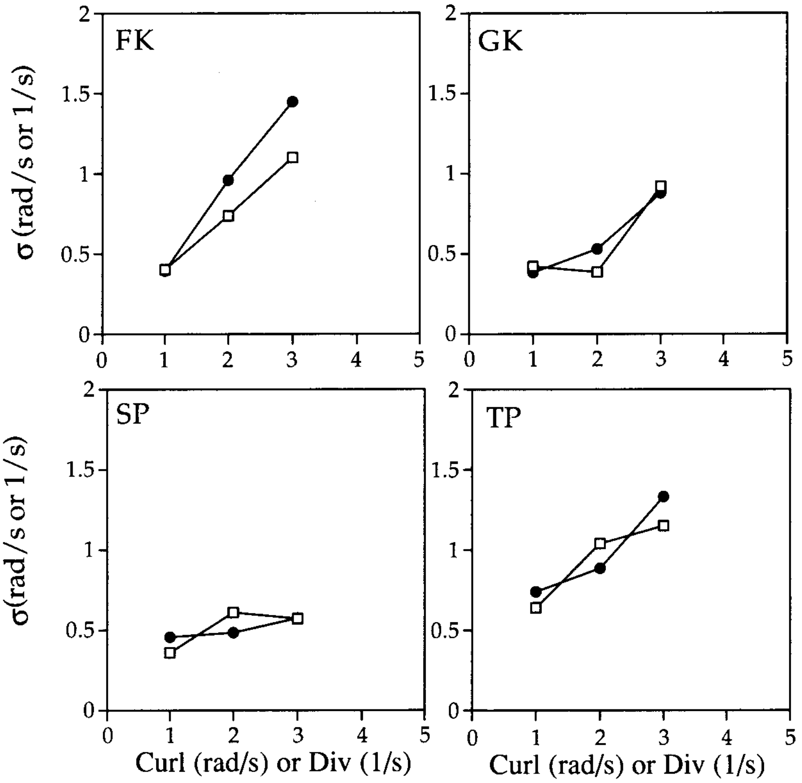

Figure 3. σ as a function of the value of div (filled circles) and curl (open squares) for all 4 subjects.

out of the analysis. From Figure 2, one might gain the impression that the difference between μ and the reference value was always positive, even when small. However, for other subjects and other conditions, this was not the case. Thus, for the data points that we present in the rest of the paper, the psychometric curve provides an adequate description of the data, and the only interesting parameter is σ.

Figure 3 shows results for σ as a function of div and curl for all 4 subjects. The value of σ depends linearly on div and curl, which means that thresholds follow a Weber-like law over a range of about half a log unit. We list the Weber fractions for all subjects and conditions in Table 1. Note that there are no systematic differences between div and curl. Thus, the subjects did not appear to use the extra cues provided by either perpendicular or parallel movement. Alternatively, the extra cue provided by perpendicular movement could be just as strong as the cue provided by parallel movement.

EXPERIMENT 2
What Causes the Difference Between Straight and Circular Discontinuities?

Naturally, we were intrigued by the large difference between straight and circular discontinuities that we found in Experiment 1. We tested a number of possible explanations, which we will describe briefly in the following section.

Method

Stimuli and Procedure. The stimuli and procedure were similar to those described in Experiment 1. Differences were in the shape and the position of the discontinuity and in the location of the center of the expansion or rotation.

Results

Straight discontinuities with a central gap. In the search for a plausible explanation of the difference between straight and circular discontinuities, the first thing that comes to mind is that, because our subjects fixated in the center of the stimulus, the straight discontinuity could be viewed foveally, whereas the circular discontinuity could not. To investigate whether this was the cause of the difference, we introduced a stimulus with a central gap with a radius of 4.2°. An example of such a stimulus is shown in Figure 4A.

If performance depends critically on foveal information, thresholds for straight discontinuities will deteriorate when this central gap is introduced. Three subjects

Table 1
Weber Fractions for the Detection of Straight Line Discontinuities in Div and Curl for 4 Different Subjects

	Subject			
Flow Type	F.K.	G.K.	S.P.	T.P.
div	0.53	0.25	0.14	0.30
curl	0.35	0.25	0.19	0.26

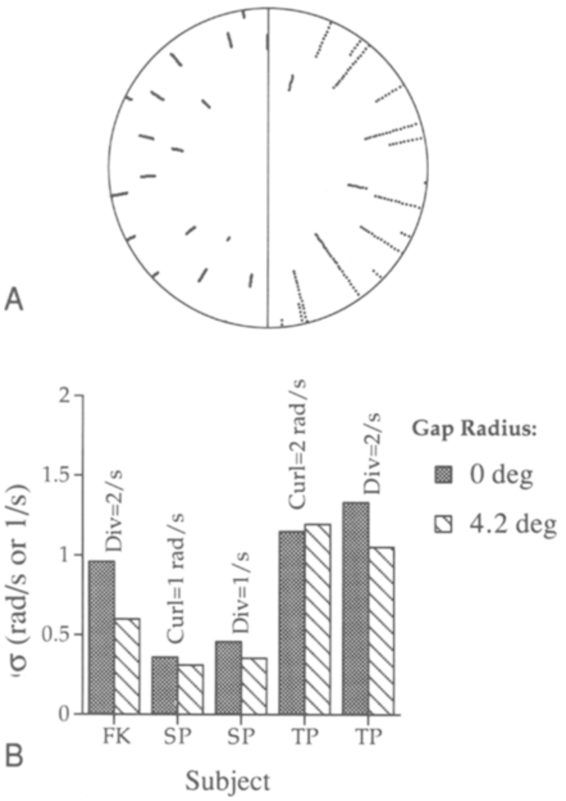

Figure 4. (A) A static example of a stimulus with a central gap. On the left, the value of the div is 1/sec; on the right, the value of the div is 4/sec. The central gap has a radius of 4.2° of visual angle. The lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus. (B) The value of σ for stimuli with and without central gap for 3 subjects. Subject F.K. measured at a reference div of 2/sec, Subject S.P. measured at reference values of 1 rad/sec and 1/sec, and Subject T.P. measured at reference values of 2 rad/sec and 2/sec. From this we can conclude that the central gap is of no influence whatsoever.

participated in this experiment. Figure 4B shows their results for stimuli with a central gap for two different values of the div and curl. The data for stimuli with no gap are taken from Experiment 1. Clearly, the central gap is of no consequence whatsoever. In most cases, thresholds were even somewhat lower with gap than they were without gap. Thus, it was not the presence of foveal information that caused the difference in performance between the straight and the circular discontinuities.

Eccentric straight discontinuities. In the previous subsection, we showed that resolution at different eccentricities was not the cause of the phenomenon. To test whether the location of the discontinuity itself might be important, we ran an experiment with eccentric straight discontinuities, as shown in Figure 5A. To create an eccentric straight line, we added a translation to an entire stimulus, such as the one shown in Figure 1A. Thus, in the stimuli that we used for this experiment, the center of expansion or rotation was no longer in the center of the stimulus. Instead, it was always located on the straight discontinuity. The location of the eccentric straight line was random. For this experiment, we chose an eccentricity of 4.2° of visual angle (the stimulus radius was 10°).

Three subjects participated in this experiment. Their results are shown in Figure 5B. Subject S.P. measured thresholds for both a reference div of 1/sec and a reference curl of 1 rad/sec. Subject T.P. measured thresholds for both a reference div of 2/sec and a reference curl of 2 rad/sec. Subject F.K. measured a threshold for a reference curl of 2 rad/sec. There are some differences between the results for 0° and 4.2° eccentricity. However, these small differences are insufficient to explain the differences between circular and straight discontinuities that we found in Experiment. 1 Subject F.K. performed somewhat better at an eccentricity of 4.2° than he did foveally. Thus, the location of the discontinuity cannot be the cause of the difference in the subjects' thresholds for straight and circular discontinuities.

There are two differences between the stimulus with the straight discontinuity that we used in Experiment 1

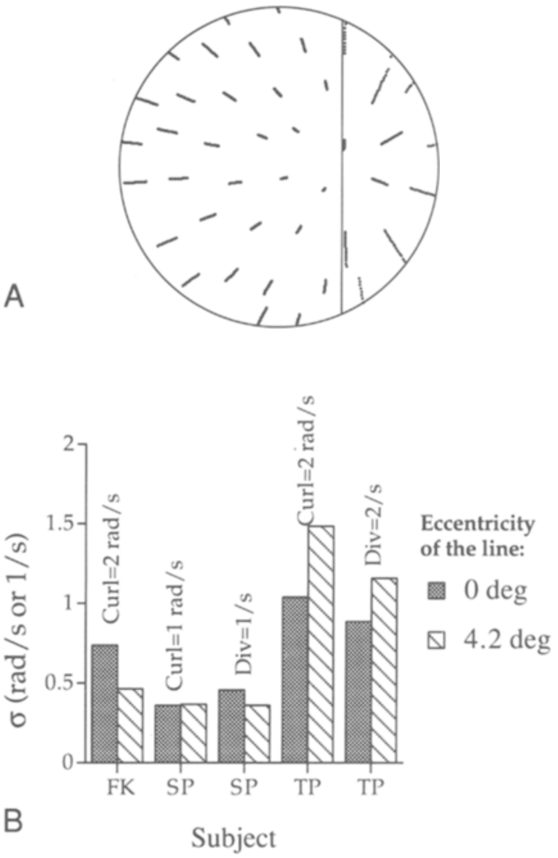

Figure 5. (A) A static example of a stimulus with an eccentric straight discontinuity. Here, the eccentricity is 4.2° of visual angle. The value of the div is 4/sec on the right and 1/sec on the left half of the stimulus. Again, the lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus. (B) The value of σ for a central and an eccentric straight discontinuity. From this, we can conclude that σ does not depend on the location of the discontinuity.

and the stimulus that is shown in Figure 5A. The first difference is the eccentricity of the discontinuity. Besides changing the eccentricity of the discontinuity, however, we also changed the eccentricity of the center of rotation (or expansion). As a control experiment, Subject S.P. again measured a threshold for a reference curl of 1 rad/sec, but with the center of rotation located in the center of the stimulus and the eccentricity of the discontinuity at 4.2°. The threshold for this stimulus did not deviate significantly from the one shown in Figure 5B ($\sigma = 0.34$ rad/sec, and $\sigma = 0.36$ rad/sec, respectively). Thus, the location of the center of rotation seems to be unimportant for this task.

Symmetry. Whereas the circular discontinuity is rotationally symmetric, the straight discontinuity is only mirror symmetric. Thus, we investigated whether this difference in symmetry could provide a possible explanation for the difference in thresholds for the circular and straight edge. We constructed a stimulus that had a semicircular stimulus window instead of a full circle. The subjects still had to fixate in the center of the circle, but because half of the circle was missing, the symmetry was destroyed. An example of such a stimulus is shown in Figure 6. The number of dots per frame and the stimulus area were doubled (we simply doubled the radius of the circle), so that the dot density remained the same.

We presented a (semi-)circular discontinuity in the large semicircular stimulus (as shown in Figure 6) to Subject S.P. for a reference curl of 1 rad/sec. Results for this semicircular discontinuity were similar to those obtained with the full circular stimulus (we were unable to obtain a threshold for either stimulus). This indicates that the rotational symmetry did not cause the difference between circular and straight discontinuities.

Curved discontinuities. One could argue that the difference in thresholds for straight and circular discontinuities was caused by the curvature of the edge in the case of the circular discontinuity. Of course, there is an entire range of curvatures between the circle that we used and the straight line. We measured performance for three different curvatures of the circular discontinuity. The

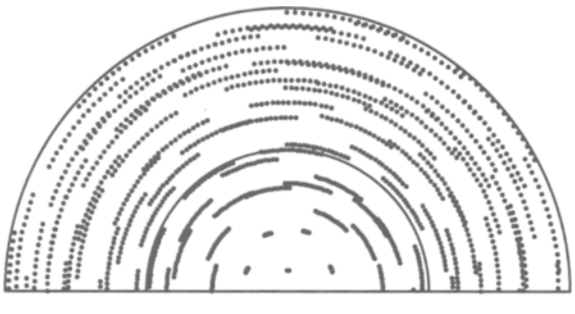

Figure 6. Static example of a large semicircular stimulus (the radius of the full circle would be 20° of visual angle). There are 100 dots per frame to keep the density the same as in the stimuli of Experiment 1. The value of the curl is 1 rad/sec on the inside and 4 rad/sec on the outside of the circular discontinuity. The lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus.

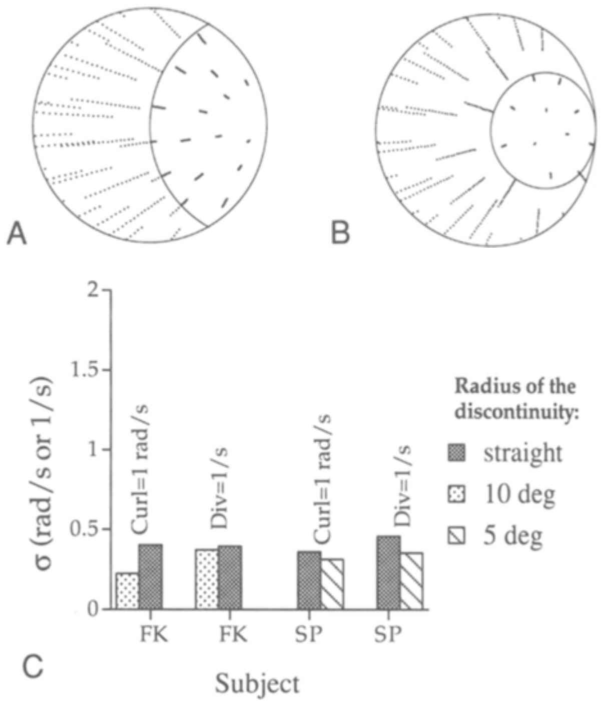

Figure 7. Panels A and B are static examples of two stimuli with a curved discontinuity. The value of the div is 1/sec on the inside and 4/sec on the outside of both stimuli. (A) A curve with a radius of 10°. (B) A curve with a radius of 5°. The total stimulus has a radius of 10°. Again, the lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus. (C) The value of σ for different curvature of the discontinuity. From this, we can conclude that σ does not depend on the curvature of the discontinuity.

curvature is defined as 1/R, where R is the radius of the circle. If the difference in thresholds for the straight and the circular discontinuities was due to the curvature of the discontinuity, then performance would depend on the radius of the circle.

Figures 7A and 7B show two examples of the stimulus we used for this experiment. We added a translation in such a way that the circular edge was always in the center of the stimulus. This means, as in the previous experiment, that the center of expansion or rotation no longer coincided with the center of the stimulus. Instead, it coincided with the center of the curved discontinuity.

Two subjects participated in this experiment. Their results for σ as a function of the radius of the curved discontinuity are shown in Figure 7C for both div and curl. Here, the div was 1/sec and the curl was 1 rad/sec. We took the results for the straight discontinuity from Experiment 1. From Figure 7C, we can conclude that σ did not depend on the curvature of the circle at all. For Subject F.K., performance was even somewhat better with curved discontinuities than with straight discontinuities. The circular stimulus depicted in Figure 7B is similar to the stimulus we used for Experiment 1 (Figure 1D). Therefore, we feel that it is surprising that results for Figure 1D and 7B differed so much. The only difference was

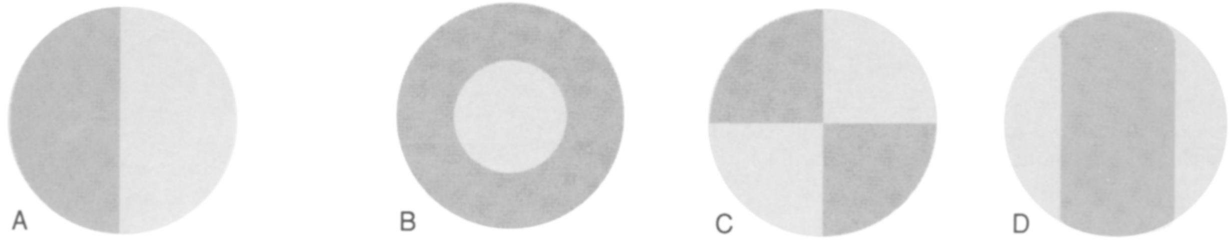

Figure 8. Schematically drawn pictures of the receptive fields of possible detectors for discontinuities. Panel A shows a first-order detector. Panels B, C, and D show second-order detectors.

the displacement of the stimulus window, which caused location of the center of the stimulus and the location of the center of the flow field to be different in Figure 7B. The fact that the two coincide in Figure 1D might be important.

Crosses and bars. The visual system might use detectors with rather large receptive fields, such as those schematically drawn in Figure 8 (Koenderink & van Doorn, 1990; Young, 1985).

One could argue that all the stimuli used so far can be detected by a coarse first-order detector, such as the one schematically shown in Figure 8A. The only stimulus that the first-order detector would not react to was indeed the symmetric circular discontinuity. If subjects use only first-order detectors for this task, other second-order stimuli should be difficult to detect as well. Figures 9A and 9B show two other second-order discontinuities, a cross (as in Figure 8C) and a bar (as in Figure 8D). First-order detectors should again be blind to these stimuli.

Results for these discontinuities for 4 subjects are shown in Figure 9C. They are similar to the results for the straight discontinuity. We found some differences in performance, but they were far smaller than the difference in performance for circular and straight discontinuities. Here, we could actually measure the small differences, whereas, in the case of circular discontinuity, we could not determine a threshold at all. Thus, the order of the detector cannot explain the difference between the straight and the circular discontinuities.

EXPERIMENT 3
Is There a Gradual Transition Between Circular and Straight Discontinuities?

Although the experiments that we described in the previous section exclude a number of plausible explanations, the cause of the difference in thresholds for the straight and the circular discontinuities remained a mystery. Therefore, we decided to construct a set of stimuli that formed a gradual transition between the straight line and the circle.

Method

Stimuli and Procedure. The procedure was the same as that used in Experiment 1. The only difference in the stimuli was the location and shape of the discontinuous line. We constructed a set of five discontinuities ranging from line to circle. Figure 10 shows the five different stimuli. The 16 consecutive frames are superimposed to create a static image. The stimuli varied in two ways: Both the curvature and the eccentricity of the discontinuous line increased monotonically from Condition A to Condition E. Since we varied the eccentricity and the curvature separately in Experiment 2, we felt that the combination of the two must have been important. Also, the stimulus became increasingly rotationally symmetric (see Figures 10A–10E). The difference between the areas that contained the small or large curl value increased as well.

Results

First, the five different conditions were presented in the same order as shown in Figure 10 in a pilot experiment.

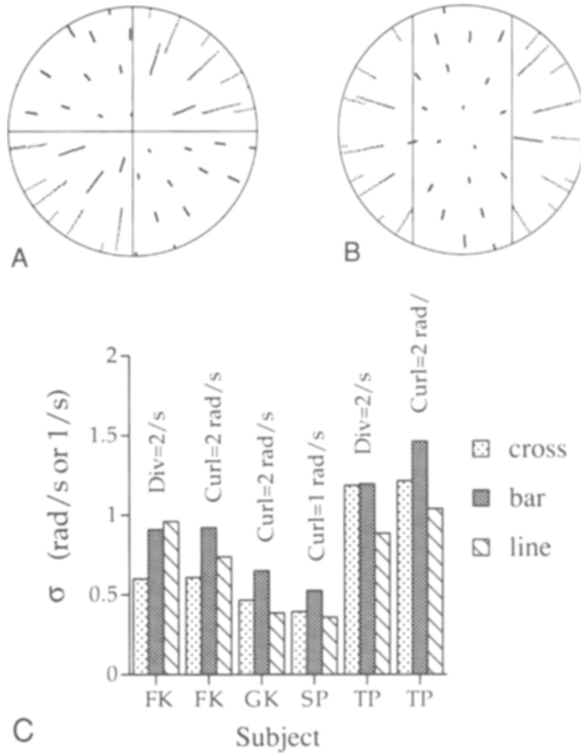

Figure 9. Panels A and B are static examples of stimuli with second-order discontinuities. (A) A cross. On the top left and the bottom right, a curl of 1 rad/sec; on the top right and bottom left, a curl of 4 rad/sec. (B) A bar. On the far right and the far left, a curl of 4 rad/sec; in the middle, a curl of 1 rad/sec. The lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus. (C) σ for three different discontinuities: the line, the cross, and the bar. On no occasion did the bar and the cross stimuli yield the high thresholds that we found for the circular discontinuity.

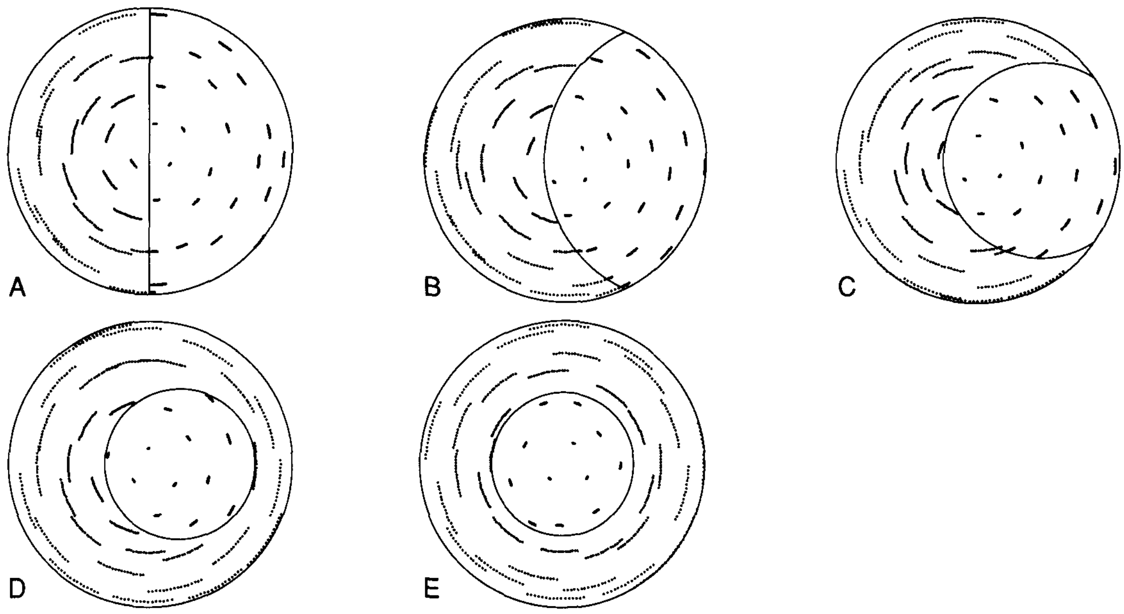

Figure 10. Five stimuli that form a gradual transition between straight and circular discontinuities. On the left side of the stimulus or outside the discontinuity, the value of the curl is 4 rad/sec; on the right side of the stimulus or inside the discontinuity, it is 1 rad/sec. (A) Radius = ∞°. The minimum eccentricity at which the discontinuity is located is 0° (where the discontinuity line is closest to the center of the stimulus). (B) Radius = 10°; minimum eccentricity = 1.6°. (C) Radius = 6.8°; minimum eccentricity = 2.4°. (D) Radius = 5.3°; minimum eccentricity = 3.1°. (E) Radius = 5°; minimum eccentricity = 5°. The lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus.

After running all five conditions several times, we found that we were able to determine thresholds for the circular discontinuity for 2 subjects (G.K. and S.P.). The thresholds for the 3rd and 4th subjects (M.A. and T.P.) remained outside our measuring range. This means that the actual thresholds were higher than 2 rad/sec (the limits of our range), but we do not know exactly how much higher. However, we do know that their overall percentage correct increased somewhat when compared with the first time this condition was measured. After only one or two pilot sessions, no further learning seemed to have taken place. Apparently, this was a case of instant learning and not of a gradual increase in performance with practice.

Next, we presented the five stimuli in random order and determined thresholds for all five conditions. The results for 4 different subjects are shown in Figure 11. Thresholds rose gradually from the straight to the circular discontinuity. We have indicated the cases where the threshold was outside our measuring range with a short dashed line in Figure 11.

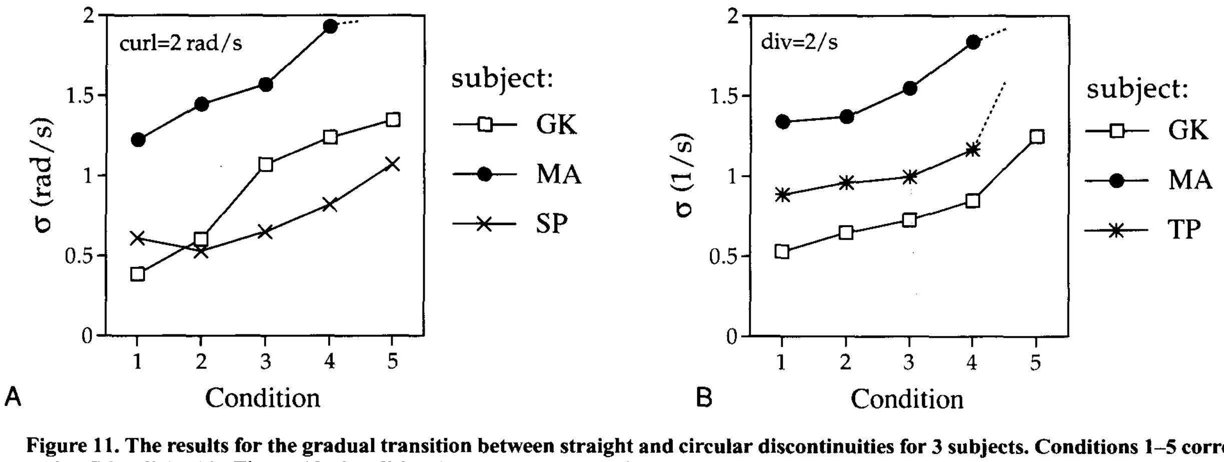

Figure 11. The results for the gradual transition between straight and circular discontinuities for 3 subjects. Conditions 1–5 correspond to Stimuli A–E in Figure 10; Condition 1 represents the straight discontinuity, and Condition 5 represents the circular discontinuity. The results indicate that there is a gradual increase in threshold between the straight and the circular discontinuities.

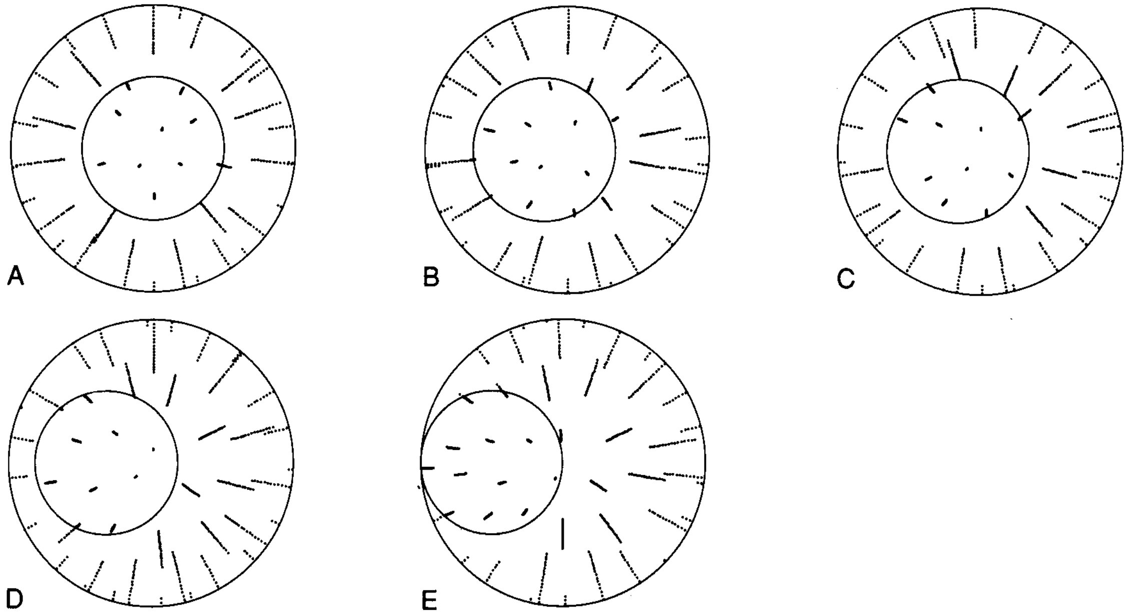

Figure 12. Five stimuli with the circular discontinuity at different eccentricities. Inside the discontinuity, the value of the div is 1/sec; outside, it is 4/sec. In all cases, the radius of the discontinuity is 5°. (A) Eccentricity = 0°. (B) Eccentricity = 0.79°. (C) Eccentricity = 1.58°. (D) Eccentricity = 3.1°. (E) Eccentricity = 5°. The lines that we have drawn to indicate the discontinuity and the stimulus window were not present in the actual stimulus.

EXPERIMENT 4
Is the Rotational Symmetry of the Stimulus Important?

From the results of Experiment 3, we can conclude that thresholds for the detection of discontinuities are impaired when we increase both the eccentricity and the curvature of the circular discontinuity. However, the center of the circular discontinuity moves away from the center of rotation or expansion with increasing eccentricity and curvature. On the basis of the results of Experiment 3, we cannot distinguish between the combination of curvature and eccentricity on the one hand and the coincidence of the center of the circle with the center of rotation and expansion on the other hand as the main cause of the difference in thresholds between circular and straight discontinuities. In Experiment 4, we varied the eccentricity of the circular discontinuity separately in order to find out whether performance is impaired when the center of the circle coincides with the center of the stimulus as well as with the center of rotation or expansion. The center of expansion or rotation remained in the center of the stimulus in this experiment, contrary to the curvature condition of Experiment 2.

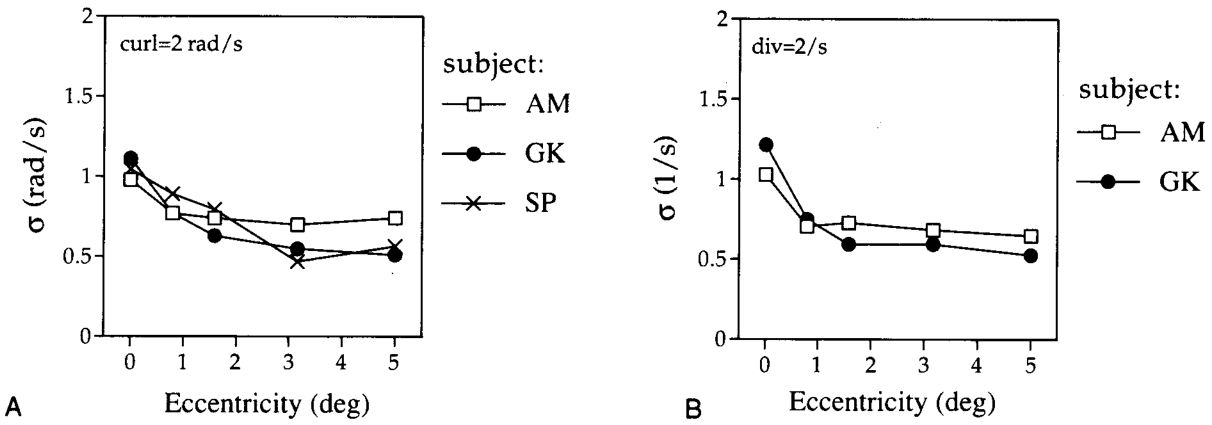

Figure 13. Detection thresholds as a function of the eccentricity of the circular discontinuity for 3 subjects. The results indicate that there is a gradual decrease in threshold with increasing eccentricity of the circular discontinuity.

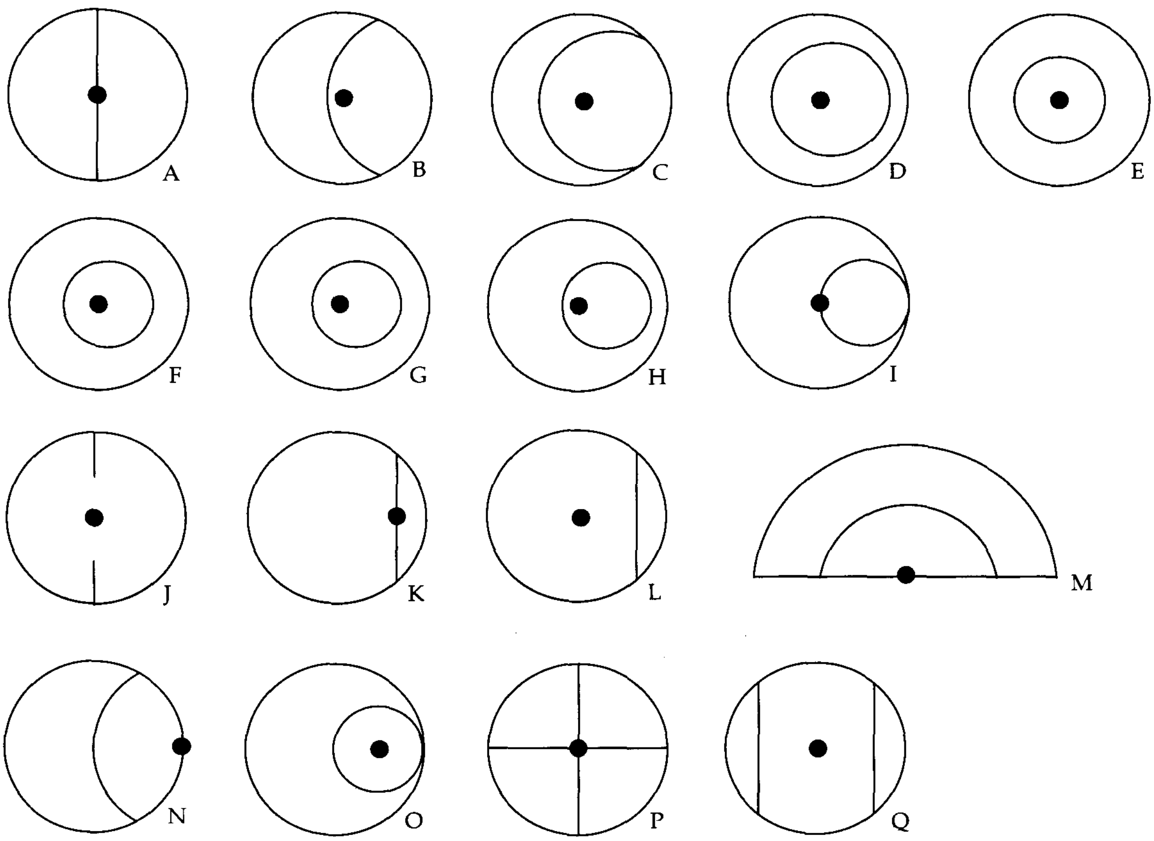

Figure 14. Schematic representation of the various stimuli that we used in Experiments 1, 2, 3, and 4. The black dot indicates the location of the center of the expansion or rotation. Panels A–E: Gradual transition between the straight discontinuity (A) and the circular discontinuity (E). Panels E–I: Circular discontinuities with decreasing stimulus symmetry from E to I. Panel J: The stimulus with the central gap. Panels K and L: The eccentric line. Panel M: The large semicircle. Panels N and O: Curved discontinuities. Panel P: Cross. Panel Q: Bar.

Method

Stimuli and Procedure. Again, the procedure was the same as that used in Experiment 1. This time, the difference in the stimuli was only the eccentricity of the discontinuous circle. We presented the center of the circular discontinuity at five different eccentricities (0°, 0.79°, 1.58°, 3.16°, and 5°). Figure 12 shows five stimuli with the discontinuity at different eccentricities. The 16 consecutive frames are superimposed to create a static image. The rotational symmetry of the stimulus decreased with increasing eccentricity of the circular discontinuity.

Results

Three different subjects (A.M., G.K., and S.P.) participated in this experiment. Subjects G.K. and S.P. participated in many of the other experiments described in this paper. Therefore, they ran one pilot session at all five eccentricities in random order to determine the measuring range. After that, they ran full sessions at all five eccentricities, again in random order. Subject A.M., who was new to the present experiments, was first presented with several training sessions at all five eccentricities in random order. As in Experiment 3, we observed that thresholds for the detection of the circular discontinuity decreased in the first two sessions. After that, we found no further effect of training. After the training sessions, Subject A.M. ran full sessions at all five eccentricities in random order. Figure 13 shows the results for Subject S.P. for a reference curl of 2 rad/sec and for Subjects A.M. and G.K. for a reference curl of 2 rad/sec and for a reference div of 2/sec. Thresholds decreased gradually with increasing eccentricity of the circular discontinuity.

DISCUSSION

We investigated whether the human visual system can detect discontinuities in first-order optical flow fields. In our experiments, we used one of the more simple discontinuities—namely, the spatial step function. We constructed two types of spatial discontinuities: a circular type and a straight type. Also, we used two different first-order optical flow components: a div and a curl. Previous experiments have shown that there are no differences in detection thresholds between first-order optical flow components (te Pas et al., 1996). However, in the experiments described here, one might expect differences in thresholds for div and curl to be caused by the movement of dots relative to the discontinuity. We did not find any difference between results for expanding and rotating stimuli, suggesting that the subjects did not use extra cues rising either from the parallel or from the perpendicular local motion. This result is in agreement with the results of van Doorn and Koenderink (1983), who found that the orientation of a discontinuous line relative to the direction of motion has no effect on performance for zero-order optical flow stimuli.

The straight line discontinuities yield Weber fractions of 10%–50%. These Weber fractions that we find for first-order optical flow are larger than the 5% thresholds for zero-order optical flow reported by Nakayama (1981) for moving Julesz patterns and by McKee (1981) for successive moving lines. However, van Doorn and Koenderink (1982b) reported much higher Weber fractions (70%–100%) for a zero-order moving Julesz pattern using a different paradigm. If the visual system compares the outputs of local velocity detectors in order to do the task, one expects the thresholds in our experiments to be somewhat higher than those found for zero-order flow fields. However, thresholds probably depend on setup and stimulus, which makes a comparison difficult.

We found an intriguing difference between straight and circular discontinuities. Whereas straight discontinuities yielded thresholds of about 10%–50%, circular discontinuities could only be detected when we presented stimuli that contained extreme differences in div or curl (about 600%). We investigated several possible explanations for this difference between circular and straight discontinuity. As a reminder, we have schematically drawn the various stimuli that we used in the four experiments in Figure 14.

Eccentricity

Whereas the straight discontinuity passes through the fovea (the center of the stimulus), the circular discontinuity is at an eccentricity of 5° of visual angle. Thus, a difference in eccentricity might well have been the cause of the difference in threshold. However, the experiment with the central gap (Figure 14J) and the experiment with the eccentric line (Figures 14K and 14L) yielded similar thresholds as did the experiment with the straight discontinuity. These results rule out the possibility that the eccentricity of the circular discontinuity alone provides an explanation for the high thresholds.

Curvature

Another difference between circular and straight was the curvature of the discontinuity. However, the experiment with the curved discontinuities (Figures 14N and 14O) yielded far lower thresholds than did the experiment with the circular discontinuity. Moreover, results for the stimulus with the large semicircular field (where the curvature of the discontinuity was lower than that for the full circular field due to a different radius of the circular discontinuity; see Figure 14M) were similar to those for the circular discontinuities. These experiments rule out the curvature of the discontinuity as a possible explanation for the difference between straight and circular discontinuities.

Symmetry

There was a difference in symmetry. Whereas the circular discontinuity was rotationally symmetric (Figure 14E), both the straight discontinuity (Figure 14A) and the curved discontinuities (Figures 14N and 14O) had only mirror symmetry. However, thresholds for the large semicircular stimulus (which did not have rotational symmetry; Figure 14M) were similar to those for the full circular stimulus (both yielded extremely high thresholds). This excludes symmetry alone as an explanation.

Order of Detectors

There was a difference in the order of detectors that could be used to detect the stimuli. All test stimuli that we have described could be detected by coarse first-order detectors, except the circular discontinuity stimulus. Thus, if the visual system were to use only first-order detectors for this task, the circular discontinuity would indeed be hard to detect. We constructed two other stimuli that could only be detected by second-order detectors: the cross stimulus and the bar stimulus (Figures 14P and 14Q, respectively). Thresholds for these stimuli were similar to those for the straight discontinuity, which rules out the order of the detectors as a possible explanation.

Combination of Eccentricity and Curvature

In Experiment 3, we investigated whether a combination of different factors might yield an explanation for our results. We constructed a set of stimuli that formed a gradual transition between the straight and circular discontinuities by covarying the eccentricity of the line and the radius of the discontinuity (Figures 14A–14E). After practice with this set of stimuli, 2 subjects improved their performance for the circular discontinuity. However, thresholds for the circular edge remained about twice as large as those for the straight edge for these 2 subjects. The other 2 subjects improved their performance as well. However, for them, we remained unable to obtain thresholds for the circular edge. Thresholds rose gradually between straight and circular edge.

Combination of Eccentricity and Symmetry

Finally, we investigated whether it is important that the center of the stimulus, the center of the discontinuity, and the center of the expansion or rotation coincide. Therefore, we varied the eccentricity of the circular discontinuity separately in Experiment 4 (Figures 14E–14I). After practice with circular discontinuities at different eccentricities, thresholds for the symmetric circular edge remained about twice as large as thresholds for the asymmetric circular edge for all 3 subjects. Thresholds rose gradually with increasing symmetry of the stimulus. From the experiment with the eccentric straight line (Figures 14K and 14L), we can conclude that it was not the eccentricity alone that caused the difference between circular and straight discontinuities.

Conclusions

From Experiments 3 and 4, we can conclude that the degree of symmetry in the stimulus, defined by the coincidence of the stimulus center, the center of the discontinuity, and the center of rotation or expansion caused the thresholds for circular discontinuities to be higher than those for straight discontinuities.

From Figure 1, we can observe that the underlying velocity distributions across the stimulus were different for circular and straight discontinuities. More importantly, the difference between test and reference stimulus was different for the two cases. The human visual system is sensitive to several statistical properties (e.g., the mean speed, the directional distribution, and the speed variance) of the speed distribution across the display (Atchley & Andersen, 1995; Watamaniuk & Duchon, 1992; Watamaniuk, Sekuler, & Williams, 1989). Difference in the underlying distribution of the velocity vectors might provide a potential explanation for our results. However, further examination of our results shows that this is not the case. We can illustrate this with an example.

When we present the circular discontinuity, the largest div or curl is presented randomly either on the outside or on the inside of the discontinuity. One can observe that the underlying velocity distributions across the stimulus are different for these two cases by comparing Figure 1C and Figure 10E. The difference in mean speed and speed variance between test and reference stimulus was larger when the highest div or curl was on the outside than when it was on the inside of the discontinuity. The difference in mean speed and speed variance between test and reference stimuli was somewhere in between the two in the case of the straight discontinuity. If the visual system is (partly) using these statistical properties in the stimulus, we expect percentages correct for cases when the highest div or curl is on the outside of the discontinuity to be higher than percentages correct for cases when the highest div or curl is on the inside of the discontinuity. However, we did not find a significant difference for any of our subjects and conditions. Thus, the subjects did not use the statistical properties in the display as a cue, probably because the differences in mean speed and speed variance between test and reference stimulus were below threshold in our stimuli.

The velocity in the displays increased from the center to the periphery of the display in both div and curl stimuli. Therefore, potential differences might have arisen due to the fact that subjects might use only the difference in the largest velocities that are present in the display in case of the straight discontinuity, but they cannot use this strategy in case of the circular discontinuity. There are two reasons why we feel that such a strategy cannot explain our results. The first is that many authors report a Weber law for velocity discrimination (e.g., Nakayama, 1981; van Doorn & Koenderink, 1982a). Therefore, it is not a priori clear that the larger differences in velocity at the edge are easier to detect than are the smaller differences halfway, because the velocities are also larger. More importantly, when this would be the case, we would expect detection of discontinuities to become easier when div and curl are higher. However, our data show that the opposite is true. Also, if we compare the conditions where the local speed difference across the circular discontinuity was the same as the largest local speed difference across the straight discontinuity, the circular discontinuity remained harder to detect.

Recently, Sachtler and Zaidi (1995) found that the phase of a square-wave velocity profile in a random-dot stimulus influenced detection thresholds. Sensitivity was lower with the sharp boundary at 1.9° eccentricity than it was when the boundary was viewed foveally. However, the fact that we did not find a decrease in sensitivity for the straight discontinuity at larger eccentricities indicates that this phase effect cannot be an explanation for our results. Orban (1992) and Lagae, Maes, Raiguel, Xiao, and Orban (1994) reported center surround cells in MST of the monkey that are dominated by either zero- or first-order optical flow fields in the annular surround. The cells' response would be similar for stimuli with or without the central part. Thus, if such cells are used to process our stimuli, the motion in the center might be completely ignored. This might explain the high thresholds that we found for the circular discontinuity. However, the existence of these cells does not predict the gradual transition between straight and circular edges. Thus, it seems unlikely that the existence of these cells can provide an explanation for our experiments.

Whereas abrupt *spatial* discontinuities in the optical flow field occur regularly (e.g., in the case of occluding objects), abrupt *temporal* discontinuities do not occur frequently in the natural environment. In a preliminary experiment, we have investigated how well subjects can detect temporal discontinuities in div and curl. Using the same paradigm and experimental conditions as for the straight spatial discontinuities, it was impossible to obtain thresholds for the detection of abrupt temporal discontinuities at all. Van Doorn and Koenderink (1982b, 1983) have reported that temporal discontinuities and gradients in zero-order flow fields are also difficult to detect. It seems that changes in the temporal structure of the optical flow field are unavailable to the human observer, whereas changes in the spatial structure are.

REFERENCES

Atchley, P., & Andersen, G. J. (1995). Discrimination of speed distributions: Sensitivity to statistical properties. *Vision Research*, **35**, 3131-3144.

Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton Mifflin.

Kappers, A. M. L., van Doorn, A. J., & Koenderink, J. J. (1994). Detection of vorticity in optical flow fields. *Journal of the Optical Society of America A*, **11**, 48-54.

Koenderink, J. J., & van Doorn, A. J. (1975). Invariant properties of the motion parallax field due to the movement of rigid bodies relative to an observer. *Optica Acta*, **22**, 773-791.

Koenderink, J. J., & van Doorn, A. J. (1976). Local structure of movement parallax of the plane. *Journal of the Optical Society of America*, **66**, 717-723.

Koenderink, J. J., & van Doorn, A. J. (1990). Receptive field families. *Biological Cybernetics*, **63**, 291-297.

Lagae, L., Maes, H., Raiguel, S., Xiao, D.-K., & Orban, G. A. (1994). Responses of macaque STS neurons to optic flow components: A comparison of areas MT and MST. *Journal of Neurophysiology*, **71**, 1597-1625.

Longuet-Higgins, H. C., & Prazdny, K. (1980). The interpretation of a moving retinal image. *Proceedings of the Royal Society of London: Series B*, **208**, 385-397.

MacMillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. Cambridge: Cambridge University Press.

McKee, S. P. (1981). A local mechanism for differential velocity detection. *Vision Research*, **21**, 491-500.

Nakayama, K. (1981). Differential motion hyperacuity under conditions of common image motion. *Vision Research*, **21**, 1475-1482.

Nakayama, K., Silverman, G. H., MacLeod, D. I., & Mulligan, J. (1985). Sensitivity to shearing and compressive motion in random dots. *Perception*, **14**, 225-238.

Orban, G. A. (1992). The analysis of motion signals and the question of the nature of processing in the primate visual system. In G. A. Orban & H.-H. Nagel (Eds.), *Artificial and biological vision systems* (pp. 24-56). Berlin: Springer-Verlag.

Sachtler, W. L., & Zaidi, Q. (1995). Visual processing of motion boundaries. *Vision Research*, **35**, 807-826.

te Pas, S. F., Kappers, A. M. L., & Koenderink, J. J. (1996). Detection of first-order structure in optic flow fields. *Vision Research*, **36**, 259-270.

van Doorn, A. J., & Koenderink, J. J. (1982a) Spatial properties of the visual detectability of moving spatial white noise. *Experimental Brain Research*, **45**, 189-195.

van Doorn, A. J., & Koenderink, J. J. (1982b). Visibility of movement gradients. *Biological Cybernetics*, **44**, 167-175.

van Doorn, A. J., & Koenderink, J. J. (1983). Detectability of velocity gradients in moving random-dot patterns. *Vision Research*, **23**, 799-804.

Watamaniuk, S. N. J., & Duchon, A. (1992). The human visual system averages speed information. *Vision Research*, **32**, 931-941.

Watamaniuk, S. N. J., Sekuler, R., & Williams, D. W. (1989). Direction perception in complex dynamic displays: The integration of direction information. *Vision Research*, **29**, 47-59.

Young, R. A. (1985). *The Gaussian derivative theory of spatial vision: Analysis of cortical cell receptive field line-weighting profiles* (Tech Rep. No. GMR-4920). Warren, MI: General Motors Research Laboratories.

(Manuscript received November 27, 1995;
revision accepted for publication June 20, 1996.)