Diamond-winged variants of the Müller-Lyer figure: A test of Virsu's (1971) centroid theory

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Diamond-winged variants of the Müller-Lyer figure were used to test predictions of Virsu's (1971) theory of the Müller-Lyer illusion based on efferent readiness for eye movements toward the figure's center of gravity. A Müller-Lyer figure with diamond-shaped wings resulted in a greater center-of-gravity distance than the corresponding, conventional Müller-Lyer figure, but fin length and the rest of the figure remained constant; in Virsu's study, fin length and center-of-gravity distance covaried. Results were consistent with Virsu's data when we used the stimulus conditions that he reported. Results from a wider range of stimuli challenge Virsu's theory, and thus are consistent with the conclusions of Brigell, Uhlarik, and Goldhorn (1977).

The Müller-Lyer (ML) illusion (see Day & Knuth, 1981) occurs with freely moving observers in normal spatial environments (see DeLucia & Hochberg, 1991). It also occurs in the spatial and temporal visual domains (Day & Duffy, 1988; DeLucia & Hochberg, 1985; Hochberg, 1968) and in the haptic mode (e.g., Over, 1966). The ML illusion is, therefore, relevant to theories of normal perception and to practical concerns about perceptual accuracy. Previous studies, utilizing a variety of stimulus conditions, have ruled out perspective and orthogonalization theories and low-level pattern explanations of the ML illusion (e.g., DeLucia & Hochberg, 1985, 1991; see also DeLucia, 1993, for a quantitative analysis of averaging theories). Theories based on overt eye movements were ruled out by demonstrations of the illusion with stabilized images (Evans & Marsden, 1966) and tachistoscopic exposures (e.g., Lewis, 1908; for a summary, see Coren, 1986; Coren & Girgus, 1978).

Theories based on eye-movement tendencies or efferent readiness are still plausible (e.g., Coren, 1986; Festinger, Burnham, Ono, & Bamber, 1967; Festinger, White, & Allyn, 1968; Virsu, 1971; see also Schiano & Jordan, 1990). According to such theories, an inappropriate set of eye movements is computed and held in readiness to be emitted across the array (for discussions of saccadic programming, see Abrams, 1992; Findlay, 1992). When issued to the extraocular muscles, the proposed inappropriate efferent programs result in saccades that

overshoot or undershoot the endpoints of the ML shaft (Festinger et al., 1968), predicting misperceived extent. Efferent readiness, rather than overt eye movements, is considered to be the basis of the illusion. Although efferent-readiness theories avoid the problems associated with explanations based on overt eye movements, they are not without difficulties (see Coren, 1986; Coren & Girgus, 1978). It is difficult to determine which eye movements are held in readiness for a given array; planned eye movements are typically inferred from overt eye movements. Moreover, it is not known whether the line in the apex-in ML appears longer because eye movements held in readiness are too long, or whether eye movements held in readiness are too long because the line appears longer. The former implies that motoric processes form the basis of the percept, whereas the latter implies that the percept elicits the motoric output. In other words, it is not known whether the relationship between eye movements and perceived extent is more than just correlational.

It is premature, however, to rule out efferent-readiness theories. Coren (1986) presented a research strategy aimed at breaking the correlational loop described above, and concluded, on the basis of empirical demonstrations, that there is some systematic motoric contribution, that is, an efferent component, to the visual perception of extent. Further, there is evidence that neural mechanisms underlie the planning of eye movements (e.g., Barash, Bracewell, Fogassi, Gnadt, & Andersen, 1991a, 1991b; Gnadt & Andersen, 1988; see also Fischer, 1992). Such mechanisms can be considered a physiological substrate for efferent readiness that may underlie the ML illusion (V. Virsu, personal communication, April 18, 1993). Finally, efferent-readiness theory is an economical tool for integrating a large set of experimental data (Virsu, 1971). In the present article, we consider a specific efferent-readiness theory of the ML illusion that was presented by Virsu (1971).

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Centroid Theory

Virsu proposed a theory of the ML illusion that was based on an assumption of efferent readiness for eye movements toward the center of gravity of the ML figure. As represented in Figure 1, the center of gravity refers to the centroid of a triangular area enclosed by a given pair of fins (Kaufman & Richards, 1969; Richards & Kaufman, 1969; Virsu, 1971; see also Proffitt & Cutting, 1980; Proffitt, Thomas, & O'Brien, 1983). He measured the illusion magnitude as a function of the distance between a vertex of the ML figure and the centroid of the fins (the center-of-gravity distance, or CGD; see Figure 1). The results indicated moderate support for the theory.

Specifically, Virsu proposed that although observers intend to fixate the endpoints of the shaft in the ML figure,¹ they actually fixate the centroid of the area enclosed by the ML fins. This postulate is consistent with the results of eye-movement studies that have indicated that observers spontaneously fixate near the centroid of outlines such as circles and angles that are less than 5° of visual angle (Kaufman & Richards, 1969; Richards & Kaufman, 1969; see also Coren & Hoenig, 1972; Findlay, 1981, 1992). Virsu proposed that the ML illusion can be attributed to efferent readiness for eye movements toward the centroid (see also Coren & Hoenig, 1972).

Virsu elaborated further that, when CGD is large enough, fixations toward the centroid are followed by corrective fixations back toward the endpoints (such corrective flicks were reported by Festinger et al., 1968). The corrective fixations provide afferent feedback, which re-

veals that efferent readiness for eye movements toward the centroid does not result in the desired fixations at the endpoints; subsequent efferent programs and fixations are adjusted accordingly. In the terminology of control systems (e.g., Porter, 1969; Toates, 1980), there is a feedback loop: afferent feedback from the corrective fixations is relayed to a comparator. The latter produces a signal that represents the discrepancy between desired fixations toward the endpoints and actual fixations toward the centroid. When the (error) signal is sufficiently greater than zero, there is a modification of the efferent programs, which leads to more veridical eye movements and perception. Such a model predicts that the illusion magnitude should decrease with prolonged inspection; this is consistent with past data (e.g., Festinger et al., 1968; see also Schiano & Jordan, 1990).

In order for inappropriate efferent programs to be adjusted, and thus for more veridical perception to occur after continued inspection, eye movements must be permitted and CGD must be large enough to produce sufficient afferent feedback to signal an error. If eye movements are not allowed (e.g., via stabilized images or tachistoscopic viewing), the illusion should occur because efferent readiness for eye movements toward the CGD still occur. However, under such conditions, afferent feedback is eliminated and the illusion magnitude should not, therefore, decrease with prolonged inspection; this is consistent with previous data (e.g., Festinger et al., 1968; Lewis, 1908).

If CGD is too small, afferent feedback regarding the discrepancy between desired and actual eye movements will be insufficient. Thus, the model predicts that, with free viewing, the illusion magnitude should first increase as CGD increases and then decrease when CGD is large enough to result in sufficient afferent feedback. Virsu (1971, p. 70) specifically predicted that a maximum illusion would occur when CGD was less than 1.5° of visual angle. This was based on the results of spontaneous-fixation studies that indicated that circles that were 3° in diameter (i.e., a CGD of 1.5°) resulted in the least scatter in fixations toward the centroid; variability increased with size (Kaufman & Richards, 1969). Virsu measured the illusion in a shaftless, apex-in ML figure. By manipulating fin length, he varied the angle between the fins while CGD remained constant. For a given fin angle, fin length and CGD covaried. Data are reproduced in Figure 2. The results were consistent with a prediction of an inverted-U relationship between illusion magnitude and CGD; further, the illusion was maximal when CGD subtended 1.5° of visual angle. However, illusion magnitude varied with fin angle, even when CGD remained constant. Virsu concluded that his results provided moderate support for his theory.

Finally, Virsu (personal communication, April 18, 1993) suggested that receptive fields of visual neurons, predominantly those in the superior colliculus, can be considered a physiological substrate for eye-movement tendencies that may underlie the ML illusion. Such neurons

Figure 1. Center-of-gravity distance (CGD). Mathematical definition of a triangle's center of gravity, or centroid, is shown at the top of the figure. A schematic representation of CGD in the Müller-Lyer and diamond Müller-Lyer patterns is shown below.

Figure 2. Reproduction of Virsu's data (1971, Figure 3), showing the magnitude of the Müller-Lyer illusion (30°, 60°, 120°) and the line-segment illusion (0°) as a function of center-of-gravity (CGD) distance. CGD is shown on the horizontal axis in both degrees of visual angle and millimeters. The parameter is the angle between the obliques.

are maximally activated when stimuli fill their receptive fields, and eye movements are executed as a result of these activations. In the ML figure, the cells are maximally activated by the centroid of the stimulus; this results in the tendency to fixate the centroid. Such activations occur independently of overt eye movements. (Note that it also can be argued that attentional focus is a substrate for saccadic planning in the ML illusion; C. W. Tyler, personal communication, April 5, 1993; see also Coren & Porac, 1983; Klein, Kingstone, & Pontefract, 1992).

Brigell et al. (1977; see also Brigell & Uhlarik, 1979) tested the predictions of Virsu's theory. In their study, subjects judged the shaft lengths of Baldwin-type figures in which a box was drawn on each end of a shaft. The results indicated that there was an inverted-U relationship between the magnitude of the Baldwin illusion (see Coren & Girgus, 1978) and contextual box width, which is consistent with Virsu's theory (CGD is one half of the box width). The authors also reported, however, that the maximum illusion occurred at a different proximal CGD size for each of two viewing distances—interpreted as a clear contradiction of Virsu's theory. Further, the results indicated an effect of shaft length on illusion magnitude, which is inconsistent with Virsu's theory because CGD does not vary with shaft length.

The above results cannot unequivocally rule out Virsu's theory of the ML illusion, however. Although the maximum illusion occurred at a different CGD for each viewing distance, it is not known whether the maxima were significantly different from each other; separate analyses of variance (ANOVAs) were done for each viewing distance, which was a between-subjects factor. Also, the

maximum illusion was less than 1.5° of visual angle, as would be consistent with Virsu's predictions.² Moreover, results from Baldwin-type figures (i.e., boxes) may not be applicable to Virsu's theory of the ML illusion (i.e., angles) because different figures are not equipotent as attractants for fixations (Kaufman & Richards, 1969; Virsu, 1971).

On the basis of results from a second experiment, Brigell et al. (1977) reported that the magnitude of the ML, Baldwin, and divided-line illusions varied as an inverted-U function of framing ratio (total figure size divided by focal or shaft length), but analyses of CGD or Virsu's theory were not reported. The authors concluded that framing ratio determines the relative magnitude of illusion of linear extent. Additional studies of the Baldwin (Wilson & Pressey, 1988), Ponzo (Jordan & Randall, 1987), and parallel-lines illusions (Brigell & Uhlarik, 1979; Schiano, 1986) also demonstrated an inverted-U relationship between illusion magnitude and framing ratio. However, geometrical analyses indicate that, in the ML figure, framing ratio (FR) and CGD covary when shaft length remains constant: $CGD = \frac{2}{3} \cdot A$, and $FR = (S + 2A)/S$, where S refers to shaft length, and A refers to the height of a triangle (see line segment WZ in Figure 1) enclosed by a given pair of ML fins. In other words, $FR = (3CGD + S)/S$; $CGD = (S \cdot FR - S)/3$. It would seem, therefore, that an inverted-U relationship between the magnitude of the ML illusion and FR can also be attributed to CGD, when shaft length remains constant.

Coren (1986) also discussed efferent readiness for eye movements toward the centroid as a basis of the ML illusion. He evaluated evidence for an efferent component in visually perceived extent with a research strategy aimed at breaking the previously described correlational loop between eye movements and perception (a weakness of efferent-readiness theories). He reported that biased percepts of extent could be predicted from stimulus conditions that produced a set of eye movements that were systematically biased toward a figure's centroid; data that supported an efferent component in such percepts were also reported. Coren suggested that the tendency for observers to fixate near the centroid of stimuli, rather than directly toward a target, is adaptive: A fixation between a target and a nearby extraneous stimulus maximizes the amount of information that falls on the fovea, because both target and nearby stimulus can be imaged on the fovea. When the distance between the target and extraneous stimulus is too large for the target to fall on the fovea, fixation becomes more centered on the target. Perceived extent should be biased, therefore, in directions that are predictable from the centroids. According to Coren's analysis, the fins in the ML figure can be considered stimuli that are extraneous to the judged (target) shaft. The magnitude of the ML illusion should vary, therefore, as an inverted-U function of the distance between fin tip and the vertex of the fins (or fin length). Coren reported data that were consistent with such expectations. The distance

covaries with CGD, however; it is not clear, therefore, how to distinguish between predictions based on the individual studies of Coren and Virsu. Nevertheless, Coren presented evidence for an efferent component in perceived extent under conditions that seemed to overcome some of the difficulties of efferent-readiness theories.

In sum, theories of the ML illusion that are based on efferent readiness for eye movements toward the centroid deserve further study. In Virsu (1971; see also Brigell et al., 1977), illusion magnitude was measured as a function of CGD, but CGD and fin length covaried. Earlier studies demonstrated an inverted-U relationship between fin length and illusion magnitude (see Coren & Girgus, 1978, p. 31). In the present study, diamond-winged variants of the ML figure were used to increase CGD while fin length remained constant, and a greater number and range of CGD values were used.

EXPERIMENT 1

Method

Subjects. Twenty-four Texas Tech University students with normal or corrected visual acuity participated as part of a psychology course. They were naive as to the experimental hypotheses.

Stimuli. The stimuli were generated with a Macintosh computer and laser printer, and consisted of shaftless, apex-in ML figures drawn with black ink on white paper. Fifteen of the 24 figures described by Virsu (1971) were included, and the point of objective equality (POE) was always 4 cm. As represented in Figure 3, the ML figure was centered horizontally at the top of the paper; a horizontal line marked with a small vertical line was located at the bottom. The angle between the fins was 30°, 60°, or 120°. The fin length of each figure was varied, as described by Virsu, so that CGD was .26°, .46°, .82°, 1.48°, or 2.67° of visual angle when the subjects viewed the pattern from 45 cm (a CGD of 4.8° was not included as done by Virsu, because diamond-winged variants, discussed below, would not fit on the paper). From a viewing distance of 22.5 cm, the same figures had CGDs of .52°, .92°, 1.64°, 2.96°, and 5.34°, respectively.

Additional figures were created by adding fins to the ML patterns to create diamond-shaped wings (see Figure 1); except for the extra fins, the "diamond" Müller-Lyer (DML) and ML figures were identical.³ As represented in Figure 1, diamond-shaped wings shift the centroid away from the end of the shaft; CGD is greater for DML figures than for ML figures. Thus, at a 45-cm

Figure 3. Schematic representation of stimuli in the present study.

viewing distance, CGDs for the five figures were .38°, .69°, 1.22°, 2.23°, and 4.01°, respectively. At a 22.5-cm distance, respective CGDs were .76°, 1.38°, 2.44°, 4.46°, and 8.02°. A figure with diamond-shaped wings results in a greater CGD than its corresponding, conventional ML figure, but fin length and the rest of the ML figure remain constant.

Procedure. The subjects used a chinrest to view the stimuli from either 45 cm (as used by Virsu, 1971) or 22.5 cm; order of distance was counterbalanced across subjects (but did not significantly affect illusion magnitude); manipulation of viewing distance also served to vary the proximal size of CGD (see Brigell et al., 1977). Replicating Virsu's method, the subjects were instructed to estimate the length between the apices of the ML pattern by reproducing the estimated length on the line crossing the paper, and using the existing vertical line as the leftmost boundary. Each subject received a unique random order of stimuli, and viewed all stimuli at one viewing distance before the latter was changed. The figures were oriented so that they were parallel to the subject's frontal plane to eliminate distortion of the fin angles in the retinal image projected by the figure; this is a deviation from Virsu's procedure, in which stimuli were placed flat on a table (but see Experiment 2).

Predictions. Virsu's theory makes several predictions about the ML illusion with the present stimuli: (1) The illusion magnitude should be an inverted-U function of CGD with a maximum at or less than 1.5° of visual angle, (2) the illusion magnitude should not vary when CGD remains constant and fin angle varies, (3) the overall illusion magnitude should be smaller for near viewing distances than for far distances, and (4) the overall illusion magnitude should be smaller for DML patterns than for ML figures. The latter two predictions were determined by estimating, from Virsu's data (1971, Figure 3), the illusion magnitude that corresponded to the CGD values in the present stimuli. Estimates were completed by two individuals; results were correlated at .97 or more; $p < .0001$.

Results and Discussion

The mean illusion magnitude as a function of CGD and fin angle for each pattern and viewing distance is shown in the four panels of Figure 4. Illusion magnitude was defined as the constant error, expressed in millimeters. Two-tailed t tests indicated that the mean constant error was significantly greater than zero for both ML and DML figures [ML, $t(23) = 5.92$, $p < .001$; DML, $t(23) = 6.31$, $p < .001$].

At a 45-cm viewing distance, illusion magnitude varied as an inverted-U function of CGD, with a peak illusion when CGD was 1.5° of visual angle—with two exceptions. In the ML figures with 60° fin angles, the curve monotonically increased (see Figure 4A). Also, for DML figures with 120° fin angles, peak illusion magnitude occurred when CGD was 2.23° of visual angle (see Figure 4B). As can be seen in panels C and D, at a 22.5-cm viewing distance, the predicted inverted-U function occurred for DML, but not for ML, figures. Further, peak illusion magnitude occurred at CGDs of 2.44° and 5.34° for DML and ML figures, respectively. Peak illusion magnitude did not always occur at a CGD of less than 1.5°, which is inconsistent with Virsu's theory.

Figure 5 shows the mean illusion magnitude as a function of the 20 different values of CGD generated by varying pattern and viewing distance. Virsu's (1971, p. 70) theory predicts that illusion magnitude should increase first as a decelerating and monotonic function of CGD,

Figure 4. Mean illusion magnitude as a function of center-of-gravity distance (framing ratio is also shown) and fin angle in Experiment 1. Vertical bars indicate ± 1 standard error. Panel A: Müller-Lyer pattern viewed at 45 cm. Panel B: Diamond Müller-Lyer pattern viewed at 45 cm. Panel C: Müller-Lyer pattern viewed at 22.5 cm. Panel D: Diamond Müller-Lyer pattern viewed at 22.5 cm.

reaching a maximum under 1.5° , and then diminish monotonically thereafter. A repeated measures ANOVA with orthogonal polynomial trend analysis of the linear through quintic components (Winer, Brown, & Michels, 1991, pp. 235-236) indicated that the linear, quadratic, cubic, and quartic components were significant [linear, $F(1,455) = 21.07$; quadratic, $F(1,454) = 43.26$; cubic, $F(1,453) = 18.87$; quartic, $F(1,452) = 25.35$; all $ps < .01$]. When considering only the CGD values used by Virsu, trend analysis indicated that only the linear and quadratic components were significant [linear, $F(1,95) = 59.65$; quadratic, $F(1,94) = 33.03$; all $ps < .01$]. These analyses suggest that an inverted-U function fit the data, as predicted by Virsu, under the range of CGD values he reported; extending the range of CGD values resulted in a multi peaked curve.

A $2 \times 2 \times 3$ (pattern $\times$ viewing distance $\times$ angle) ANOVA indicated a main effect of fin angle [$F(2,46) = 10.80$, $p < .0006$, $w^2 = .23\%$], pattern [$F(1,23) = 8.60$, $p < .0075$, $w^2 = .10\%$], and viewing distance [$F(1,23) = 4.50$, $p < .0448$, $w^2 = .24\%$]. Tukey's *HSD* tests indicated that the mean illusion was significantly smaller ($p < .05$) for figures with 30° fin angles than for the other two angles; the illusion magnitude was not significantly different between figures with fin angles of 60° and 120° . Such results are partly consistent with Virsu's prediction that illusion magnitude is constant for a given CGD even when fin angle varies. These results go beyond Virsu's study, which did not include statistical analyses of fin angle.

Mean illusion magnitude as a function of pattern and viewing distance is shown in Figure 6. Predictions based

Figure 5. Mean illusion magnitude as a function of center-of-gravity distance in Experiments 1 and 3.

Figure 6. Mean illusion magnitude as a function of stimulus pattern and viewing distance in Experiment 1. Vertical bars indicate ± 1 standard error.

on Virsu's data are not consistent with the results; that is, illusion magnitude was significantly greater for DML figures than for ML figures (at both viewing distances), and was greater for near than for far viewing distances (with both patterns). Brigell et al. (1977) also reported a greater illusion magnitude at the nearer of two viewing distances. In the present study, however, although the peak illusion magnitude occurred at a different CGD for each viewing distance (as found by Brigell et al., 1977), the difference was not significant.⁴

Pattern and viewing distance were used to manipulate, and thus covaried with CGD. Thus, four one-way ANOVAs were performed to determine the effect of CGD on illusion magnitude for each pattern $\times$ viewing distance combination. A significant main effect of CGD occurred in all cases [for ML at 45 cm, $F(4,92) = 27.63$, $p <$

.0001, $w^2 = 2.9\%$; for DML at 45 cm, $F(4,92) = 4.55$, $p < .009$, $w^2 = .81\%$; for ML at 22.5 cm, $F(4,92) = 17.38$, $p < .0001$, $w^2 = 2.29\%$; for DML at 22.5 cm, $F(4,92) = 2.79$, $p < .04$, $w^2 = .43\%$].

EXPERIMENT 2

In Experiment 1, results obtained with ML figures that had the same characteristics as those reported by Virsu were not completely consistent with his findings (e.g., figures with 60° fin angles); this may have been due to the frontoparallel orientation of the stimuli used in Experiment 1. In Experiment 2, Virsu's study (1971, Experiment 2) was replicated completely.

Method

Subjects. Twenty-two new subjects had the same characteristics as those in Experiment 1.

Stimuli. The stimuli were as described by Virsu (1971). The figures were drawn with black ink on white paper, as specified in Experiment 1; POE was always 4 cm. The angle between the fins was 0° (line segment), 30° , 60° , or 120° , and fin lengths were such that, for each fin angle, CGD was .26°, .46°, .82°, 1.48°, 2.67°, or 4.80° of visual angle.

Procedure. The stimuli were placed flat on a table, about 45 cm from the subjects. As in Experiment 1, the subjects were instructed to reproduce the apparent apex-in distance by placing a mark on the horizontal line. Each subject viewed the 24 stimuli in a unique random order.

Results and Discussion

The results are summarized in Figure 7. A 4×6 (angle $\times$ CGD) completely within-subjects ANOVA indicated significant effects of angle [$F(3,63) = 11.19$, $p < .0001$, $w^2 = 3.16\%$] and CGD [$F(5,105) = 7.16$, $p < .0001$, $w^2 = 3.62\%$], but no interaction. As in Experiment 1, the mean illusion magnitude increased as fin angle increased; only the difference between figures with

Figure 7. Mean illusion magnitude as a function of center-of-gravity distance and fin angle in Experiment 2. Vertical bars indicate ± 1 standard error.

0° and 30° fin angles was significant, however. Thus, illusion magnitude did not differ significantly among the three fin angles of the ML figure (i.e., when CGD remained constant), as predicted by Virsu.

For figures with 30°, 60°, and 120° fin angles, curves represent an inverted-U function; this is consistent with Virsu's data, and with the results of ML figures with 30° and 120° fin angles in Experiment 1. Illusion magnitude peaked when CGD was 1.5° for only figures with 30° and 120° fin angles, however; figures with 60° angles resulted in a peak illusion at 2.67°. This pattern of results is not consistent with the data reported by Virsu (see the present Figure 2), in which illusion magnitude peaked at 1.5° for all fin angles. In both Experiments 1 and 2, most of Virsu's results were replicated; however, the pattern of results from figures with 60° fin angles was not consistent with Virsu's findings (regardless of stimulus orientation). Additional details about Virsu's methods that may explain such discrepancies are not available.

EXPERIMENT 3

In Experiments 1 and 2, to replicate Virsu's methods, each subject completed one trial in each stimulus condition. To obtain better estimates of the ML illusion, an additional experiment was completed with 8 new subjects, who completed three replications per stimulus condition.

Method

Procedure. Details of the methods were identical to Experiment 1, but only stimuli with fin angles of 60° and 120° were included.

Results and Discussion

The mean illusion magnitude as a function of CGD and fin angle for each pattern and viewing distance is shown in the four panels of Figure 8. An inverted-U relationship between illusion magnitude and CGD occurred in all conditions. The peak illusion magnitude occurred when

Figure 8. Mean illusion magnitude as a function of center-of-gravity distance (framing ratio is also shown) and fin angle in Experiment 3. Vertical bars indicate ± 1 standard error. Panel A: Müller-Lyer pattern viewed at 45 cm. Panel B: Diamond Müller-Lyer pattern viewed at 45 cm. Panel C: Müller-Lyer pattern viewed at 22.5 cm. Panel D: Diamond Müller-Lyer pattern viewed at 22.5 cm.

CGD was 1.5° or less when ML or DML figures were viewed at 45 cm; this is consistent with Virsu's predictions. However, when viewing distance was halved, the maximum illusion for DML and ML figures occurred at CGDs of 2.44° and 2.96° , respectively (i.e., above 1.5°). As in Experiment 1, although the peak illusion occurred at a different CGD for each viewing distance, the difference was not significant. Trend analysis indicated the same pattern of results as in Experiment 1, with each significant component accounting for a much higher percentage of the variance due to relatively lower variability in the data. Illusion magnitude as a function of all the CGD values used in Experiment 3 can be seen in Figure 5.

Mean illusion magnitude, averaged across replications, was analyzed with a $2 \times 2 \times 2 \times 2$ ANOVA (viewing distance order $\times$ fin angle $\times$ pattern $\times$ viewing distance, with repeated measures on the last three factors). Results indicated a significant four-way interaction among angle, pattern, viewing distance, and viewing distance order [$F(1,6) = 70.99$, $p < .0002$, $w^2 = .31\%$], which cannot be explained without further studies. A main effect of pattern was not statistically significant [$F(1,6) = 10.55$, $p < .0508$], which is inconsistent with predictions based on Virsu's data that the illusion should be relatively greater with ML figures.

Four one-way ANOVAs were performed to determine the effect of CGD on illusion magnitude for each pattern $\times$ viewing distance combination. As in Experiment 1, a significant main effect of CGD again occurred in all cases [for ML at 45 cm, $F(4,28) = 9.49$, $p < .005$, $w^2 = 20.59\%$; for DML at 45 cm, $F(4,28) = 7.90$, $p < .003$, $w^2 = 15.66\%$; for ML at 22.5 cm, $F(4,28) = 8.33$, $p < .0053$, $w^2 = 21.94\%$; for DML at 22.5 cm, $F(4,28) = 7.21$, $p < .0049$, $w^2 = 19.02\%$].

GENERAL DISCUSSION

Virsu's (1971) results were, for the most part, replicated when we used the stimulus conditions he reported. Results obtained with a wider range of stimulus conditions than that reported by Virsu were less consistent with his predictions. Specifically, the present data suggest that the relationship between illusion magnitude and CGD, when the range of CGDs is extended beyond Virsu's, may be multi-peaked. Moreover, predictions regarding the peak illusion magnitude, and the effect of diamond-shaped wings and viewing distance on illusion magnitude, were less consistent with Virsu's findings. Virsu's results may have been due to a limited range of stimulus conditions. The present results further challenge Virsu's theory, and thus are consistent with the conclusions of Brigell et al. (1977). Such results do not lend support, necessarily, for framing-ratio theory (Brigell et al., 1977); the geometrical analyses presented here indicate that CGD and framing ratio covary in the ML figure when shaft length is constant.

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NOTES

1. The definition of, or basis for, the assumption regarding an observer's "intention" to fixate the endpoints of the ML figure is not clear in Virsu (1971). For example, it is not known whether such an intention invokes an efferent program for eye movements toward the endpoints; this would seem to make the model more difficult to evaluate. It is assumed here that such "intention" reflects the task demands; that is, because observers were instructed to judge the distance between the endpoints, fixations between the endpoints were the desired behavior.

2. Virsu's (1971) prediction that maximum illusion magnitude should occur when CGD is less than 1.5° of visual angle is based on fixation studies of circle figures that were 3° in diameter (Kaufman & Richards, 1969); such figures resulted in the least variability in fixations. However, a tendency to fixate near a figure's centroid occurred for figures as large as 5°, albeit with greater scatter. Thus, a less stringent version of Virsu's theory would predict a maximum illusion when CGD is as high as 2.5°. The more stringent version is considered here.

3. For potentially related figures, see McClellan, Bernstein, and Garbin (1984), Metzger, Vukovich-Voth, and Koch (1970, Figures 3 and 4), Schumann (1900, cited in Robinson, 1972, pp. 24-25, 53-54), and Worrall and Firth (1974).

4. This was indicated by Tukey's *HSD* test, and based on results of a one-way ANOVA for all values of CGD used here.

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