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Investigation of the Perception of Three-Dimensional Geometric Figures from the Rotational Movement of Their Two-Dimensional Image in Children with Ophthalmopathology

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Abstract—Manifestations of the illusion of a three-dimensional structure appearing when rotating a flat projection of a three-dimensional object (structure from motion (SfM)) were studied in three groups of children aged 7 to 17 years: (1) 40 children of the control group with orthotropy, the normal state of visual functions (including binocular and stereovision) and fundus; (2) 33 children with non-paralytic strabismus and normal fundus condition; (3) 50 children with non-paralytic strabismus on the background of congenital partial atrophy of the optic nerve (PAON). As a test image, we used the figure of a hexagon with diagonals passing through its center, presented in binocular and monocular observation conditions in the form of a still image, and when it rotates at a speed of 5, 10, 15, 20, 30, and 40 rpm. It was shown that the perception of a three-dimensional structure in the form of a cube is possible with a stationary presentation of a test image in 2–3% of children of both the control group and groups of children with strabismus in binocular and monocular observation conditions. When rotating the test image in both binocular and monocular observation conditions, the number of children who perceived the cube in all groups increased with increasing image rotation speed, reached maximum values at 15–30 rpm, and decreased significantly at 40 rpm. In the control group, during the transition from binocular observation conditions to monocular, the number of children perceiving the image as a cube significantly increases at rotational speeds of 5 rpm ($p = 0.023$), 10 rpm ($p = 0.005$), 20 rpm ($p = 0.002$), and 30 rpm ($p = 0.001$). In groups of children with strabismus (both on the background of normal fundus and on the background of PAON), binocular and monocular indicators were statistically comparable ($R > 0.05$). Comparison of indicators in different groups demonstrated a greater number of children perceiving a three-dimensional figure in the control group than in both groups of children with strabismus at certain speeds of rotation of the test image (from 10 to 20 rpm). In groups of children with strabismus on the background of normal fundus and children with strabismus on the background of PAON, binocular and monocular indicators are statistically comparable for all image rotation speeds. There was no significant dependence of the nature of the perception of the test image on age in all the study groups of children. Thus, along with the general patterns of SfM manifestations in children of the studied groups, differences were revealed due to the nature of the interaction of monocular and binocular mechanisms of perception in normal and ophthalmopathology. Thus, the SfM study can be used to evaluate the effects of depth and force relations of the monocular and binocular mechanisms of spatial perception in normal and ophthalmopathology.

Keywords: structure of movement, strabismus, amblyopia, depth effect

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INTRODUCTION

Spatial visual perception is a complex process, including the analysis of individual features of the visual signal, the creation of adequate hypotheses about the nature of the stimulus, assigning it to a certain category, and comparison with the existing internal standard of extrapersonal space and the body scheme [1–7].

The physiological basis of spatial perception is more often associated with the binocular system, which integrates the signals entering the brain from each eye into a single image of the three-dimensional external world. At the same time, signals from objects that fall into the zone of the binocular field of view (which is approximately 120° horizontally) arrive at neighboring columns of eye dominance in the visual cortex and then to the binocular neurons of each hemisphere. Identical (corresponding) elements are the central fovea of the retina of both eyes, as well as retinal zones located symmetrically with respect to the central fovea (the elements of the nasal retina of one eye are corresponding to the elements of the temporal half of the retina of the fellow eye, and vice versa). Due to this, the corresponding zones of the retinas of both eyes have the same subjective visual direction. Mismatched points of the retinas are called disparate. Horizontal disparity serves as a necessary reference point for the perception of relief and depth [1–7].

Meanwhile, the surrounding world seen with one eye is not flat for the observer due to a sufficiently large number of monocular depth features that allow one to assess the three-dimensionality of space (closer objects partially cover more distant objects, texture gradient, proximity to the horizon, linear perspective, distribution of light and shadow, etc.) [3, 4].

The most pronounced effect of depth in monocular conditions occurs when the projections of objects at different distances are mutually shifted on the retina when the observer or the objects themselves move, reflecting the geometry of the visual scene. In this case, a sequence of "frames" is obtained on the retina, which can be combined into stereo pairs, which makes it possible to ensure the accuracy of spatial analysis that is not inferior to binocular observation conditions. [1–4, 8].

Currently, research on depth effects arising from the observation of moving flat images, several similar terms are used: stereokinetic effect, kinetic depth effect, and structure from motion [8].

The term stereokinetic effect (SE) is commonly understood as the depth effect arising from the rotation of flat elliptical or ring images with a displaced center (eccentricity) [1, 2, 9–12]. One of the earliest known descriptions of SE was made by C. Musatti in 1955 [9].

To describe the effect of perceiving a three-dimensional structure created by the shadow of a rotating three-dimensional object, H. Wallach and D. O'Connell first used the term kinetic depth effect (KDE) [13]. The occurrence of this effect is explained by association processes at the level of the central part of the visual analyzer between the retinal projection and a three-dimensional object. In some cases, such associations may be the cause of perception of 3D structures even in the absence of object projection movement [13].

Later, thanks to S. Ullman [14], devoted to the study of the effect of depth and volume during the movement of projections of two transparent cylinders with dots applied to their surface in a random order, the term structure from motion appeared (SFM), which is more common than KDE [14–17].

Currently, SE is the most studied in terms of the characteristics of the vector relations of the binocular and monocular mechanisms of spatial vision in the norm, as well as in neurological and ophthalmic pathology [1, 2, 18–20]. In the studies carried out in this direction, features of the manifestation of SE were revealed, characterized by a decrease or disappearance of the difference between binocular and monocular estimates of SE (both due to an increase in binocular estimates, and due to a decrease in monocular ones) in adults and children with binocular vision disorders (with neurological pathology, amblyopia, strabismus) [1, 2, 18, 20]. It has been shown that in organic pathology of the fundus (for example, in patients with (PAON)), there is also a decrease in the difference between monocular and binocular indicators due to a decrease in monocular indicators [19, 21–26].

Along with SE, it is no less important to study the possibilities of other ways of creating depth effects based on successive visual images when observing rotating flat geometric figures. For example, in their study of SFM in a group of healthy adults (aged 19 to 24), U. Vanzelli and M. Farne [27] used a test image in the form of a light hexagon on a black background with diagonals passing through its center. The image was projected using a light projector onto a black flat screen in a dark room at a distance of 1 m from the subject's eyes. The authors showed the dependence of the perception of a rotating two-dimensional flat image of a hexagon by healthy subjects (subjects) on the speed of its rotation, the maximum number of subjects who perceived a flat image as a three-dimensional figure (cube or pyramid) was maximum at an image rotation speed of 10 rpm. [27].

Meanwhile, studies of the possibilities of this technique for studying the features of spatial perception in patients with binocular vision disorders and other ophthalmic pathologies have not yet been carried out. It is also important to note that these studies were not carried out using computer technology, but a light projector, so the results could have some errors.

Given the great interest of modern neurophysiology and ophthalmology in the problem of studying the neural structures and mechanisms involved in the organization of spatial vision, the study of the ability to perceive three-dimensional structures when observing the rotational movement of flat images not only in healthy adults, but also in children with PAON (which is a degenerative process in retinal ganglion cells and their axons) and amblyopia (associated with inhibition processes at the level of the central part of the visual analyzer) are of particular importance.

Objective—To explore the possibilities of the visual analyzer to detect the effect of a three-dimensional structure at different speeds of rotational movement of its two-dimensional image presented on the monitor screen.

MATERIALS AND METHODS

Under observation there were 123 children aged 7 to 17 years old, who, as a result of a standard ophthalmological examination, were divided into 3 groups: (1) 40 children of the control group (mean age 11.9 ± 0.5 years; 19 boys and 21 girls) with orthotropy, normal visual functions (including binocular and stereo vision), as well as the retina and optic nerve; (2) 33 children with concomitant (non-paralytic) strabismus and normal condition of the fundus (mean age 12.1 ± 0.5 years; 15 boys and 18 girls); and (3) 50 children with concomitant strabismus against the background of congenital partial atrophy of the optic nerve of both eyes (mean age 12.5 ± 0.03 years; 23 boys and 27 girls).

All children in the control group had normal binocular and stereo vision with classical ophthalmological tests. Refraction was emmetropic in 16 (40%) children, hyperopic in 5 (12.5%) children, myopic in 18 (45%) children, and mixed astigmatism in 1 (2.5%) child. Visual acuity (in children with emmetropia without correction, in children with ametropia with correction) was at least 0.9 (for a better seeing eye, on average 0.92 ± 0.02, for a worse seeing eye, on average 0.91 ± 0.02).

The group of children with strabismus against the background of a normal fundus included 25 (75.8%) children with convergent strabismus and 8 (24.2%) children with divergent strabismus. All children in this group had binocular vision disorders and the absence of stereo vision with classical ophthalmological tests. Refraction was hyperopic in 26 (78.8%) children, myopic in 4 (12.5%) children, and 3 (9.1%) children had unilateral pseudophakia. All children had mild dysbinocular bilateral amblyopia. Visual acuity in the better seeing eye ranged from 0.65 to 0.8 (0.77 ± 0.03 on average), and in the worse seeing eye from 0.45 to 0.65 (0.54 ± 0.05 on average).

The group of children with strabismus associated with congenital partial optic atrophy (POA) in both eyes included 32 (64%) children with convergent strabismus and 18 (36%) children with divergent strabismus. All children in this group had binocular vision disorders and the absence of stereo vision with classical ophthalmological tests. Refraction was hyperopic in 19 (38%) children, myopic in 22 (44%) children, mixed astigmatism in 5 (10%) children and 4 (8%) children had bilateral pseudophakia. The visual acuity of the better seeing eye ranged from 0.2 to 0.4 (mean 0.32 ± 0.03), the worse seeing eye ranged from 0.1 to 0.25 (mean 0.18 ± 0.02).

According to the results of the previous examination by a neurologist as part of a dispensary examination, none of the children included in the study showed neuropsychic developmental disorders.

The presented test image was a figure in the form of a white hexagon with six diagonals passing through its center against a black background of the monitor screen (Fig. 1).

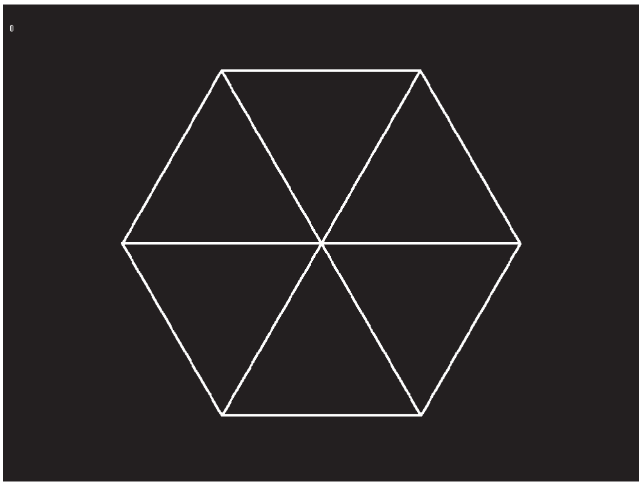

Fig. 1. Test image.

The diameter of the figure was 20 cm, the thickness of all lines was 3 mm. This test image was presented to the subject at a distance of 2 m from the eyes under mesopic illumination conditions (250 lux in our studies). The options for presenting the test image on the monitor screen were as follows: (1) static (fixed) presentation, (2) with a rotation speed of 5 rpm; (3) with a rotation speed of 10 rpm; (4) with a rotation speed of 15 rpm; (5) with a rotation speed of 20 rpm; (6) with a rotation speed of 30 rpm; and (7) with a rotation speed of 40 rpm. The center of rotation coincided with the center of the figure. We used both binocular observation conditions (with two eyes open) and monocular conditions (one eye is open and the other is covered with a shutter). The options for presenting the test image and the observation conditions were changed randomly. The observation time was not limited, but usually it was 1–2 min for each variant of stimulus presentation. The subject's task was to describe his visual impressions (a flat figure or a three-dimensional one, what it looks like). The following main three gradations of responses were noted: (1) a flat figure (described as a flat hexagon with diagonals, a wheel, a snowflake, a pizza, a propeller, a jellyfish), (2) a slight sense of volume (an umbrella, a hexagon with a convex or slightly sinking middle, a small pyramid), and (3) a three-dimensional figure (most often described like a cube with transparent sides). Sometimes the perception of the cube was unstable, the cube periodically turned into a flat figure, but then the cube appeared again. In such cases, the description of the perception of the figure was fixed as the presence of a cube. The study was organized in such a way that children who passed and did not pass the test did not communicate with each other.

Statistical processing of the material was carried out using the program SPSS. To compare related sam-

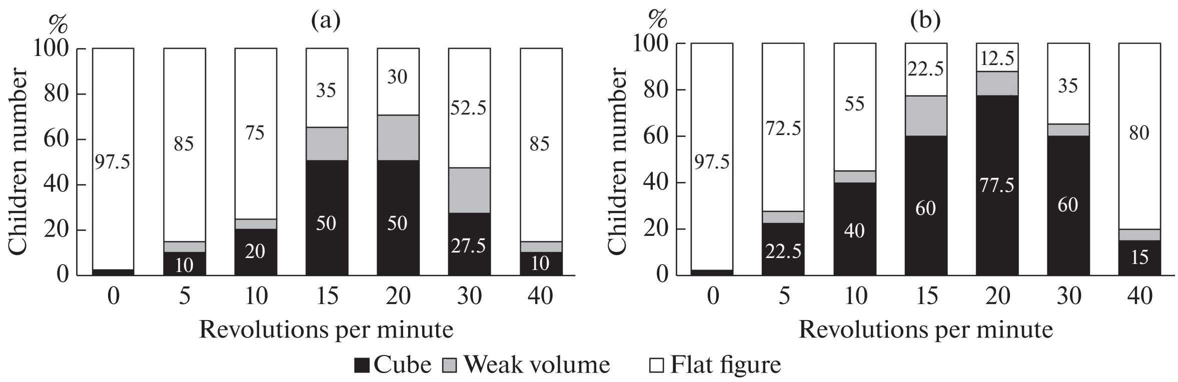

Fig. 2. The distribution of children in the control group depending on the perception of the image presented with different speeds of rotation in binocular (a) and in monocular (b) observation conditions.

ples, we used the Wilcoxon test, for intergroup comparisons, the Mann–Whitney test. Statistical significance was set at 0.05.

RESULTS OF THE STUDY

Analyzing the data, it should be noted that when the test image was presented as immobile, no more than 2–3% of children in each group, both in binocular and monocular conditions of observation, were able to perceive this image as a cube frame, the rest of the children perceived it as a flat figure (variants of descriptions by children were a hexagon with diagonals, a pizza, a spoked wheel, or a snowflake).

On moving presentation of the test image in all children of the control group under monocular conditions, the nature of the perception of visual information from the better seeing eye corresponded to the nature of the perception of visual information from the worse seeing eye. Presentation of an image at a minimum speed of 5 rpm caused the effect of its perception in the form of a cube in 10% of children under binocular conditions of observation, and in monocular conditions, in 22.5% of children (2 times more). The maximum number of children in the control group who perceived the cube under binocular conditions was detected at image rotation speeds of 15 and 20 rpm (50% of children) and under monocular conditions at a speed of 20 rpm (77.5% of children). With a further increase in the rotation speed of the figure to 40 rpm, the number of children who perceived the image as a cube decreased and amounted to only 10% in the control group under binocular conditions and 15% in monocular conditions (Fig. 2).

At the maximum image rotation speed (40 rpm), most children in all groups described it as a fan, a bicycle wheel, a jellyfish with wavy edges, or a propeller.

The increase in the number of children in the control group who perceive the image as a cube under monocular conditions compared to binocular conditions was statistically significant at rotation speeds of 5 rpm (R = 0.023), 10 rpm (R = 0.005), 20 rpm (R = 0.002), and 30 rpm (R = 0.001). At rotation speeds of 15 and 40 rpm, the performance for monocular and binocular conditions were comparable (R > 0.05).

In all children with strabismus against the background of a normal fundus in monocular conditions, the nature of perception of visual information (a flat image, a weak volume, or a cube) from a better seeing eye corresponded to the nature of perception of visual information from the worse seeing eye, however, seven children from this group with a difference in acuity of vision 0.3–0.4 noted a more pronounced volume and a clearer perception of the figure when viewed with the better seeing eye compared to the worse seeing one. With an increase in the speed of rotation of the test image in this group, as well as in the control group, an increase in the number of children perceiving the image in the form of a cube was observed. The maximum number of children who perceived the image as volumetric was detected under binocular conditions at a rotation speed of 20 rpm (51.5% of children), and under monocular conditions at a rotation speed of 30 rpm (60.6% of children). With a further increase in the rotation speed of the figure to 40 rpm, the number of children who perceived the image as a cube decreased and amounted to 18.2% of children in this group under binocular conditions of observation and 21.2% of children under monocular conditions (Fig. 3). At the maximum speed of rotation of the image, the majority of children, as in the control group, described it as a fan, a bicycle wheel, a jellyfish with wavy edges, or a propeller.

Comparison of the number of children in this group who perceived the cube in binocular and monocular conditions of observation showed no significant difference at all image rotation speeds (R > 0.05).

No significant correlation with visual acuity was found (R > 0.05), probably due to the fact that all children of this group had mild amblyopia, and the maximum difference in visual acuity was 0.15–0.2.

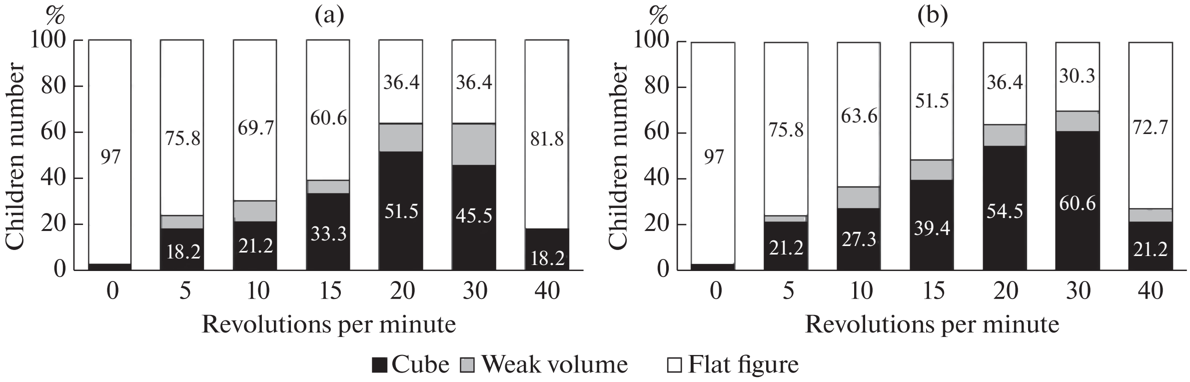

Fig. 3. The distribution of children with strabismus against the background of a normal fundus, depending on the perception of the image presented with different rotation speeds in binocular (a) and in monocular (b) observation conditions.

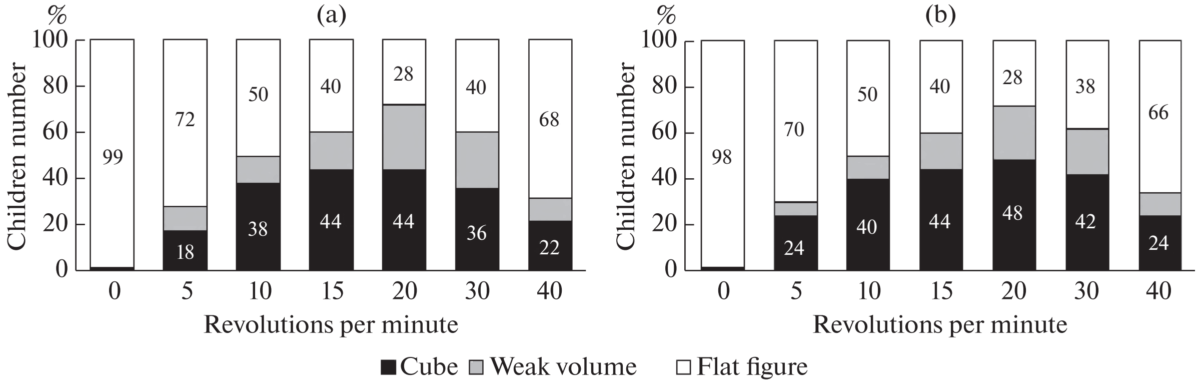

Fig. 4. The distribution of children with strabismus against the background of partial atrophy of the optic nerve (PAON) depending on the perception of the image presented with different speeds of rotation in binocular (a) and in monocular (b) observation conditions.

In the group of children with strabismus against the background of PAON, in all cases under monocular conditions, the nature of the perception of visual information from the better seeing eye corresponded to the nature of the perception of visual information from the worse seeing eye. The maximum number of children who perceived the cube was under binocular conditions at rotation speeds of 15 and 20 rpm (44% of children) and under monocular conditions at a rotation speed of 20 rpm (48% of children). With a further increase in the speed of rotation of the figure to 40 rpm, the number of children who perceived the image as a cube decreased and amounted to in the group of children with strabismus against the background of PAON, 22% in binocular conditions and 24% in monocular conditions (Fig. 4). The description of the visual image at such a maximum speed in most children in this group was similar to the comments of children in other groups (fan, bicycle wheel, jellyfish with wavy edges, propeller). A significant correlation with visual acuity in this group of children was also not found ($R > 0.05$), presumably due to the fact that all children in the group had low visual acuity without significant differences (maximum difference 0.2).

Comparison of the number of children in this group who perceived the cube under binocular and monocular observation conditions also showed the absence of a significant difference at all image rotation speeds ($R > 0.05$).

An intergroup comparative analysis showed that a comparison of the nature of image perception between the control group and a group of children with strabismus against the background of a normal fundus at each rotation speed made it possible to identify a significantly larger number of children who perceive the image as a cube in the control group than in children with strabismus under monocular conditions. at rotation speeds of 15 and 20 rpm ($R = 0.03$ and $R = 0.02$, respectively). No significant difference was found for binocular conditions. Comparison of the indicators of the control group and the group of children with strabismus against the background of PAON showed a significantly greater number of children who perceive the image as a cube in the control group under monocular

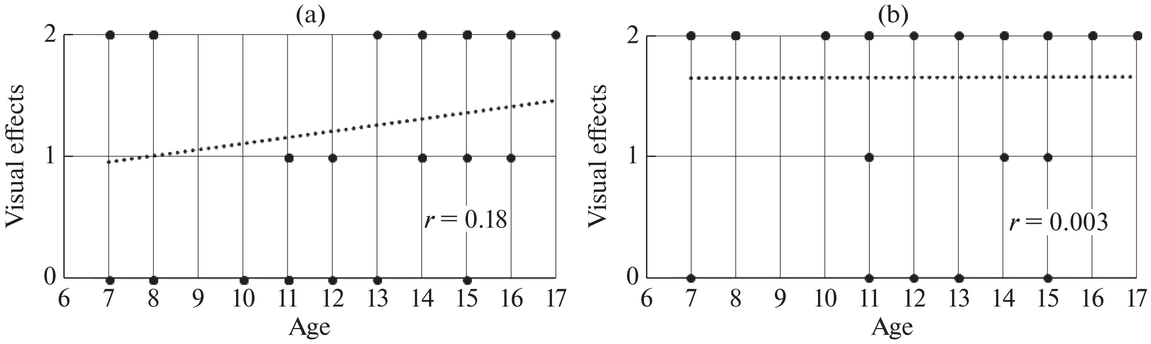

Fig. 5. The dependence of the visual effect on the age of children in the control group in the study in binocular (a) and monocular (b) observation conditions.

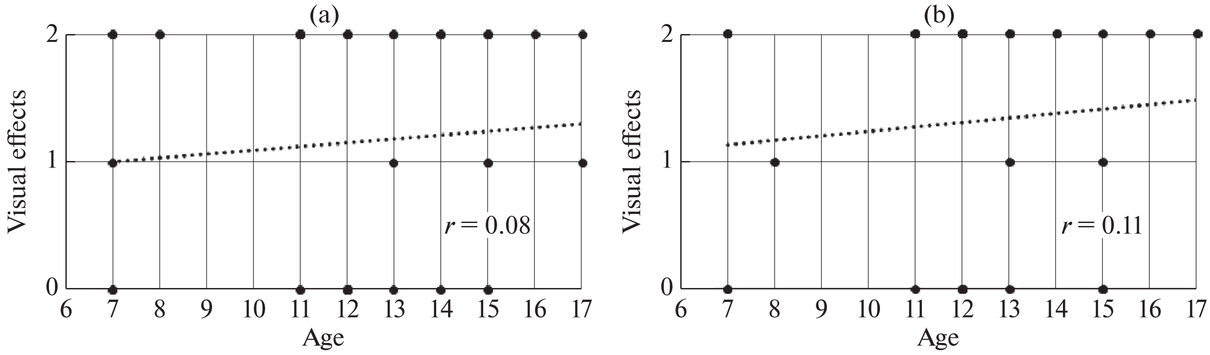

Fig. 6. The dependence of the visual effect on the age of children with strabismus against the background of a normal fundus in the study in binocular (a) and monocular (b) observation conditions.

conditions at a rotation speed of 20 rpm ($R = 0.006$) and under binocular conditions at a rotation speed of 10 rpm ($R = 0.02$). In other cases, no significant difference was found.

When comparing groups of children with strabismus against the background of a normal fundus and children with strabismus against the background of PAON, binocular and monocular indicators were statistically comparable for all image rotation speeds ($R > 0.05$).

In all groups of children, the results for boys were comparable to those for girls ($R > 0.05$ according to the χ-squared criterion).

Correlation analysis did not reveal a significant relationship between the nature of the perceived image and the age of the subjects in all groups ($R > 0.05$). The diagrams show the results of a correlation analysis of the nature of the perceived image versus age at a test image rotation speed of 20 rpm, since at this speed the volumetric image perception frequency was maximum in most cases (Fig. 5–7). At the same time, it should be noted a statistical trend towards an increase in the frequency of perception of a three-dimensional image with the age of children in the control group in binocular conditions of observation (Fig. 5a).

DISCUSSION OF THE RESULTS

The results of this study are in good agreement with the data obtained by us in previous studies devoted to the study of SE in children with PAON and in children with operated concomitant (non-paralytic) strabismus [19, 20].

In studies of the SE effect in children with PAON, we used ring test images with an eccentricity (off center) of 0.2, 0.4, 0.6, and 0.8. Test images were presented on a monitor screen at different rotation speeds (from 2 to 90 rpm) [19]. It was shown that in the majority (63.9%) of children with PAON, when observing a ring test image with a minimum eccentricity (0.2) and a minimum rotation speed (2 rpm), there was no depth effect, unlike children in the control group, and with an increase rotation speeds of more than 30 rpm SE appeared in all children (both in the control group and in the group with PAON) with any eccentricity [19]. It was also shown that binocular assessments of the severity of SE in the group of children with PUNS were comparable to monocular assessments, in contrast to children in the control group, in whom monocular assessments of the severity of SE were significantly higher than binocular ones. Based on the data obtained, an assumption was made

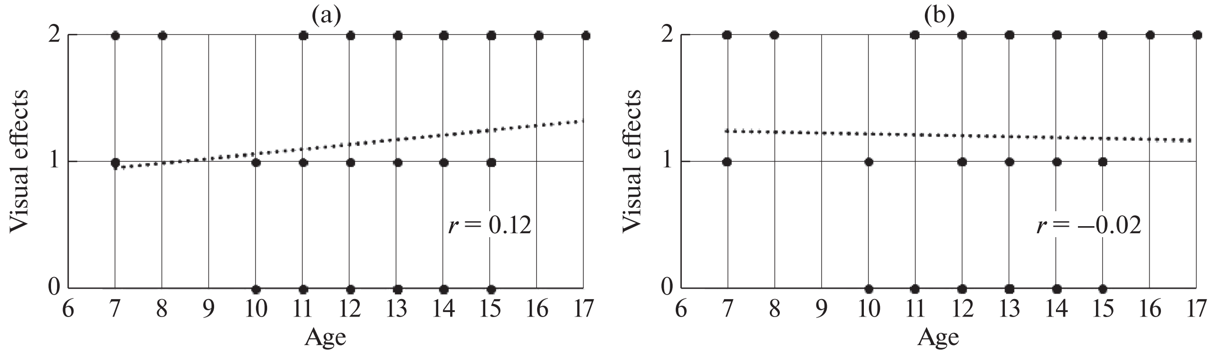

Fig. 7. The dependence of the visual effect on the age of children with (PAON) in the study in binocular (a) and monocular (b) observation conditions.

about a shift in the power relations of the monocular and binocular mechanisms of spatial vision towards monocular [19].

In our other study [20], devoted to assessing the dynamics of SE as a result of functional treatment of children with residual microdeviation after surgical treatment of concomitant strabismus, data were obtained demonstrating the possibility of using SE in monitoring the power relations of the binocular and monocular mechanisms of spatial vision during treatment. Positive dynamics was shown in the form of a shift in the vector relations of the mechanisms of spatial vision in the direction of strengthening the influence of the binocular mechanism [20].

Analysis of the results of this study of SfM, as well as the analysis of the results of the previous SE study, suggests that the differences in the nature of the perception of the test image in monocular and binocular conditions of observation in children of the control group are due to the normal power ratios of the binocular and monocular mechanisms of spatial vision. In both groups of children with strabismus (against the background of a normal fundus and against the background of PAON), in contrast to children in the control group, disturbances in the binocular mechanism lead to a shift in the power relations of the mechanisms of spatial vision towards monocular. It should be noted that binocular vision disorders are obviously more important in this process than the state of the fundus, given the comparability of the indicators of children of the two groups with strabismus.

Decreased visual acuity due to both central inhibition (in patients with dysbinocular amblyopia) and degenerative changes in retinal ganglion cells and their axons (in patients with PAON) can obviously be the cause of a decrease in the severity of SfM, judging by the difference in monocular indicators of children in the control group and children of both groups with strabismus at certain image rotation speeds.

Thus, it is shown that the study of SfM, as well as the study of SE can be used to assess the effects of depth and power relations of the monocular and binocular mechanisms of spatial perception in the norm and in ophthalmopathology.

CONCLUSIONS

(1) Perception of a three-dimensional image is possible with a motionless presentation of a two-dimensional test image in 2–3% of children in both the control group and groups of children with strabismus in binocular and monocular observation conditions.

(2) When the test image was rotated under both binocular and monocular conditions of observation, the number of children who perceived the three-dimensional structure increased in all groups with an increase in the image rotation speed, reached maximum values at 15–30 rpm, and significantly decreased at 40 rpm/min.

(3) In the control group, during the transition from binocular to monocular observation conditions, the number of children who perceive the image as a cube increases significantly at rotation speeds of 5 rpm (R = 0.023), 10 rpm (R = 0.005), 20 rpm (R = 0.002), and 30 rpm (R = 0.001).

(4) In groups of children with strabismus (both against the background of a normal fundus and against the background of PAON), binocular and monocular parameters are statistically comparable (R > 0.05).

(5) Comparison of indicators in different groups shows a greater number of children who perceive a three-dimensional figure in the control group than in both groups of children with strabismus at certain test image rotation speeds (from 10 to 20 rpm).

(6) There was no significant dependence of the nature of the perception of the test image on age in all the studied groups of children.

COMPLIANCE WITH ETHICAL STANDARDS

All studies were carried out in accordance with the principles of biomedical ethics, formulated in the Declaration of

Helsinki of 1964 and its subsequent updates, and approved by the local bioethical committee of the Institute for Information Transmission Problems, Russian Academy of Sciences (Moscow).

Informed Consent. Each study participant provided a voluntary written informed consent signed by him or his legal representative (for minors) after explaining the potential risks and benefits, as well as the nature of the upcoming study.

Conflict of interest. The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

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