Depth perception of stereokinetic cone and absolute distance information¹

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Magnitudes of the apparent depth of eccentric circles and real cone stimuli were measured as a function of viewing distance when they were rotated on a circular disc and viewed monocularly. The diameters of the largest circle and base of the cone were 5, 10, 20, and 40 cm at the viewing distances, 0.5, 1, 2, and 4 m, respectively. The height of each cone was equal to the diameter of its base. The cones were tilted 15 deg from the fronto-parallel plane so that their retinal images approximated to those of the eccentric circles stimuli. Eight observers produced the magnitude of depth of the perceived stimuli at each of the four viewing distances. The mean magnitude of the apparent depth for the eccentric circles stimulus increased linearly as a function of the viewing distance. The height of the cone stimulus was perceived veridically. The results of the experiment are consistent with the motion parallax hypothesis which states that the visual system calibrates motion parallax according to absolute distance information in processing stereokinetic depth.

Key words: stereokinetic effect, motion parallax, depth perception, absolute distance.

When a two-dimensional (2-D) pattern of eccentric circles is rotated on a circular disc, a three-dimensional (3-D) rigid cone appears to rotate with well-defined height and tilt. Since Musatti (1924) referred to this depth illusion as "stereokinetic" phenomenon, various 2-D patterns producing the stereokinetic effects have been reported (Braunstein, 1976; Duncan, 1975; Kanizsa & Gerbino, 1982; Metzger, 1953; Proffitt, Rock, Hecht, & Schubert, 1992; Sumi, 1989; Wilson, Robinson, & Piggins, 1983). The essential characteristic of this phenomenon is a compelling impression of depth evoked by the 2-D patterns when they are rotated on the fronto-parallel plane without changes in distance between any pair of pattern elements; in this sense, the phenomenon seems to be different from the kinetic depth effect, originally

reported by Wallach and O'Connell (1953), which contains changes of the distance between the pattern elements.

How does the visual system extract depth information from the rotational motion of the 2-D pattern? Musatti (1975) proposed that the visual system "interprets" the retinal projections as those from a rotating solid cone tilted in depth and "calculates" the height of the perceived cone on the basis of projective geometry. According to Musatti (1955), since the projection produced by a rotating ellipse or circular pattern approximates extremely to that produced by a rotating real cone tilted in a small angle, the visual system interprets the proximal stimulus as the rotat-

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ing cone. Musatti's hypothesis, however, has two defects. Firstly, for a circular stimulus, the visual system should not be able to calculate the extent of depth of the perceived cone on the basis of projective geometry (Zanforlin, 1988a, b). But we perceive the rotating cone with a well-defined depth even for the circular stimulus. Secondly, the hypothesis cannot explain depth impression produced by a rotating 2-D pattern that should not exist in reality as a 3-D object: for instance, randomly nested polygons as reported by Proffitt, Rock, Hecht, and Schubert (1992).

Alternatively, Wilson, Robinson, and Piggins (1983) and Robinson, Piggins, and Wilson (1985) proposed the motion parallax hypothesis which states that the visual system processes relative motion to produce apparent depth. In general, motion parallax is defined as the relative motion of images across the retina resulting from movement of the observer or the translation of objects across his field of view (Rogers & Graham, 1979). Wilson et al. (1983) thought that motion in the direction of the circular contour is not registered to the visual system 'since the contour slides along itself without changing the stimulation of receptors' (Wilson et al., 1983, p.190; Kondo, Haraguchi, Yanagida, & Shimono, 1988, p.99). As a consequence, the relative motion between the eccentric circles is produced even though there is no changes in distance between any pair of pattern elements. The visual system processes the relative motion to produce an illusory depth.

The motion parallax hypothesis has three advantages; one is theoretical and the other two empirical. Firstly, it specifies a definite cue to depth; motion parallax is one of the relative distance cues such as binocular disparity which specifies a scalar depth. Secondly, it is consistent with ambiguous directions of depth observed in the stereoki-

netic phenomena; for eccentric circles, observers perceive either a cone pointing outward or a funnel receding inward (Proffitt et al., 1992; Robinson et al., 1985). In the motion parallax studies (e.g., Rogers & Graham, 1979), observers perceive either concave or convex surface when relative motions of 2-D random dot pattern simulating a 3-D corrugated surface are presented to them without head movement. Thirdly, it is also consistent with observations that greater eccentricity produces greater depth of the perceived cone (Nakamizo, Kondo, & Shimono, 1994; Robinson et al., 1985; Zanforlin, 1988a, b) and that greater disc diameter produces greater apparent depth (Zanforlin, 1988a, b). According to Robinson et al.'s hypothesis, the greater eccentricity or greater disc diameter produces greater motion parallax.

If depth impression observed in the stereokinetic phenomena is mainly due to motion parallax, the question of whether the extent of perceived depth of the stereokinetic cone is a function of viewing distance is particularly interesting; because, recent studies on motion parallax showed that depth perception arising from motion parallax is contingent upon absolute distance information (Nakamizo & Saida, 1990; Ono, Rivest, & Ono, 1986; Saida & Nakamizo, 1987). Saida and Nakamizo (1987) found that when the proximal size of the random dot pattern was held constant the depth perception arising from motion parallax was described by the inverse square law at viewing distances up to 4 m. Although Robinson et al. stated that the apparent depth of the rotating figure is independent of viewing distance (Robinson et al., 1985, p.683), they did not report their experiment examining the effect of viewing distance on apparent depth in detail.

The aim of this study was primarily to examine whether depth perception of the rotating eccentric circles stimuli while their

proximal sizes were kept constant in different viewing distances up to 4 m was contingent upon the viewing distances. If it is the case, the motion parallax hypothesis is strengthened. Secondary, we examined depth perception of the rotating *real* cone stimulus in different viewing distances. If the perceived depth of the cone stimulus is veridical, it can be inferred that the visual system processes properly distance information as well as motion parallax as a cue to depth. The proximal size of the cone stimulus was also kept constant in different viewing distances; subjects observed monocularly the cone stimulus tilted from the fronto-parallel plane so that its retinal image approximated to that of the eccentric circles stimulus.

Method

Subjects

Eight subjects (aged from 20 to 45 years) with normal or corrected-to-normal visual acuities participated in the experiment. Two (the authors) of the eight were experienced in psychophysical experiments and the other six were naive as to the purpose of the experiment.

Figure 1. Eccentric circles stimulus.

Stimuli and Apparatus

Two types of stimuli were used: 2-D patterns of eccentric circles (circle-stimuli) and 3-D real cones (cone-stimuli). Four circle-stimuli with different diameters and four cone-stimuli with different heights and diameters of their base were used for holding proximal size of the stimulus constant in different viewing distances. Each of the circle-stimuli, similar to that used by Robinson et al. (1985, Figure 1f), has seven black and white bands which were drawn in black on a white card disc (see Figure 1). The diameters of the largest circle were 5, 10, 20, and 40 cm, at the viewing distances of 0.5, 1, 2, and 4 m, respectively; therefore, they subtended a constant visual angle of 5.72 degrees. The eccentricity of the smallest circle in each circle-stimulus was 2.0 deg in visual angle.

The cone-stimuli were made of white paper with seven black and white bands spaced equally. The diameters of the base of the cone-stimuli were 5, 10, 20, and 40 cm, at the viewing distances of 0.5, 1, 2, and 4 m, respectively; therefore, they subtended a constant visual angle of 5.72 degrees. The height of each cone-stimulus was equal to the diameter of its base. These stimuli were presented to observers tilted 15 deg from the fronto-parallel plane by using a wedged stand located on a rotating table so that their retinal images were approximately equal to those of the corresponding circle-stimuli.

Two types of apparatus to present the rotating stimulus to the subjects were used: one for the near viewing distances of 0.5 and 1 m, and another for the far viewing distances of 2 and 4 m (see Figure 2). For the near distances, the rotating table (T in Figure 2a) turned counterclockwise in the fronto-parallel plane. For the far distances, the rotating table (T in Figure 2b) turned clockwise in the horizontal plane and was observed through a mirror (M in Figure 2b)

tilted 45 deg from the fronto-parallel plane. Both tables rotated at a speed of 22.5 rev min⁻¹. Each stimulus was set on the rotating table so that the center of the stimulus corresponded to the axis of rotation of the table. A white cardboard screen with a square window (W in Figure 2) of 6.1 by 6.1 deg visual angle was located in the fronto-parallel plane 28 cm away from the subject's corneal plane. The centers of the window and the rotating table were at the same level of the subject's eye. The subjects observed the stimulus in a well-illuminated room. The luminance of the stimuli was 27.6 cd/m².

Procedure

The subject's head was fixed by a chin- and forehead holder through experimental trials. When the subjects observed the rotating stimulus monocularly through a viewing window, they were asked to report verbally the apparent shape of the stimulus and then to equate the length of a tape measure held in her/his hands with the extent of apparent depth when the apex of the perceived cone was pointing outward. (Apparent depth refers to a height of the perceived cone.)

Each of the two types of stimuli was presented in each of the four viewing distances. Four trials were run for each stimulus in each viewing distance. The eccentric circles stimulus was presented first to half of the subjects and the cone stimulus was presented first to the other half of the subjects. The order of the

four viewing distances was randomized.

Results

All subjects perceived the rigid cone and reproduced the extent of apparent depth of the cone in all trials for both eccentric circles and real cone stimuli. Mean magnitude of the perceived depth averaged over four trials for each subject for each stimulus was the basic unit for further analyses. The data were analyzed separately for the eccentric circles and cone stimuli.

The Eccentric Circles Stimulus

The results for the eccentric circles stimuli showed that depth perception of the stereokinetic cone when its proximal size was held constant was contingent upon the viewing distances; that is, the mean magnitude of the perceived depth increased linearly as a function of the viewing distance. Figure 3 shows the mean magnitudes of the perceived depth averaged over the eight subjects, which are plotted as a function of the viewing distance. Vertical bars on the data points indicate the standard deviations. The results of a repeated measure one factor analysis of variance showed the main effect was statistically significant [$F(3, 21) = 63.206$, $p < .001$].

The Real Cone Stimulus

The results for the real cone stimuli

Figure 2. Schematic representations of the two types of apparatus: (a) for the near viewing distances and (b) for the far viewing distances. T: rotating table; M: mirror; W: viewing window.

showed that depth perception of the real cone when its proximal size was held constant was veridical; that is, the mean magnitude of the perceived depth coincided with the physical depth of the stimulus in each viewing distance subcondition. Figure 4 shows the mean magnitudes of the perceived depth averaged over the eight subjects, which are plotted as a function of the viewing distance. Vertical bars on the data points indicate the standard deviations. The solid line represents the physical depth of the cone stimulus. The results of a repeated measure one factor analysis of variance show the main effect was statistically significant [$F(3, 21) = 63.644$, $p < .001$]. Each value of the physical depth for each viewing distance was contained in the 95 % confidence interval (CI) calculated from the obtained value of the perceived depth in each viewing distance subcondition [95%-CIs for the viewing distances: 4.85 to 8.63 cm for 0.5 m; 9.64 to 17.54 cm for 1 m; 18.53 to 32.57 cm for 2 m; 30.05 to 45.87 cm for 4 m].

Figure 3. Mean magnitudes of perceived depth plotted as a function of the viewing distance for the eccentric circles stimulus. The solid line is a linear regression equation fitted to the data points.

Discussion

We obtained two main findings from the present experiment. First, depth perception evoked by the stereokinetic cone was contingent upon absolute distance information. Second, depth perception of the real cone was veridical.

The first finding strengthens Robinson et al.'s motion parallax hypothesis of the stereokinetic effect; that is, the visual system calibrates motion parallax according to absolute distance information in processing stereokinetic depth. However, the obtained magnitude of apparent depth appears to deviate from predictions from the inverse square law of motion parallax (Ono et al., 1986; Saida & Nakamizo, 1987). The inverse square law of motion parallax predicts that for a constant motion parallax depth perception increases in proportion to the square of the absolute distance; for instance, the magnitude of apparent depth for viewing distance

Figure 4. Mean magnitudes of perceived depth plotted as a function of the viewing distance for the real cone stimulus. The solid line represents the physical depth of the real cone stimulus.

of 4 m should be approximately four times larger than that for viewing distance of 2 m. The obtained value, however, for viewing distance of 4 m was approximately two times larger than that for viewing distance of 2 m.

Two reasons for such discrepancy can be thought. For one thing, the extent of perceived depth from motion parallax without head movements is smaller than that with head movements. Ono and Steinbach (1990) found that the magnitude of perceived depth obtained in the no-head-movement condition was smaller than that obtained in the head-movement condition for all motion gradients with sine, triangle, sawtooth, and square waveforms. The subjects in the present experiment observed the eccentric circles stimuli without head movements. Second, the visual system transforms motion parallax information partially to motion perception instead of depth perception, in particular, for a large motion parallax and without head movement. This issue is a "trade-off" between motion and depth in processing motion parallax. The trade-off in stereokinetic cone has been reported by Robinson et al. (1985), who found the trade-off between the height of the stereokinetic cone and angle of wobble: a deep cone with a small wobble and a shallow cone with a large wobble. A similar trade-off in the motion parallax domain has been reported by Ono et al. (1986), who found the trade-off between the depth and motion seen with head movement, and by Ono and Steinbach (1990), who found the trade-off of perceived depth and motion with and without head movements. Although the origin of such a trade-off is not clear to us, future studies should measure the extent of perceived wobbling of the cone as well as the extent of perceived depth as a function of viewing distance and motion parallax.

The second finding that depth perception of the real cone was veridical suggests that absolute distance information as well as

motion parallax was processed properly. Although depth information processed by the visual system for a real object is not restricted only to motion parallax, motion parallax is most likely used for the visual system to 'calculate' the depth, because it is only a cue to scalar depth available in the monocular viewing of the present experiment.

Finally we discuss the "minimization" principle which is proposed by Zanforlin (1988a, b) to explain the stereokinetic phenomena. The principle hypothesizes that a minimization process of the relative velocity differences between all the points of the rotating pattern occurred in the stereokinetic phenomena. According to the hypothesis the perceived depth of a rotating eccentric circles stimulus is predicted quantitatively by the equation, $h = 2r + e$, where h = apparent depth of the cone, r = radius of the largest circle of the stimulus, and e = the absolute value of eccentricity. Although the principle is not inconsistent with results of previous studies, it has two difficulties. For one, the equation cannot predict apparent depth smaller than the diameter of the largest circle of the stimulus. Our informal observations showed that depth smaller than the diameter of the largest circle was perceived for the small eccentricity and viewing distance. Second, the equation predicts that when the physical size of the stimulus is held constant, the magnitude of apparent depth is constant in different viewing distances. Recent experiments, however, has reported that the magnitude of apparent depth of stereokinetic cone covaried with the viewing distance when both the eccentricity and the viewing distance were small (Nakamizo et al., 1994).

References

- Braunstein, M.L. 1976 *Depth perception through motion*. New York: Academic Press.
- Duncan, F.S. 1975 Kinetic art: psychokinematic objects. *Leonardo*, 8, 97-101.

- Kanizsa, G., & Gerbino, W. 1982 Amodal completion: Seeing or thinking? In J. Beck (Ed.), *Organization and representation in perception*. Hillsdale, NJ: Lawrence Erlbaum Associates. Pp.167-190.
- Kondo, M., Haraguchi, M., Yanagida, T., & Shimono, K. 1983 Theoretical and experimental research on the stereokinetic effect. *Bulletin of Faculty of Literature, Kitakyushu University*, **20**, 97-103. (In Japanese)
- Metzger, W. 1953 *Gesetze des Sehens*. Frankfurt: Waldemar Kramer & Co.
- Musatti, C.L. 1924 Sui fenomeni stereocinetici. *Archivio Italiano di Psicologia*, **3**, 105-120.
- Musatti, C.L. 1955 La stereocinesi e il problema della struttura dello spazio visibile. *Rivista di Psicologia*, **49**, 3-57.
- Musatti, C.L. 1975 Stereokinetic phenomena and their interpretation. In G.B.Flores d'Arcais (Ed.), *Studies in perception*. Milan: Martello-Giunti. Pp.166-189
- Nakamizo, S., & Saida, S. 1990 Motion parallax: a brief history and perspectives. *Bulletin of Fukuoka University of Education*, **39**, 239-264. (In Japanese)
- Nakamizo, S., Kondo, M., & Shimono, K. 1994 Magnitude of perceived depth of stereokinetic cone as a function of absolute distance and eccentricity. *Perception*, **23**, 45. (In preparation)
- Ono, M., Rivest, J., & Ono, H. 1986 Depth perception as a function of motion parallax and absolute distance information. *Journal of Experimental Psychology: Human Perception and Performance*, **12**, 331-337.
- Ono, H., & Steinbach, M.J. 1990 Monocular stereopsis with and without head movement. *Perception and Psychophysics*, **48**, 179-187.
- Proffitt, D.R., Rock, I., Hecht, H., & Schubert, J. 1992 Stereokinetic effect and its relation to the kinetic depth effect. *Journal of Experimental Psychology: Human Perception and Performance*, **18**, 3-21.
- Robinson, J. O., Piggins, D.J., & Wilson, J.A. 1985 Shape, height and angular movement in stereokinesis. *Perception*, **14**, 677-683.
- Rogers, B., & Graham, M. 1979 Motion parallax as an independent cue for depth perception. *Perception*, **8**, 125-134.
- Saida, S., & Nakamizo, S. 1987 Motion parallax and absolute distance information. *Proceedings of Meeting of Applied Physics*, 604.
- Sumi, S. 1989 Kinetic contours in rotation objects. *Perception*, **18**, 293-302.
- Wallach, H., & O'Connell, D.N. 1953 The kinetic depth effects. *Journal of Experimental Psychology*, **45**, 205-217.
- Wilson, J.A., Robinson, J.O., & Piggins, D.J. 1983 Wobble cones and wobble holes: the stereokinetic effect revisited. *Perception*, **12**, 187-193.
- Zanforlin, M. 1988a The height of a stereokinetic cone: a quantitative determination of a 3-D effect from 2-D moving patterns without a "rigidity assumption". *Psychological Research*, **50**, 162-172.
- Zanforlin, M. 1988b Stereokinetic phenomena as good gestalts. *Gestalt Theory*, **10**, 187-214.

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