ISSN 0362-1197, Human Physiology, 2020, Vol. 46, No. 4, pp. 366–372. © Pleiades Publishing, Inc., 2020.
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Quantitative Study of the Poggendorff Illusion in School Children upon Presentation of 3D Images

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Received September 10, 2018; revised February 4, 2019; accepted September 3, 2019

Abstract—Quantitative estimation of the strength of the Poggendorff illusion has been performed in school children upon presentation of three-dimensional images created via anaglyphic separation of vision fields. The study included 34 school children with normal binocular vision. We used three-dimensional variants of the classical image that causes the Poggendorff illusion; the test line segment and the reference line segment were located at an angle of 45 degrees to the parallel vertical lines. We found that the strength of the Poggendorff illusion depends on the three-dimensional spatial orientation of the details of test objects. The maximal strength of the illusion was observed when the parallel lines were inclined in the sagittal plane; the minimal strength of the illusion was observed when the vertical lines and the oblique segments were located in different frontal planes.

Keywords: Poggendorff illusion, quantitative estimate, three-dimensional images, anaglyphic separation of vision fields

DOI: 10.1134/S0362119720020164

Visual illusions, including the Poggendorff illusion, provide a way to a more complete comprehension of the mechanisms involved in visual image formation. The investigation of illusory perception has a great significance in architecture and visual art and represents an important task in the development of modern virtual reality technologies [1–4].

In the classical Poggendorff illusion, a diagonal line (transversal) is crossing behind an occluding vertical bar formed by two parallel lines (Fig. 1b; variant No. 1). In the classical Poggendorff configuration, the two oblique line segments do not appear collinear [5–9].

Currently, many theories have been proposed to account for the Poggendorff misalignment bias. Many researchers explain that the effect is caused by a misperception of perspective representation, by metric and orientation effects, influence of the spatial domain, overestimation of acute angles [7, 10–13]. According to other theories, the Poggendorff illusion arises because of retinal and cortical processes involved in the processing of relative position, orientation, and the collinearity of spatial separated lines and the objects [14–17]. Others argue that the Poggendorff illusion, as well as the Müller–Lyer and Zöllner illusions, are attributable to the same basic effect, that of an underestimation of the difference between the parallels [18, 19]. In addition, the Poggendorff illusion was approached by applying Emmert's law, which results in the shrinkage of the occluding space between the verticals; the shrinkage of the occluding entity necessitates the dragging inwards of the transversals in order to eliminate the gaps in the cortical representation for the sake of complying with the retinal information which contains no gaps [20].

In experiments with separate presentation of the distorting and distorted components of the illusions to the right and left eye, the researchers employed anaglyphic separation of vision fields using color filter glasses (a red filter for one eye and a blue or green filter for the other eye) [21] or mechanical separation of vision fields using a stereoscope [22, 23]. The results of these experiments showed that the illusion continued to exist, although the illusion was weaker due to difficulties of binocular alignment of the image parts presented separately to the right and left eyes. Based on the results, the authors concluded that the central mechanisms of visual processing are involved in occurrence of geometric illusions. However, the researchers used only two-dimensional images upon separation of vision fields.

The investigations of visual illusions under the conditions of virtual reality conducted by Men'shikova et al. [1] showed that an addition of such an important

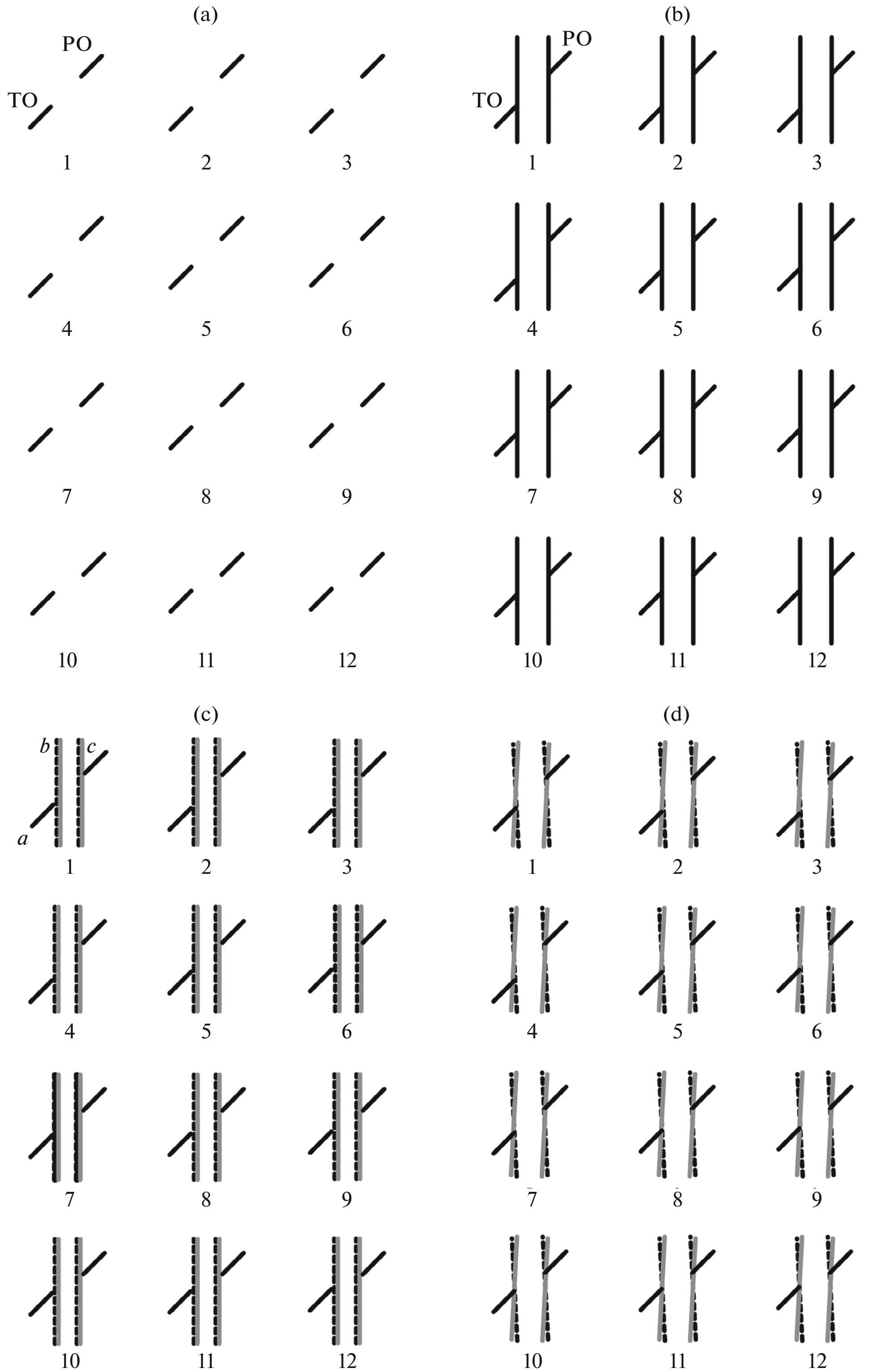

Fig. 1. Test charts for the (a) control test and quantitative estimation of the range in which the Poggendorff illusion exists: (b) flat test images of the Poggendorff figure, (c) 3D test images of the Poggendorff figure creating the effect of frontoparallel separation of the vertical parallel lines and oblique segments, (d) 3D test images of the Poggendorff figure creating the effect of the parallel lines inclined in the sagittal plane. A total of 12 variants of TL position relative to the RL are shown (for the control test and the illusion). In initial test image (variant No. 1), TL and RL correspond to one straight line. In test images from No. 2 to No. 4, displacement of the test segment downward is –2, –4 and –6 mm, respectively, relative to the initial "zero" position. In test images from No. 5 to No. 12—displacement of the test segment upward is 2, 4, 6, 8, 10, 12, 14, 16 mm, respectively. RL, reference line segment; TL, test line segment. Colors: *1*, purple (solid black line), *2*, red (black dotted line), *3*, blue (grey solid line).

feature as binocular disparity to the visual scene changed the strength of illusory effect compared to 2D images in simultaneous contrast illusion and the Vasarely illusion, but did not affect the strength of the Müller–Lyer illusion.

Due to the diversity of views and approaches to the study of the situation, it is necessary to objectively compare the results. A previous work devoted to quantitative study of the Poggendorff illusion in school children with normal binocular vision and strabismus [24] revealed that quantitative estimation of the range in which the Poggendorff illusion exists makes it possible to fully and objectively investigate the manifestations of this bias. Quantitative estimation of the illusion strength showed that the age and the state of binocular functions of the subjects, as well as the spatial orientation of line segments of test objects, influence the strength of the illusion. However, the investigation was conducted only using two-dimensional images, which caused this illusion.

The purpose of this study was to assess the range of the appearance of the Poggendorff illusion in school children upon presentation of a three-dimensional image created using anaglyphic separation of vision fields.

MATERIALS AND METHODS

The ophthalmological examination of all participants included standard methods of examination, the Worth test at a distance of 1 and 5 m from the eyes, and investigation of stereoscopic vision using the Lang stereo test.

A total of 34 school children aged 8 to 16 years (average age was 11.2 years) were examined. All participants had good visual acuity (at least 0.8, without correction or corrected with glasses), binocular vision in the Worth test and stereo vision in the Lang test.

The test charts containing the Poggendorff figure and simple lines for the control test were presented at the center of the screen on black background (Figs. 1a–1d). The position of the parallel lines in the classic Poggendorff figure (Fig. 1b; variant No. 1) corresponded to 90°, the test line segment (TL) and the reference line segment (RL) were located at an angle of 45° to the parallel lines. The size of each test image on the screen was 6 × 8 cm, the line thickness was 2 mm. A total of 12 variants of positioning the TL relative to the RL (both for the control test and the illusion) were created. In the original test chart (variant No. 1), TL and RL lied on the same straight line (shift of the test line segment is 0). In the test images from No. 2 to No. 4, the test line segment was shifted downward by –2, –4, and –6 mm, respectively, relative to the original "zero" position. In the test images from No. 5 to No. 12, the test line segment was shifted upward by 2, 4, 6, 8, 10, 12, 14, 16 mm, respectively.

In addition, we created the Poggendorff images perceived as three-dimensional images upon anaglyphic separation of vision fields: (i) images that create the effect of frontoparallel separation of the vertical lines and oblique segments (Fig. 1c); (ii) images that produce the effect of vertical lines inclination in the sagittal plane (Fig. 1d).

The participants viewed all presented images in glasses with red-blue filters (when ametropy correction was needed, the filter glasses were put on glasses for vision correction). The presented images contained purple details (visible on black background through both light filters by the right and left eyes), red details (visible only through the red light filter), and blue details (visible only through the blue light filter). Herein, the position of the filters (the red filter for the right eye and blue for the left eye or vice versa) determined the spatial position of the details in three-dimensional images. If the red filter was placed for the right eye and blue for the left one, the vertical lines on the images, which create the effect of frontoparallel separation of the details, were perceived to be located in front of the oblique line segments; in images with the inclination effect, the vertical lines were perceived as inclined forward at the upper ends. When the filters were changed (red for the left eye and blue for the right eye), the vertical lines in images, which produce the effect of frontoparallel separation of the details, were perceived as located behind the oblique segments; in images with the inclination effect, the vertical lines were inclined backward at the upper ends.

The test images and the position of the light filters were changed randomly. The distance from the screen to the eyes of a participant was 50 cm; the position of the head was fixed using a chin rest. In each figure, TL was on the left side and RL was on the right side.

The participants were tasked to assess the position of the TL relative to the RL.

A statistical analysis of the digital data was performed using the Microsoft Excel 2007 and StatSoft Statistica 6.0 software. The difference significance was evaluated using Student's *t* test for samples with normal distribution; a *p* value of 0.05 was the criterion of significance.

RESULTS AND DISCUSSION

It was established that all participants reported a certain range of displacements of the TL, within which TL was perceived as located on the same straight line as RL (the range between TL_{min} and TL_{max}) for both classical and 3D Poggendorff figures (Fig. 2).

It is important to note that the conditions used for presenting the stimuli did not cause discomfort to the participants. Double vision was absent in all cases, both in considering flat and three-dimensional images. When viewing three-dimensional images, all subjects reported a good stereo effect and described

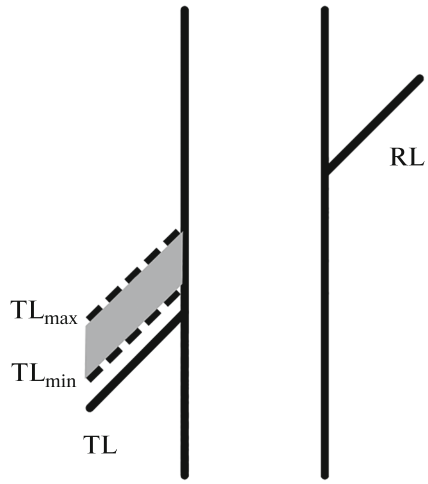

Fig. 2. Schematic diagram of the range between TL_{min} and TL_{max} in which TL is perceived to be located at the same diagonal line with RL.

correctly the spatial position of the details relative to one another.

This fact deserves attention, since, in the previous study with separation of vision fields using a stereoscope, the authors pointed to that the participants had significant difficulties in perception of the image parts, which were presented to the right and left eyes, as a whole image. Many participants in such experiments reported that the details fell apart and then superimposed on each other, leading to visual discomfort [22, 23]. Obviously, this occurred due to the fact that images, which were presented to the right and left eyes, differed much in shape and orientation and did not have the same or at least similar details to ensure a successful fusion. In our experiments, the images that did not elicit the three-dimensional effect (Figs. 1a, 1b) were perceived similarly in shape and orientation by the right and left eye. In the images that create the three-dimensional effect, oblique segments were also perceived similarly in shape and position by the right and left eye and were successfully fused; the spatial position of the central elements was determined by the corresponding disparity.

The results of our work are shown in Fig. 3. The range of errors for the control test in all subgroups of the participants was no more than from TL_{min} -1.8 ± 0.2 mm to TL_{max} 1.65 ± 0.3 mm.

The values reflecting the strength of the illusion were characterized by a systematic shift of TL_{min} and TL_{max} to a much higher level ($p < 0.001$) compared to the results for the control test both when presenting flat and three-dimensional images. For the control (2D) Poggendorff figure, the error range was from TL_{min} 1.8 ± 0.3 mm to TL_{max} 9.9 ± 0.5 mm. For the three-dimensional Poggendorff figure with the effect of frontoparallel separation of the vertical parallel lines and oblique segments, the error range was from TL_{min} 0.2 ± 0.4 mm to TL_{max} 7.4 ± 0.6 mm in perception of the vertical parallel lines ahead of the oblique seg-

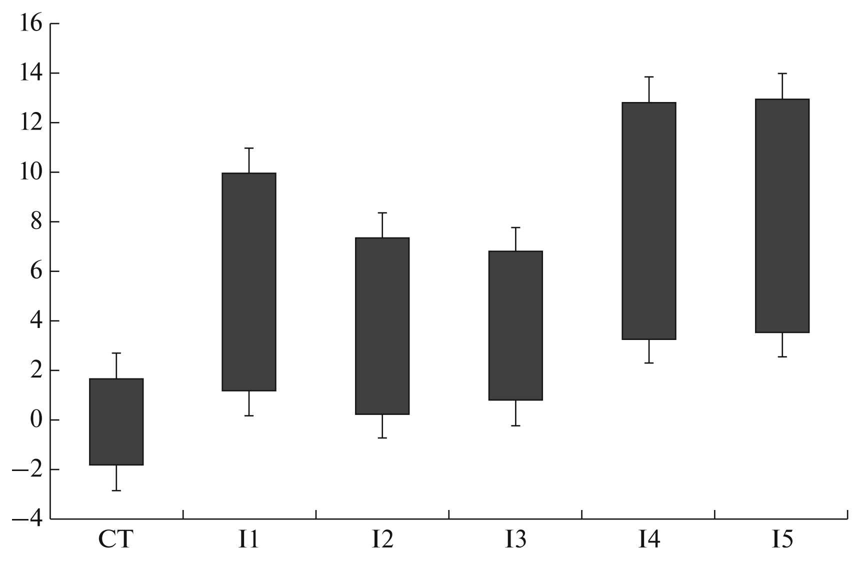

Fig. 3. The ranges of estimation errors of the TL position relative to RL in the figures for the control test, classic Poggendorff figures and its three-dimensional versions. Vertical, the mean range for the maximum and minimum values of TL relative to RL for illusion and the control test. Horizontal: CT, values for the control test; I1, values for two-dimensional images of the Poggendorff figure; I2, values for three-dimensional images of the Poggendorff figure which produce the effect of frontoparallel separation of the details and position of the vertical parallel lines in front of the oblique segments; I3, with position of the vertical parallel lines behind the oblique segments; I4, values for three-dimensional images of the Poggendorff figure which create the effect of the parallel lines inclined in the sagittal plane at upper ends backward; I5, creating the effect of the inclination forward at upper ends.

ments and from TL_{min} 0.8 ± 0.5 mm to TL_{max} 6.8 ± 0.4 mm in perception of the vertical parallel lines behind the oblique segments. For variants of the three-dimensional Poggendorff figure with effect of the parallel lines inclination in the sagittal plane, the error range was from TL_{min} 3.5 ± 0.5 mm to TL_{max} 12.8 ± 0.5 mm with the parallel lines inclination backward at the upper ends and was from TL_{min} 3.2 ± 0.5 mm to TL_{max} 12.9 ± 0.5 mm with inclination of the parallel lines forward at the upper ends.

A comparison of control two-dimensional Poggendorff figure and its three-dimensional versions revealed a significant shift of TL_{max} downward in three-dimensional images with frontoparallel separation of the vertical parallel lines and oblique line segments ($t = 3.52$, $p < 0.002$ for perception of the parallel lines in front of the oblique segments and $t = 5.1$, $p < 0.001$ for perception of the vertical lines behind the oblique segments) as well as a significant shift of TL_{max} upward in three-dimensional images with inclination of the parallel lines in the sagittal plane ($t = 4.5$, $p < 0.001$ for perception of the parallel lines inclined forward at the lower ends and $t = 4.7$, $p < 0.001$ for perception of the parallel lines inclined backward at the lower ends).

There was a significant difference in TL_{min} values between three-dimensional images with frontoparallel separation of the parallel lines and oblique segments and the images that create the effect of parallel lines inclined in the sagittal plane: $t = 4.5$, $p < 0.001$ in comparing TL_{min} for images with position of the parallel lines ahead of oblique segments and TL_{min} for images with effect of the parallel lines inclined forward at the lower ends; $t = 4.7$, $p < 0.001$ in comparing TL_{min} for images with position of the parallel lines in front of the oblique segments and TL_{min} for images with the effect of the parallel lines inclined backward at the lower ends; $t = 3.7$, $p < 0.002$ in comparing TL_{min} for images with position of the parallel lines behind the oblique segments and TL_{min} for images with effect of the parallel lines inclined forward at the lower ends; $t = 4.1$, $p < 0.002$ in comparing TL_{min} for images with position of the parallel lines behind the oblique segments and TL_{min} for images with effect of the parallel lines inclined backward at the lower ends.

Comparison of the range in which the illusion exists revealed a significant difference between the ranges for three-dimensional images with frontoparallel separation of the parallel lines and oblique lines and three-dimensional images with inclination of the parallel lines in the sagittal plane: $t = 3.8$, $p < 0.002$ in comparing the range for images with frontoparallel separation of the details during perception of the parallel lines in front of the oblique segments and the ranges for images with inclination of the parallel lines; $t = 6.5$, $p < 0.001$ in comparing the range for images with frontoparallel separation of the details during perception of the parallel lines behind oblique segments and the ranges for images with inclination of the parallel lines. There was a significant difference between the range for control flat image and the range for three-dimensional image with frontoparallel separation of the details during perception of the parallel lines ahead of the oblique segments ($t = 2.5$, $p < 0.05$) and during perception of the parallel lines behind the oblique segments ($t = 5.2$, $p < 0.001$).

There was no significant difference in the strength of the illusion in comparing three-dimensional images with inclination of the parallel lines in the sagittal plane at the upper ends backward and three-dimensional images with inclination of the parallel lines in the sagittal plane with the upper ends forward.

Our data are well consistent with the results of Gillam et al. [7, 25], who proposed the *depth-processing theory* to explain the Poggendorff illusion, involving mechanisms related to perception of depth and spatial layout. Like other researchers [21, 26, 27], they argued that geometrical illusions in general arise from the tendency of the perceptual system to process a two-dimensional figure as a representation of a three-dimensional scene and, consequently, the study of the processes involved in perception of three-dimensional scenes will lead to a better understanding of such illusions. In regard to the Poggendorff illusion, Gillam's theory asserts that in the classical Poggendorff figure, oblique lines are typically the perspective view of receding horizontal lines and, as such, automatically processed as if receding in horizontal planes of three-dimensional space. The height differences of such isolated oblique segments are simultaneously processed as depth differences. However, when endpoints of the oblique segments are attached to the vertical parallel lines from a Poggendorff figure, they are perceived as attached to a frontoparallel plane defined by the parallels. Consequently, the height difference between endpoints of the oblique lines in this case is not processed as a difference in depth in three-dimensional space but as a difference in height between two receding lines. Subsequent studies showed that when oblique segments and a virtual line connecting the oblique lines are perceived ahead of the plane defined by the parallel vertical lines, the apparent misalignment of oblique segments diminishes significantly (oblique segments often appear located on the same line). In other experiments, the authors varied shape of the upper and lower edges of a figure defined by the vertical parallel lines, which was either collinear with the obliques, in the frontal plane (non-collinear with oblique segments), or perpendicular to the plane defined by the obliques. These studies revealed that the strength of the illusion was increased significantly in a configuration non-collinear with obliques and, conversely, the illusion was reduced in configuration with the collinear shape of the edges, i.e., the same plane as the obliques; the authors argued that the geometrical three-dimensional layout affects significantly the size of the illusion [25].

A model proposed by Men'shikova suggests that flat images that cause geometric illusions are mainly processed by mechanisms of the middle level of visual information processing, while introduction of binocular cues that provide depth information initiates mechanisms of the cognitive level. The introduction of depth cues makes it possible to change the localization and orientation of individual elements in the illusion pattern in three-dimensional space. Such transformations lead to the fact that a three-dimensional scene of a visual illusion is processed according to different rules than the rules characteristic of a two-dimensional pattern [1].

CONCLUSIONS

(1) Quantitative estimation of the range in which the Poggendorff illusion exists makes it possible to fully and objectively investigate its manifestations when presenting both two-dimensional and three-dimensional images.

(2) Among the proposed variants of the Poggendorff figure, the greatest strength of the illusion was revealed in configuration when the parallel lines were inclined in the sagittal plane.

(3) The lowest strength of the illusion was in configuration with frontoparallel separation of the vertical lines and oblique segments, especially when the oblique segments were perceived in the plane located ahead of the parallel lines.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

Statement of compliance with standards of research involving humans as subjects. All procedures performed in studies involving human participants were in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments and were approved by the institutional bioethics committee of the Institute for Information Transmission Problems, Russian Academy of Sciences (Moscow). Informed consent was obtained from all individual participants or official representatives (for minors) involved in the study.

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Translated by M. Novikova