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Perceptions of depth elicited by occluded and shearing motions of random dots

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Abstract. A computer-controlled display of random dots was used to study perceptions of depth. In this display, a field of stationary random dots surrounded a rectangular area in which random dots moved with uniform velocity in a single direction. The boundaries of this rectangle did not move. When dot motion was perpendicular to the longer boundary of the rectangle (occluded motion), the rectangle seemed to be behind the stationary background surround. Motion parallel to the longer boundary of the rectangle (shearing motion) made it appear in front of the surround. The relative lengths of the sides of the rectangle determined which effect predominated. Thus, for motion perpendicular to the long axis of the rectangle the occlusion predominated and naive subjects reported that the central area seemed farther away than the surround. For shearing motion parallel to the long axis, the subjects reported that the rectangle was closer than the surround and the strength of both effects also depended on the length-to-width ratio of the rectangle. If there was occluded motion along the long axis, as the length-to-width ratio increased so did the likelihood that subjects would report seeing the rectangle behind the surround. Conversely, with shearing motion along the long axis, increasing the length-to-width ratio increased the likelihood that the rectangle would appear unambiguously in front of the surround. Some subjects integrated the two cues with the resulting perception being a rotating cylinder. The occlusion effect was stronger than the shearing effect. In fact, this 'far' depth effect was so powerful that it tended to override conflicting depth cues such as height in the visual field or stereopsis. The 'near' depth effect produced by shearing motion was definite but these other depth cues could often override it.

1 Introduction

The movements of objects in the visual field provide an array of powerful depth cues such as the familiar motion parallax (Helmholtz 1909/1962), which can yield strong and unambiguous depth information (Rogers and Graham 1979). We have investigated another set of depth cues, that are produced by occluded and shearing motions. The illusions were produced on a television screen which was filled with a dense random-dot display of the sort used by Julesz (1964). The display contained a central area of adjustable length and width. Within this area the random dots could be moved together in a desired direction at an adjustable speed. The boundaries of the central area did not move on the screen. When the dots in the rectangular central area moved in a direction perpendicular to its long axis (figure 1a) the central area appeared to be behind the larger surrounding region, as if one were looking through a narrow window at the scenery behind it. We refer to this stimulus as occluded motion. A similar stimulus has been illustrated in a motion picture film (Gibson 1968). When the long and short axes of the rectangular area were exchanged, but the direction and speed of dot motion left unchanged (figure 1b), the central area usually appeared in front of the surround. We call this stimulus shearing motion. Intrigued by the vivid impressions of

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depth produced by occluded and shearing motion, we undertook a quantitative investigation of these cues and their interactions with each other and with other depth cues.

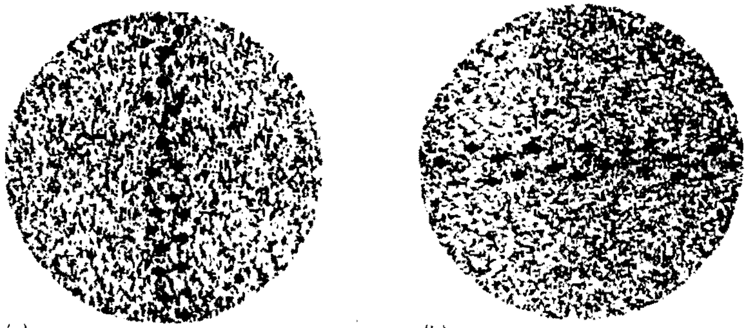
(a) (b)

Figure 1. A representation of the stimulus display. Arrows are used to represent random-dot motion orthogonal (a) or parallel (b) to the long axis of the central area which contains motion. [In (b) the long and short axes of the rectangular central area have been exchanged, but the direction and speed of dot motion is unchanged.] The boundaries of the central area remain fixed, so in the examples illustrated a sheet of random dots appears at the left border and disappears at the right border. A still photograph of the stimulus shows a uniform random-dot field; the boundaries of the central area are defined only by the random-dot motion. The motion-defined borders are much more salient in reality than is apparent in these photographs.

2 Experiment 1: Illusions of depth produced by occluded and shearing motion

2.1 *Method*

The computer-controlled video stimulator was designed and built by John Power and Michael Walsh of the California Institute of Technology Electronics Shop (Allman et al 1985). The stimulator contains two independent pseudorandom binary sequence generators operating at 7 MHz. These are reset to their initial values once in each vertical frame time ($\frac{1}{30}$ s, interlaced scan) of a US standard 19 in television monitor. The exact reset point of each generator determines the dot velocities. This point is determined in real time by an interrupt driven microprocessor which controls direction and velocity of the two independent displays. Separate analog circuits switch between the two generators. This causes the television screen to consist of two regions, a central rectangle and a background area. Each region contains a separately controlled random-dot pattern. The resulting display is generated by applying the composite signal directly to the red and green gun drives of an otherwise unmodified television set with standard phosphors. The display was comprised of 50% bright dots and 50% dark dots. Each pixel (dot) of the display was approximately 2.5 min wide and 1.25 min high at the viewing distance. Subjects viewed the display through a circular aperture, which limited the field of dots to approximately 120 pixels by 240 pixels. The display luminance had no apparent effect on the phenomena we observed.

In our initial experiments we tested ten naive subjects for perception of the illusions. We used computer-controlled, randomly ordered stimulus presentations. Each presentation lasted 3 s, with 3 s between presentations. Five central rectangles were tested: 0.75 deg horizontally × 0.75 deg vertically, 0.75 deg × 1.75 deg, 0.75 deg × 5.0 deg, 1.75 deg × 0.75 deg, and 5.0 deg × 0.75 deg. Each of these rectangles was presented with four directions of dot motion: up, down, left, and right. A pseudorandomly ordered sequence of these twenty stimuli was repeated five times. The surrounding random-dot texture was viewed binocularly through a 5.0 deg circular aperture placed 20 mm in front of the television screen. The ends of the longest stimuli were terminated by this aperture, and not by the random-dot surround. The random dots within the central rectangle moved at 0.75 deg s^{-1} (0.6 pixels $frame^{-1}$) in this first experiment. The subjects viewed the screen from a distance of 2.5 m. They were told to look within the circular aperture but were given no instructions to fixate. Subjects were told to press one of three buttons during or immediately after each stimulus to indicate where the rectangle appeared relative to the surround. One button indicated that the rectangle was closer than the surround; the second indicated that it was farther away than the surround; the last indicated that the rectangle and surround were at the same depth or that the observer was uncertain as to the relative depths. The computer recorded the data for later analysis.

2.2 *Results and discussion*

The results of this experiment are diagramed in figure 2. When the stimulus was a vertical rectangle containing horizontal random-dot movement, subjects reported that the central rectangle appeared to be behind the surround ('far' responses in figure 2). Subjects also frequently reported that the central area appeared behind the surround when the stimulus was a horizontal rectangle containing vertical dot movement. The effect seemed to be stronger for vertical rectangles than for the horizontal rectangles since far responses were more frequently reported for vertical rectangles with horizontal dot motion than for horizontal rectangles with vertical dot motion.

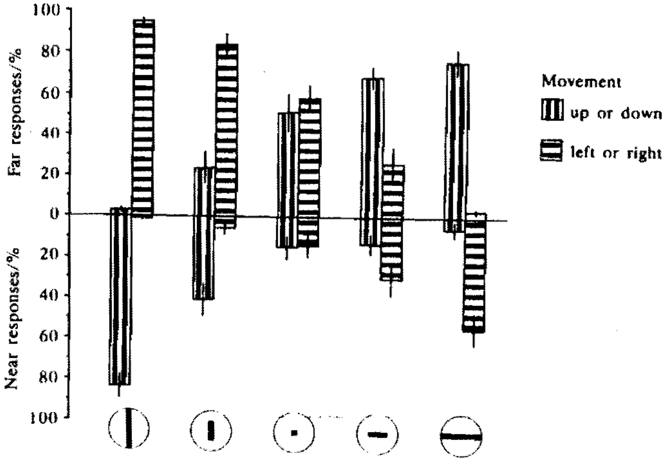

Figure 2. Report of depth for up or down and left or right motion in five shapes of central area. The circled figure below each pair of bars corresponds to the shape tested. The bars with vertical stripes show the combined data for up or down motion and those with horizontal stripes the combined data for left or right motion. The percentage of responses which indicated that the central area appeared to be behind the surround (far responses) is displayed above the horizontal line, and the percentage of responses which indicated that the central area appeared in front of the surround (near responses) is displayed below the horizontal axis. The uncertain responses can be calculated by taking the difference between 100% and the total length of the bars (far responses and near responses). Thus when there are a large number of uncertain responses the total length of the bars will be much less than 100%. The error bars indicate ±1 standard error.

The longest rectangles, 5.0 deg × 0.75 deg, with movement across the long edges were more frequently seen behind the surround than were the shorter rectangles or the square. Motion in the square elicited an appreciable number of uncertain or equal-depth responses, as shown by the shorter bars in figure 2. Thus, the frequency of far responses was increased as the length or length-to-width ratio was increased. We attempted to assess the effects of occluded motion in directions other than perpendicular to the long axis of the central rectangle (30°, 60°, 120°, and 150°). We concluded that directions other than 90° (which gives the shearing effect) produce depth effects which are qualitatively similar to the occluded motion effect.

Shearing movement parallel to the long axis of the rectangles frequently resulted in the subjects reporting that the stimulus appeared in front of the surround ('near' responses). As with occluded motion, the strength of the illusion increased with increasing length-to-width ratio, and the effect was stronger for vertical as opposed to horizontal rectangles. Two observations indicate that this near illusion is clearly weaker than the far effect. First, the number of near responses elicited by shearing motion along an edge of the central rectangle was never as high as the number of far responses elicited by occluded motion along an equivalent edge. Second, when equal amounts of occluded and shearing motion were present, ie for the square stimulus (0.75 deg × 0.75 deg), the far effect dominated the near effect. This is shown by the larger number of far responses for the middle stimulus in figure 2, irrespective of the direction of dot motion.

Both illusions were weaker for the horizontal rectangle than for the vertical one. The horizontal stimuli were associated with a greater number of uncertain responses. In particular, subjects commented that horizontal movement in the long horizontal rectangle produced an impression of three planes of depth. They mentioned that the surround below the rectangle appeared closest, the rectangle containing the motion appeared at an intermediate depth, and the upper portion of the surround appeared farthest away. This suggested that height was acting as a depth cue. To explore the effect of relative height in the visual field we carried out experiment 2.

3 Experiment 2: Effect of height in the visual field

3.1 *Method*

Experimental evidence (Weinstein 1957) supports the observation of everyday experience that objects placed higher in the visual field tend to appear more distant. We tested the relative strength of the depth cue provided by height in the visual field compared with that afforded by occluded and shearing motions. We presented ten subjects with a 5 deg circular aperture. In one half of the aperture dots moved in one of four directions: up, down, left, or right. In the other half the dots remained stationary. This created a vertical or horizontal edge in the center of the aperture at the interface between moving and stationary dots. Dots moved at 0.75 deg s^{-1}. Stimuli were presented in a random sequence that was repeated five times. Subjects were asked to signal where the moving half appeared in depth with respect to the stationary half.

3.2 *Results and discussion*

As can be seen in the right half of figure 3, horizontal motion in the lower half of the display tended to elicit near responses. This is consistent with the results for shearing motion in the rectangles. In fact, this lower position in the visual field seemed to enhance the near effect, as shearing motion along a vertical edge elicited many more ambiguous responses. However, horizontal motion in the upper half of the display tended to evoke far responses. This result reveals that the depth cue arising from height in the visual field tends to override the 'near-effect' resulting from shearing motion.

Horizontal motion in the right and left halves of this display evoked occluded motion and far responses for the side in motion. This is consistent with the data from the rectangular fields and confirms an earlier study by Kaplan (1969) of random texture accretion and deletion at a vertical edge. The near effect for the single vertical edge was much less obvious than for the vertical rectangle. This could be because a single edge provides only half the amount of depth cue as the two edges of the rectangle.

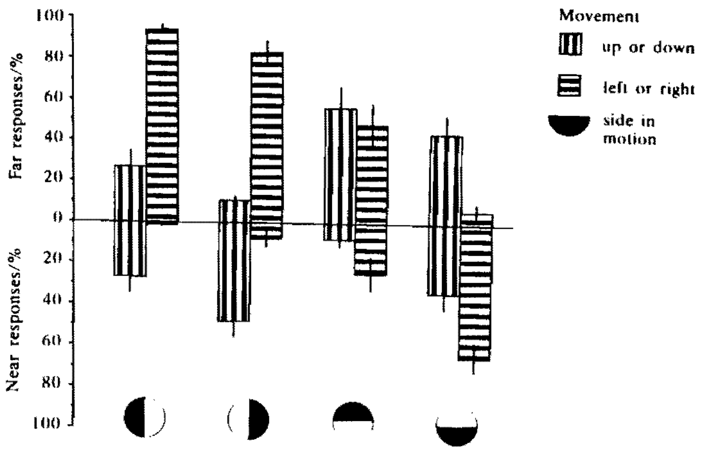

Figure 3. Effect of height in the visual field on reports of depth, with motion along a single edge. The conventions are the same as in figure 2. The half-field in motion is shown as the darkened half of the disc below each pair of bars. Subjects were asked to indicate where the moving half appeared in depth with respect to the stationary half. The error bars indicate ±1 standard error.

4 Experiment 3: Effects of velocity

4.1 *Method*

We tested ten subjects for the effects of velocity on the perception of depth resulting from occluding and shearing motions. Horizontally and vertically oriented rectangular areas (0.75 deg × 1.75 deg and 1.75 deg × 0.75 deg) were used. Stimuli were presented at five pseudorandomly ordered velocities in each of the four directions. The sequence was repeated five times. The design of our random-dot generator allowed us to test higher speeds when the motion was horizontal (4.7 deg s^{-1}; 3.8 pixels frame^{-1}) than when motion was vertical (2.8 deg s^{-1}; 2.3 pixels frame^{-1}).

4.2 *Results and discussion*

The left graph in figure 4 shows that the frequency of far responses tended to increase with the velocity of random-dot movement across long edges. The effect saturated at about 3 deg s^{-1}. The far illusion was quite strong at the highest velocities our equipment allowed us to test. Presumably the illusion would diminish at some higher velocity because the image would begin to blur. Near responses were most frequent when motion was parallel to the long axis at about 1 deg s^{-1} (0.8 pixels frame^{-1}). The lower frequency of near responses at higher velocities could be due to either a reduction of the effect of shearing motion or an enhancement of the effect of occluding motion along the short sides of the rectangle.

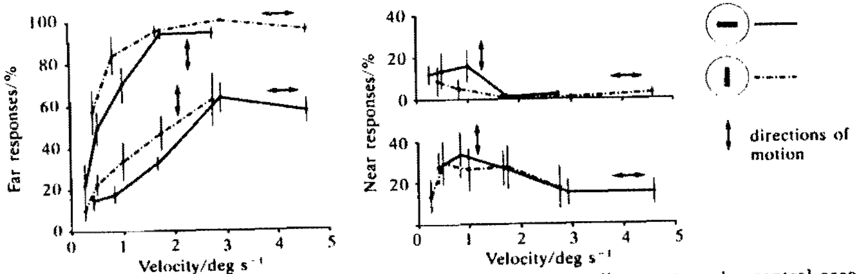

Figure 4. The effect of velocity on reports of depth. Two intermediate rectangular central area shapes were tested with up or down and left or right motion. Responses which indicated that the central area was behind the surround are recorded on the graph on the left, and central area in front responses are recorded on the two graphs on the right. On both sides of the figure, the upper pair of lines shows data for stimuli with motion orthogonal to the long axis of the central rectangle, and the lower pair of lines shows data for stimuli with motion parallel to the long axis of the central rectangle. The error bars indicate ± 1 standard error.

5 Experiment 4: Interaction with stereoscopic depth

5.1 *Method*

We tested the influence of stereoscopic cues on the occluded and shearing motion cues in ten subjects. Stereoscopic cues were produced by the Pulfrich effect. We placed a 1.2 log unit neutral density filter over the right eye of each subject. The tests were conducted with the original five stimulus shapes and with movement to the left and right at 1 deg s^{-1}, the optimal speed for the near effect. The stimuli were presented in a random sequence repeated five times.

5.2 *Results and discussion*

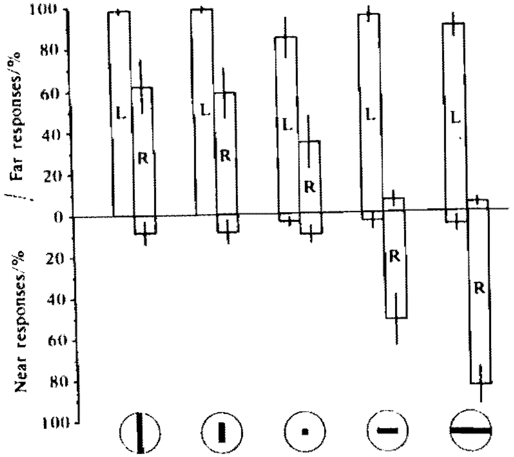

Figure 5. The effect of disparity produced by the Pulfrich effect on reports of depth. A 1.2 log unit neutral density filter was placed over the right eye of each subject. The original five stimulus shapes were tested with crossed disparity (motion to the right) and uncrossed disparity (motion to the left). L and R indicate movement to the left and right respectively. The error bars indicate ± 1 standard error.

These results, illustrated in figure 5, should be compared with the columns in figure 2 that display combined data for left and right movement (horizontal bars). The addition of uncrossed disparity (movement to the left) almost always caused the central rectangle to appear behind the surround (far responses). The addition of crossed disparity (movement to the right) generally decreased the far responses and increased the near responses. Thus, uncrossed disparity strengthens the far effect and completely overrides the near effect. Crossed disparity considerably strengthens the near effect, but it merely weakens the far effect. Antagonistic disparity had a much greater effect on the frequency of near responses elicited by shearing motion than on the frequency of far responses elicited by occluding motion. These results together with the findings in experiment 2, on the effect of height in the visual field, indicate that the near effect is more easily overriden by conflicting depth cues than is the far effect.

Some subjects reported that the crossed disparity tests which contained motion perpendicular to the long edges of the rectangle produced a pronounced perceptual ambiguity. In these cases the central area appeared both farther and closer than the surround, or the center and surround appeared deep while the long edges between them seemed much closer.

6 General discussion

Our results indicate that the far effect elicited by occluded motion is a powerful depth cue that can sometimes override conflicting height and stereoscopic cues. The near effect elicited by shearing motion is a definite cue, but is overridden by an equivalent amount of the occluding cue as well as by conflicting height and stereoscopic cues.

The occluded motion cue has been variously called accretion and deletion (Gibson et al 1969; Kaplan 1969), appearance and disappearance (Gibson et al 1969), or wiping and unwiping (Gibson 1966). The powerful ilusion of depth created by occlusion and disocclusion is related to the cue of stationary interposition, which is also a strong indicator of depth (Helmholtz 1909/1962; Ratoosh 1949; Kling and Riggs 1971). The moving random dots defined the contour of the stationary surround by appearing and disappearing at that contour. The appearance and disappearance also indicated that the contour of the moving object was being interrupted by that of the surround, and thus the surround was interposed between the observer and the moving object.

The near effect elicited by shearing motion does not seem to have been recognized previously as a distinct depth cue. The near effect may result in part from an inference that motion at a contour that is not occluded or disoccluded by the surround is likely to be either coplanar or in front of the surround. This effect may be related to motion parallax cues for depth (Rogers and Graham 1979).

Alternatively, the perceived depth relations may represent the brain's best solution to the problem of identifying objects and judging their distance given minimal perceptual clues. Specifically, the central rectangle is seen as an object because of the common fate (Wertheimer 1923) of the random dots that move together in that area. The lack of relative motion of dots in the rectangle reinforces the perception that this object is rigid, like a wall or sheet of sandpaper (Johansson 1950). When dot motion is across an edge of the surround, interposition dictates that the central object must be behind the border. When dot motion is parallel to a long edge, then the perception that a central sheet or belt lies on top of a surrounding sheet becomes possible. This appears to be the preferred interpretation in the absence of any cues at the edges (for example stereopsis or motion parallax) that would place the central object behind the surround.

The depth ambiguity of some of the stimuli is consistent with the notion that there is a perceptual conflict between information provided by occluded and shearing motion. When the ends of the stimulus were blocked off by the mask in front of the screen (eg for the 5 deg long rectangles), only the effect of the unblocked edges was perceived.

In these situations depth was relatively unambiguous. When all four edges of the central area were visible, the two cues competed. Motion in a square of texture has been previously reported to produce ambiguous depth (Tynan and Sekuler 1975). After repeated exposure to the rectangular stimuli, the experimenters began to notice that stimuli with motion perpendicular to the long axis appeared to be rotating cylinders with the closest part of the cylinder in front of the surround and the sides behind it. Several subjects also spontaneously reported this percept. The perception of the cylinder provides a better resolution of the conflict between the two cues than any planar figure. A similar perception of textured surfaces going around rollers was reported by some of Kaplan's (1969) subjects in an experiment with motion at a single edge. When the stimulus was an intermediate-length rectangle with motion parallel to the long axis, some subjects reporting seeing a belt emerge from behind the surround, run in front of it, then pass behind it again at the end of its travel. The perception of a moving belt also takes into account the cues of both occlusion–disocclusion and shearing motion. Analogous perceptual resolutions of conflicting stereoscopic and pictorial depth cues have been reported by Collett (1985).

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The psychophysics of retrospective and prospective timing[†]

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Abstract. In two experiments, different groups of subjects heard four musical selections and then estimated the duration of each selection. Some groups made retrospective time estimates while others made prospective estimates. In both experiments, analyses of the psychophysical relation between perceived and actual duration showed that the slopes of straight-line fits were flatter and accounted for a smaller proportion of the variance under retrospective as compared with prospective conditions. In addition, in experiment 1, retrospective subjects were less accurate in rank ordering the selections from longest to shortest. There was also a serial-order effect, with selections estimated longer when they occurred early in the sequence. In experiment 2 the slopes decreased as the selections in a series became longer. Both retrospective and prospective estimates also exhibited a context effect, in that estimates of a given selection were influenced by the relative durations of the other three selections in the series. The results on inaccurate retrospective judgments raise questions about prior research on stimulus factors and retrospective timing. However, similarities under retrospective and prospective conditions suggest that timing under these conditions, although different in some respects, reflects a similar process.

1 Introduction

Events necessarily take place in time, and people can make judgments about the duration of these events as well as their other characteristics. These judgments come under the label of time perception, a topic of long-standing interest to psychologists. Several thousand papers on this topic have been published over the past century, covering a wide range of issues (see general reviews by Allan 1979; Block 1979; Doob 1971; Eisler 1976; Fraisse 1963, 1978, 1984; Michon and Jackson 1985; Richelle and Lejeune 1984). Although numerous experiments have been done for many reasons and have involved different methodologies, most of the research shares the common feature of the use of the prospective paradigm. The distinguishing characteristic of prospective procedures is that the subject knows that the task is about time and that temporal judgments are to be made. In contrast to the widespread use of prospective procedures, the past fifteen years have been accompanied by increasing use of an alternate method, the retrospective paradigm. In this case, the subject is not aware that the experiment involves time judgment until the relevant events have elapsed. Thus, the person might be told to watch or listen to stimuli or to engage in some task, often with a relatively vague explanation that there will be later questions about what was seen, heard, or done. Only after the events or task are finished does the experimenter ask for an estimate of how long the interval lasted.

The retrospective paradigm would seem to offer at least two advantages over the prospective paradigm. First, retrospective timing seemingly is more closely related to

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