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Influence of the spatial structure and contrast of the stimulus on shape perception distortions

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The strength of an illusion of curvature created by an equilateral triangle, square or pentagon inscribed in a circle has been measured in psychophysical experiments. The arcs of the circle looked as if they were bowed outwards in the stimuli of various sizes, but, at a fixed diameter of the circumscribed circle, the triangles produced the strongest and the pentagons the weakest illusion. The strength of the illusion augmented with the stimulus diameter. Concave and convex sides of the inscribed figures caused a less illusory effect than the straight ones. The illusion strength is greater in the presence of the luminance contrast between the inscribed triangle or circumscribed circle and the background than in the presence of color contrast. These data might be interpreted as a result of different sensitivity of chromatic and achromatic vision to spatial frequencies. Similar distortions of the stimuli have been observed in the output of a neurophysiological model of spatial frequency filtering of images, and the computational curves resembled those of the experimental data in respect to their shape and quantitative values.

Key words: distortions of perceived curvature, spatial frequency filtering

INTRODUCTION

A live being perceiving changes of the outer world and responding to them adequately must be able to assess various characteristics of the stimuli. For vision, it may be the proportions of the lengths or orientations of the compound elements of the image. Under certain circumstances, such as marginal ones in respect of its parameters, the visual system may mistake and the so-called illusions appear. Illusions, as a discrepancy between the perceptible, or subjective, and the physical, or objective, parameters are characteristic of all sensory systems – visual [1], hearing [2], tactile [3]; they result from the properties of the structure of the nervous system as well as from the processes of information processing. The best known and studied are visual geometrical or optical illusions. When observing illusory figures their spatial parameters may be misperceived. Some parts seem to be longer, or shorter, other seem to be varied in curvature, or in angle size [4]. The quantitative value of the illusion may amount to 20–30% of the size of the figure and may be measured quantitatively, since the experimental results are stable and alike for all observers.

Many geometrical illusions have been thoroughly described and named after the authors of the description during the 19th century; nevertheless, their neurophysiological mechanisms are not quite clear up to now. Many authors tend to explain illusions by the psychological aspects of perception of depth and perspective, by the constancy of the perceived size of objects situated at different distances [5–7]. Depth perception seems to operate on the size constancy mechanism which is based on the linear-perspective scale [8, 9]. The visual system, balancing between the estimation of the two image parameters, performs errors [10].

The concept of gravity center [11–14] mostly emphasizes the influence of eye movements and postulates that perceptual distortions might occur due to an involuntary tendency to shift the attention to the end-points of the figure when attempting to fixate the focal shaft.

Other investigators explained the illusion phenomenon referring to the functional organization of the nervous system [15]. It is known that line detectors are able to set the orientation of an edge or a line according to the ratio of vertical and horizontal orientations; however, the precision in the visual field centre and in its periphery varies [16].

One of the hypotheses suggests that distortions of size perception appear due to the image spatial-frequency filtering in the receptive fields of neurons at different levels of the visual system. Such a filtering system influences the frequency spectrum of the image, thus creating distortions of perception [17–20].

The present research is a follow-up of our previous experimental and theoretical investigations dedicated to the quantitative measures of the perceived shape distortions. We wish to answer the question whether the neurophysiological properties of the visual system together with the spatial-filtering parameters could be considered to cause not only size but also shape illusion. An illusion caused by a regular polygon, for instance, triangle or pentagon, inscribed into a circle was taken as an object of investigation. While observing such a figure, the circle is perceived as an irregular ring with bulging arcs. The strength of such an illusion was measured as a function of the size of the stimulus and of variations of the curvature of the sides of the inscribed polygons, as well as the luminance and color contrast between the whole stimulus, its parts (polygon or circle) and the background. The obtained data were compared with the modeling data.

MATERIALS AND METHODS

The experiments were controlled by a computer program of our own design. The stimuli were generated against a dark background on the EIZO T562 monitor with gamma correction. For the generation of the stimuli, the Cambridge Research Systems VSG 2/3 was used. The viewing distance was 400 cm. A chin holder limited the movements of the subject's head. The experiments were carried out in a dark room, and the display frame could not be discerned. The subjects viewed the stimuli monocularly through an artificial pupil with the diameter of 3 mm. The stimuli were formed of an equilateral triangle, square or pentagon inscribed in a circle (Fig. 1A). The width of the lines was about 0.3 min arc. The diameter of the circumscribed circles varied from 7 to 70 min arc and indicated the stimulus size. During an experiment, the stimuli of 50 size values were exposed at a random order. In the experiments of the first group, the inscribed geometrical figures had straight-line sides; in the second, the sides were curved, concave or convex, at various degrees (Fig. 1B). In the experiments of the third group, various combinations of luminance and color of the stimulus and background were presented (Fig.1C). In one series of the third group, varied either the luminance of the circle (the luminance of triangle being constant), or the luminance of the triangle (the luminance of a circle being fixed). In the other series of this group, the subjective luminances of the gray background and the colored triangle or circle were equal. The illusion strength was measured under the conditions of either luminance or color contrast, or both.

In all the experiments, the observers' tasks were: (i) to estimate visually the distortions of the arcs of the circles, and (ii) to change the radii of the arcs with the help of keyboard buttons until the illusion of the puffy arcs was reduced to zero, and the circle appeared to be regular. A single button press changed the radius length by a pixel, which corresponded to 0.3 min arc in our experiments. After a required regular shape was achieved, the difference between the radius length made by the observers and that of the regular circle was recorded and considered as the strength of the illusion. In a single experiment, the illusion strength was measured as a function of independent variables: stimulus size, internal angle, and luminance of the figure. All values of the stimulus parameters were repeated two times. In a single session series, the same experiment was performed thirty times on different days. The data were collected from four observers, females and males, aged from 25 to 65. No observers had a history of an eye disorder or injury.

For the statistical treatment of the results, Statistica mathematical package was used. With the help of it the root-mean square and the parameters of linear regression (the coefficient of correlation r and the coefficient of slope b_1) were counted, and the statistical hypothesis of the linearity of the data was tested.

RESULTS

For all the observers, the results of the performed experiments were qualitatively similar. The experiments of

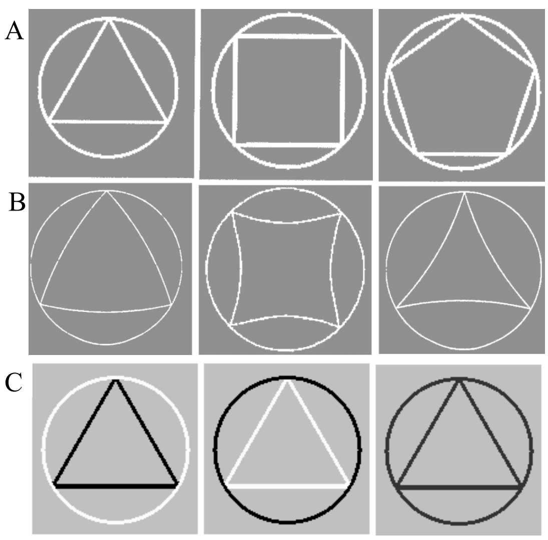

Fig. 1. Facsimiles of the stimuli: A, inscribed figures with straight sides; B, examples with curved sides; C, figures with different contrast

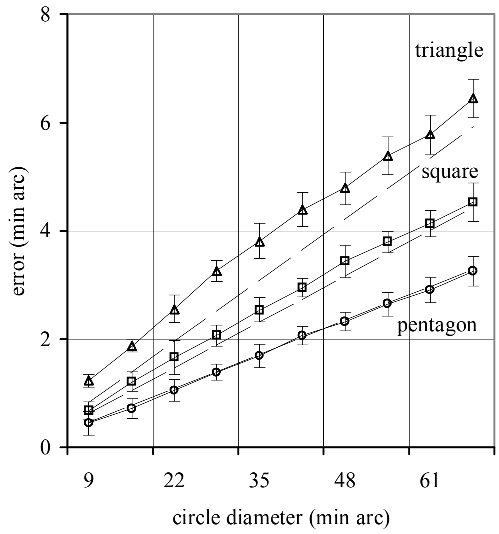

Fig. 2. Illusion strength as a function of stimulus size. Solid lines, experimental data; dashed lines, modeling data. Vertical bars, standard deviation

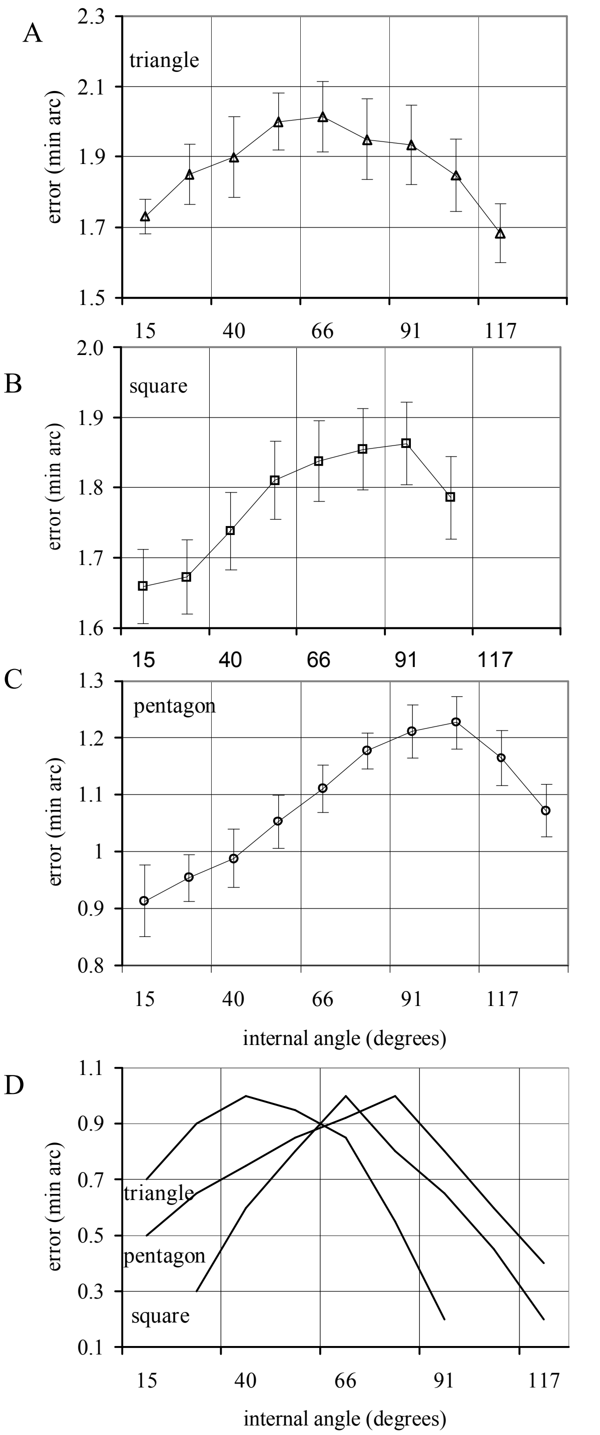

Fig. 3. Illusion strength as a function of the internal angle of the figure. Stimulus size 21 min arc. AC, experimental data for three figures; D, modeling data. Vertical bars, standard deviation

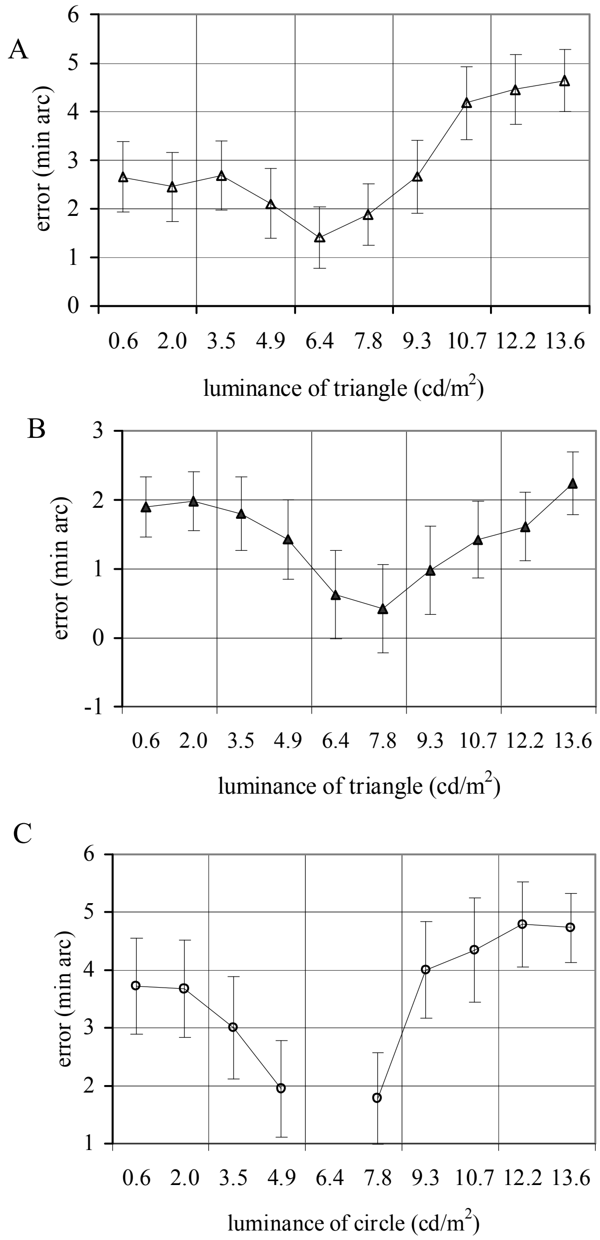

Fig. 4. Illusion strength as a function of the luminance contrast. Stimulus size 58 min arc, background luminance 7 cd/m^2. Luminance of circle is 14 cd/m^2 in A, 0 cd/m^2 in B; luminance of triangle is 14 cd/m^2 in C. Vertical bars, standard deviation

the first group with straight-side figures yielded the following data. Illusion strength gradually increased with the stimulus diameter (Fig. 2); the growth of illusion strength with stimulus size was approximately linear (for triangles, r = 0.995; b_1 = 0.088; $F(1.48) = 4553.4$ $p < 0.0001$; for squares, r = 0.995; b_1 = 0.066; $F(1.48) = 4736.35$ $p < 0.001$; for pentagons, r = 0.997; b_1 = 0.049; $F(1.48) = 7136.73$ $p < 0.001$).

From all the stimulus sizes tested, triangles produced a comparatively strong illusion; squares produced a less strong illusion, and the pentagons evoked a relatively weak illusion.

The experiments of the second group with the curved-side figures showed the illusion strength changes in dependence on the internal angles of the inscribed figures (Fig. 3). The inverted U-shaped functions with maximum values were obtained. There was a correspondence between the maximum values of the illusion strength and the minimum values of the curvature for all three figures: for the triangles, with the inner angle size close to 60°; for the squares, close to 90°; and for

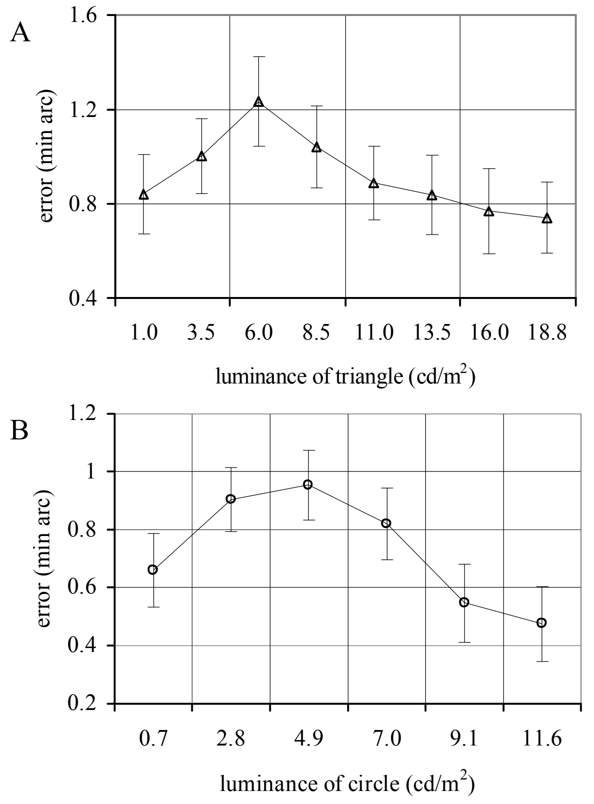

Fig. 5. Illusion strength as a function of the luminance of the colored stimulus. Luminance of gray background is 6.0 cd/m^2. Luminance of red circle is 4.9 cd/m^2 in A; luminance of blue triangle is 4.4 cd/m^2 in B. Vertical bars, standard deviation

the pentagons, close to 108°. In other words, the strongest illusion was achieved when the figures became approximately straight line-sided. Both distension and sag of the figure sides decreased the illusion strength. As in the experiments of the first series, the strongest illusion was caused by triangles, and the weakest illusion was caused by pentagons.

Therefore, in experiments of the third group with the luminance contrast, the illusion strength was measured using the inscribed triangle, a figure producing the strongest illusion. The stimuli were shown against a gray 7 cd/m^2 background. The illusion strength varied with the luminance changes of the inscribed triangle in both cases: 14 cd/m^2 when the circumscribed circle was bright (Fig. 4A), and 0 cd/m^2 when it was dark, (Fig. 4B). U-shaped curves were obtained. The minimum values of illusion strength were achieved at the luminance of the triangle approaching that of the background, i.e. when the triangle could not be discerned. The strength of illusion increased if the triangle luminance grew above (or decreased below) the equiluminance region. The experimental curves punctuate reliable differences between illusion strength at the luminance of triangles 6–8 cd/m^2 and 11–14 cd/m^2, and between 6–8 cd/m^2 and 0.5–1 cd/m^2 (Fig. 4A, B). In general, the data obtained illustrate the manifestation of illusion at different luminance contrasts of the circle and the triangle. The illusion occurred irrespective of whether one or both of the figures were dark or bright. There was a monotonous decrease of illusion strength when the circle luminance was approaching the background luminance and when the luminance of the triangle was constant (Fig. 4C). Within the luminance interval from 5 cd/m^2 to 8 cd/m^2 of the circle, no illusion could be present, because the circle could not be discerned against the 7 cd/m^2 background.

In experiments of the third group with color, the circles and triangles of the stimuli were red or blue and the background was gray. The luminance of one figure (triangle or circle) varied, but the luminance of the other figure (circle or triangle, respectively) was equiluminant with the gray background. On the contrary to the previous data (Fig. 4), inverted U-shaped curves were obtained here (Fig. 5). The maximum values of illusion strength (1.2 min of arc in Fig. 5A and 1.0 min of arc in Fig. 5B) appeared at isoluminance set for all three stimulus components: the background, circle, and triangle. When the luminance of one of the figures (the red triangle in Fig. 5A or the blue circle in Fig. 5B) receded from the isoluminance level upwards or downwards, the strength of illusion diminished. The reliable differences are presented between the maximum and minimum values of illusion strength in Fig. 5A and Fig. 5B.

It is worth noting that at the luminance contrast, the greatest values of illusion strength were 4–5 min of arc (Fig. 4), whereas at the color contrast, the illusion strength did not exceed 1–1.2 min of arc (Fig.5).

DISCUSSION

The experimental data obtained with color stimuli demonstrate the illusion effect in chromatic vision. In the experiments, at complete isoluminance of the color stimulus components – the background, circle, and triangle – the achromatic networks of vision could not be activated because of the absence of luminance contrasts. The figures of the stimuli were identified due to a color contrast in the networks of chromatic vision exclusively. But the illusory effect was qualitatively the same as that produced by the white-and-black stimuli in the networks of achromatic vision: the arcs of the circle appeared puffy and they could be corrected by manipulations with the arc radius. Consequently, the illusion mechanisms in the achromatic and chromatic systems of vision seem to be the same in their nature. In both systems, the mechanisms of the illusion are parallel and autonomous: when a circumscribed circle was perceived due to color contrast and the inscribed triangle was identified due to increasing luminance contrast, the illusion strength decreased (Fig. 5) – the higher the luminance amplitude of the triangle, the weaker the illusion. Separate processing of the sensory signals from the circle and triangle in the parallel visual pathways diminished the illusory effect.

Starting a discussion on the nature of the illusion mechanism, we compared the data obtained in our ex-

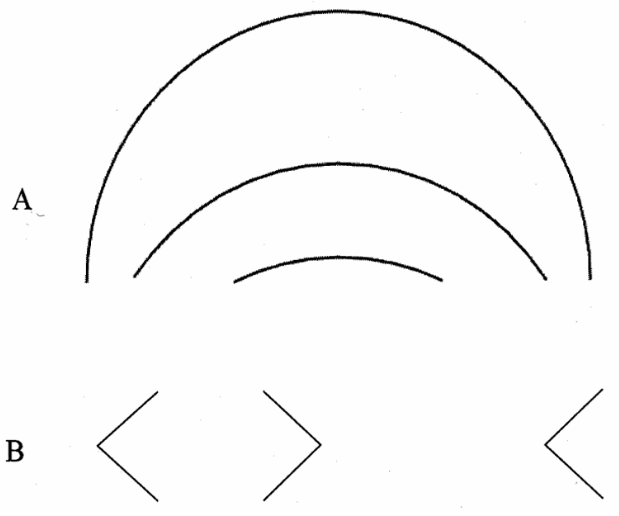

Fig. 6. A, the three-arc stimulus; B, the stimulus with the wings. Explanations in the text

periments with data of two other investigations in which the stimuli, different in structure, caused an illusion of curvature or an illusion on length. One of them is a three-arc distortion [25], other being the well-known Müller–Lyer illusion [26, 27]. The first is caused by a pattern composed of three circle arcs different in size but equal in the radius of curvature and arranged one above the other, the smallest being at the bottom and the largest at the top (Fig. 6A). The size proportions of the arcs are fitted in such a way that the tips of the three arcs become situated in a linear sequence producing an imaginary border in the pattern. For the observer, the perceived curvatures of the arcs seem to be different: the larger the arc, the smaller its radius. Consequently, the distortion strength is in proportion with the arc length and the distance from the middle point of the arc to the span. A similar proportion was obtained in our experiments with geometric figures inscribed in a circle. A relatively strong illusion was caused by inscribed triangles, a less strong by squares, and the weakest by pentagons. Triangles divide a circle into three parts, producing the largest arcs, squares produce four smaller arcs; and pentagons give the smallest five. This is to say that in our experiments the strength of illusion is also in proportion with the arc length and the distance from the middle point of the arc to the span. In addition, it should be noted that in our experiments the illusion was stronger when the ends of the arcs were connected by straight but not curved lines (Fig. 3).

Nevertheless, a comparison of the results of these two illusions of curvature does not elucidate the origin of the perceived distortions. It only indicates the similarity of the two effects in appearance. In both cases, an illusion of curvature is caused by similar details and spatial parameters of the two patterns.

Some other details of our stimuli, the inner angles of the inscribed patterns, which resemble the wings of the Müller–Lyer figure, might contribute to the distortions of perception (Fig. 6B). The inward facing wings of the Müller–Lyer figure make the distance between them to appear shorter than its physical length. Therefore, the question arises whether or not the inner angles of the inscribed figures make the distance between them to appear shorter and the circle arcs seem puffy. The experimental data give the negative answer to the question. In our experiments, the strength of the illusion of puffy arcs decreased with increasing the inner angles of the figure from 60° to 108° (Fig. 2). However, the Müller–Lyer illusion shows no clear tendency to become weaker with the inner angle of wings changing from 60° to 108° [28]. Consequently, the similarities of details in shape of various patterns do not necessarily condition the same result and do not explain the mechanism of the illusions.

Therefore, we have tested the concept of the spatial-frequency filtering procedure as one of the major causes of generating the geometrical illusions. The concept is based on the statements of the signal processing theory determining a filter as a linear-shift-invariant system which transforms an input signal into a "filtered" output signal. Filtering, in terms of Fourier's transform, indicates a certain relation between the extentions of the signal and its spectral characteristics [29]. Particularly, the spatial-frequency filtering of the sensory signals performed in the visual neural networks unavoidably produces distortions of the perceived size and shape relations of various parts of an image. Our previous experimental data, as well as the results of modeling, favor the concept of spatial-frequency filtering [21–24]. Therefore, we have applied the filtering model [30, 31] to the present experimental data. The calculated curves appeared similar to those obtained in the experiments (Fig. 3D). The images of the stimuli taken at the output of the model demonstrated the distortions corresponding to those visually perceived (Fig. 7): the changes in the radius length of the circumscribed circles were usually perceived in the sites of intersection of lines and arcs.

Our experimental results concerned with the color contrast support the assumption on the spatial-frequency filtering as a possible neural mechanism of the illusion of puffy arcs. The spatial frequency characteristics of the chromatic and achromatic systems are different. This might be taken as an explanation why the luminance contrast caused a stronger illusion than did the color contrast (Fig. 4 and Fig. 5).

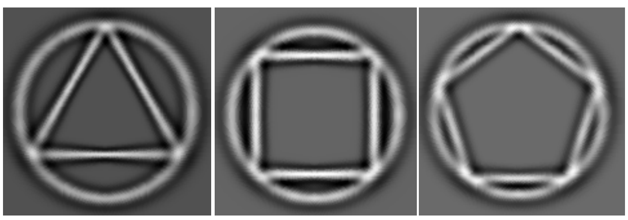

Fig. 7. Facsimiles of the output patterns of the model. Explanations in the text

CONCLUSIONS

1. Psychophysical experiments have demonstrated a relatively strong illusion of curvature produced by triangles inscribed in a circle, a less strong illusion by squares, and a relatively weak by pentagons.

2. The curved sides of the inscribed geometrical figures yielded the illusion lower in strength than did the straight sides.

3. The strength of illusion was much greater in the conditions of luminance contrast between the inscribed triangle and the background or between the circumscribed circle and the background in comparison with the conditions of color contrast.

4. The neurophysiological spatial-filtering model was applied to the experimental data: the computational curves were similar in shape and the quantitative parameters were close to those obtained in the psychophysical experiments.

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STIMULO ERDVINĖS STRUKTŪROS IR KONTRASTO POVEIKIS SUVOKTO KREIVUMO DEFORMACIJAI

Santrauka

Psichofizikiniais eksperimentais buvo matuojama kreivumo iliuzija, kurią sukelia lygiakraštis trikampis, kvadratas arba penkiakampis apibrėžtame apskritime. Apskritimo lankai atrodo išlinkę į išorę esant įvairiems stimulo diametrams, tačiau kiekvienam dydžiui trikampis sukelia didžiausią, o penkiakampis – mažiausią suvokto kreivumo deformaciją. Didėjant stimulo diametrui, iliuzija stiprėja. Į išorę arba į vidų išlenktos įbrėžtų figūrų kraštinės sukuria silpnesnę iliuziją negu tiesių kraštinių figūros. Iliuzija yra didesnė esant ryškio kontrastui tarp įbrėžto trikampio ir fono ar apibrėžto apskritimo ir fono, palyginus su spalvos kontrasto sąlygomis. Šie duomenys gali būti aiškinami skirtingu spalvų ir ryškio sistemos jautrumu erdviniams dažniams. Analogiškos apibrėžto apskritimo lankų deformacijos, gautos panaudojus neurofiziologinį erdvinės dažninės vaizdų filtracijos modelį, ir apskaičiuotos kreivės savo forma bei kiekybinėmis reikšmėmis yra panašios į eksperimentines.

Raktažodžiai: suvokto kreivumo deformacija, erdvinė dažninė filtracija