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Curvature extrapolation in dependence on visual stimulus orientation

Lina Mickienė,

Algis Bertulis,

Aleksandr Bulatov

Department of Biology,
Kaunas University of Medicine,
Mickevičiaus 9, LT-44307 Kaunas,
Lithuania
E-mail: mickiene@vision.kmu.lt

On a dark monitor screen, bright circle arcs of various length and orientation were presented. In each presentation, a test-dot was shown at some distance apart from one of the ends of the arc. A gap between the test-dot and the arc was considered as an invisible stimulus segment to be extrapolated by test subjects. They moved the test-dot with the panel keys and placed it on the trajectory of the invisible part of the circle. In experimental sessions both with asymmetric one-arc and symmetric two-arc stimuli, the subjects demonstrated periodic changes of error values of curvature extrapolation in dependence of stimulus orientation. They made the extrapolated trajectories more flat at the oblique than at vertical and horizontal orientations of the stimulus. Moreover, the error magnitudes for horizontal and vertical orientations, left and right, upward and downward positions were different. The magnitudes for various oblique positions differed as well. In general, the experimental data showed a radial non-homogeneity of the human visual field while performing the curvature extrapolation task.

Key words: anisotropy, oblique effect, extrapolation of curvature

INTRODUCTION

To perceive the surrounding world, the human brain possesses the capacity of spatial extrapolation [1]. The accuracy with which vision can locate the spot on the tennis-court at which the ball is landing or forecast the position on the road-side which a vehicle is approaching might be of importance for practical and theoretical requirements. Human vision is highly sensitive to curved lines and deviations from a straight line [2–7]. Vision is still more sensitive to distortions of curves [8–11]. Human vision can estimate the curvature of an isolated segment of a line or contour in the absence of any other stimulus giving opportunities for comparisons and providing cues for estimation [12]. Apparently, the visual mechanisms of curvature estimation are closely interrelated with those of spatial interpolation and extrapolation of the fragments of curved lines and surfaces [13–20]. Subjects are able to a certain extent forecast the trajectory of an invisible part of the stimulus segment, but the trajectory extrapolated is permanently more flat than that indicated by the visible referent fragment [21]. The errors of flattening depend on the curvature type: they are greater for the exponential spiral and still greater for the shifted circle than for the centered circle. The error values increase with the extrapolation distance and decrease with the referent fragment length. The error values are much the same for stimuli formed of a single referent fragment and for stimuli formed of two identical fragments presented symmetrically to each other [22]. In these experiments, two stimuli orientations were used and yielded qualitatively similar results. Both the experiments and the literature data have not provided a clear answer whether the accuracy of curvature extrapolation is independent of the stimulus orientation in the visual field or, on the contrary, the non-homogeneity of the visual field causes additional distortions of curvature extrapolation which combine with those determined by the curvature mechanisms. Visual field non-homogeneity, also known as anisotropy, may be a consequence of topographical interrelations between the retina and the primary cortex, the area V_1. The ratio of the horizontal to vertical diameters of the visual field is about 1.23 for monocular and 1.54 for binocular vision [23, 24]. The stimulus size estimation varies with the stimulus orientation which causes perceptual distortions of various parts of an image projected on the different regions of the retina [25–27]. Visual field anisotropy is observed when measuring contrast sensitivity [28, 29], vernier acuity [30–32], orientation discrimination [33, 34], as well as in curvature [35, 36], spatial frequency [37], and movement [38] perception.

In the present communication, we report experimental data on the influence of orientation anisotropy on curvature extrapolation accuracy. In psychophysical experiments, subjects performed extrapolation tasks with the static two-dimensional white stimuli having different orientations in the visual field.

METHODS

Equipment

The experiments were conducted under computer control with software of our original design. The computer programme arranged the order of the stimuli, presented them on the monitor, introduced alterations according to the subject's command, recorded the subjects' responses, and handled the results. The experiments were carried out in a dark room, so that the display frame could not be discerned. The subjects viewed the stimuli monocularly. The right eye was usually tested irrespective of whether it was the leading eye, but in some series of experiments, for comparison of experimental effects, the left eye was also examined. The viewing distance was 400 cm. An artificial pupil (3 mm in diameter) was used. A chin holder limited the movements of the subject's head. The Sony SDM-HS95P monitor was used for the stimuli presentations. A Cambridge Research Systems OptiCAL photometer was applied for the luminance range calibration and gamma correction of the monitor.

Stimuli

The circle arcs *m* were formed of 50 cd/m^2 luminance lines, which were 0.25 min of arc thick and varied in length within the interval 20–70 min of arc (Fig.1). The arcs were presented against a dark background on the monitor screen. All stimuli used in the experiments had the same radius size – 25 min of arc. The centre of the imaginary system of orthogonal co-ordinates of the stimuli, X and Y, coincided with the centre of the monitor. Consequently, the arcs *m* always were situated on the same imaginary circle (Fig.1A).

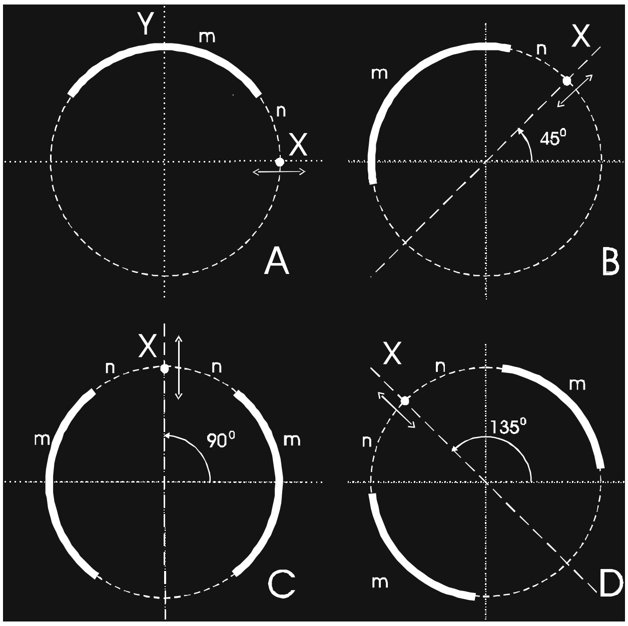

Fig. 1. Facsimiles of the horizontal (0°), vertical (90°), oblique (45° and 135°) orientations of single-sided (A, B) and two-sided symmetrical (C, D) stimuli

m, visible segment of the circle; *n*, invisible segment of the circle. For other explanations, see the text.

The arcs *m* crossed the Y-axis. Two sides of the arcs were equal in length and symmetric to each other in accordance to the Y-axis, irrespective of the total arc length. Therefore, the imaginary chords of the arcs *m* were parallel to the X-axis. Fifty different orientations of the arcs within the circle perimeter were produced by rotating of the orthogonal coordinates, X and Y, in the experiments. The orientations were identified by the X-axis orientations distributed evenly within the range of 0°–360°. In each stimulus, the test-dot of 0.5 min of arc in diameter was shown on the X-axis. The gap between the test-dot and the arc was considered as the invisible stimulus segment *n*, which had to be extrapolated by subjects. The subjects were able to move the test-dot with the panel keys along the imaginary X-axis forward or backward with 0.3 min of arc steps. The task was to perform the extrapolation procedure by placing the test-dot into position that corresponded to the intersection of the X-axis and the trajectory of the invisible part of the circle. Five values of the invisible circle segment *n* length – 10, 15, 25, 35, and 45 min of arc – were checked in the experiments. The single-sided and two-sided stimuli were used. The facsimiles of the horizontal (0°) and oblique (45°) orientations of the single-sided stimuli are shown in Fig. 1A and 1B respectively. The vertical (90°) and oblique (135°) orientations of the two-sided symmetrical stimuli are presented in Fig. 1 C and D. Prior to the experiments, the subjects were informed about the structure of the stimuli.

Procedure

The test subjects operated the buttons 1 and 2 of the keyboard moving the test-dot forward and backward until the desired position was achieved. Then they pressed button 3 to transfer the response into the computer. Auditory feedback was provided. A single press of button 1 or 2 varied the position of the test-spot by one pixel, which corresponded to 0.25 min of arc. The manipulation time was unlimited. No instructions concerning gaze fixation point were given to the subjects. The errors of the subjects were calculated by subtracting the theoretical value x_0 from the experimental value x_i, respectively.

During the presentations, stimulus orientation was changed in a random order. The initial position of the test-dot on the radius of the circle was also randomized. The positions were distributed evenly on both sides of the theoretical x_0 value within a range of ±5 min of arc, and the subjects did not know in advance which of them had been taken for the stimulus. Fifty values of stimulus orientation were repeated two times in a single experiment. The experiment was repeated six times during a session. In sessions, different length of the invisible segment *n* of the single and two-sided stimuli was examined. Ten sessions of experiments were performed. In all sessions, the accuracy of extrapolation of stimulus trajectory was measured as a function of the stimulus orientation in the visual field.

Subjects

Data were collected from 5 subjects, women and men, students and teachers of the university, aged 20 to 50 years. None of the subjects had a history of visual disorder. The visual acuity of both eyes was 1. The data obtained showed the same regularities of visual accuracy in the curvature extrapolation procedure for all the subjects. The left and the right eye testing yielded the same results.

RESULTS

In the first five sessions of experiments, the single-sided stimuli with different sizes of the extrapolation gaps *n* (10, 15, 25, 35 and 45 min of arc) were studied. In the second five sessions, the two-sided symmetrical stimuli with different sizes of the extrapolation gaps *n* were studied. In all sessions, the subjects demonstrated periodic changes of error values of curvature extrapolation in dependence of stimulus orientation (Fig. 2).

At most orientations, the subjects produced errors with the positive sign, what indicated the experimental values x_i being larger than the theoretical ones, x_0, because the subjects placed the test-spot farther from the circle centre than it was expected and somewhat flattened the invisible trajectory of the stimulus circle. The errors were relatively small in amplitude, reaching up to 2–4 min of arc, but for certain stimulus orientations, the errors were still smaller and approached zero (Fig. 2A and 2B). For some subjects and for cardinal orientations, i. e. 90°, 180°, the errors obtained the negative sign (Fig. 2A). The sign variations did not alter the periodic character of the experimental curves and just emphasized the difference of the error amplitudes at different stimulus orientations, indicating permanent distortions of curva-

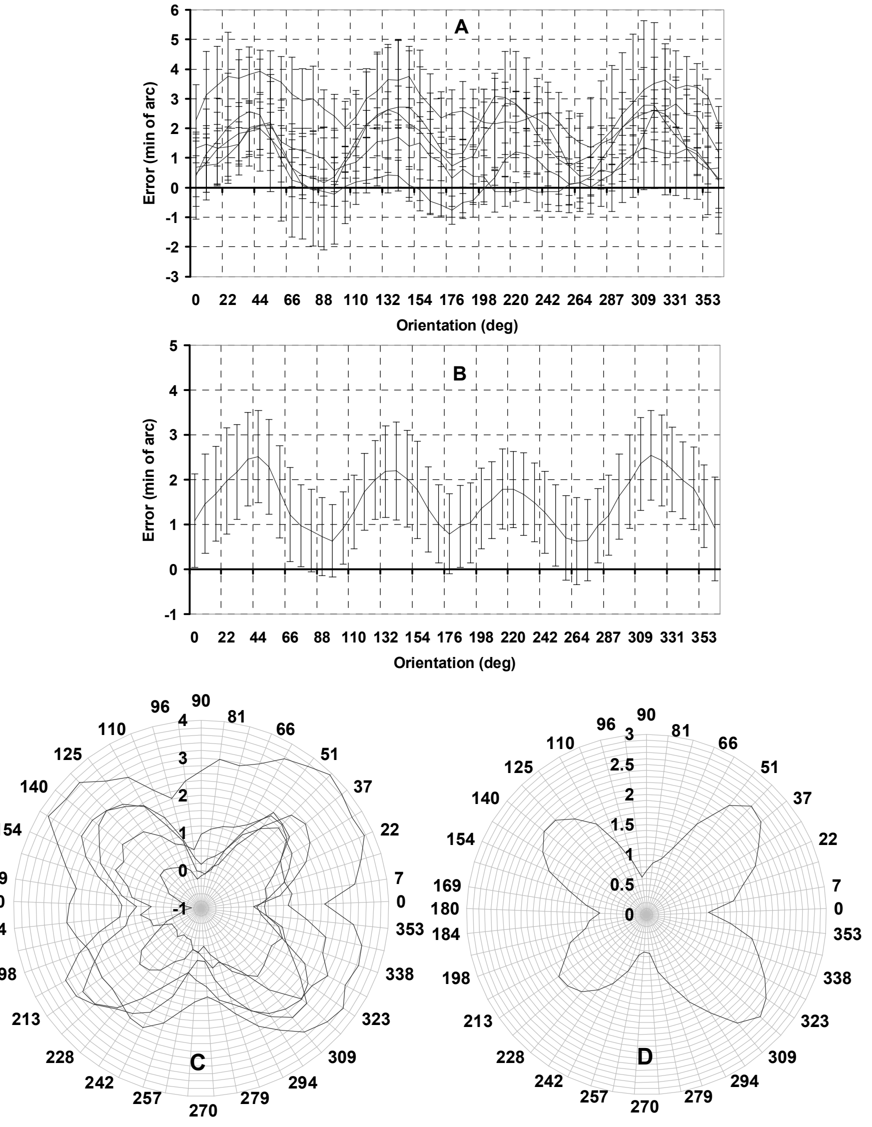

Fig. 2. Periodic changes of error values of curvature extrapolation in dependence on the single-sided stimulus orientation

The gap between the visible segment, and test-dot is 25 min of arc. Data from five observers are shown in panel A and the averaged data from the same observers in panel B. The same results are shown for various directions in polar graphs C and D.

ture perception and the effect of visual field anisotropy on extrapolation performance.

The periodic character of extrapolation accuracy is obvious in the polar graphs (Fig. 2C, 2D).

In these plots, radial distance indicates error values and shows an overestimation of the diagonal orientations compared to the vertical and horizontal meridians. The subjects made the trajectories more flat at the oblique (45°, 135°, 225°, and 315°) than at the horizontal (0° and 180°) or vertical (90°, and 270°) orientations of the stimulus. Also, error magnitudes for horizontal and vertical orientations, for the left and right, the upward and downward positions were different, and the magnitudes for various oblique positions differed as well (Fig. 3).

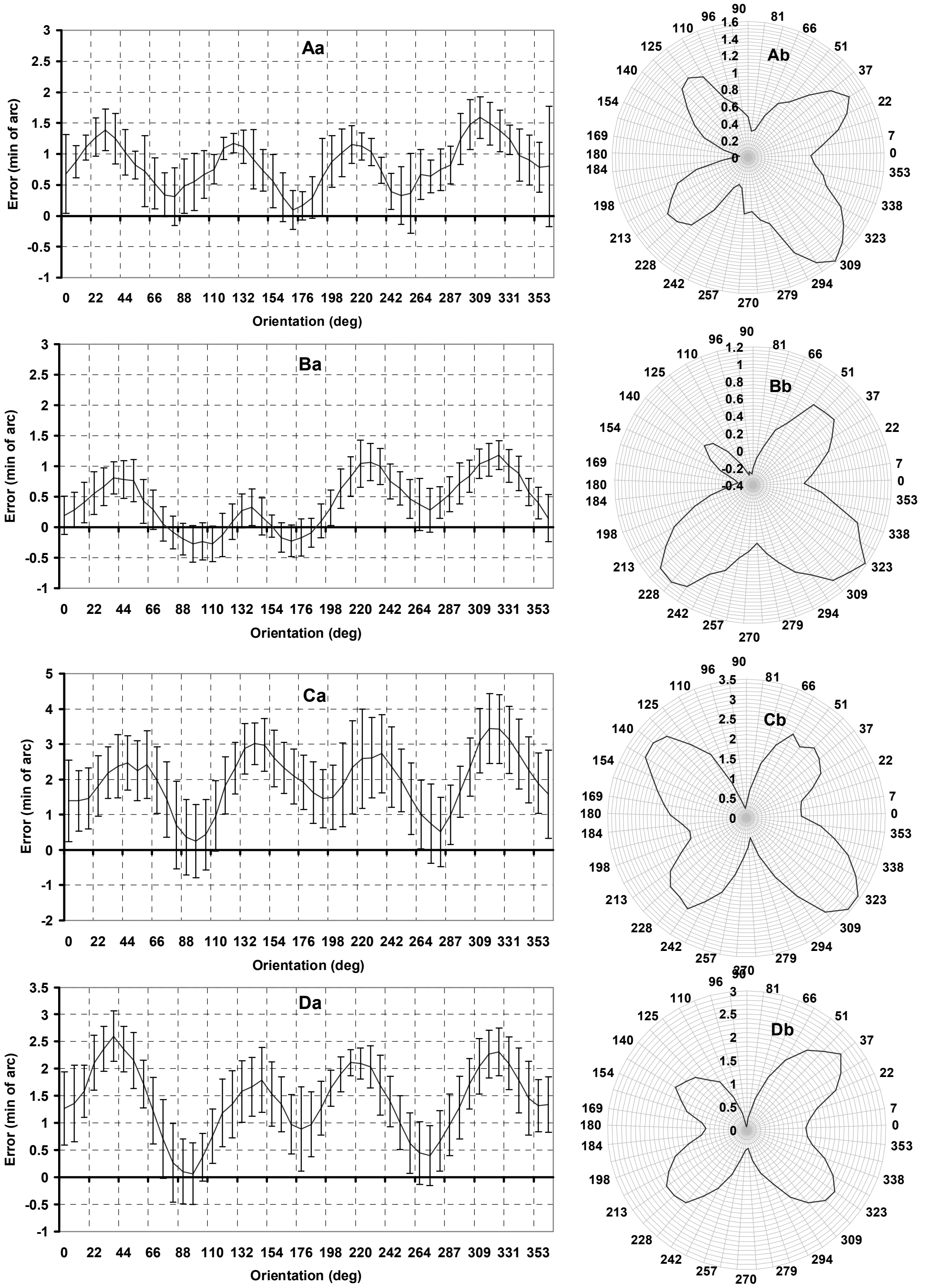

Fig. 3. Periodic changes of error values of curvature extrapolation in dependence on stimulus orientation: single-sided (Aa, Ab and Ca, Cb) and two-sided (Ba, Bb and Da, Db) stimuli

The gap between the visible segment and the test-dot is 15 min of arc in Aa, Ab and Ba, Bb, and 35 min of arc in Ca, Cb and Da, Db. Averaged data from five observers are presented.

The effect of anisotropy on curvature extrapolation was the same with symmetric and asymmetric stimuli. This result is in agreement with the previous experimental findings [21, 22].

DISCUSSION

Originally, orientation anisotropy of the visual field was interpreted as an oblique effect [39, 40]. The effect is linked to subjects' superior psychophysical performance with static or moving stimuli presented on the cardinal (vertical and horizontal) orientations compared to the oblique meridian. A number of theories have been advanced to account for the oblique effect mechanism: oblique channels could be more broadly tuned to stimulus orientation, spatial frequency, etc., more asymmetrically tuned, or noisier than their cardinal counterparts. In terms of the neural substrate for the anisotropy phenomenon, there is evidence for both a reduction in the number of neurons that are selective to oblique orientations as well as a broadening of their receptive field spatial frequency characteristics [41]. The oblique effect mechanism may be explained in terms of the "framing effect" of the elliptical shape of the visual field [42], and by means of low-level neural models, such as neuronal sensitivity [43], neuronal tuning [44], neuronal density [45, 46] or non-homogeneity of the factor of magnification of the retinal representation on the striate cortex [47]. Nevertheless, the possibility of a "higher level" contribution to orientation anisotropy was also discussed [48].

The data obtained in our experiments revealed a system of radial non-homogeneity of the human visual field. The scale of perceived distortions appears to be individual for various radii.

The reported characteristics of the oblique effect for curvature extrapolation are consistent with data on the visual field non-homogeneity for motion perception. Contrast detection thresholds for stimuli moving in oblique directions were elevated [49]. Also, direction discrimination thresholds for patterns moving with oblique directions were significantly higher than for patterns moving in the cardinal directions [50].

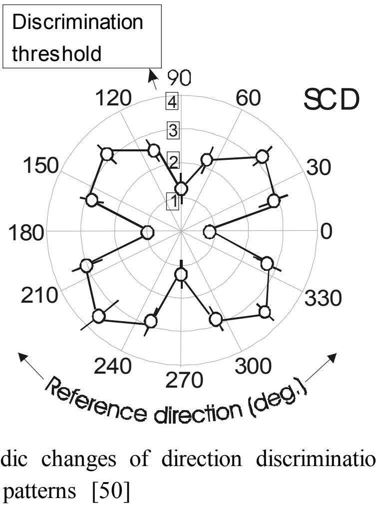

Fig. 4. Periodic changes of direction discrimination thresholds for moving patterns [50]

A robust oblique effect was evident for all non-cardinal directions at low levels of directional source data, but it was greatly attenuated at large directional ranges. The result was thought to be interrelated with two stages of human perception of motion. The first stage is the estimation of local direction over a small area and was carried out by cells in the primary visual cortex V_1. The second stage involves pooling the signals from V_1 across the space to estimate the overall or global direction; it was carried out by neurons in the area MT. Evidence from a study of the visual cortex [51] indicated that the oblique stimuli led to a lower activity in the cortical area V_1 but not in higher levels areas.

The manifestation of the oblique effect was similar in experiments with the right angle reproduction and with the right angle side length matching [52]. The results were characterized by a periodic change in the amplitude of errors plotted as a function of orientations present in the range from 0° to 360°. The errors increased at the oblique orientations of the test side (45°, 135°, 225°, 315°) and decreased approaching the zero value at cardinal orientations. The periodicity of the error curve was significant for stimuli of different structure consisting of line segments or dots, or both.

The comparable experimental data allow to assume that the psychophysical performances like right angle reproduction, length matching, straight or curved line extrapolation, or direction determination are based on the information on the coordinates of the visible stimulus parts. This implies a vector description of the visual space. It is of interest to consider a specific neuronal structure responsible for manipulations with the spatial coordinates of stimuli elements [52]. The visual field can be organized so that a shift of a test-dot (stimulus) relative to the vertical meridian causes a linear change in the response of a subsystem. A shift of the dot relative to the horizontal meridian produces a linear change in the response of another subsystem. Then the response space of each subsystem is a plane and the response itself is proportional to the projection of the stimulus position to the vertical or horizontal meridian. The totality of the responses of the above subsystems is enough for a quantitative description of the geometry of a stimulus. The neural formation of the vector description of the visual field requires involvement of various parts of the visual system at rather high levels of its hierarchy, while the oblique effect and geometric illusion mechanisms seem to be related to lower cortical or even retinal-cortical levels [51, 53].

The neural mechanisms of curvature detection and identification evidently encompass the networks of simple and complex neurons (of the areas of visual cortex V_1, V_2, V_4) with their receptive fields of various size, orientation and spatial organization tuned to different spatial and temporal frequencies [41, 54–60]. The mechanism of curvature detection and identification is likely to be interrelated with the structures for description of stimulus geometry and with the structures for the vector description of the visual field.

According to our experimental data, the mechanism of curvature evaluation is rather precise: errors of extrapolation of a circle of radius size 25 min arc were relatively small. Even the maximum values (2–3 min of arc) were obtained under the influence of distortions caused by the oblique mechanisms. Curvature extrapolation appears to be an ordinary procedure for the human visual system. The system can become well adapted for evaluating the curvature of contours and surfaces.

CONCLUSIONS

In psychophysical experiments, the visual accuracy of curvature extrapolation was measured.

The error values of curvature extrapolation varied with changing stimulus orientation within 0° to 360° in the visual field.

The effect of visual field anisotropy on the errors of curvature extrapolation was similar for different sizes of symmetric and asymmetric stimuli.

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Lina Mickienė, Algis Bertulis, Aleksandr Bulatov

REGIMOJO STIMULO ORIENTACIJOS ĮTAKA KREIVUMO EKSTRAPOLIACIJAI

Santrauka

Psichofizikinių eksperimentų užduotis – įvertinti žmogaus regos gebą numatant apskritimo segmento menamą tąsą duotose regos lauko ribose. Monitoriaus ekrane stebėtojams po vieną buvo pateikiami šviesūs įvairaus ilgio ir skirtingos orientacijos apskritimų segmentai bei viena netoli segmento galo esanti to paties šviesio dėmelė. Stebėtojai, naudodamiesi klaviatūros mygtukais, stumdė dėmelę pirmyn ir atgal išilgai įsivaizduojamo apskritimo spindulio ir pastatydavo ją to spindulio ir menamos apskritimo tąsos susikirtimo taške. Skirtingoms eksperimentų serijoms buvo naudojami asimetriniai stimulai, sudaryti iš vieno lanko, ir simetriniai stimulai, sudaryti iš dviejų vienodų, vienas priešais kitą atsuktų lankų. Stebėtojų daromos kreivumo ekstrapoliacijos klaidos rodo, kad įsivaizduojamosios apskritimų trajektorijos yra lėkštesnės negu tikrosios. Klaidų absoliučiosios reikšmės auga trumpinant apskritimo lanko ilgį bei didinant atstumą tarp lanko ir dėmelės. Klaidų reikšmės kinta periodiškai, kintant stimulo orientacijai regos lauke, ir jos kur kas didesnės įžambiųjų orientacijų negu horizontaliųjų ir vertikaliųjų. Be to, įžambiųjų orientacijų klaidos skiriasi tarpusavyje, nevienodos savo reikšmėmis ir vertikaliųjų bei horizontaliųjų orientacijų klaidos. Tai leidžia manyti, kad kreivumo ekstrapoliacijai turi įtakos regos lauko radialinė anizotropija.

Raktažodžiai: anizotropija, įžambinės efektas, kreivumo ekstrapoliacija