Delboeuf illusion study

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Key words: *perceived distortions of size, equiluminance, spatial-frequency filtering.*

Summary. *In psychophysical experiments, the Delboeuf illusion was measured as a function of spatial parameters of the stimulus pattern. During the experiments, the stimulus shape, size, luminance, and the dimensions of inducing surround varied. Subjects were asked to change the size of the test part of the stimulus by adjusting its diameter to value that made the test part appear equal to the perceived size of the referent part. The difference in diameters between the test and referent parts of the stimulus, determined after the perceived equality was achieved, was considered to be the value of the illusion magnitude. The magnitude of the Delboeuf illusion was dependent on the type of the stimuli and their contrast: the filled circles with the luminance contrast yielded stronger illusion than the open circles and the stimuli with isoluminant colors. The magnitude of the illusion did not change noticeably with variations of the luminance of the stimulus, but diminished when the luminance of the stimulus approached the level of isoluminance with the background. The neurophysiological spatial filtering model, applied to the Delboeuf stimuli patterns, has provided computational results similar to the present experimental findings.*

Background

A test-circle surrounded by a larger circle appears larger than a test-circle containing a smaller inside circle, but both the test-circles are, in fact, the same in size. Such an illusion has been invented by Franz Joseph Delboeuf, a Belgian philosopher (1). Similarly, an effect of distortions of perceived size has been demonstrated by a British psychologist Edward Bradford Titchener (2): the apparent size of a circle is dependent on its surroundings. A circle surrounded by a ring formed from other circles will appear smaller if the surrounding circles are enlarged. This effect is especially striking in cases with the inducing circles respectively smaller and larger than the referent circles.

The Delboeuf and Titchener effects seem to be slightly different from other prominent misrepresentations, the so-called geometrical illusions of size.

Among the most famous distortions of the perceived size, the Müller–Lyer illusion is present both in vision and in haptics and, probably, is the result of similar processes in both the two modalities (3). The vertical-horizontal illusion also exists in vision and haptics but is due partly to similar processes (bisection) and partly to processes specific to each modality: anisotropy of the visual field and overestimation of manual exploratory movements (3). In the Ponzo and Oppel–Kundt figures, haptic illusions equivalent to the visual illusions are also present (4). Yet more, an auditory Oppel–Kundt illusion has been described: a subdivided sound interval appears lasting longer than an empty interval of the same duration (5). On the contrary, the Delboeuf illusion might be considered as a physiological characteristic of vision only. In the haptic Delboeuf stimuli, the illusion of the inner circle was not observed (4), probably, because exploration with the index finger may exclude the misleading context from the tactile perception (3).

In vision, perception of any image is accompanied by larger or smaller misrepresentations, the strength of which is determined by spatial composition of the image. The Delboeuf effect is one of those easy to demonstrate.

Nevertheless, it is not clear whether the Delboeuf illusion is due to the perceived distortions of extent, like the Müller–Lyer and Oppel–Kundt illusions, or due to the distortions of curvature perception, like the three-arc effect (6), or the circumscribed circle illusion (7), or the illusion illustrates a specific distortion of the area perception. It has not been discovered, what cues are used by subjects for size judgments while observing the Delboeuf figure: either distances or contour curvatures or areas. The neural nature and mechanism of size misleading due to the Delboeuf figure have not been specified.

In the present communication, we report our psychophysical testing of the Delboeuf illusion and mea-

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surements of the illusion magnitude variations in dependence on spatial parameters of the stimulus pattern. We have used the original Delboeuf figure made of circles, but also, we have taken a modified illusory pattern formed of two filled circles, one of which with a surrounding annulus. The modified stimulus combines the elements of both the Delboeuf and Titchener figures. It provides an opportunity to test the stimulus with the luminance contrast and with the color contrast at equiluminance. The aim of the present study was to determine the quantitative characteristics of the perceived distortions that could supplement available hypotheses of the illusion's origin.

Material and methods

The experiments were carried out in a dark room. A Cambridge Research Systems VSG 2/3 and Eizo T562 monitor with gamma correction were used to generate stimuli. The distance between the subject's eyes and the screen was 400 cm. A chin holder limited the movements of the subject's head. The subjects viewed the screen monocularly. An artificial pupil with a diameter of 3 mm was used. The right eye was usually tested irrespective of whether or not it was the leading eye, but in some series of experiments, the left eye was also examined. The experiments were conducted under control of computer software of our own design arranging the order of the stimuli, presenting them on the monitor, introducing alterations according to the subject's command, recording the subject's responses, and processing the results. In the experiments, green stimuli were presented against a red background with luminance of 3 cd/m^2. The stimuli were made of pairs of either open or filled circles presented side by side and arranged horizontally (Fig. 1). The left circles were provided with concentric inducing objects: a larger outside (Fig. 1A) or a smaller inside (Fig. 1B) circle or an annulus (Fig. 1C). The left circle of the stimulus with the inducing surround was considered to be the referent part, and the right circle without any inducer, the test part of the stimulus. The lines forming the open circles were 2 min of arc in thickness. The diameter of the referent circle was 40 or 20 min of arc. The diameter of the inducing circle or annulus varied in such a way that the width of the gap formed by the referent circle and inducing object changed from 1.3 to 14.5 min of arc by 0.66 min of arc steps. The inducing annulus width varied from 1.3 to 10 min of arc by 0.4 min of arc steps (or from 1.3 to 18 by 0.8 min of arc steps). The luminance of the green illusory figures ranged from 0 to 18 cd/m^2 by 0.7 cd/m^2 steps. The isoluminant stimuli were tested

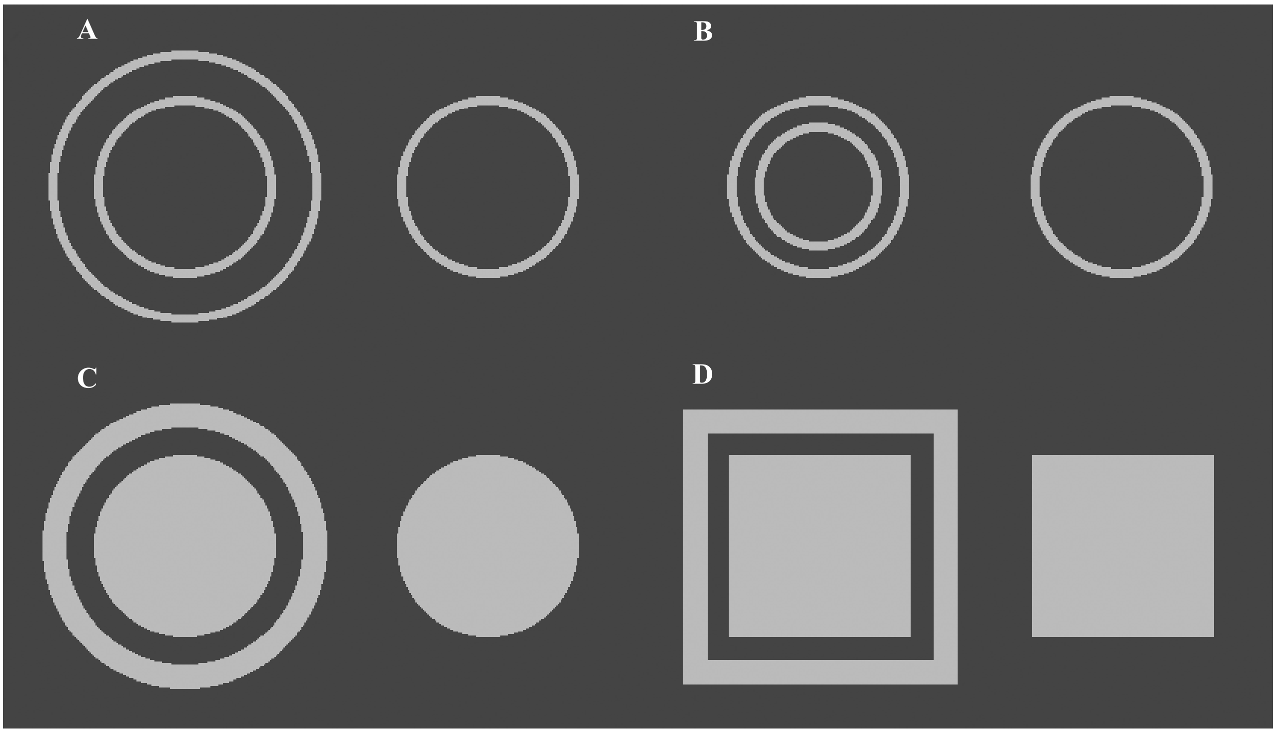

***Fig. 1.* Types of the stimuli**

Open circles with the outer (A) and the inner (B) inducing rings. Filled circles (C) and squares (D) with the outer inducing objects. For explanations, see the text.

as well. The isoluminance of the green stimuli and red background was established for each subject individually by the "minimum motion" method (8).

To extend our experimental testing, we used, in parallel, a stimulus made of filled squares and an inducing rectangle frame (Fig. 1D). The side of the referent square was 40 min of arc in length, and the frame was 5 min of arc in height and width.

During the experiments, the subjects were asked to change the diameter of the test part of the stimulus by adjusting it to what appeared to them to be equal to the perceived diameter of the referent interval. The initial size of the test part of the stimulus was randomized according to the given size of the referent part. The differences between the diameters or side lengths of the referent and test parts of the stimulus were distributed evenly within the range of ±2 min of arc.

The subjects were provided with the keyboard buttons and instructed to manipulate them in order to achieve perceived equality. A single button push varied the diameter of the test part by one pixel which corresponded approximately to 0.33 min of arc. The difference in diameters (or side lengths) between the test and referent objects, determined after the perceived equality was achieved, was considered to be the value of the illusion magnitude. The subjects were given no instructions concerning the fixation point of gaze. Observation time was unlimited. Forty-four presentations were included in a single experiment, *i.e.*, 22 values of each parameter were randomized and repeated twice. In the experiments with stimulus luminance changes, 26 values were randomized and repeated two times. For each independent variable, the observers carried out at least eight experimental runs on different days.

We performed four series of psychophysical experiments. The size of the referent circle, the width of the inducing object, the width of the gap formed by the referent and inducing objects, and the stimulus luminance were considered as independent variables in the experiments.

Three subjects (AB, TS, and NB) with appropriate previous experience in performing similar psychophysical tasks were tested. Nine naive subjects participated in different series of experiments but did not come through the complete program. All the observers were refracted professionally prior to the experiments. Since all 12 observers showed qualitatively similar results, we have selected the two most distant data for illustrations in the present communication. In the graphs presented, every point was obtained out of 16 measurements. The given intervals refer to the standard error (±SE) of mean (except for Fig. 7, where there are confidence intervals of 0.95 level). The decisions on data significance were made using the alpha value of 0.05.

Results

In our experiments, the surrounding inducers caused an overestimation of the referent object size, and the inside inducers caused an underestimation of the size in accordance to the Delboeuf and Titchener effects. The referent objects appeared enlarged (or reduced) in comparison with the test object when, physically, both were of the same size. Quantitatively, the Delboeuf illusion was weaker than the prominent illusions of extent, the Müller–Lyer and Oppel–Kundt effects, but resembled the circumscribed circle distortions. Maximum of the Delboeuf illusion approached 6 min of arc, *i.e.*, 15% of the referent circle size in diameter, while the Müller–Lyer illusion reached 20–25% of the referent interval length (9, 10), and the circumscribed circle illusion measured about 12% of the circle radius (7).

The results obtained showed that the Delboeuf illusion magnitude was dependent on the type of the stimulus and on its contrast. The filled circles with the luminance contrast yielded stronger illusion than the open circles and the stimuli with isoluminant colors did.

In the first series of experiments, the stimuli made of open circles were used, and the illusion was measured as a function of the size of the gap between the referent and inducing circles. For the outside inducing circles, the magnitude of the illusion increased within the range of the gap sizes from 1 to 7 min of arc (Fig. 2, subject TS, squares) or even to 10 min of arc (Fig. 2, subject AB, squares) reaching its maximum. At larger sizes of the gap, the magnitude of the illusion showed a tendency to decrease. For the inside inducing circles (Fig. 2, triangles), the illusion had negative values because the referent circles appeared reduced in size, and the subjects made the test circles smaller to obtain the required equality of sizes. Here, the maximum value of the illusion was about –4 min of arc for subject TS and about –2.5 min of arc for subject AB. The maximum was achieved at the gap width of 4–6 min of arc for subject TS and around 2 min of arc for subject AB. If the gap width was larger than those indicated and increased up to 15 min of arc, the illusion showed monotonous decrease (even to the zero level for subject AB). In general, the curves for the outside and inside inducers were different quantitatively and qualitatively. It has to be noticed that the inside inducing circles could show an equivocal effect on our stimulus and might cause two distortions of perception – the Delboeuf and Oppel–Kundt effects instead of one. The inside inducing circle formed a certain filling pattern within the referent stimulus area. The test part area had no filling. Therefore, during the size-matching procedure in our experiments, the Oppel–Kundt effect could induce the referent circle with the filling to appear larger than the empty test circle while the Delboeuf effect could make the referent circle to appear smaller than the test one. An interaction of the two opposite processes, probably, provided the distinctive shape of the curves for the inside inducers. Due to some uncertainty in the present data, we concentrated attention on the stimuli with the outside-inducing objects in the following series of our experiments.

In the second series of experiments, the illusion was measured as a function of the size of the gap between the filled circle and surrounding annulus. The curves of the illusion magnitude for the filled circles (Fig. 3A, squares) were similar in shape with the curves for the open circles (Fig. 2, squares). However, the illusion for the filled circles was stronger than that for the open circles, and the maximum appeared at smaller gap sizes: at about 5 and 7 min of arc for subjects TS and AB, respectively. The curves for isoluminant stimuli (circles) ran below the curves of the stimuli with the luminance contrast.

The maximum of the illusion magnitude for smaller circles (20 min of arc in diameter) was approximately the same, but in the region of small gaps (1–5 min of arc), the illusion magnitudes were higher (Fig. 3B). Therefore, the profiles of the functions in Fig. 3A and Fig. 3B are slightly different.

The same type of Delboeuf effect was observed in the second series of experiments with the filled squares surrounded by the square-shaped frames (Fig. 4). The frame induced overestimation of the size of the referent square. The magnitude of the illusion varied with the gap size in a similar way as the illusion for the filled circles changed, but the maximum values differed from those of illusion with circles and were higher for subject TS and lower for subject AB.

In the third series of experiments, illusion magnitude was measured as a function of the width of the inducing annulus. The magnitude of the illusion grew up with the increase in the width of the annulus from 1 min of arc to 8–11 min of arc and slightly decreased afterwards for subject TS, but it saturated for subject AB (Fig. 5). The curves for isoluminant stimuli ran below the curves for the luminance contrast stimuli.

In the fourth series of experiments, the illusion was measured as a function of stimulus luminance (Fig. 6). The magnitude of the illusion did not change noticeably with variations of the luminance of the stimulus but decreased if the luminance of the stimulus approached the level of isoluminance (4 cd/m^2) with the background. These data provided a direct support for the results obtained in the previous experiments (Fig. 3–5).

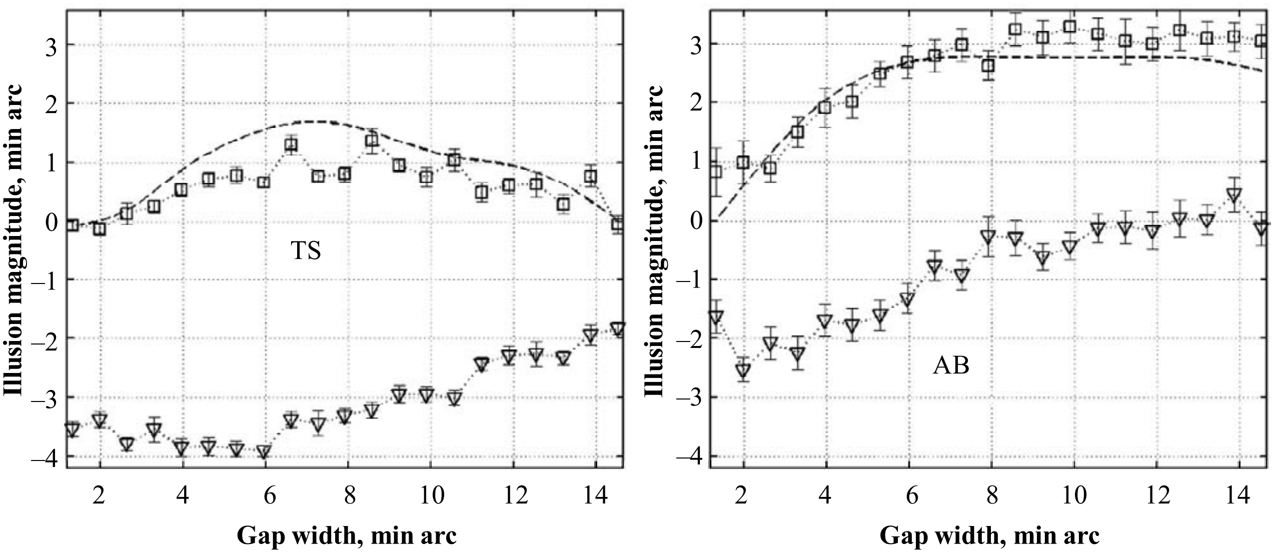

Fig. 2. **Experimental data for the open circles: illusion as a function of the width of the gaps formed by the referent and inducing circles**

The diameter of the referent circle is 40 min of arc. The luminance of the red background is 3 cd/m^2. The luminance of the stimulus lines is 18 cd/m^2. Squares and triangles are the data for outer and inner inducing circles, respectively. Dashed lines represent the modeling data. Subjects TS and AB.

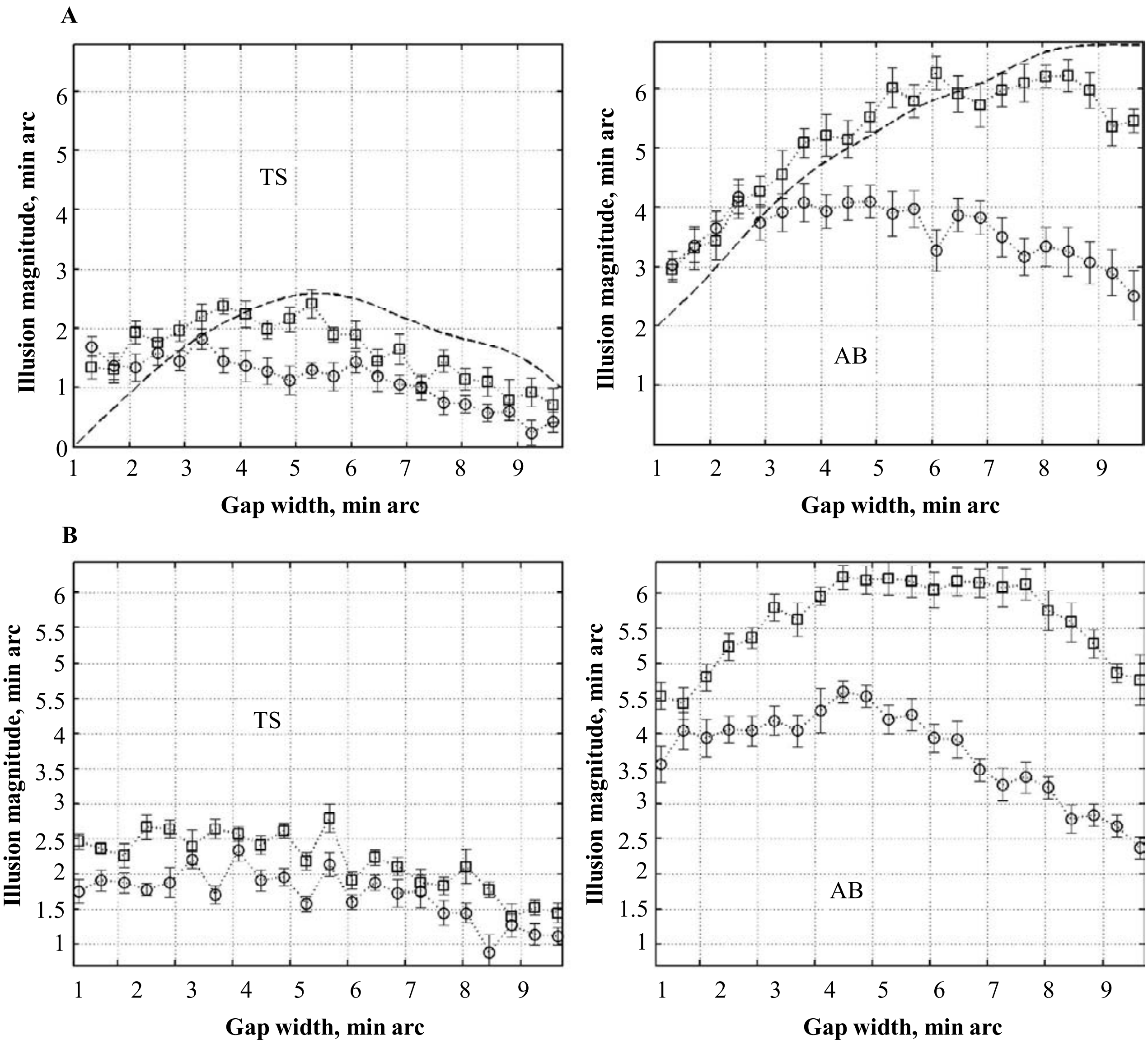

Fig. 3. **Experimental data for the filled circles: illusion as a function of the width of the gap between the referent circle and inducing annulus**

The diameter of the referent circle is 40 min of arc (A) or 20 min of arc (B), and the width of the inducing annulus is 5 min of arc. The luminance of the red background is 3 cd/m^2. The luminance of the green stimulus is 18 cd/m^2 (squares) and 4 cd/m^2 (circles) for both subjects. Dashed lines are the modeling curves.

In the Fig. 7, the quantitative data of the 12 subjects are shown. In 10 cases, the difference of illusion strength between isoluminant stimulus and the stimulus with the luminance contrast is statistically significant.

Discussion

The experimental data reported in the present communication are in agreement with the effects described by Delboeuf and Titchener. The presence of a concentric circle inside or outside the other circle affects its apparent size. An outside inducing circle makes the original circle to appear larger, and the inside inducer makes it to appear smaller. Consequently, the Delboeuf illusion might be considered as a well-known physiological characteristic of vision, "the contour attraction." The effect of attraction of different stimulus parts to each other is produced by various types of contextual objects like the Müller–Lyer wings (11), Obonai rectangles (12), simple stripes (13), separate spots (14) appended to the shaft line or to the three-spot stimulus. The neighboring objects in an image are perceived closer in distance.

The effect of attraction of neighboring parts might

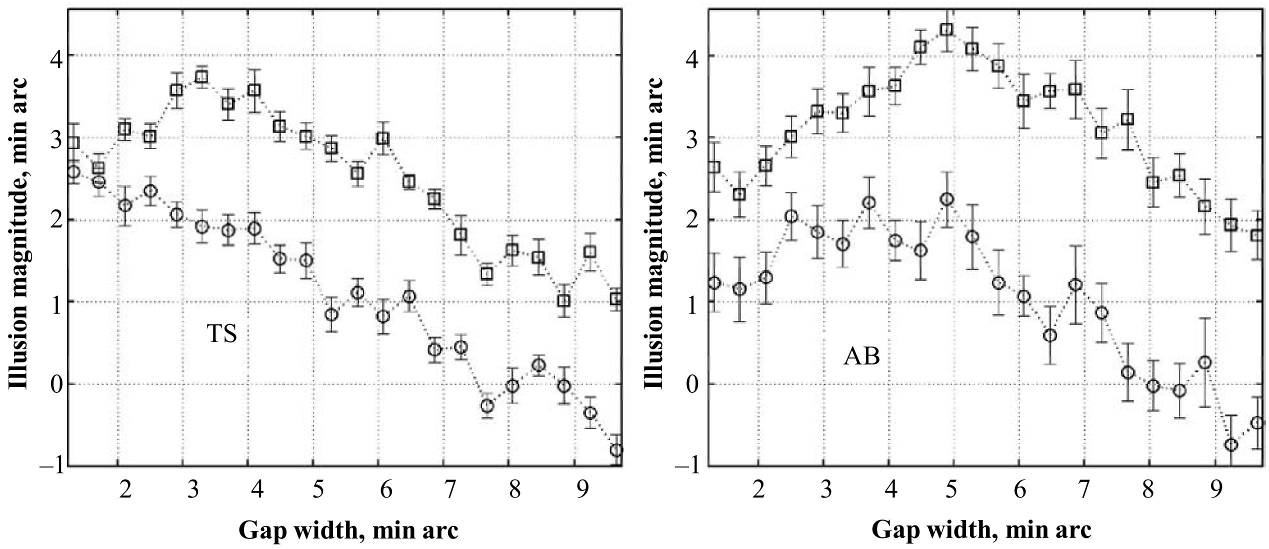

Fig. 4. **Experimental data for the filled squares: illusion as a function of the width of the gap between the referent square and the inducing frame**

The side length of the referent square is 40 min of arc; the width of the inducing frame is 5 min of arc. Further details as in Fig. 3.

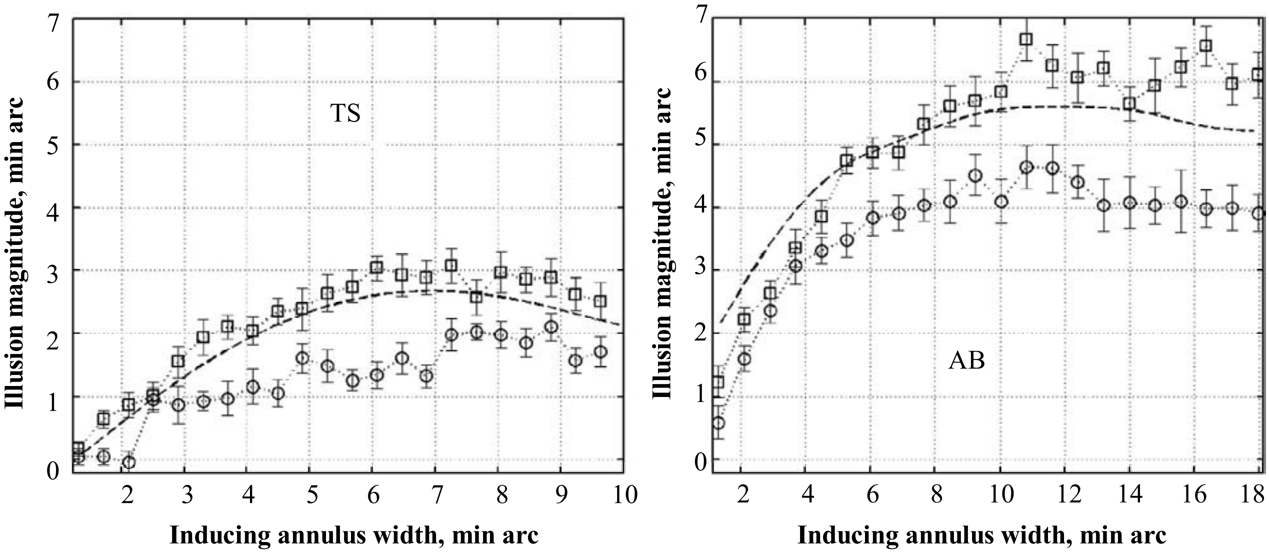

Fig. 5. **Experimental data for the filled circles: illusion as a function of the width of the inducing annulus**

The diameter of the referent circle is 40 min of arc. The width of the gap is 4 min of arc. Further details as in Fig. 3.

be interpreted as some local positional averaging (13). Neighboring parts of a stimulus placed close together produce overlapping excitatory areas in the visual pathways. An interaction of the areas yields a shift of the peaks of excitation toward each other. In vision, the local positional averaging procedure might be performed by the processes of spatial-frequency filtering which is determined by properties of organization of receptive fields in the retina, *lateral geniculate nucleus*, and visual cortex. Spatial filtering causes neural blurring of the excitation pattern evoked by an image. The blurring effect results in an integration of excitatory profiles and influences on the perceived locations of the neighboring stimulus parts making them closer in distance. Therefore, spatial-frequency filtering is considered as a reason of geo-

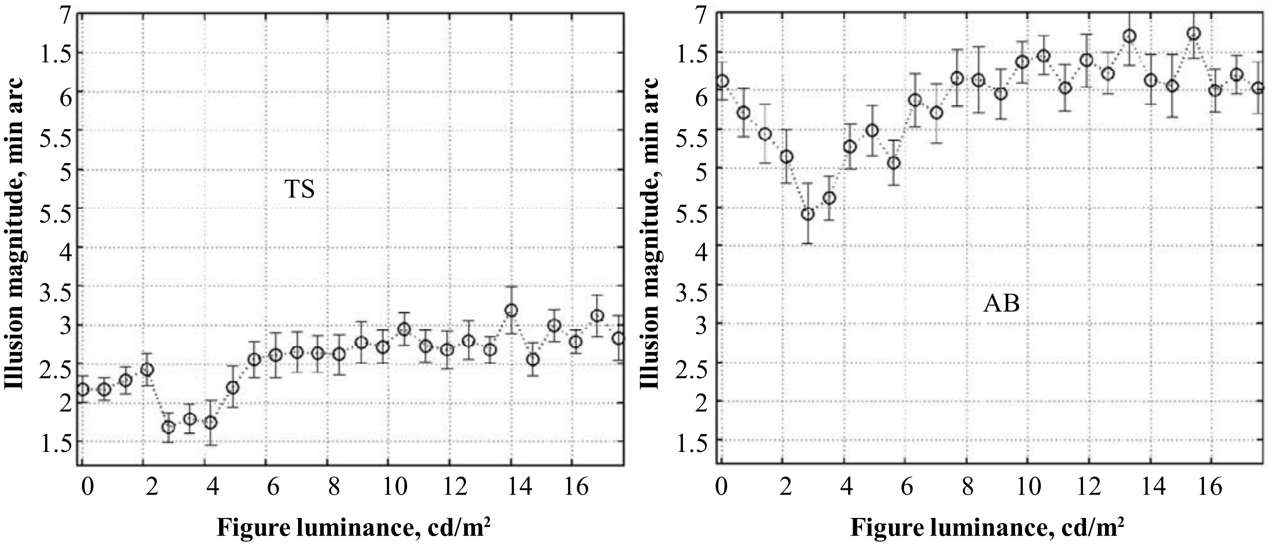

Fig. 6. **Experimental data for the filled circles: illusion as a function of stimulus luminance**
The diameter of the referent circle is 40 min of arc, the gap width is 4 min of arc, and the annulus width is 5 min of arc.

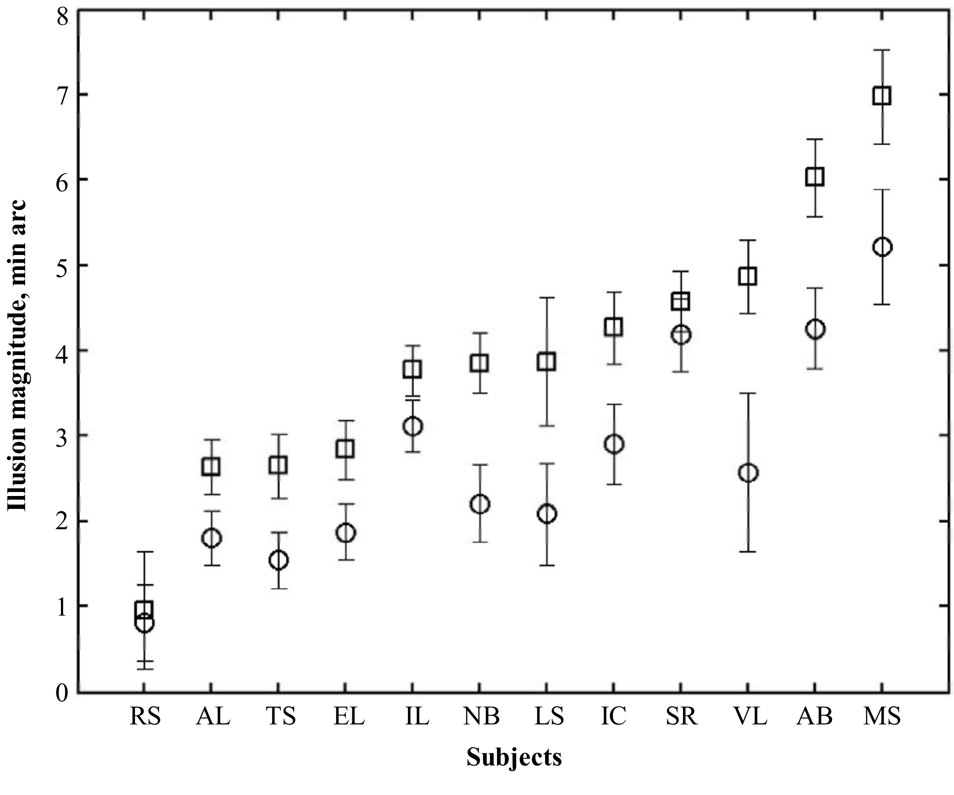

Fig. 7. **The Delboent illusion strenght for 12 subjects**
Luminance contrast (squares) and isoluminan color (circles). The diameter of the referent circle is 40 min of arc, the gap width is 4 min of arc, and the annulus width is 5 min of arc. The given intervals are of 0.95 confidence level.

metrical illusions of extent (10).

The Delboeuf illusion might be interpreted in terms of the positional averaging as well. In the visual pathways, the overlapping excitatory areas are produced by the contours of two concentric circles. Due to a filtering procedure, the sum of excitatory profiles yields a shift of the peaks of the excitation annuli toward each other. This makes the outer circle to appear smaller and the inner to appear larger than their real sizes are.

To check whether the spatial filtering might cause the Delboeuf illusion, we have applied the neurophysiological filtering model (15) to our stimulus patterns. With a certain approximation, the results of the modeling fit the data obtained in the experiments both with the inducing circles (Fig. 2) and inducing annuli (Fig. 3A and Fig. 5) performed with different subjects (Fig. 3A).

In the model and at early stages of visual processing, the stimulus contours are marked off due to some kind of the second derivative procedures. The procedures cause the contour enhancement effect in the stimulus excitation pattern. The inducing annuli in our stimuli possess two concentric contours, and each could have its own effect of attraction over the contour of the referent circle. Presumably, the combined influences of two contours cause a stronger illusory effect of an annulus than the influence of a single circle. Consequently, the model output and the experimental data suggest the contours of the objects being important cues for the size judgments in our experiments with the Delboeuf stimuli.

The Delboeuf illusion is significantly stronger for the stimuli with the luminance contrast than for the stimuli with isoluminant colors (Fig. 3–6). In the human vision, the chromatic pathways are less sensitive to higher spatial frequencies than the achromatic pathways. The dominance of the spatial filters tuned to lower frequencies in the chromatic pathways, probably, reduce the contour enhancement effect and, consequently, decrease the positional averaging result.

The effect of "contour attraction" is demonstrated in our experiments by the stimuli made of squares and inducing frames (Fig. 4). Squares, just the opposite of circles, are formed of straight contours. This is an indication that the contour shape and curvature do not play an essential role in the Delboeuf illusion manifestation but may show an influence upon the illusion's strength and its changes in accordance with variations of spatial parameters of the stimuli: the gap size and annulus width. The functions in Fig. 3 and in Fig. 4 differ from each other.

The area of the referent and test parts of the stimuli does not appear to be an important cue for the size judgments in our experiments. When the area of the referent circle is reduced about four times, the magnitude of the illusion remains near the same (Fig. 3A and Fig. 3B).

In summary, the present experimental data have provided evidence that the Delboeuf illusion may occur due to spatial-frequency filtering in the visual pathways. Apparently, the illusion could be of the same origin as perceived distortions of extent.

Conclusions

In psychophysical experiments with the illusory stimuli of the Delboeuf type, the surrounding inducers cause an overestimation, and the inside inducers cause an underestimation of the referent object size.

The magnitude of the Delboeuf illusion is dependent on the type of the stimulus and its contrast: the filled circles with the luminance contrast yield stronger illusion than the open circles and the stimuli with isoluminant colors.

The magnitude of the illusion does not change noticeably with variations of the luminance of the stimulus but diminishes when the luminance of the stimulus approaches the level of isoluminance with the background.

The illusion of the Delboeuf type is observed in the experiments with stimuli formed from filled squares and inducing square-shaped frames.

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Delboeuf iliuzijos tyrimai

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Raktažodžiai: dydžio suvokimo iškraipymai, subjektyviai vienodas ryškis, erdvinė dažninė filtracija.

Santrauka. Psichofizikinių eksperimentų metu matuojama Delboeuf iliuzijos priklausomybė nuo erdvinių stimulo parametrų. Eksperimentuose kinta stimulo forma, dydis, ryškis ir indukuojančio objekto matmenys. Stebėtojai keičia stimulo bandomosios dalies diametrą taip, kad jis atrodytų lygus referentinės stimulo dalies diametrui. Diametrų skirtumas tarp referentinės ir bandomosios dalių, gautas po subjektyvaus abiejų dalių sulyginimo, laikomas iliuzijos stiprumo dydžiu. Iliuzijos stiprumas priklauso nuo stimulo tipo ir ryškio kontrasto: skrituliai ir ryškio kontrastas sąlygoja didesnes iliuzijos reikšmes negu apskritimai ir spalvų kontrastas, kai spalvos yra vienodo ryškio. Kintant stimulo ryškiui, iliuzijos stiprumas lieka apytikriai pastovus, tačiau žymiai sumažėja artėjant jam prie reikšmės, subjektyviai lygios fono ryškiui. Neurofiziologinio erdvinės dažninės filtracijos modelio skaičiavimų duomenys panašūs į mūsų eksperimentų.

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