Evidence for a boundary effect in roll vection

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Large circular displays rotating around the line of sight produce an illusion in which the seen orientation of the true vertical is shifted in a direction opposite to the display's motion. Two experiments were performed to determine whether the magnitude of this illusory tilt is a function of the area of display elements, of their boundary length, or of their spatial frequency. In Experiment 1, 12 subjects viewed each of nine displays across which the number and area of the circular elements were independently varied. Three of the displays were equated for the area of their elements. The results suggested that tilt magnitude and onset latency could be explained by a boundary length effect. A second experiment tested eight subjects on two displays, equated for element boundary length but differing in the spatial frequency of the elements. The displays produced closely similar illusory tilts corroborating the view that, within broad limits, element boundary length—and not spatial frequency or area—determines the size and onset latency of illusory tilt. A third experiment confirmed previous research in finding greater tilt and more rapid onset with more peripherally projected displays.

This paper is concerned with the structural characteristics of large circular displays rotating around the line of sight and their effects upon the magnitude and onset latency of the illusory tilt produced in the seen orientation of the true vertical. Using such a stimulus, Dichgans, Held, Young, and Brandt (1972) demonstrated that the illusion increases as a negatively accelerated function of display velocity, reaching a maximum around 30 deg/sec, while Held, Dichgans, and Bauer (1975) observed that it grows as a roughly linear function of the logarithm of the total display area. It has also been found that elements within the display falling on the periphery of the retina yield substantially greater illusory effects than those projecting onto more central areas (Brandt, Dichgans, and Koenig, 1973; Brandt, Wist, and Dichgans, 1975; Held et al., 1975).

The first experiment reported here deals with the interaction between the number and size of the circular elements within the display. It has been shown that tilt magnitude increases as a logarithmic function of the number of small circular elements present within the rotating display (Brandt et al., 1975). Since element size was held constant in this study, it was possible for these investigators to equate their number with the total moving area of the stimulus and to suggest that the observed relationship between tilt magnitude and element number was due either to an area effect (in which the presence of more elements stimulated a larger number of motion-receptive units) or to a spatial frequency effect (in which larger tilts arose as the result of the increased density of the moving elements within the visual field).

There is, however, a third and as yet unexplored possibility—namely, that the motion-receptive units were responding to an increase in the total boundary length of the moving elements, or to a boundary

effect. With all the elements the same size, the total boundary length (or the sum of the element diameters $\times \pi$) is linearly related to both the number of elements and the area of the display covered by them. But when both the size and the number of the elements are varied, as in Experiment 1, this simple relationship no longer holds and the possibility of a boundary effect can be discriminated. These primary stimulus characteristics were so arranged that three of the nine displays were equated for the proportion of the display covered by moving elements, although they differed with regard to their boundary length characteristics.

While this experiment provided for a direct test between the area and boundary effect hypotheses, it could not eliminate the possibility that spatial frequency was involved since this inevitably increased as a function of total boundary length. Consequently, a second experiment was carried out to test between the boundary and frequency effect hypotheses. This involved two displays equated for boundary length but with widely differing frequency characteristics.

A final experiment was conducted to examine the effects of retinal location upon displays having equal boundary lengths. Four annular displays, each made up of the same number of equally sized elements but located at different retinal eccentricities, were compared. This experiment also provided an opportunity to replicate previous findings with regard to the important influence exerted by more peripheral elements.

EXPERIMENT 1

Method

Apparatus. A circular visual display, capable of rotating at constant angular velocity in either direction, was generated by

Visual displays. These were constructed by attaching self-adhesive circular labels to the surfaces of nine clear Perspex disks. When projected onto the screen, they formed an array of solid black circles in a relatively texture-free and evenly illuminated field. Three element diameters, 27, 43, and 76 mm (subtending visual angles of 6.2, 9.8, and 17.4 deg, respectively), and three number values, 15, 46, and 120 elements, were used to construct the nine displays. The number values were chosen so that for three disks (Disks C, E, and G—see Table 1) approximately 7.5% of the total area of the display was covered by the elements. The dimensions of the stimulus displays are given in Table 1, and their configurations are shown in Figure 1.

The subject's task. Using binocular vision, the subject was required to fixate a point 5 cm (11.5 deg) above the center of the rotating display at which the plumb line intersected the top of the protractor. The illusion was always seen as an apparent tilt of the protractor and the plumb line around an axis through the center of the display in a direction opposite to the stimulus motion. The extent of this illusory tilt was measured directly by asking the subject to read from the protractor the angular value that then appeared to be vertical. These judgments were made at 5-sec intervals as indicated by an auditory signal. Subjects were also required to indicate the onset of tilt.

Subjects. Twelve subjects took part, eight men and four women. Their average age was 30 years (range 22-50 years). All were capable of reading the protractor scale without corrected vision, and none had had any prior experience with the phenomenon.

Dimensions of the Stimulus Displays

N	PA	SD	PA	SD	PA	SD
15	A	.9	405	B	2.4	645
46	D	2.9	1242	E	7.4	1978
120	G	7.6	3240	H	19.4	5160
				I	60.5	9120

Note—*N* = number of elements; *PA* = percentage of total area covered by elements; *SD* = sum of diameters of elements (in millimeters).

Figure 1. Element configurations of the nine displays used in Experiment 1. The displays are labeled sequentially from A-I, with Display A (top left-hand corner) having the fewest and smallest elements and Display I (bottom right-hand corner) having the most and largest elements.

Results

Three measures were used: (1) average tilt, the arithmetic mean of the angular judgments recorded on each 1-min trial; (2) maximum tilt, the greatest tilt recorded for any one trial; and (3) latency, the interval between the onset of display rotation and the first report of the illusory tilt.

Tilt magnitude increased with both element size and number. A mixed model ANOVA revealed significant main effects for these two primary stimulus variables in both the average and maximum tilt measures ($p < .01$). With the latency measure, however, only size yielded a significant F ratio ($p < .05$). The number $\times$ size interaction was significant for both measures of tilt ($p < .05$) but not for latency. For the two larger element sizes (43 and 76 mm diameter), the tilt increased as a negatively accelerated function of element number, but for the smallest element size (27 mm diameter) this relationship was linear.

Of particular interest was the comparison of the latencies and tilts produced by the three disks (C, E, and G) in which the total area of the display covered by elements was the same. Disk C produced less than half the average and maximum tilts elicited by Disks E and G. Wilcoxon matched-pairs signed-ranks tests showed that these differences were significant ($p < .01$). Moreover, the latencies associated with Disk C were, on the average, four times longer than the corresponding values for Disks E and G ($p < .02$).

Figure 2 shows the relationship between the experimental measures and the sum of the element diameters ($\Sigma\pi$ = sum of element circumferences, or total

Figure 2. The relationship between magnitude of tilt (both maximum and average values), latency of tilt onset, and the sum of the element diameters (Experiment 1).

boundary length). The tilt magnitudes increased as negatively accelerated functions of the sum of the element diameters, suggesting that the illusion of tilt is linearly related to the logarithm of total boundary length.

There was a clear inverse relationship between latency and tilt magnitude: The smaller the tilt induced, the longer was its time of onset up to about 200 cm of total boundary length. At values greater than 200 cm, latency remained stable at approximately 1.5 sec, while the tilt measures showed only very small rates of increase compared with those associated with smaller boundary values.

EXPERIMENT 2

The results of Experiment 1 indicated that when both the size and number of elements were systematically varied, their combined influence upon tilt magnitude and onset latency could be accounted for in terms of a boundary length effect. However, the configuration of these displays was such that an increase in total boundary length was confounded with an associated increase in spatial frequency. The present experiment was directed at resolving this issue by comparing the effects of two displays in which boundary length, angular velocity, and approximate retinal location were held constant, but in which the frequency characteristics were markedly different. The low-frequency display (Display A) contained four large circular elements, while the high-frequency display (Display B) contained 48 small elements.

If frequency were the important factor, it would be expected that Display B should yield a significantly greater tilt magnitude. However, if some feature of large elements (not explored in the range of element sizes used in Experiment 1) proved to be crucial, then Display A could elicit the greater tilt. But, if boundary

length were the critical factor, one would expect that both displays should produce approximately the same degree of tilt. The only other way this result could occur would be if the hypothetical spatial frequency and area effects exactly counterbalanced each other.

Method

Visual displays. The configurations of Displays A and B are shown in Figure 3. The four elements in Display A each subtended 70 deg (1.2 rad); the 48 elements in Display B each subtended 6.5 deg (.11 rad). The sum of the element diameters for both displays was close to 142 cm, and, in both, the elements were regularly located between 30 and 65 deg of retinal eccentricity.

Procedure. To minimize order effects, each subject initially received a continuous 3-min exposure to a third display, comprising 96 radially located elements, each subtending 8 deg of visual angle. During this period, the subject was required to give tilt magnitude judgments at 5-sec intervals. Following a 1-min rest interval, each subject received two 1-min exposures to each of the two experimental displays (A and B). Each trial was separated from the next by a 1-min rest interval. Both the order of display presentation and the direction of rotation were counterbalanced over the eight subjects. Display velocity was 35 deg/sec throughout, as it was previously.

Subjects. The subjects were eight undergraduates, four males and four females. Their ages ranged from 19-27 years.

Results

Table 2 shows the mean tilt and latency values for each subject, together with the group means and stan-

Figure 3. Element configurations of the two displays used in Experiment 2. Display A is on the left, B on the right.

Table 2
Summary of Results for Experiment 2

	Comparing Displays A and B			
	Mean Tilt (in Degrees)		Mean Latency (in Seconds)	
	A	B	A	B
Subject 1	5.2	6.6	2.5	2.5
Subject 2	2.6	5.3	5.0	6.0
Subject 3	11.6	7.8	4.5	3.3
Subject 4	6.1	5.3	2.5	2.5
Subject 5	8.5	6.9	4.3	2.8
Subject 6	12.1	13.6	4.3	3.3
Subject 7	6.1	9.5	3.8	3.8
Subject 8	5.2	6.3	3.3	2.5
Grand Mean	7.2	7.7	3.8	3.3
Standard Deviation	3.3	2.8	.9	1.2

dard deviations for each display. There were no significant differences in either case. For three subjects, Disk A elicited a greater tilt than Disk B, and for the remaining five the direction of these differences was reversed.

EXPERIMENT 3

Neither of the two previous studies took any special account of retinal locations; boundary length comparisons were made within equivalent areas of the visual field. However, it seemed highly probable that a given boundary length would exert an increasing effect the further away the elements are located from the central field. Accordingly, this third experiment was conducted to examine the effects of annular displays, possessing the same total boundary length (at least in terms of stimulus geometry), at varying degrees of retinal eccentricity.

Method

Visual displays. Using the same method of projection as in the two previous experiments, a comparison was made of four displays, each comprising single annuli made up of 48 equally spaced circular elements. Each element subtended 9.8 deg of visual angle. The retinal eccentricities of these four displays were 53, 56.5, 60, and 63.5 deg, as measured from the center of the display to the center of each element.

Procedure. Each subject received two 1-min exposures to each display, separated by 1-min rest intervals. The order of presentation was randomized and was different for each subject. As before, the angular velocity was 35 deg/sec throughout, and all the trials were conducted in the counterclockwise direction of rotation.

Subjects. Five men and three women were used as subjects. Their average age was 29, ranging from 21 to 37 years. None had acted as subjects previously.

Results

The principal findings are summarized in Figure 4. Analyses of variance revealed that retinal location

exerted a significant effect on both tilt magnitude ($p < .01$) and onset latency ($p < .05$). The larger angles of retinal eccentricity produced markedly greater illusions of tilt than did the smaller ones, although the overall relationship was somewhat complicated by the reversal in this trend occurring between the two most centrally located annuli. But this difference was not statistically reliable. In interpreting these findings, it should be noted that the interelement separation was inevitably confounded with retinal eccentricity, such that gap size reduced with increasing eccentricity. It was therefore likely that the gaps between the circular elements were poorly resolved in the extreme periphery. As noted in Experiment 1, onset latency was inversely related to tilt magnitude.

GENERAL DISCUSSION

Taken together, the results of Experiments 1 and 2 failed to support the suggestion made by Brandt et al. (1975) that tilt magnitude is determined in part by the total moving area of the display. Three equal-area displays in Experiment 1 elicited reliable differences in tilt magnitude. These findings also failed to provide support for their alternative hypothesis, the spatial frequency effect, in which larger tilts were thought to arise as the result of the increased density of the moving contours. In Experiment 2, two displays having quite different frequency characteristics yielded no difference in mean tilt magnitude. Rather, these findings suggested that, within the limits imposed by these particular display configurations, the size and number of the circular elements influenced tilt magnitude only to the extent that they contributed to total boundary length, or the sum of the element diameters.

As expected, the results of Experiment 3 confirmed previous observations (Dichgans, Brandt, & Held, 1975; Held et al., 1975) that tilt magnitude increased with the retinal eccentricity of the moving elements. This also indicated that the boundary effect is influenced by retinal location, such that elements falling in the periphery of the visual field have a greater impact on the mechanisms underlying illusory tilt than do more centrally located elements of the same boundary length.

Before pursuing further the implications of these findings, we need to consider the visual motion stimulus in relation to the other sensory inputs providing concurrent kinesthetic information. With large-scale seen motion around the line of sight, a conflict exists between the visual motion information (which is consistent with body rotation around the x-axis of the head) and the information derived from the vestibular system and other proprioceptors (which is consistent with the reality of an upright static posture). The establishment of illusory shifts in the visual vertical (and postural disturbances when

Figure 4. The relationship between magnitude of tilt (both maximum and average values), latency of tilt onset, and retinal eccentricity (Experiment 3).

the body is unrestrained) clearly indicates that the visual motion signals can override the veridical information supplied by these other modalities. If we postulate the existence of some central integrating center whose function it is to compute body position on the basis of inputs from all the position and motion senses (Young, Note 1), then it is reasonable to assume that vision is accorded a high weighting relative to other inputs in this sensory "mix." Furthermore, this visual weighting factor can be increased by attenuating the veridical vestibular contribution. A number of studies have demonstrated that with a rollvection stimulus, comparable to the one used here, tilt magnitudes are increased by lateral head tilts that diminish the sensitivity of the otoliths (Brandt & Dichgans, 1978; Reason & Mayes, Note 2).

In view of the widespread support it has received from a variety of studies (see Brandt & Dichgans, 1978), it would seem appropriate to evaluate our present findings in the light of this "weighting hypothesis." From previous investigations, we know that visual weighting is a function of the total area of the rotating field, its angular velocity, and the retinal location of the moving elements. In the present investigation, we have confirmed the importance of retinal eccentricity and have identified an additional factor, the boundary effect. Thus, the visual weighting factor appears to increase as a negatively accelerated function of total boundary length.

Although the findings of Experiment 2 were correctly predicted on the basis of a boundary effect, it is nevertheless surprising that the visual motion detectors should remain so apparently insensitive to the differences in the size and number of the displayed elements, as well as to the considerable variation existing in such derived factors as spatial and temporal frequency. The fact that these two quite disparate displays, albeit equated for total boundary length, were evidently treated as functionally equivalent with regard to their visual weighting contribution suggests that this factor depends upon some relatively straightforward algebraic summation over the outputs of the various motion detectors responding to the passage of element boundaries. Although this is clearly the most parsimonious conclusion to be drawn from these findings, it is still one that needs to be treated with some caution. In the first place, we need to establish the influence of the boundary effect with displays made up of noncircular contours. Second, there are obvious limits to the boundary effect. We know, for example, that a display consisting of one large circular element situated centrally would be unlikely to elicit illusory tilt (Dichgans & Brandt, 1978). Thus, the boundary effect can only be influential to the extent that it provides visual motion information. At the other extreme, it is likely

that when there are a very large number of densely packed contours in a display, the effect of total boundary length will be diminished by mutual masking between contours (Kahneman, 1968; Uttal, 1973).

Experiments 1 and 3 also demonstrated the existence of an inverse relationship between tilt magnitude and onset latency. Within the terms of the weighting hypothesis outlined previously, it is reasonable to assume that onset latency reflects the time taken by the visual information to override the veridical inputs from the vestibular and muscle-skin-joint systems. That the influence of these proprioceptive cues is still present even after the visual motion information has been accepted by the comparator system is evident from the limits imposed upon the shift in the visual vertical. During any one exposure to the visual motion, tilt magnitude rises to some maximum and then remains moderately steady—except for occasional phase shifts in which perception momentarily reverts to a true assessment of the orientation of the vertical. However, when an identical rotating display is viewed from beneath by a supine observer (for whom the otoliths are in their least sensitive orientation relative to the gravito-inertial vector), the sense of self-rotation, orvection, is continuous—presumably because no check is given by the otolithic information as it is in the upright stance. But, with the otoliths in their optimal position, as in the present situation, it seems reasonable to conclude that the variations in tilt magnitude primarily reflected differences in the potency of the rotating display. The more potent the display, the sooner it will make its influence felt. This inverse relationship between tilt and latency is therefore quite consistent with the notion of variable visual weightings within the intersensory mix.

It is also apparent from these data that the central comparator, or spatial integrating system, does not respond indiscriminately to visual signals informing it of whole-field motion. In Experiment 1, for instance, the elements, although varying in size and number, were distributed over the same wide retinal areas. In one sense, therefore, each display provided essentially the same message to the comparator—namely, that there was uniform motion of a large portion of the visual field. Yet our results indicate that the central comparator distinguished between these displays and gave more weight (at least up to some asymptotic value) to those with greater total boundary length. This implies that the integrating system is working on the outputs of fairly low-level analyzers. To put it another way, it suggests that we are dealing with a fairly "unintelligent" system, at least in terms of its visual analysis.

If we should now apply these deductions to the more "ecologically valid" case of active locomotion,

they would lead us to the conclusion that our visually obtained sense of self-motion will vary according to the visual structuring of the environment, even though our actual rate of progress remains constant. In other words, richly structured visual environments should create the sensation of faster motion than should more impoverished environments. While this is indeed true of passive locomotion in a vehicle (Denton, Note 3), it does not normally appear to be the case in self-propelled locomotion, probably because subjective speed computations are based upon reafferent inputs from many modalities and upon efference considerations as well (Held, 1961; von Holst, 1955).

The absence of a comparable volitional component in our experimental situation, as well as its other artificial features, imposes serious constraints upon extrapolations from this to the natural environment. Nevertheless, the roll vection technique used here, with its capability for both precise stimulus control and response measurement, commends itself as one of a number of possible routes toward the elucidation of the visual stimulus characteristics influencing our impressions of position and motion.

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