

UNIVERSITY OF LATVIA



Correlation between stereothreshold and  
quality of monocular stimuli

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## ***Abstract***

The aim of the present work was studies of correlation between the stereothreshold and the quality of eye stimuli in different eyes. To achieve this aim the following tasks have been set: assessment and comparison the characteristic values of stereovision in cases of real and induced cataract, amblyopia and uncorrected anisometropia as well as the comparison of the estimated stereothreshold values in cases of induced uncorrected myopic and hypermetropic anisometropia. It was supposed to develop a method for training the stereovision by determining the stereothresholds in cases of artificial amblyopia and cataract that could help people with lowered visual acuity in one eye to see the stereo images.

Three methods to determine the stereothreshold have been used in the present work: defocusing, monitor stimuli and eye occluder methods. The quality of the stimulus of one eye is being changed (blurring and contrast); the quality of the stimulus of the second eye remains all time constant. During the investigation positive and negative features of each method are stated to assess the application of these methods in order to induce different eye pathology conditions in laboratory. The subjects' stereothreshold was assessed simulating amblyopia, cataract and uncorrected anisometropia. To characterize the quality of the stimulus and to find ways to compare different stereostimuli spatial characteristics, three different methods have been used – the average of modulation amplitude, Fourier images spectral power density frequency distribution of stimuli and cross-correlation.

The developed methods are approved in stereothreshold studies: the defocusation method in cases of uncorrected anisometropia and amblyopia, the monitor stimuli method in cases of amblyopia and cataract, the eye occluder method as a good cataract simulation. The relationship between stimuli created by different method has been obtained allowing unambiguous their comparison with literature data.

The obtained results prove that the stereothreshold increases if the quality of visual stimulus is decreased in one eye. The determined threshold of stereovision are approximately the same comparing cases when decreasing of monocular visual acuity is simulated in laboratory with similar situation for real people with visual acuity lowering in one eye since childhood or due to the progress of cataract. The results of studies show, that in the case of hypermetropic anisometropia the stereothreshold is higher in comparison with myopic anisometropia under the same vision conditions. A method and conditions of vision perception are described to help people with a manifest difference of visual acuity between the eyes and weak binocular vision to see the latent image of random elements stereotests.

**Keywords:** stereovision, visual acuity, blurring, contrast, defocusation, monitor stimuli, eye occluder, PLZT and PDLC plates.

## ***Publications in periodics and proceedings***

The thesis is based on the following papers:

- I. Papelba\* G., Cipane I. & Ozolinsh M.  
**“Stereovision studies by disbalanced images.”** In: *“Advanced optical materials”* Ed. by J.Spigulis, J.Teteris, M.Ozolinsh, and A.Lusis, *Proc.SPIE* Vol.5123, pp.323-329, 2003
- II. Papelba G., Ozolinsh M., Petrova J. & Cipane I.  
**“Stereoaucuity determination at changing contrast of colored stereostimuli.”** In: *“Advanced optical materials”* Ed. by J.Spigulis, J.Teteris, M.Ozolinsh, and A.Lusis, *Proc.SPIE* Vol.5123, pp.330-338, 2003
- III. Ozolinsh M., Papelba G. & Andersson G.  
**“Liquid crystal goggles for vision science application.”** In: *“19th Congress of the International Commission for Optics: Optics for the Quality of Life”* Ed. by A.Consortini and G.C.Righini, *Proc.SPIE* Vol.4829, pp. 1056-1058, 2003
- IV. Papelba G., Ozolinsh M., Cipane I. & Petrova J.  
**“The effect of blurring degree, and chromatic contrast in one eye on stereovision.”** *“Perception”* Vol.31, supplement, p. 156, 2002
- V. Krumina G. & Ozolinsh M.  
**“Clinical investigation of stereoaucuity for patients having real or induced anisometropia and cataract.”** *“Optometry and Vision Science”* Vol.80 (12s), p.41, 2003
- VI. Ozolinsh M. & Papelba G.  
**“Eye cataract simulation using polymer dispersed liquid crystal scattering obstacles.”** *“Ferroelectrics”* (in print 2004)
- VII. Krumina G., Ozolinsh M. & Lyakhovetskii V.A.  
**“Stereovision by visual stimulus of different quality.”** In. Proc. of the IV interregional seminar of Moscow Helmholtz Research Institute for Eye Diseases *“Ocular biomechanics 2004”*, Ed. by E.N.Iomdina, I.N.Koshitz, pp.82-89, 2004

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\* surname at birth

## ***Reports in conferences***

- I. Sixth International Meeting of American Academy of Optometry “Academy 2000” – Madrid, Spain, 7.-9. April 2000
  - Papelba G., Lacis I., Ozolinsh M. & Daae K.I.  
***“Stereoresistance – a new characterisation of stereothreshold under external influence”***
- II. 99.Tagung der Deutsche Ophthalmologische Gesellschaft – Berlin, Germany, 29.September – 2.Oktober 2001
  - Papelba G. & Ozolinsh M.  
***“Blurring effect to stereoscopic vision”***
- III. 3<sup>rd</sup> International Conference “Advanced Optical Materials and Devices – AOMD-3” – Riga, Latvia, 19.-22.August 2002
  - Ozolinsh M., Papelba G. & Andersson G.  
***“Spatial and temporal transmittance of liquid crystal goggles used in vision tests”***
  - Papelba G., Ozolinsh M. & Petrova J.  
***“Method of determination of colour contrast to stereoacuity”***
  - Papelba G., Ozolinsh M. & Cipane I.  
***“Evaluation of image’s quality to stereovision acuity”***
- IV. The XXXV Nordic Congress of Ophthalmology – Tampere, Finland, 24.-27.August 2002
  - Papelba G., Cipane I. & Petrova J.  
***“Stereovision acuity studies by disbalanced eye image quality”***
  - Papelba G., Petrova J. & Cipane I.  
***“The influence of blue-red colour’s contrast to stereoacuity”***
- V. 25<sup>th</sup> European Conference on Visual Perception – Glasgow, UK, 25.-29.August 2002
  - Papelba G., Ozolinsh M., Cipane I. & Petrova J.  
***“The effect of one eye image blurring degree, luminance and chromatic contrast to stereovision”***
- VI. 3<sup>d</sup> International Conference “Television: Transmission and Processing of Images” – Sankt-Peterburg, Russia, 5.-6.june 2003
  - Lyakhovetskii V.A. & Papelba G.  
***“Spectral composition description of images for objects in the perception of depth”***
- VII. Academy 2003 “The future in sight: Today’s Research, Tomorrow’s Practise” – Dallas, USA, 4.-7.December 2003
  - Krumina G. & Ozolinsh M.  
***“Clinical investigation of stereoacuity for patients having real or induced anisometropia and cataract”***

## ***Abbreviations and key-terms***

*Amblyopia*

*Aniseikonia*

*Anisometropia*

*Cataract*

*D* – dioptre

*Disparity* – difference between the locations of the two retinal projections of a given point in the space, relative to the corresponding points

*Hypermetropia*

*LC shutters (goggles)* – liquid crystal goggles

*Myopia*

*PDLC plate* – light scattering polymer dispersed liquid crystal cells plate that becomes transparent when voltage is applied

*PLZT plate* –  $\text{Pb}_{0.905} \text{La}_{0.095} \text{Zr}_{0.35} \text{Ti}_{0.65} \text{O}_3$  ceramic plate with semitransparent gold electrodes that it becomes uniformly blurred when voltage is applied

*Presbyopia*

*Stereoacuity* – the lowest disparity value, measured in angle units, by which subjects perceive stereostimuli as a spatial image; this term is used more in clinics to evaluate the quality of stereovision

*Stereogram*

*Stereothreshold, stereovision threshold* – the lowest disparity value by which subjects perceive stereostimuli as a spatial image, a term having the opposite meaning to stereoacuity, by high stereoacuity the stereothreshold is low, both measured in angle units

*Visual acuity*

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## *Introduction*

A human has two eyes with which he perceives 80% of information from the surrounding world. As our living environment is a three-dimension space the human's ability to orientate in the space can be called the highest phenomenon of visual perception. There have been endless attempts to explain the formation of spatial perception, and still there is a lot to do. Even the latest technologies do not allow us to study and understand our brain completely. New robots are being built the visual system of which is designed just like the human's spatial and visual perception. Recent neurological investigations (*Grossberg & Howe 2003*) based on the working principles of the animals' primary vision cortex cells (*Hubel & Wiesel 1979, 1998*) try to explain the formation of human's stereovision (*Cumming & DeAngelis 2001*). Other scientists try to use the same newly discovered algorithms in the formation and perfection of robots stereovision. How do the human's binocular vision and stereovision operate? What outer conditions and inner neurophysiologic factors can influence the formation of stereovision, its development and even its destruction? These questions have been important in the XX century and they have not lost their significance now. There are new technologies to investigate and to produce a similar visual system and to study it, but the question has not been answered: "How is the human's perception formed?"

The idea of the present investigation was to determine values of the stereothreshold under conditions when one eye sees a bad (or worse comparing with other eye) quality stimulus. To explain why a subject with weak binocular vision does not have a stereosense and does not see spatial tests – images by which most of the people are fascinated. Was it a coincidence or was it a desire to see stereo images by myself and to understand how stereovision is formed under conditions when the vision perception ability of one eye is reduced. But now I can be proud of the fact that three people feel happier as they have found themselves able to see the world as spatial. Nobody will ever say that they do not have stereovision. Using our method these people have been taught to see the complicated stereoscopic images produced on the basis of random element principle and recognized only when a subject possesses stereovision.

In its turn people who do not have stereovision do not feel worse because they can find their way to compensate it in the conditions of monocular stereovision such as perspective, the relative size of the image on the retina, light scattering in the atmosphere and others. However, a subject who has lost the ability to see with one eye feels what it means to perceive the world with one eye only. It is difficult and takes a long time to adapt to such conditions.

**The aim of my work** was to study and to determine values of the stereothreshold when the quality of the stimulus of one eye (blur and contrast) changes. Studies of factors influencing the stereothreshold using monocular stimuli of different quality for well seeing subjects allowed to develop a method to evoke and facilitate the formation of stereovision for the people with a real decrease of visual acuity in one eye, who have not previously had the stereovision.

In stereovision studies two classes of smart materials with controllable optical properties were applied to set up stimuli simulation experiments.

## ***Experimental part***

### **1. Aim and tasks of the study**

The aim of the study is to investigate binocular vision and to determine values of the stereothreshold if stimuli of different quality are formed in subjects eyes. To fulfil the aim the following tasks have been set:

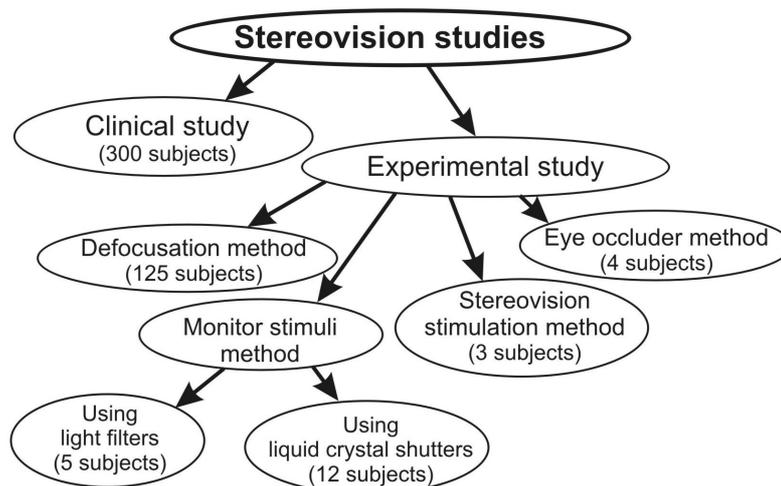
- 1) To assess binocular vision and to study the values of stereothreshold in cases of real and induced cataract, amblyopia and uncorrected anisometropia;
- 2) To compare the values of stereothreshold of uncorrected myopic and hypermetropic anisometropia;
- 3) To develop a method how to teach subjects with lowered visual acuity in one eye to perceive random elements stereotests.

Additionally it was necessary to perform tasks related with classification of stimuli and the application of different methods to create artificial conditions for subjects when the eyes receive images of different quality on the retina:

- 1) To characterize stimuli using the average of modulation depth, the frequency distribution of Fourier images and cross-correlation and to build scaling to compare the differently obtained stimuli during the studies of stereovision.
- 2) To evaluate the stereothreshold by simulating the eye pathologies by:
  - a) defocusation method (with optical lenses) – in cases of uncorrected myopic and hypermetropic anisometropia and amblyopia;
  - b) monitor stimuli method (using liquid crystal shutters and light filters) – in cases of amblyopia and cataract;
  - c) one eye occluder method (with PLZT ceramics and PDLC plate) – in cases of cataract.

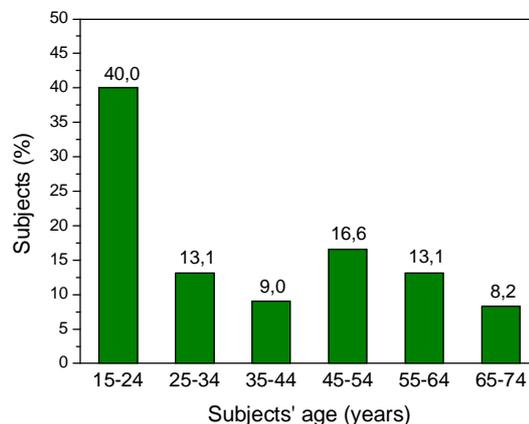
## 2. Subjects

Total 445 subjects – in each part the different number of subjects (see Figure 2.1) – participated in stereovision study. The age of subjects varied from 15 to 74 years (see Figure 2.2), with the average age  $39 \pm 17$  years. The major part of subjects is clinics patients that agreed voluntarily to participate in experiments. The second smallest part is students from Department of Optometry and Vision Science of University of Latvia. From more of 400 patients there were selected only 101, because some had not binocular vision or were very old with tingled hand and had difficulties to look very long time on stereotests. All selected subjects had a binocular vision determined with *Schober* and *Worth* tests, and a stereovision with TNO test.



**Figure 2.1.** Subjects' distribution in different studies of stereovision.

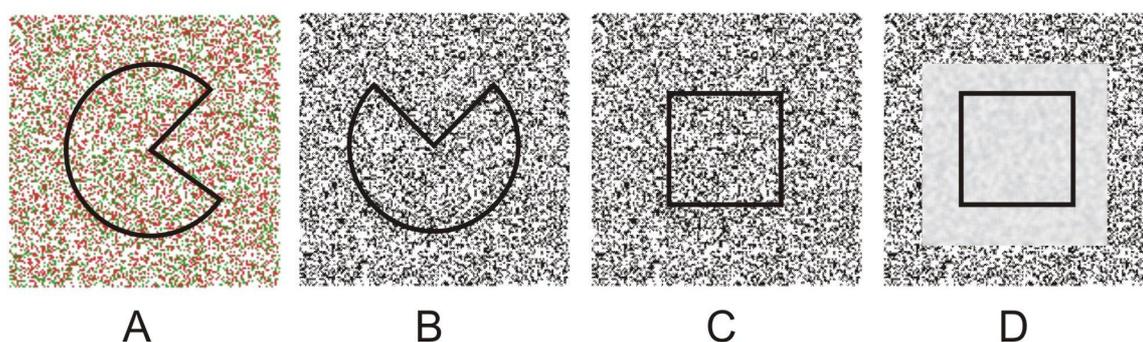
All of them had full correction for the distance vision. Presbyopes had been corrected for a 40 cm distance although their most convenient working distance in the near was different. The good visual acuity was not the main condition to participate in experiments, and selected patients had decreased visual acuity from cataract or/and amblyopia. Subjects refractions were different – ever emmetropia, ever myopia, ever hyperopia. The dominant eye for all was determined in the distance by the *Dolman* method, in the near – by the *Crider* method. Assessment of stereovision using a TNO test was carried out for 300 optical patients out of whom 77 subjects had lowered visual acuity caused by amblyopia or cataract.



**Figure 2.2.** Distribution of all subjects that participated in stereovision studies.

### 3. Stimuli

In stereovision studies we used random dot stereotests. There is no monocular evidence about stereoscopic image in such tests, and subject could not predict the image location. In one part of the experiment the stereothreshold was assessed by the standard near TNO stereotest assigned for the distance of 40 cm. TNO test also is based on the random dot principle, in combination with the anaglyph method. Both eye stereostimuli are formed by scattered fine red and green elements printed on the TNO plate, and stimuli separation is achieved by red and green filters placed in front of the left and right eye, respectively. Trial case lenses with custom colour filters were used in experiments. Monocularly the subject perceives the red elements with one eye and the green elements with another one. If the subject looks simultaneously with both eyes, then in the case of binocularity a spatial image appears – a circle with a cut out sector (see Figure 3.1 A), and the perceived image looks greyish.

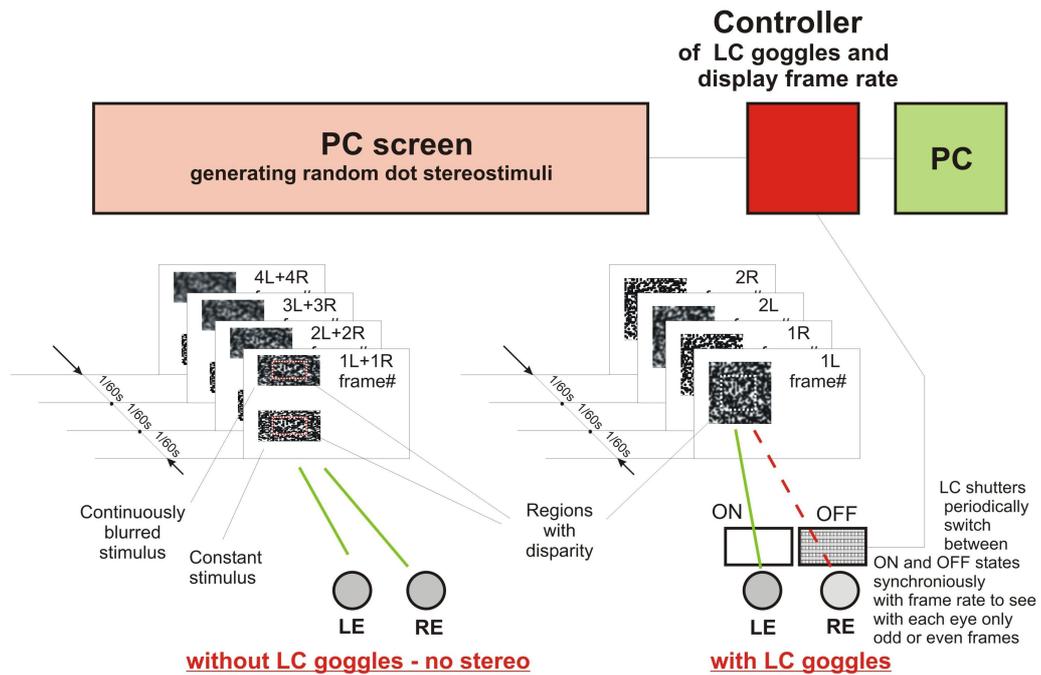


**Figure 3.1.** The stimuli of stereotests. A – standard TNO stereo image, B, C – stereo images on the computer screen for monitor stimuli method and eye occluder method. One eye had a constantly sharp image during the experiment, second eye had successive approximation image from sharp to blur and vice versa. D – one eye stereostimulus with an additional decrease of contrast in the centre of the field of vision.

In studies we created some computer programs that represented the random dot stereopair stimuli on PC screen with the blurring or contrast changes. Basically they represented an area comprising black and white or blue and red random dots. In the central part of the stimuli a smaller circle (a segment of which is cut-out) or a square is contoured (see Figure 3.1 B,C,D). The contoured area also is hidden by random dots, however in one eye stimulus the marked out region is displaced to the right or to the left by a small distance – the stereoscopic parallax. If an individual has developed stereovision he can see a three-dimensional object at the stimulus centre after two non-identical figures are fused in his brain. The stereopair images were merged by use of liquid crystal goggles. A special adapter was used doubling the frame frequency (see Figure 3.2). Thus the upper part of the frame (blurred stimulus) was displayed as whole even frames for one eye, and bottom part of the initial frame – as uneven frames displayed for other eye. The frame frequency was doubled from 60 to 120 Hz. The blur threshold at which the stereo sensation appeared was experimentally determined for one eye at different stereodisparities under the condition that the other eye saw a constant image of high contrast. The program fixed the number of the relevant blurring image (the radius of the blur effect).

In a case the coloured (red and blue) stereograms we used colour spectacles. Here each eye distinguishes its own stimulus since colour filters block the information assigned to the other eye. As well light filters as the liquid crystal goggles decrease the stimuli luminance and, correspondingly, the retinal illuminance. The controllable computer program created the stimuli for crossed and uncrossed disparity of stereosense.

In method with light scattering eye occluder (PLZT and PDLC plates) it is possible to estimate stereothreshold using standard TNO test and stereostimuli on PC screen. Additionally in all methods visual acuity was determined as criterion for comparing results about blurring and contrast influence to stereothreshold.



**Figure 3.2.** Experimental set-up to study stereovision with frame frequency doubling technique using LC goggles for random dot stereostimuli phase separation. The stimulus is demonstrated to each eye 60 times per second. Since relaxation of the human visual system is slower as compared to the stimuli delay demonstrated to each eye, the stimuli are superimposed by the brain and perceived “simultaneously.”

#### 4. Assessment of the image quality

In the computer experiment the degree of blurring was scaled in terms of pixels (using Gaussian filter). In other methods (defocusation and eye occluder methods) the blurring degree was scaled with lens optical power or the value of voltage applied to the obstacle was used as the measure. To specify the degree of blurring it was necessary to find a measure independent of the way the stereo image is obtained. Such measure would describe the stereostimulus and qualify the stereovision itself if images are used as stereostimuli. Each image of the stereopair might be analyzed separately using:

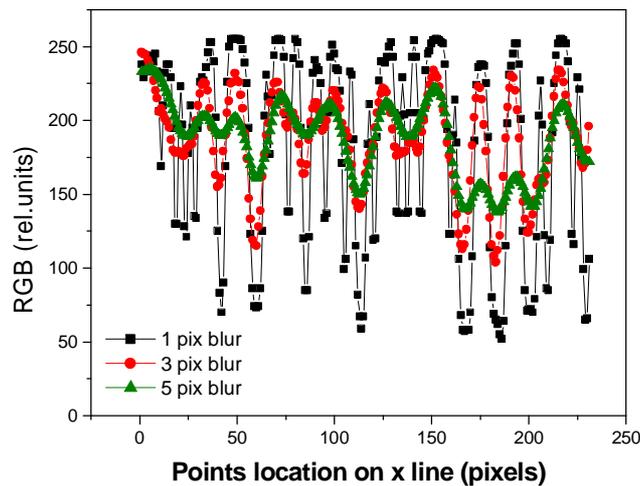
- the average modulation amplitude,
- frequency analysis of stimuli Fourier images,
- cross-correlation.

In the computer experiments the stereothreshold was fixed as a function of the blurring radius in pixels for different values of the stereodisparity. In the TNO test the value of minimum resolvable stereothreshold was determined. One way to estimate blur was using a CCD camera ( $f = 18\text{mm}$ ) as an eye model to take blurred and clear computer simulated random dot images, and further comparing images taken through light scattering PLZT ceramic plate with images blurred by optical lenses (in the latter case using for defocusing different positive and negative lenses placed in front of camera lenses).

As other criterion to measure blur we used the average modulation amplitude in the following way. One pixel wide line (in the centre of the square) of the blur images was selected to draw the sequence of RGB values. For each dip on the obtained graphs the modulation depth (MD) was estimated:

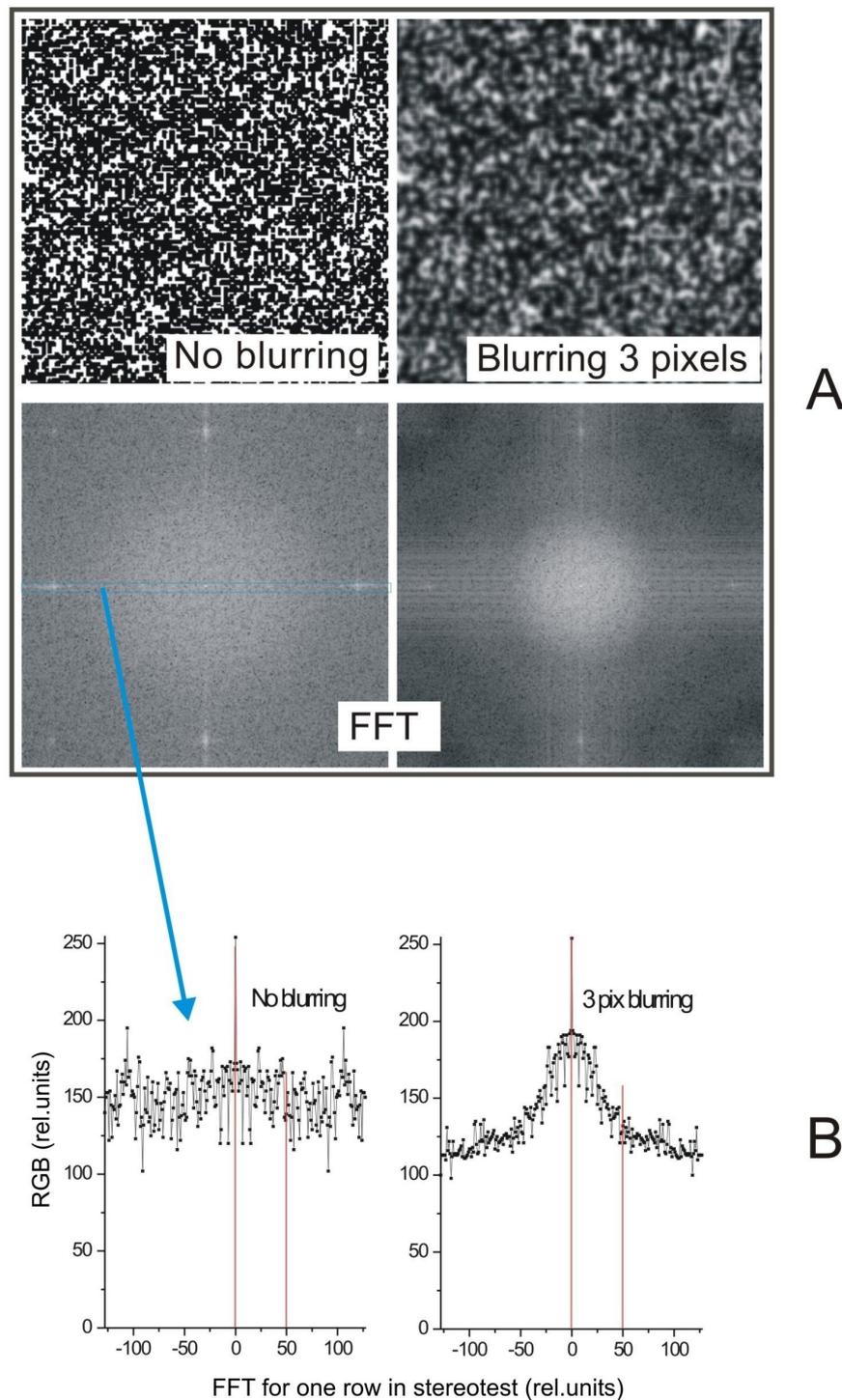
$$MD = 100 - \frac{I_{MIN} \times 100}{I_{MAX}} \quad [1]$$

and, sequently, the average  $MD$  value characterizing the given image was calculated (see Figure 4.1).



**Figure 4.1.** One version of the stimuli quality analysis. We have determined the modulation depth, which is an objective parameter that characterizes degree of blurring. Figure shows modulation depth for one pixel row.

Another method to describe stereostimuli was using fast Fourier transformation and analysed by high frequencies. The profiles representing functions of spatial frequency power density with respect to the spatial frequency obtained from 1 pixel wide lines in centres of Fourier patterns of the stereo images are shown in Figure 4.2.



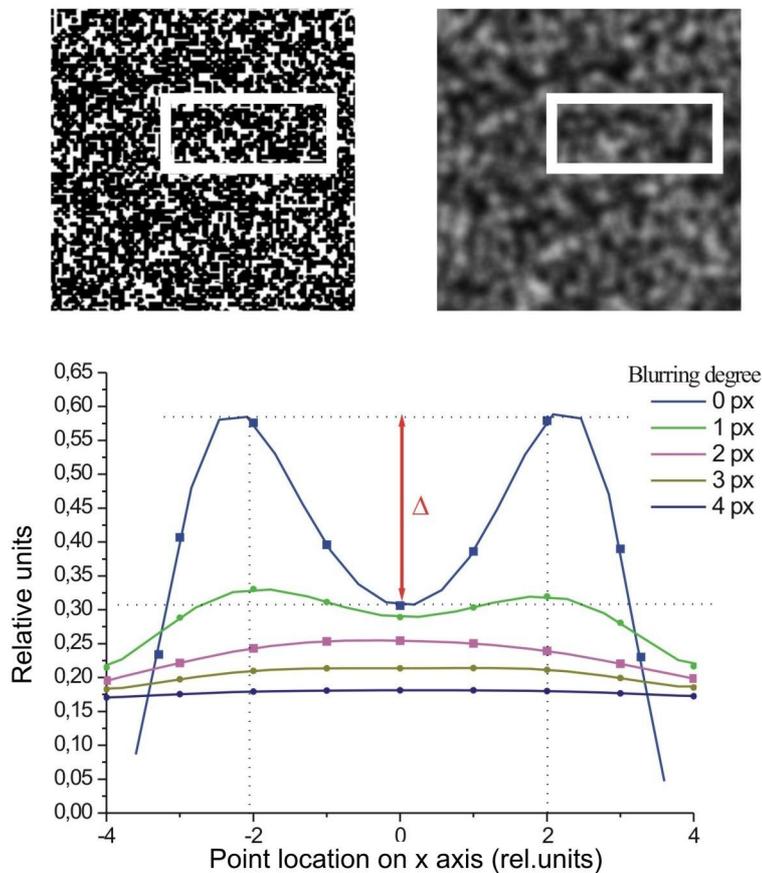
**Figure 4.2.** The blurred image quality can be analyzed with FFT (fast Fourier transformation). In figure A – the upper images are real stimuli, while in the bottom images – stimuli are analyzed with FFT. The corresponding profiles of FFT central part (1 pixel horizontal row) are shown in Figure B. The decreases of the integration's area at high frequencies are used as an objective parameter.

The curve corresponding to a clear image has a gentle slope – a contribution of higher spatial frequencies as compared with spatial zero frequency at the centre is higher. The integral:

$$\int_0^{V_{0x}} I(V_x) \cdot \partial V_x = K_F(V_{0x}), \quad [2]$$

where  $I(V_x)$  is the spectral power density frequency distribution and  $V_{0x}$  – an arbitrary frequency, may be considered as a parameter specific to the image characteristics (pixel size of clear image, and eventually disparity if used for stereostimuli). If a small enough  $V_{0x}$  is chosen, then the more blurred the image, the bigger the corresponding integral [2].

The third method for comparing all stereostimuli should be cross-correlation. Cross-correlation was made to compare two images and to find the degree of similarity by looking for similar regions in both images (see Figure 4.3).



**Figure 4.3.** The figure shows cross-correlation results of stimuli. One stimulus is blurred with Gaussian distribution (A – left image). Such processing would be similar to neural signal processing in the human brain. B – the stereo image can be perceived at positive and close-to-zero values of DELTA.

This way characterizes two correlated stimuli facility to evoke stereosense. The cross-correlation function  $\Gamma(a)$  was calculated within the stimuli areas needed to be fused in the human visual cortex. In the brain function similar to that is performed by “cross-correlation” neurons. Cross-correlation is performed for two stimuli – black-white random dot image  $S_1$  with dot intensities  $S_1(ij)$  either 0 or 255, and other stimuli  $S_2$  obtained using

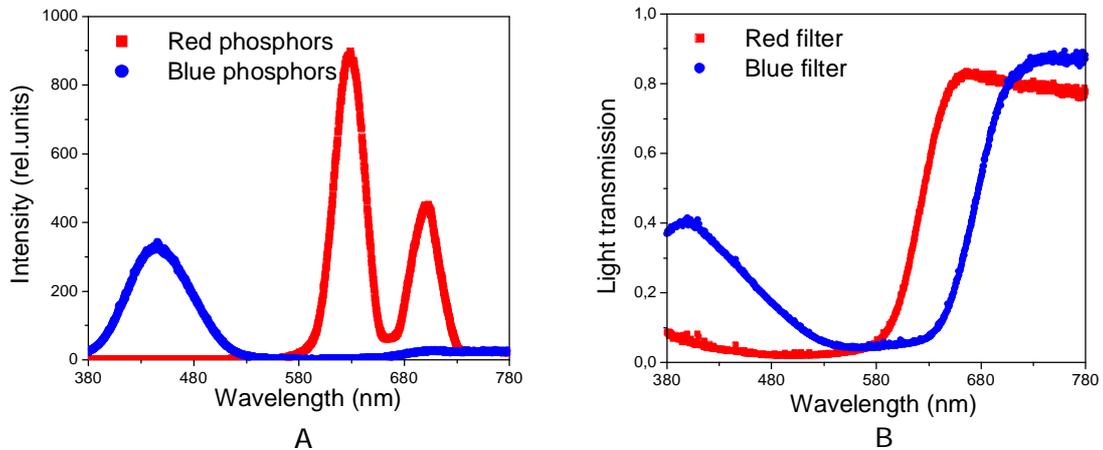
continuously increased blurring  $0 < S_2(ij) < 255$ . Correlation  $\Gamma(a)$  is calculated within an area including the contour of the disparity region symmetrically to the disparity region border:

$$\Gamma(a) = \frac{1}{i \times j \times 127^2} \sum_{i,j} [S_1(i-a, j) - 127] \times [S_2(i, j) - 127] \quad [3]$$

Two maxima on cross-correlation function of two images  $S_1$  and  $S_2$  show a presence of correlated regions in both images separated horizontally by a parameter equal to disparity. The more manifest are these maxima the easier is the task for the visual cortex to fuse these parts and to evaluate the value of disparity – the depth of protrusion.

In vision experiments using computer monitors it is necessary to evaluate the physical parameters of the black-white and colour stimuli. Using the *OceanOptics S2000 Fiber Optics* spectrometer the transmission spectra of the light filters were measured as well the spectral distribution of the screen phosphors radiation to ensure that each of the subject eye would see a single colour stimulus in the colour stereotests (see Figure 4.4 A).

The spectral analysis of colour filters was made with data from transmission measured separately for the red and the blue filter, the results being normalised with respect to the spectrum of incident light (%). The light source was the natural daylight. There were accomplished 10 measurements with exposition time 150 msec. For spectral analysis of colour filters were accomplished through gotten out spectral part for colour and blue filters (see Figure 4.4 B).

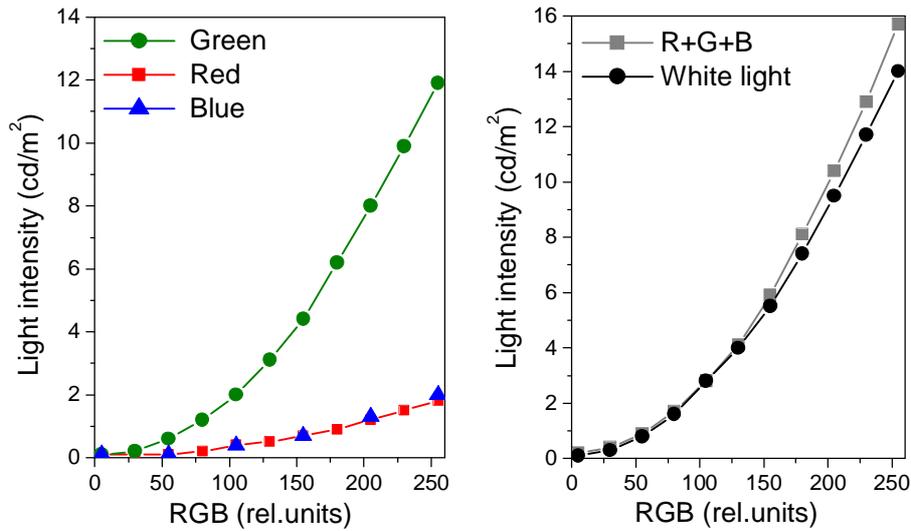


**Figure 4.4.** PC screen’s red and blue phosphors emission spectra (A) and in experiments used filters transmission spectra (B)

In case the coloured spectacles are used, each eye distinguishes its own stimulus since colour filters block the information assigned to the other eye. In case of liquid crystal shutters unnoticeable occlusion in each eye is changed at the frequency of 120 Hz. Thus, the stimulus is demonstrated to each eye 60 times per second. Since relaxation of the human nervous system is slower as compared the stimuli delay demonstrated to each eye, stimuli are superimposed by the brain and perceived “simultaneously “.

The monitors used in experiments have 15 inch screens (0.27 mm/pix), The frame frequency in the experiment equals 85 Hz. The screen brightness as function of the RGB video signal values was obtained by means of a digital luxmeter LUX LD12Q-631. The photometric radiation characteristics of red, green, blue and composite white channels are

shown in Figure 4.5. Determined data with luxmeter were calculated in the units of light brightness ( $\text{cd}/\text{m}^2$ ).



**Figure 4.5.** PC screen calibration's curves. Vertical axis – screen luminance ( $\text{cd}/\text{m}^2$ ) measured by a luxmeter attached to the screen. Horizontal axis – monitor video signal in RGB units. R+G+B – summation of three phosphors luminance.

Additionally the values of visual activity are used as a subjective criterion. Values of visual acuity are obtained psychophysically, firstly, simulating the blurring in one eye by optical lenses and, secondly, by light scattering PLZT, PDLC plates. To compare all different kind of stimuli used in experiments, the visual acuity together with another criterion – objectively obtained mean modulation depth are used to create the scaling scheme of the stimuli created in different ways (see Table 4.1). Using the mean of modulation depth of the blur caused by optical lenses taking “retinal image” snapshots by artificial eye CCD camera, we can equalize the effect of optical blur with Gaussian filtering of stimulus demonstrated on the PC screen. The decrease of the visual acuity in its turn can be useful to equalize the effect of optical blur using the defocusing lenses with light scattering effect caused by PLZT or PDLC occluders.

**Table 4.1.**

**Conversion table of stimuli**

Lens power (D)	Modulation depth (%)	Blurring of monitor stimuli (pixels)	Visual acuity (decimal system)	PDLC blurring (V)	PLZT blurring (V)
-2.00	27	2.1	0.23	-	1715
-1.00	58	0.7	0.48	15	1320
0.00	100	0.0	0.97	30	130
+1.00	68	0.5	0.82	20	925
+2.00	28	2.0	0.49	15	1320

The table summarize the obtained results characterizing all the used stimuli. As we know the average of modulation depth of an optical lens and the determined average visual acuity when looking through the lens, we can find a similarly blurred monitor stimulus and in the same way the value of the eye occluder voltage characterizing the light scattering of the PDLC and PLZT plates.

## 5. Methods

To determine the stereothreshold three methods are used (defocusing, monitor stimulus and eye occluder) which simulate the changes in the quality of the stimulus in one eye. The fourth method describes the conditions when the formation of stereovision is stimulated for the people with lowered visual acuity in one eye to see the stereo images of the random elements test.

**Defocusation method.** In this part of the experiment the stereothreshold was assessed by the standard near TNO stereotest using defocusing optical lenses. TNO stereotest is also based on the random dot principle, in combination with the anaglyph method (see Figure 3.1 A). Red and green filters were placed in front of the eyes to separate stereostimuli. Far correction was provided for young subjects and near correction in case of presbyopia.

The TNO stereoscopic test was held at the distance of 40cm. The subject should recognize the orientation of the cut circle segment for stimuli with equal disparity. The test always began with the highest stereothreshold for all trials. There is possible to determine stereothreshold from 15 to 1000 arc sec using the TNO test.

After the stereothreshold was determined for the optimum correction, the refraction was changed for the right eye with a +2.50 D lens (the maximum positive overcorrection) and the stereothreshold was assessed for this +2.5D – the maximum value of the positive overcorrection. Further the power of lens was reduced by 0.50 D and with each step the last visible stereoscopic image was recorded. When the starting point had been reached (zero overcorrection), stereovision was tested once again making it clear, whether the subject distinguished the same as in the beginning. The same procedure was repeated with the left eye.

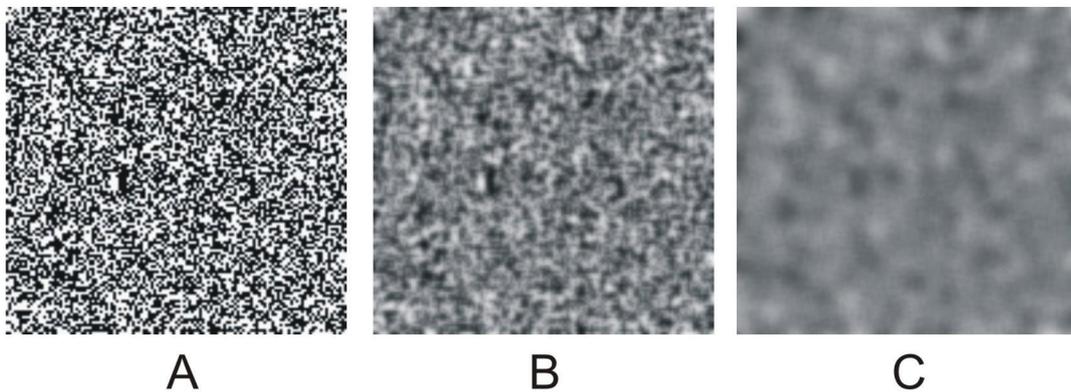
The method was also used for both eyes with a negative overcorrection. In the beginning the stereothreshold was stated without overcorrection. Then, again a negative 2.50 D lens was placed in the front of the right eye and further overcorrection was diminished by a step of 0.50 D to determine the stereothreshold dependence on overcorrection. The presentation time of each stimulus was limited – it was no longer than 30 sec for each lens overcorrection. If within 30 sec time subjects could not recognize the cut-out of the stereoscopic image, then the disparity of the previous correctly named stereo image was the one that counts. For elder subjects that needed correction in the near, visual acuity were additionally monocularly tested with the near table (which corresponds to a 40 cm distance) beginning with +0.50 D up to +2.50 D by step 0.50 D. For younger people it wasn't necessary to determine visual acuity monocularly because having good facility of accommodation, these patients had visual acuity at the distance of 40cm also with negative lenses. However with positive lenses, looking at a distance 40cm accommodation relaxed and the finest test text could still be seen with +2.50 D overcorrection.

This method simulates artificially uncorrected anisometropia of myopia and hyperopia that sometimes is the main reason for development of amblyopia or should arise for subject with increasing of unilateral cataract. The investigators (*Lovasik & Szymkiw* 1985) showed that a stereoacuity of 40 arc sec was possible with 20% aniseikonia, and 50-100 arc sec with 30% aniseikonia in conditions if stimuli were clear. The highest aniseikonia in my experiments was 7% from optical lenses, thus the stereoacuity was influenced by blurring as well by aniso-accommodation.

**Monitor stimuli method.** A random dot stereopair was displayed on the monitor screen (see Figure 3.1 B,C,D). Separation can be realized by colour filters or applying so

called phase separation technique with liquid crystal (LC) goggles. The blurring intensity, contrast and colour were possible to change for stimuli. There used two psychometric methods to measure stereovision – method of limits and method of constant stimuli. Each image of the pair was a square with a smaller square or circle (a segment of which is cut-out) with in its centre. The latter, imperceptible at monocular observation, appeared as a three-dimensional object out of the plane of reference at superposition of the images. The top image was constant during the experiment – it was clear with 50% black and 50% white random dots, the smallest of which was 1 pixel. The bottom image varied from blurred to clear. The program performed 40 series of measurements and the central square in a series was randomly shifted to right or left by 1 to 4 pixels. Within one series each blur image was displayed for 1 sec. The size of the square stereopairs was  $7\pm 0.1$  cm. The size of central squares was  $3.5\pm 0.1$  cm.

The blurred stimuli were formed with the help of *Corel Photo Paint* program using the Gaussian distribution of radius half-width value. The size of the half-width of blurred band changed from 0.1 (the less blurred image No.1) up to 5.0 (the most blurred image No.50) with a step 0.1. Some examples of the blur are shown in Figure 5.1.



**Figure 5.1.** The stimuli of stereotests. A – one eye had sharp image, B, C – the second eye had a successive approximation image from sharp to blur and vice versa. B – 1 pixel blurring, C – 3 pixels blurring with Gaussian filter.

The stereopair images were merged by use of liquid crystal goggles, where one eye sees clear image and second eye bad quality image. In the computerized experiment was used a 15 inch monitor. The measurements were made at artificial illumination of 200 – 400 lx. It has been reported (*Lovasik & Szymkiw 1985, Yap et al. 1994*) that such oscillations of illumination do not affect the stereovision. Subject’s head was fixed during experiment.

The blur threshold at which the stereo sensation appeared was experimentally determined for one eye at different stereodisparities under the condition that the other eye saw a constant image of high contrast. The program fixed the number of the relevant blurring image (the radius of the blur effect). The magnitude of stereovision  $\omega$  (in radians) was calculated from the formula:

$$w = \frac{PD \times \Delta l}{l^2}, \quad \Delta l = \frac{l \times y_p}{PD \pm y_p}, \quad [4]$$

where  $\omega$  is the stereothreshold value (rad),  $y_p$  – the stereo parallax or displacement of images (or disparity) (m),  $l$  – the distance of the fixed point to eyes (m), PD – the pupil distance (m).

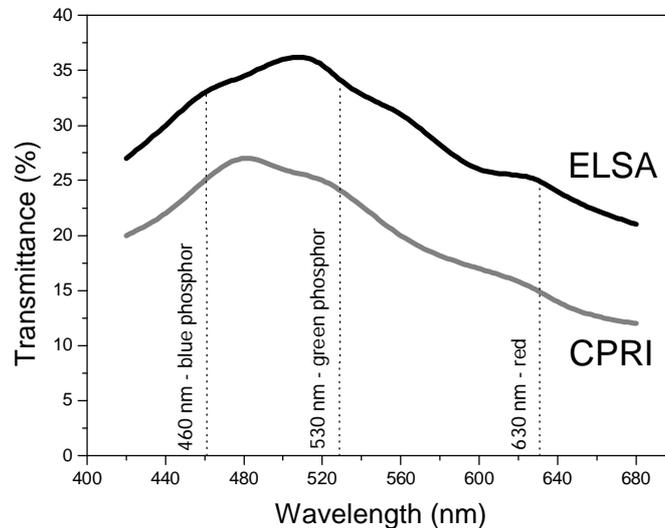
Before the tests the essence of the experiments is explained to subjects and operation of programs is demonstrated. At least five minutes are allowed for a training experiment. Subjects are seated at a distance of  $60\pm 1$ cm from the monitor and provided with liquid crystal shutters or colour filter goggles. As soon as the stereo sensation is experienced the subject takes part in test cycles. He specifies the corresponding forced choice. At a given distance 40 measurements are made in each cycle. The measurements taking about 60 minutes include twelve different disparities: six crossed and six uncrossed.

As different optical materials are used in the studies: light filters, PLZT ceramics, PDLC plate and liquid crystal glasses, it is very important to know the optical properties of each material in the visible part of the spectrum. Light filters are used both in the standard TNO test and in the experiment where the stimuli are shown on the monitor. The transparency of light filters must be the same throughout so, that the intensities of stimuli of the neural signal that reaches the primary visual cortex are also the same. Using the method where people with lowered visual acuity in one eye are trained for stereovision light filters with different transparency are specially chosen. Thus an effect is reached when for the well-seeing eye the intensity of the stereostimulus is reduced. The transparency of the light filter for the well-seeing eye is at least three times smaller.

In the experiment of coloured monitor stimuli it is important to adjust the filters so, that one eye sees only the stimulus of one colour while the other eye sees the stimulus of different colour. If isoluminant red and blue stimuli are formed on the monitor our brains have to perceive them as the stimuli of equal intensity. In standard tests red and green light is used but the green light emitted by the monitor is of very high luminance (see Figure 4.5). Thus it is not adequate to use them in the experiments where it is important to observe the changes in the colour contrast at the formation of stereovision. Another, a more complicated variant is to calibrate and to modify the green light forming an algorithm, where the alteration of the contrast of green light for each intensity of the stimulus is estimated corresponding to the intensity of the stimulus of the other colour. The calibration has its disadvantages, as there remain fewer possibilities to change the contrast of the green light in a wide range. Simpler method uses two monitors and a system of mirrors. Here the monitor luminance can be altered accordingly to preliminary calibration and it is possible to adjust all the contrasts to the light intensities of stimuli.

In monitor stimuli experiments eye separation can be realized by liquid crystal (LC) goggles applying so called phase separation technique, when stimuli for both eyes are displayed periodically for a short while only for the left or right eye. In most cases stimuli are simulated by computer and showed on the PC screen and synchronised by switching LC goggles. LC goggles used in such experiments can be of different quality – the best ones based on ferroelectric liquid crystals. Besides these expensive goggles, one can find in market other kind of LC goggles. They have a lower switching speed, a lower contrast ratio. However due to the great popularity of various virtual reality, mass production of such glasses sharply has decreased their price. The spectral and switching characteristics for LC goggles of different origin are very important in stereovision experiments. If the liquid crystal goggle cell of each eye does not close fully, while the cell of the other eye is already opening, then we can face a situation when both the eyes see the motion parallax of the stimulus. This can help the subject to see the location of the stimulus and other mechanisms will switch on in the brains (the depth perceived from the motion) producing the stereo sensation. Two types of liquid crystal shutters were compared during the investigation: “ELSA” and the shutters of the Institute of Cinematography, Moscow (CPRI). The spectral transparency as well as was the opening-closing velocity controlled by the voltage were assessed for these shutters (see Figure 5.2).

**Eye occluder method.** The situation of cataract is very well simulated in this experiment by using the eye occluders. It is not easy to realize this on the monitor because then we have to produce both the blur and the changes in contrast. The PLZT plate (Ozolinsh *et al.* 1999) becomes less transparent steadily (see Figure 5.3) if the applied voltage is increased. The plate does not produce precisely the same conditions as with the real cataract because as we know cataract can develop both in the periphery of the eye lens and in the central part of the eye lens. In the first case the central vision remains quite good while in the second case it has a great influence on visual acuity. However the light scattering characteristics of such plate is similar as for the people with a blurred eye lens, i.e. the short waves are scattered more and visual acuity decreases in the range of short waves the same way as it does for a subject with a cataract (see Figure 5.4). Visual acuity is determined by optotypes in different colours to assess the visual acuity if a blue colour stimulus is seen on the monitor and the same stimulus is observed through the PLZT or PDLC plates. It is seen in Figure 5.4 that looking through the PLZT plate even without the blur the visual acuity has decreased for the blue optotype. People with real cataract present the same situation.

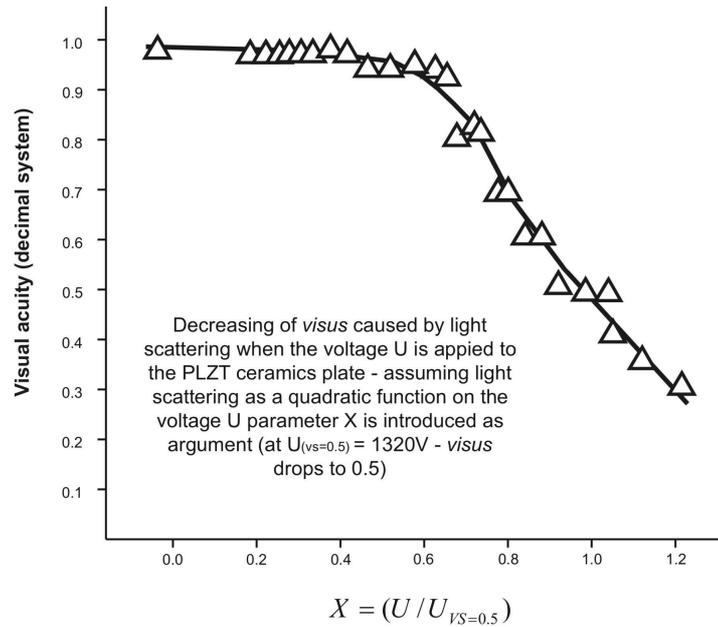


**Figure 5.2.** Open state transmission spectra of two tested nematic liquid crystal goggles ELSA and CPRI. Display phosphor emission maxima are at 460, 530 and 630 nm.

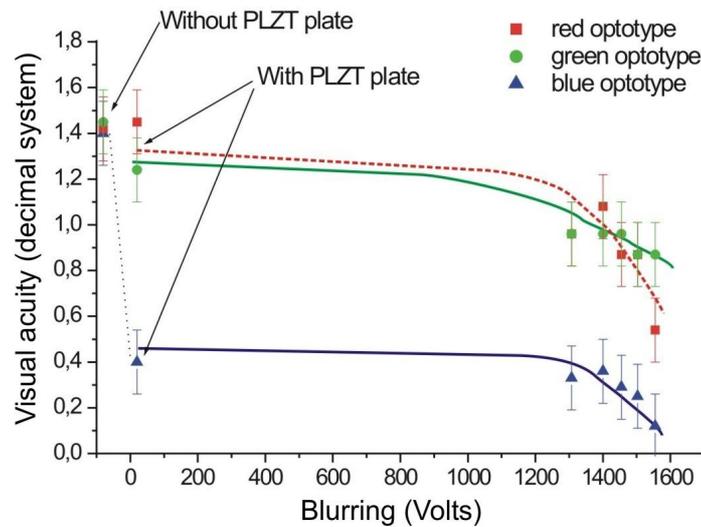
The blue image of the stereopair was chosen as a stimulus with changing contrast partially due to the greater scattering of the blue light present in a cataract case. We have used a test (by displaying Landolt **C** figures with only **R**, **G** or **B** monitor phosphors) to determine visual acuity for three primary colours. The dependence of visual acuity on the light scattering (caused by a special PLZT plate, allowing continuously increase the light scattering depending on the voltage applied to the plate) is shown in Figure 5.4.

The scattered light of PDLC plate is strongly wavelength dependent in visible spectral range. Figure 5.5 shows the spectral dependencies of attenuation of the directly transmitted light. As such plate are used detecting visual stimuli demonstrated on colour CRT, the emission wavelengths of the red **R**, green **G** and blue **B** phosphors are depicted in the same graph. Comparing transparent PLZT ceramics with PDLC plate, the effective scattering coefficient of PDLC is much higher (up to  $3 \times 10^3 \text{ cm}^{-1}$  for blue light), however

the active PDLC layer thickness is much less than the scattering PLZT ceramics plate thickness 1.5mm.



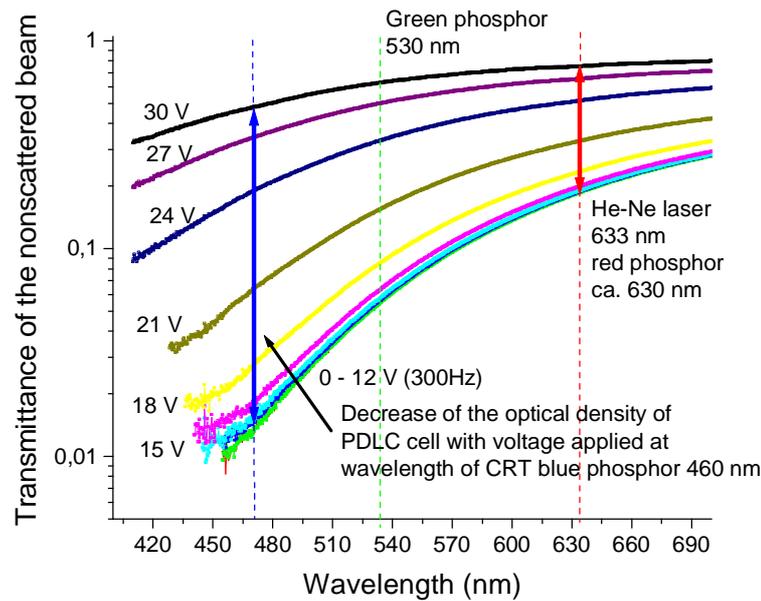
**Figure 5.3.** Visual acuity changes by applying voltage to PLZT ceramic plate.



**Figure 5.4.** Visual acuity determined with three primary colours. Without PLZT plate visual acuity are approximately similar, with PLZT (but without voltage) visual acuity for blue colour to come down with a run.

Visual acuity at different degrees of the induced light scattering was determined from psychometric function using constant stimuli method. In this method subject was forced to choose one of four available orientation of the standard Landolt C demonstrated on PC screen in series with random size and orientation. Scattering has remarkable wavelength dependence, thus we used the following stimuli: high contrast black on white background, black-blue, white-yellow, and white-grey with luminance contrast similar to those of white-yellow stimuli. An eye of humans has a complicated structure of retinal photoreceptors and receptive fields. In the eye central part (*fovea*), responsible of the visual

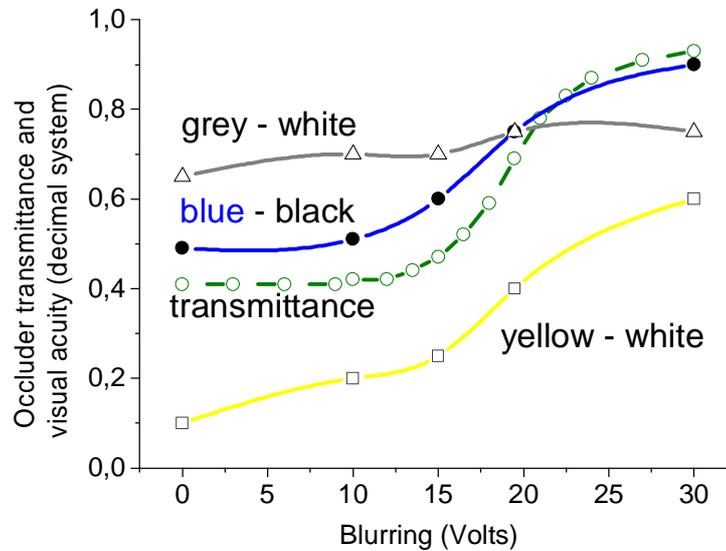
acuity, the density of red (long wavelength **L**) and green (middle - **M**) cones is much higher and intermediate distance much shorter as for blue (short - **S**) cones (Roorda & Williams 1999).



**Figure 5.5.** Spectral dependencies of transmittance of PDLC for directly transmitted light at different voltages applied to the cell. CRT phosphor emission maxima wavelength at 460 (blue), 530 (green) and 630 nm (red) are marked with dashed lines.

Figure 5.6 shows results of three subjects visual acuity obtained in a subjective way. The most drastic decrease of the visual acuity is observed for black-blue (display RGB values – 0,0,0 for black and – 0,0,255 for blue) and for white-yellow (255,255,255 – for white and 255,255,0 – for yellow) Landolt **C** stimuli. In both of these cases the only colour channel participating in stimuli recognition is the most scattered **B** channel. Comparing results for the white-yellow and white-grey stimuli with the same luminance contrast, a lower specific contribution of the **B** channel in white-grey case determined much less decrease of the visual acuity comparing to the white-yellow stimuli.

**Method of stimulation of stereovision.** From the previously determined values of the stereothreshold we have obtained knowledge about the size of horizontal disparity for the stereotests shown to the people with lowered visual acuity in one eye to stimulate the formation of stereovision. The stimulus of the well-seeing eye is also blurred by the Gaussian filter using the conversion table (see Table 4.1), which shows the relationship between the quality of the stimulus and the optical power of the lens, visual acuity and the blur in pixels. The stereodisparity is chosen a little larger than the determined values of stereothreshold in cases of induced amblyopia or cataract. To stimulate the stereovision applying the liquid crystal shutters uses a method of phase shifting. If the stereovision is obtained by this method then the stereothreshold is determined once again using the clinical TNO stereotest at first allowing to hold the test plate nearer than 40 cm and look for so long until the stereo image is seen. To specify the stereothreshold the test is placed at a correct distance and stereovision checked one more time.



**Figure 5.6.** Occluder transmittance and visual acuity vs. voltage applied to PDLC cell. Stimuli: high contrast blue on black background, low contrast (10%) white on grey and white on yellow background.

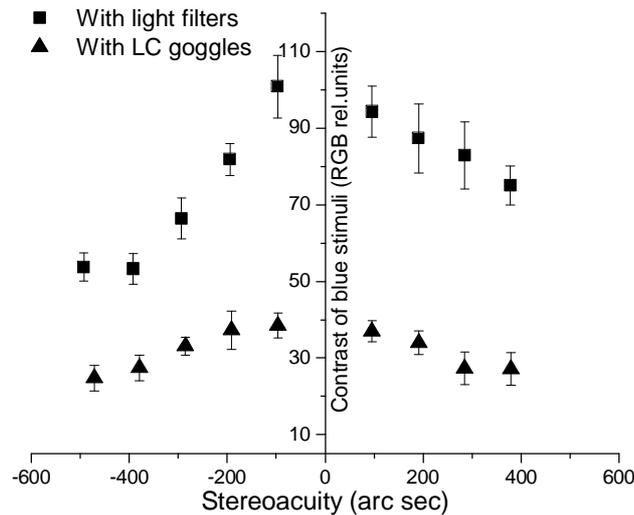
To simulate the lowering of visual acuity in one eye and to assess the formation of stereovision in a real situation caused by amblyopia, cataract or uncorrected anisometropia three different methods were used. Using the method of defocusing the vergence of image in one eye is altered by optical lenses thus simulating the uncorrected anisometropia. In this method it is not possible to eliminate aniseikonia of the images produced by optical lenses the number of which does not exceed 7% in this study and according to references (Lovasik & Szymkiw 1985) it is of no great importance.

In the method of monitor stimuli the contrast or blur is being changed. By this method better comfort is achieved for the subject because lenses create a little chaos in the process of accommodation for a short period of time. Using this method it is not possible to simulate the optical differences of the eye but the blur simulates the lowering of visual acuity in one eye. In the third method to worsen the quality of stimulus the eye occluders are set between the eye and the stimulus (PLZT and PDLC plates). Thus the progress of cataract is simulated in one eye and the values of stereothreshold are estimated for a stimulus of bad quality. By this method we can well observe that visual acuity decreases more rapidly in the range of short waves (blue stimulus) that is characteristic for a blur of the lens in the case of cataract. The changes of visual acuity in one eye that influence the stereothreshold are shown in Figure 5.4 and 5.6.

Statistical analysis including correlation coefficient (probability  $r^2$ ), t-test of all results were performed with personal computer programs *MS Excel* and *Microcal Origin*.

## 6. Results

In the method of monitor stimulus different methods to induce the stereosense (light filters and use of liquid crystal glasses) and wide choice of different stimuli (squares and circles with a cut-out) were used. The colour contrast threshold of stereovision experimentally determined by method of limits using light filters for stimuli separation are higher than using the liquid crystal glasses. The transparency of glasses is comparatively larger than that of light filters (see Figure 6.1). This is a serious condition when studying the threshold of colour stereovision.



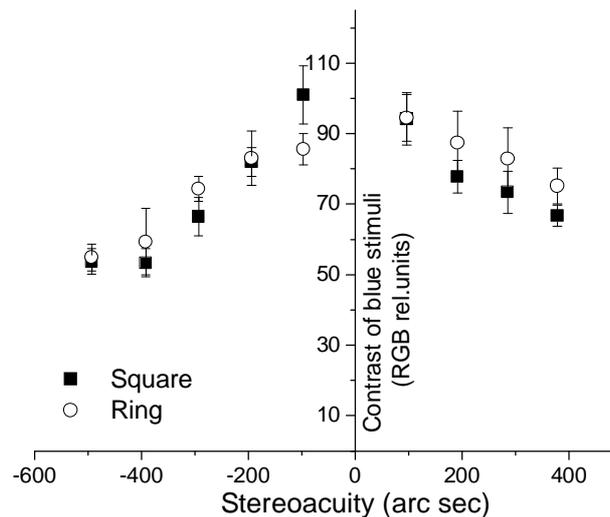
**Figure 6.1.** Colour contrast threshold values were determined by changing blue colour contrast and stereodisparities, and stereosense was stimulated using colour filters and LC shutters.

Concerning first results of studies of the colour contrast effect on stereothreshold, here the best of all is to use liquid crystal glasses. It was concluded also during the study that the choice of objects for the test gives little diversity. Statistically it is of no importance ( $p > 0.1$ ) whether the stimulus to be shown is chosen as a simple object (square) or more complicated (circle with cut-out). The obtained results with stereo images of different stimuli type are given in Figure 6.2. After control experiments of the testing equipment and the initial inspection, experiments have been carried out to determine the threshold values of colour contrast at fixed stereodisparity with one colour (blue) stimuli contrast change.

In the first test series the contrast of the stimulus was changed continuously – the threshold was determined by method of limits with stimuli being separated by colour filters. Results obtained for five subjects at repeated tests with square stimuli are shown in Figure 6.2 (black square). In the second test series the hidden stereo image was the circle with sector cut-out. The blue colour contrast changed continuously, and subject should respond if he could catch direction of cutting circle sector. The results using circle stimuli are showed in Figure 6.2 (open circle). With respect to dispersion, results obtained using constant stimuli method with circle stimulus are not much different from the square stimulus test with colour filters. A lasting attention is required from subjects during experiments when approaching the contrast threshold of stereovision gradually (method of limits). Besides, due to binocular rivalry, – the dominating tint of the perceived binocularly

colour stimulus periodically varies. This “pumping” of colours is one of the factors causing a rather wide dispersion of results since the subject has difficulties to concentrate.

Afterwards the values of the threshold of colour contrast at different stereodisparities for subjects were determined at variable blue stimulus contrast by determining the threshold values using the method of constant stimulus. At great disparities about 500 arc seconds the psychometric functions are steep (see Figure 6.3) and the determined blue colour contrast threshold is with lesser dispersion. The disparity being decreased the psychometric curves are sloping, and the obtained values of the threshold have less credibility. Also in this series of experiments the results obtained with the circle stimulus are of little difference from the quadratic stimulus test using coloured light filters.

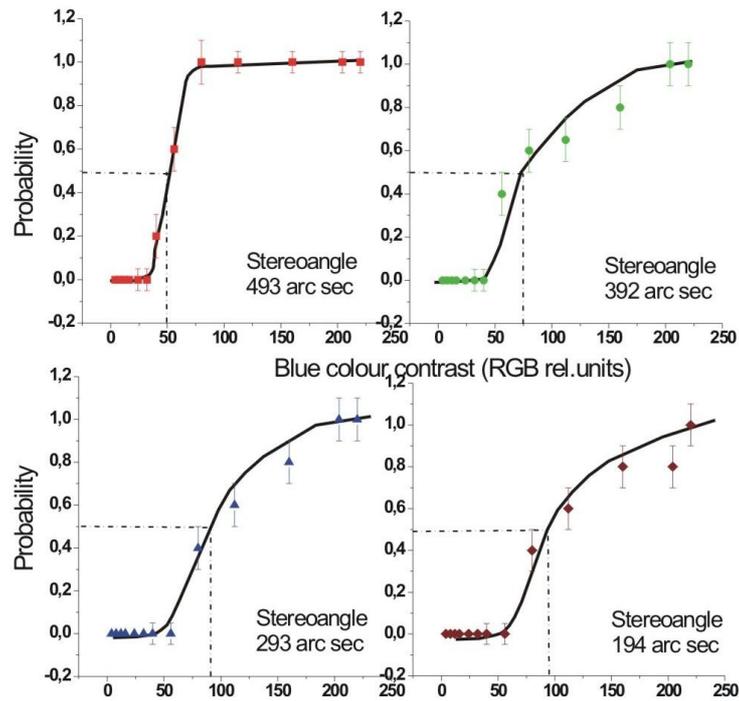


**Figure 6.2.** Using method of limits colour contrast thresholds for colour stimuli are determined with different type stimuli (square and circle with cut-out sector) at different stereodisparities. Results obtained with circle stimuli are not much different from the square stimuli test ( $p > 0,1$ ).

Using liquid crystal shutters it was possible to soften the effect of binocular rivalry on the perception and on results of the experiment, and we partly succeeded. The comfort of observing improved, and dispersion of results, compared with demonstration of similar stimuli separated by colour filters, decreased (see Figure 6.1).

The stereogram disparity is one of parameters affecting the contrast threshold of stereovision. The value of the stereothreshold  $\omega$  [4] (stereodisparity given in angular units) calculated from the pupil distance ( $PD$ ) and the distance of subject from the screen is small. By changing the  $PD$  from 55 mm to 70 mm the corresponding change of the stereothreshold is less than 1% within a fixed viewing distance between 45 cm and 180 cm. A more effective factor is the monitor pixel size – the change of the dot size on the screen from 0.28 mm to 0.27 mm gives a difference  $\approx 4\%$ . Subject head was fixed in range  $\pm 1$ cm that gives 3-4% error. For the screen stereo parallax measured in pixels (if the monitor horizontal and vertical scanning are calibrated correctly) the corresponding crossed and uncrossed stereodisparities for different operating distances are given in Table 6.1.

In most studies of effects of monocular contrast on stereovision (*Wilcox & Hess 1998; Rohaly & Wilson 1999*) relation between the contrast and stereodisparity threshold is described by a power function and data are analyzed in the logarithmic scale. As in our experiments a comparatively narrow range of disparities was analyzed it was assumed that the connection between the stereothreshold and the blur or contrast of the stimulus in this district could be called linear. Thus I could do the analysis in linear coordinates. In Figure 6.4 we can see the average values of the contrast threshold (alterations of black-white and blue contrast) of the monocular image for all 11 subjects averaged at each demonstrated stereostimuli disparity.



**Figure 6.3.** Psychometrical measurements with constant stimuli. Colour contrast thresholds are showed with dashed lines.

**6.1. Table**

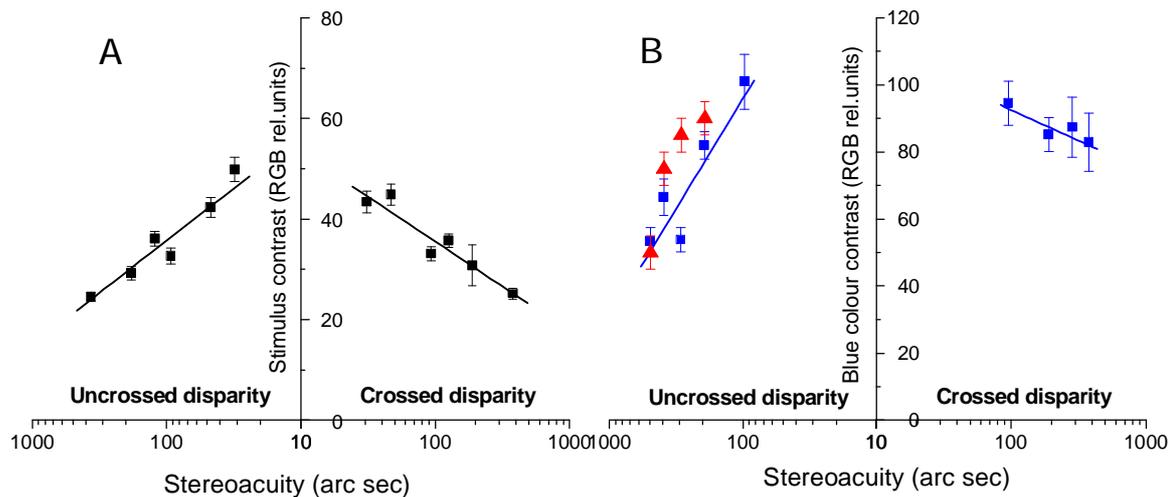
**Dependence of stereothreshold value on distance to monitor and disparity type**

Distance between monitor and subject	Image deviation in pixels									
	Uncrossed disparity					Crossed disparity				
	5	4	3	2	1	1	2	3	4	5
0.45 m	606"	487"	367"	246"	123"	124"	250"	376"	504"	633"
0.60 m	454"	365"	275"	184"	92"	93"	187"	282"	378"	475"
0.80 m	341"	274"	206"	138"	69"	70"	141"	212"	284"	356"
1.20 m	227"	183"	138"	92"	46"	47"	94"	141"	189"	237"
1.80 m	151"	122"	92"	61"	31"	31"	62"	94"	126"	158"

Average values of stereothreshold in cases of crossed and uncrossed disparities. Stereothreshold values are calculated for the condition that the distance between the pupils (PD) is 62 mm and the values of monitor pixels are 0.27 mm. All working distances used during the stereotests are given in the Table.

The technique used in our experiments allows to assess both the coarse and fine stereovision both for crossed and uncrossed disparity. Random-dot stereograms exclude any indications where the stereo image is going to form when looking only with one eye.

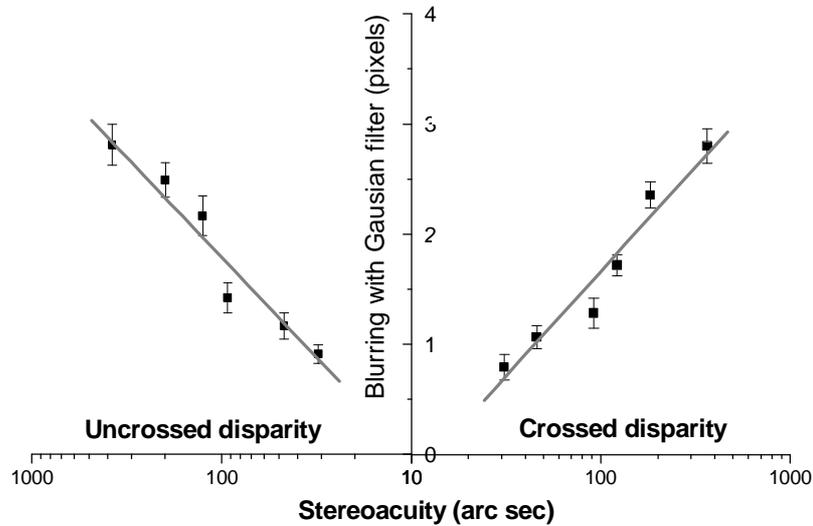
Using this method it is possible to create artificial conditions for amblyopia and cataract where the degree of blur of the stimulus changes on the monitor. It is concluded in the investigation that the stereothreshold increases both in the case of crossed and uncrossed disparity if the intensity of blur of the stimulus increases in one eye (see Figure 6.5).



**Figure 6.4.** One eye stereostimuli contrast thresholds at different stimuli stereodisparities were determined using method of limits. A – greyscale stereotest results; B – red-blue stereotest results. Colour contrast was measured in RGB relative units (colour coding system units from 0 to 255). The red triangles (in B) show the blue colour stimuli contrast thresholds that are appreciated with the constant stimuli method.

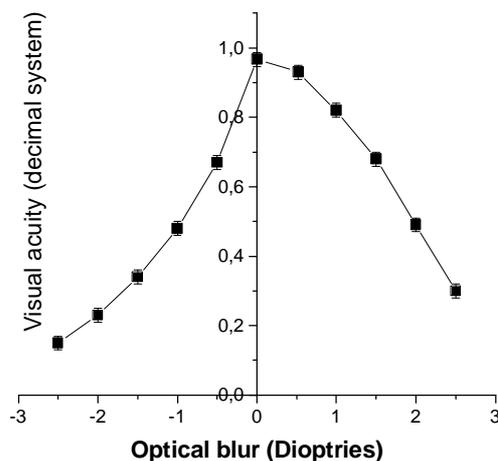
In other experiment part we have assessed also the decrease of visual acuity applying overcorrection with additional lenses for elder patients. Younger people have large facility of accommodation; they can compensate the effect of negative lenses. To avoid this one need to apply cycloplegia to block eye accommodation. Results of applying of overcorrection on monocular visual acuity are shown in Figure 6.6. It is seen that applying the negative overcorrection causes stronger decrease of the visual acuity as compared with positive overcorrection. That occurs in spite of that values the average of modulation depth of the blurred images are equal if blurring is performed either by positive or negative lenses – blurring degree is similar (see conversation 4.1 Table). However positive lenses little increase the size of retinal image comparing with action of negative lenses and the spatial resolution of eye stays higher for stimuli blurred by positive lenses.

In the next part of the investigation the stereothreshold was assessed under the conditions of artificially produced uncorrected anisometropia and the obtained results compared with the data obtained for the clinics patients in the situations of real amblyopia and cataract. Uncorrected anisometropia can be the cause of amblyopia and facilitates the progressing of cataract in one eye.



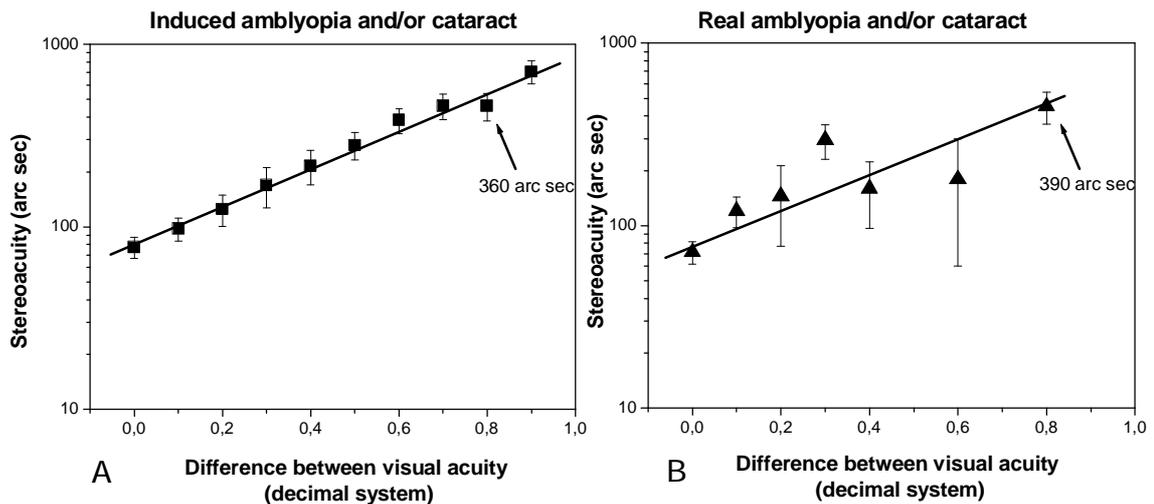
**Figure 6.5.** Relationship between stereothreshold and stereodisparity values when one of the stereopair image demonstrated on PC screen is blurred using Gauss filter for two kinds of stereodisparities – crossed (right side of graph) and uncrossed (left side of the graph) disparities.

Considering the obtained results for more than one hundred subjects on the influence of artificial amblyopia on the quality of stereovision one can see a pronounced diminishing of the stereoacuity on difference in the both eye visual acuity (close to linear in the reference frame  $\log(\text{stereothreshold})$  vs. difference in visual acuity). For the visual acuity difference  $\Delta VS=0.8$  (decimal) the stereothreshold value is  $360 \pm 50$  arc sec. For patients with real amblyopia and cataract the stereothreshold value at  $\Delta VS=0.8$  equals to  $330 \pm 90$  arc sec (see Figure 6.7). Though there are subjects whose stereothreshold under conditions of real amblyopia or cataract can be even lower than in cases of induced amblyopia or cataract. This is clearly seen in the graph (see Figure 6.7 B) that in real cases the dispersion of values is bigger than at the lowering of induced visual acuity of one eye.



**Figure 6.6.** Dependences of visual acuity on optical blur using monocular overcorrection.

At induced anisometropia we have observed a tendency that the decrease of stereoacuity depends on the eye refraction (hypermetropia, myopia) (see Figure 6.8). If there is emmetropia in one eye and hypermetropia in other then for the difference of eye refraction 2.5 diopters the stereothreshold is very low – about  $530 \pm 35$  arc sec. The artificial simulation of hypermetropia is carried out using negative optical lenses, which form a sharp image behind the retina and a dim image – on the retina. Contrary, if the individual has emmetropia in one eye and myopia in another, then the stereothreshold at same 2.5 diopters refraction difference equals to  $214 \pm 21$  arc sec (see Figure 6.8).



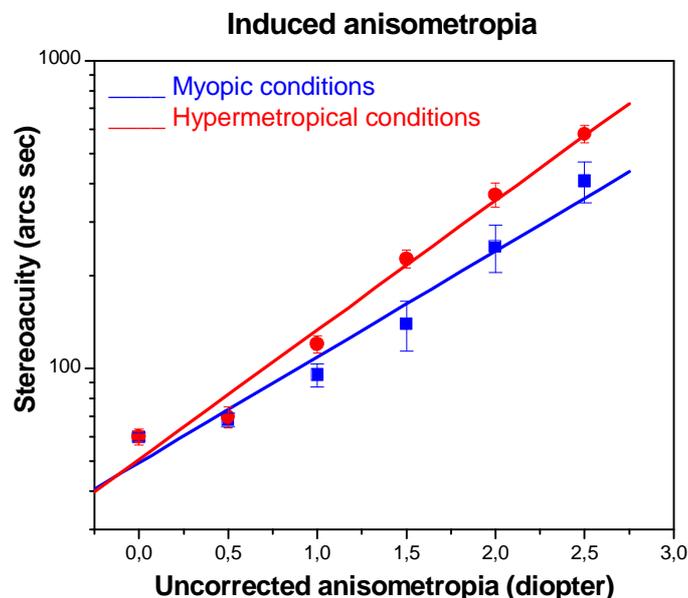
**Figure 6.7.** Dependence of stereothreshold – minimum resolved stereodisparity in arc sec on difference between the left and right eye visual acuities: A – for subjects without eye pathologies when amblyopia was induced by blurring one eye retinal image using positive and negative lenses, B – for subjects with real amblyopia and cataract.

It means that in cases when the difference of the left and right eye visual acuities is very big we could predict that an approximate stereothreshold is comparatively high and tests and trainings of stereovision is reasonable to begin at high stereothreshold. For such patient having the primary binocular level determined by *Schober* and *Worth* tests we would still predict the presence of the coarse stereovision.

In order to diminish the great eye dominance of amblyopic subjects we have used stereostimuli phase separation. It was accomplished alternately switching stimuli for the left and the right eye with the liquid crystal goggles. Here even PC frame sequence displays stimuli for stimulating the right eye and the odd sequence – for stimulating the left eye. The alteration of sequences is sequential and quick in order not to destroy the perception mechanism of binocular vision. Such separating of stereo images forms compulsory conditions so that both images – the clear and the blurred one reach the brain and possibly are not suppressed at once.

Three subjects with a high degree of amblyopia were involved in the experiment stimulating the stereovision. The cause of amblyopia is hypermetropic anisometropia. The difference in both eye refraction for all the subjects is in the range 2.0-2.5 D. Three subjects have low binocular vision, and in the beginning of experiments stereovision using the clinical TNO stereotest was not diagnosed. Then the subjects were asked to look at the monitor at the displayed stereotest using liquid crystal glasses. The images had a great horizontal stereodisparity (1000-2000 arc sec). The procedure of teaching subjects with amblyopia to recognize stereo images had several stages. At first subjects looked at these

tests for a long time (40-60 seconds) trying to catch sight of the hidden depth object. The initial stereodisparity of the random-dot stimuli was within the range of 1000-2000 arc sec. The following actions was taken in further steps: a) the stimulus for the well seeing eye was blurred, and subjects should to look for a long time at the stereotest; b) the stimuli for both eyes were blurred. When the stereosense was eventually provoked, it was checked once again with the clinical TNO test. Besides a neutral filter was applied in the front of the well seeing eye. Bringing the test plates closer to the eyes continuously enlarged the stereodisparity, and that could be more to stimulate stereovision. Afterwards the plates were held at the correct distance and the stereoacuity was assessed repeatedly. Results for three subjects are given in Table 6.2. Besides the steps of the procedure outlined above, the well seeing eye was deliberately covered with a lens blurring the stimulus. Placing in the front of the better seeing eye a filter reducing the stimulus luminance much below the bad seeing eye stimulus luminance turns out as contributory means. Such action diminished neural activity flowing out of the non-amblyopic eye, and similarly the dominance of this eye could be depressed for the reasons described above.



**Figure 6.8.** Stereothreshold dependences on induced anisometropia by positive lenses (myopic conditions) and by negative lenses (hypermetropic conditions) placed in front of one eye. One can see that in induced hyperopic anisometropia stereothreshold increases more rapidly as in conditions of induced myopic anisometropia ( $p < 0,05$ ).

In the clinical study when assessing the stereothreshold 223 subjects were tested, divided into three age groups. The visual acuity for all was not less than 0.9 (decimal system). Each subject had an individual minimal stereothreshold at which he could distinguish the depth effect and see the details in the image. From the graph (see Figure 6.9 A) it can be concluded that a subject in the advanced age has a higher stereothreshold than young subjects. However, the visual acuity 1.0 does not mean that subjects will have a very good stereothreshold (see Figure 6.9 B). It can be seen from the obtained data that the most frequent value of the stereothreshold for participated subjects lies within 60 to 120 arc sec.

Using the method of defocusing with 125 subjects under study it was concluded that in 50 % of cases the stereothreshold lowers after the experiment (it lasted *ca.* 20 minutes),

i.e. the procedure of the experiment works like a stereovision training improving stereoacuity. During this time the subject learns to concentrate and to distinguish the finest details of the stereo image (the cut in a circle).

Table 6.2.

**Obtained results in method of stimulation of stereovision**

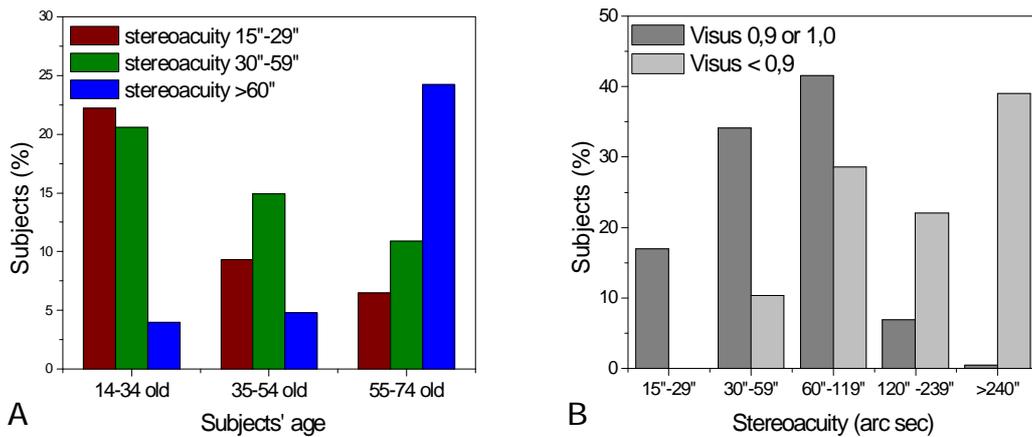
	Stereovision with TNO test before experiment	Stereovision with new method	Stereovision with TNO test after the experiment
<b>Subject 1</b>	Not found	Forms in 5-10 minutes	Sees 480''-240''
<b>Subject 2</b>	Not found	Forms in 5-10 minutes	Sees 480''
<b>Subject 3</b>	Not found	Forms in 20-25 minutes	Sees 480''-800''

The obtained values of the stereothreshold for three subjects after the method of stimulation of stereovision.

Data from blurring degree and contrast changes of one eye are presented in a semilog graph. Averaged data lie along a straight-line for positive as well for negative lenses, for applied voltage or for values of pixel with a slope coefficient  $k$ :

$$k = \frac{\Delta \log y}{\Delta x}, \quad [5]$$

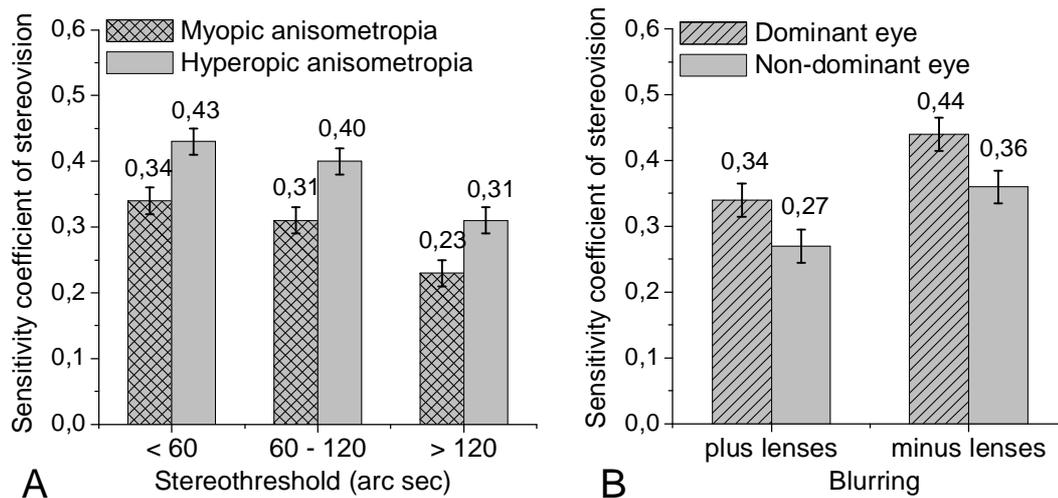
where  $y$  – stereothreshold (arc sec),  $x$  – parameter that characterizing the degree of stereostimuli blurring or contrast decreases,  $k$  – the coefficient. Parameter  $k$  can be defined the sensitivity coefficient of stereovision, which characterizes the fastness of change of the stereothreshold according to the intensity of contrast or blur. Analysing the obtained values of the sensitivity coefficient of stereovision it can be concluded that it depends on the subject's age, initial stereoacuity (at zero overcorrection) and on other factors.



**Figure 6.9.** A – stereothreshold values for all subjects participated in our studies. B – stereothreshold of 300 patients. Data reveals that a good visual acuity not always is a satisfactory demand for well developed stereovision. One interpretation of that would be insufficient vision training, due to the lack of need for high vision stereoacuity in everyday conditions.

This sensitivity coefficient of stereovision  $k$  depends on the initial minimal value of stereothreshold under other factors. For example, if the subject's initial stereothreshold is 30 arc sec, then in this case the coefficient will be larger, i.e. the line characterizing the process will be steeper (see Figure 6.10 A). Using this coefficient we can easily characterize the alterations of the stereothreshold under other factors. For example, how does the blur in the dominant eye change the stereothreshold in comparison with the

monocular blur in the non-dominant eye. Similarly using this coefficient it can be stated how much hypermetropic anisometropia influences the stereothreshold in comparison with the myopic uncorrected anisometropia (see the calculated sensitivity coefficients of stereovision) if the blur is placed in front of the dominant eye or the non-dominant eye (see Figure 6.10 B). Experimentally we obtained that doing monocular overcorrection the eye dominance played role, there is statistically significant ( $p < 0.05$ ) difference in the values of the stereovision sensitivity coefficients if blur is applied to the dominant or non-dominant eye.

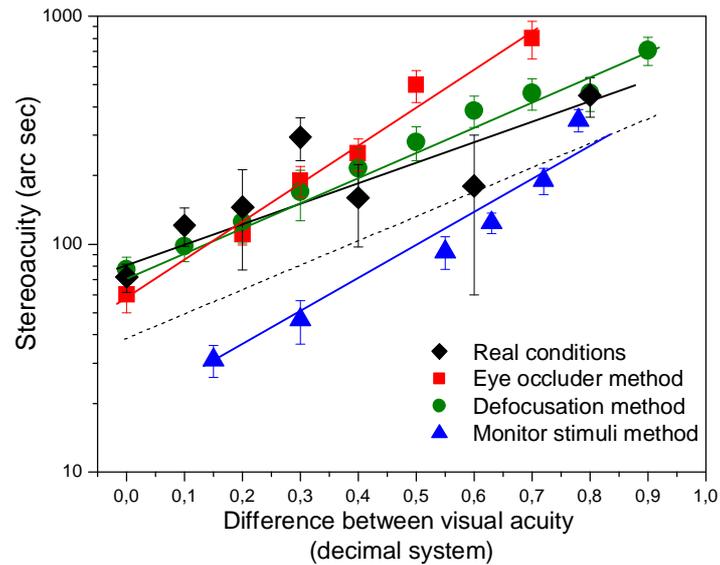


**Figure 6.10.** The sensitivity coefficients of stereovision in myopic and hypermetropic anisometropia conditions (A) and of monocular overcorrection of the dominant and non-dominant eye (B). It is seen that stereovision is more sensitive to overcorrection of the dominant eye as of the non-dominant eye; statistically significant values ( $p < 0.05$ ).

In Figure 6.11 there is a summary for all the methods applied to assess the value of stereothreshold performing different blur conditions. We can conclude that the highest stereothreshold is assessed blurring with eye occluder that simulate the cataract (see Figure 6.11 – squares). In this graph the unifying value is the distinction in visual acuity. From here it follows that for people with cataract the stereothreshold increases due to combination of the blur and reduced contrast. However, using the method of defocusing the value of stereothreshold changes only under the influence of blur. Thus we can calculate the value of the influence of contrast between two curves in the case of cataract.

Considering the determined values of the stereothreshold at different blur using the method of monitor stimuli and taking into account that one group of subjects of the experiment were with very good stereothreshold (about 30 arc sec), one can observed a tendency that the stereothreshold for these subjects due to blurring increases faster than for subjects whose average stereothreshold at zero overcorrection is about 60-80 arc sec. Thus also the sensitivity coefficients of stereovision calculated for these two groups have different values. Comparing values of the stereothreshold obtained in our studies with quoted in references, and particularly for data obtained by TNO test with colour stimuli and colour filter separation, one should always take into account differences in threshold values obtained using colour filters and liquid crystal glasses (see Figure 6.1). Here the assessed stereothresholds with colour filters are almost greater than those with liquid crystal glasses.

Thus the values of stereothresholds obtained by TNO test are greater as prospective for the case when they would be assessed with equivalent black-white test in conditions of uncorrected anisometropia (see Figure 6.11 – the dashed line shows the approximate stereothreshold if TNO test would be substituted with an equivalent black-white test).



**Figure 6.11.** Stereothreshold values assessed using techniques of the present studies. Diamonds – for subjects with real diminished visual acuity of one eye, squares – thresholds using light scattering eye occluders, having the highest values, circles – using defocusing with optical lenses, triangles – using monitor stimuli method. Dash line shows prospective stereothreshold values for TNO test if red-green test would be substituted with black-white test.

So all the methods on equal conditions would produce the same results, which coincide with real stereothresholds for the subjects with amblyopia and/or cataract. It should be noted that the method of eye occluder could be very well used to simulate cataract and to study vision functions.

## 7. Discussion

The aim of the study was to assess the values of the stereothreshold if the visual system is stimulated by the stimuli of different quality in each eye and the quality of the stimulus in one eye is altered. To realize this it was necessary to study the applications of different methods in the assessment of the stereothreshold. The different methods used during the research to determine the values of stereothreshold gave the possibility to obtain a wide field of information.

In addition of disturbances of mechanisms, which underlay stereopsis, stereoacuity can be reduced by optical, sensory and motor aberrations, which degrade the stimulus for stereoscopic depth discrimination. Optical factors such as cataract, ametropia and aniseikonia produced measurable loss of stereoacuity. The main criterion in such situations is visual acuity. If cataract is formed up in the centre of eye lens than visual acuity decreased very quickly and stereoacuity is lost or very poor (*Scarpattetti* 1983; *Katsumi et al.* 1992; *Kwapiszewski et al.* 1996; *Sucker et al.* 2000). The difference between both eyes optical system (anisometropia) could be produced aniseikonia on the retina. Aniseikonia is another factor that initiates interocular suppression and a loss of stereovision sensitivity in the central visual field (*Lovasik & Szymkiw* 1985; *Jimenez et al.* 2002; *Holopigian et al.* 1986).

Using the defocusing method the uncorrected conditions of anisometropia can be well simulated that is impossible to create on the monitor screen. Very small optical differences between the eyes can cause the process of aniso-accomodation, which is mentioned as a positive contribution to development of the fine stereovision (*Marran & Schor* 1998), especially if the observable object lies nearer than 40cm, when then the aniso-accomodation is more pronounced (*Marran & Schor* 1999). However a subject looking with one eye through an additional optical lens still has a slight feeling of discomfort because aniseikonia has been formed all of a sudden. It is not great, in these studies the greatest reaches 7% but for a moment it gives unpleasant feelings. This feeling can be well avoided with the method of monitor stimuli where the stimuli have equal linear size. Here the intensity of blur or contrast of one image changes. As an unpleasant side effect in this method is switching of frames not seen by a human's eye, however existing in neural signal flow. There are subjects who have had a feeling of discomfort using the liquid crystal glasses for a long time. Consequently the duration of the experiment was shortened reducing the number of measurements introducing greater scatterings of results.

Using the occluder method the situation of cataract is easily simulated and we could not study only the formation of stereovision but also other visual functions. It should only be remembered that in real life the manifestation of cataract could be very different. Cataract can be with blurs in the periphery, which do not influence the central visual acuity and stereovision. If the cataract has formed in the central part of the lens then the visual acuity decreases fast and stereovision also changes. The authors measured aniseikonia and stereoacuity in patients with both bilateral and unilateral posterior chamber intraocular lenses and have concluded that average stereoacuity evaluated with *Titmus* test was less than or equal to 100 arc sec (*Scarpattetti* 1983; *Katsumi et al.* 1992), but it depends on the lens implant and on the success of positive results cataract operation.

*Scarpattetti* (1983) quoted the mean stereothreshold values after successful cataract surgery equalled to 480 arc sec detected with TNO test. If the cataract develops in one eye and its visual acuity decreases down to 0.5-0.1, then it is an indication to have an operation though the visual acuity of the well seeing eye is 1.0. Comparing the data before and after

the operation *Kwapiszewski et al.* (1996) and *Sucker et al.* (2000) concluded that the stereoacuity improved for most of subjects as well the second operation need to be done if the first was not successful (*Elliott et al.* 2000).

*Larson* (1988) investigated that local stereoacuity was reduced when red-green TNO anaglyph glasses were worn. Such reduction ranged from 2 to 34 arc sec. Stereoacuity has been reported decreasing significantly in the seventh decade of life. Results of *Lovasik & Szymkiw* (1985) and *Yap et al.* (1994) suggest that the reduced retinal illuminance resulting from normal ageing is not a cause of the decreased stereoacuity found with ageing.

From literature data (*Hofstetter & Bertsch* 1976; *Coutant & Westheimer* 1993; *Brown et al.* 1993) it is known that stereovision in age range 8 to 50 is very good, subjects are able to see a depth difference at horizontal disparities of 2 arc min or smaller and in the age range 20-25 stereoacuity is achieving a maximal sensitivity. In studies *Brown et al.* 1993 and *Schneck et al.* 2000 was found that stereoacuity declines for subjects with age over 50-60 years. This loss of stereoacuity after age 60 could be due to a decrease in the optical quality of the retinal images (*Brunette et al.* 2003). The decline in the modulation transfer function (MTF) of the optics of the eye takes place for subjects between ages of 20 to 70 years. Wave aberrations of the eye increase with age and this increase is consistent with the loss of contrastvision sensitivity for subjects' age from 61 to 82 years (*Guirao et al.* 1999; *McLellan et al.* 2001). The relative contributions of optical and neural factors to the decrease in visual function with aging were investigated by *Greene & Madden* (1987), *Schneck et al.* (2000), *Scialfa et al.* (2002) and *Pardhan* (2004). Authors have detected some loss of contrast sensitivity due to changes in the central nervous system for subjects elder as 60 years. A decrease in stereoscopic vision performance, particularly in people over 60 years of age, has been described as degenerative changes of the visual pathways – the visual cortex loses its cells. The cells, which remain have fewer synapses and fewer receptor sites (*Marshall* 1987).

In many studies researchers have used various stereotests and their results differed each from other. However experimentally it is detected that for selected subjects under the best conditions, stereoacuity lies within the range 2 to 6 arc sec (*Westheimer & McKee* 1978; *Bach et al.* 2001). Most of human population has stereoacuity 120 arc sec or better – about 97% of adults, and 80% of them have a stereoacuity of 30 arc sec. But that is very important to consider which methods are used by authors estimating the stereovision of adults and children, because diverse methods give different results (*Lovasik & Szymkiw* 1985; *Goodwin & Romano* 1985; *Broadbent & Westall* 1990; *Hatch & Rickman* 1994; *Schmidt* 1994; *Ciner et al.* 1996).

It is mentioned in literature that a higher stereothreshold is detected in the case of uncrossed disparity in comparison with the stereothreshold level formed by the crossed disparity (*Woo & Sillanpaa* 1979; *Landers & Cormack* 1997), because stereoacuity of crossed disparity develops earlier (*Birch & Gwiazda* 1982) but at approximately the same rate as stereoacuity of uncrossed disparity. *Richards* (1970, 1971) estimated that about 30% of the population have a stereoanomaly. Stereoanomalous subjects have stereovision either at only crossed or only at uncrossed disparities. Revealing of stereoanomaly is possible only with special tests (*Larson* 1990; *Van Ee & Richards* 2002; *Van Ee* 2003), but all clinical tests are based on crossed disparity stereovision. However also stereoanomalous subjects can see these stereotests. They still can compensate one disparity type with other, however it takes longer time to see stereotests. Other explanation (*Becker et al.* 1999) is that differences between crossed and uncrossed disparity is from effects related to occlusion. *Lam et al.* (2002) showed results that suggest stereoacuity can be effect by

heterophoria. Subjects with orthophoria have the best stereoacuity, followed by subjects with exophoria and esophoria. Exophoric subjects have a better crossed than uncrossed stereoacuity. For esophoric subjects it is not yet known which stereodisparity crossed or uncrossed can be better perceived. In my opinion the stability of bifocal fixation and the mechanism providing it are of great importance.

In the studies of stereovision the subjects had to look at stereotests for a very long time in order to assess the stereothreshold. Both the accommodation of the eye and eye movement muscles participate in the formation of spatial perception. That is how we can explain the weariness of eyes continuously looking at the stereo images (*Fisher & Ciuffreda* 1988; *Koh & Charman* 1998; *Takeda et al.* 1999). Using the light filters the subjects experience additional binocular colour rivalry (*Boynton & Wisowaty* 1984; *Erkelens & Van Ee* 2002; *Van Lier & De Weert* 2003), i.e. occasionally the image turns in one colour, then in another. That can influence the stereothreshold in the experiments of the colour contrast because the subject has to exert hard himself to concentrate. In its turn comparing the test results with different stimuli shape – a circle or a square then here we do not have any differences. Using the liquid crystal glasses we can reduce the effect of colour “pumping” and the obtained stereothresholds are also lower.

*Livingstone & Hubel* (1987) and *Simmons & Kingdom* (1997, 1998, 2002) try to explain how the chromatic contrast influences stereoscopic judgments. One way – the influence of colour contrast is artifactual. Second way – chromatic- and luminance-contrast-sensitivity mechanisms summate linearly before stereoscopic judgments are made. The third is that chromatic and luminance mechanisms summate nonlinearly before stereoscopic judgments. The fourth way – there are separate mechanisms for chromatic and luminance stereopsis that influence each other only by virtue of probability summation. It could be one reason of great deviations in perceiving of colour stereotests. Subject needs to be more concentrated as in greyscale stereotests.

The liquid crystal glasses are more transparent comparing with colour filters, sequently, the loss of intensity of the stimulus also decreases. The obtained types of stimuli and responses also differ. If the subject has to choose between the preferences whether he sees something or not, then in this case the subject can notice something and press the keyboard button at once. But if the task is made more complicated then the subject has to state whether the image is inwards or outwards or to state the direction of the circle cut-out sector. Thus more precise values of the stereothreshold are determined.

When doing the colour stereotest the subject experienced unpleasant feelings created by binocular rivalry, the colour of the image changed – first blue, then red. Thus the subject could not do the experiment for more than twenty minutes at a time. Considering the anatomical structure (formation) of the retina it is known that cones perceive only colour. **L** cones sensitive at the long wave range perceive pulses at highest degree if the stimulus is in the red wave range of the visible light. **S** cones sensitive at the short wave range react only if the stimulus is within the blue light wave range. The **S** cones in blue are less in number on the retina (*Roorda & Williams* 1999), and a hypothesis is being considered that while looking at colour stereotests only some disparate fields forming the stereovision participate in the perception of the stimuli. If the subject looks at black and white stereotests then in this situation all the disparate fields of cones creating the stereovision participate. Thus the determined contrast threshold for the black-white stimuli decreases more than for colour stimuli when one stimuli contrast is changed. *Kingdom & Simmons* (1996) obtained that stereothreshold is higher for chromatic stimuli as compared with isohromatic stimuli

If stereoacuity is determined with a colour test then the obtained stereothresholds are higher, i.e. stereovision is worse. Thus the stereoscopic colour test should be applied less frequently, but with this test it is possible to determine the adaptation of stereovision to colours. The maximum transparency of the red and green light filters in the visible light spectrum is very close. It would be interesting to observe the adaptation of stereovision to colours with greater difference of maximum spectral light transparency.

The obtained and calculated data consistently show that the quality of stereovision is changing if we manipulate with the optical overcorrection. One of the experiment aims was to observe the changes in stereopsis values without cycloplegia (without blocking of accommodation), i.e., under natural conditions. The experiments mentioned in references were carried out under conditions of cycloplegia when the process of accommodation is blocked. The optical overcorrection (Lovasik & Szymkiw 1985; Goodwin & Romano 1985; Schmidt 1994) was performed at binocular cycloplegia with the near tests – *Random-dot* and *Titmus* to study the influence of visual acuity and aniseikonia on the stereoacuity.

The influence of artificially produced aniseikonia (from 1.2% to 32.3%) on the stereovision was studied by Lovasik & Szymkiw (1985), Lubkin *et al.* (1999) and Jimenez *et al.* (2002). The stereothreshold values were measured with *Titmus* and *Random-dot* tests using special afocal magnifiers placed in front of the leading eye. Similar experiments were done increasing overcorrection by step of 0.5 D up to the moment when either monocular suppression or diplopia switched on, or it was not more possible to recognize stereostimuli. The stereoacuity decreases with increasing of aniseikonia. Lovasik & Szymkiw (1985) suggest that a stereoacuity 40 arc sec was possible with 20% aniseikonia, and 50-100 arc sec with 30% aniseikonia. Lovasik & Szymkiw (1985) had determined that +1.50 D overcorrection, resulting in magnification of only 4%, caused the same decreases of stereovision as 8% pure aniseikonia. On the basis of experimental data it can be proved that the low visual acuity is not the most decisive factor causing the reduction of stereovision.

Our studies results showed that induced anisometropia decreased visual acuity and stereoacuity. However in practice I have met different contradictory cases of the real life. Humans with high visual acuity sometimes do not manifest good stereovision (see Figure 6.9 B), eventually due to non-optimum correspondence of the both eye corresponding receptive fields (that are not anatomically equal). A mechanism is adopted to the brain and adjusted to definite living conditions during the first years of life. Now it is destroyed and the quality of stereovision is reduced.

Lovasik & Szymkiw (1985), Goodwin & Romano (1985), Schmidt (1994) and Lam *et al.* (1996) carried out similar experiments. They had a goal to investigate the influence of artificially produced amblyopia on stereovision. Authors used cycloplegia for both subject eyes. After that the vision near correction was applied resulting in difference of the eye visual acuities – 20/20 for one eye and 20/200 for other eye. Within a half of hour the stereothreshold was measured vs. difference of the eye visual acuity till both eyes had equal 20/20 acuity. The second experiment was done with an artificially produced binocular amblyopia. Due to the applied positive overcorrection the visual acuity of both eyes was 20/200 in the start of experiment, afterwards it gradually improved up to 20/20. The stereoacuity was determined by *Titmus* test. Authors observed 2-3 times worsening of stereovision threshold while visual acuity due to overcorrection decreased by a half. Using a spectacle magnification formula it can be shown that a +4.00 D lens creates an aniseikonia of approximately 11%. The strongest lens used in my experiments is 2.50 D that creates the highest aniseikonia 7%. Lovasik & Szymkiw (1985) observed if visual

acuity decreased by a half, the stereovision threshold increases 2-3 times. In our experiment the same relation is observed for elder subjects, who need the near correction.

*Goodwin & Romano* (1985) have found that good visual acuity only does not prove the existence of stereopsis or the quality of stereovision. I have observed in my practice cases when visual acuity in one eye was decreased for three or four decimal visual acuity lines together with good visual acuity for another eye, however subjects still had good stereoscopic vision. In opposite, in 0.8% cases out of 793 optical patients we found good visual acuity and binocular vision but no stereoscopic vision was tested with standard clinical tests.

*Donzis et al.* (1983), *Lovasik & Szymkiw* (1985), *Goodwin & Romano* (1985) *Schmidt* (1994) and *Lam et al.* (1996) concluded the influence of relative monocular blurring (loss of monocular visual acuity) on stereovision. The authors represent different outlooks, presented experimental data differ – eventually as a result of different research methods and initial conditions. A quantitative comparison of data on stereoacuity as a function of induced aniseikonia or monocular blur indicates that stereoacuity decreases approximately 1.8 times faster by *Titmus* test than by the *Randot* test for identical levels of aniseikonia or blur (*Lovasik & Szymkiw* 1985). Authors would suggest to use *Titmus* test for detecting ocular abnormalities compromising binocular function. Consequently, it would be the test of choice for detecting binocular abnormalities in children.

In standard clinical tests stereo images are separated using colour filters or polarizators, and both eyes perceive images simultaneously. In such case the eye that sees a clear image becomes the leading eye. The blurred image from the eye not seeing well can be suppressed (*Simpson* 1991, *Schmidt* 1994) due to competition of the brain activities. Due to that the images from the both eyes are not fused together, and the subject does not see the stereotests.

In order to diminish the great eye dominance of amblyopic subjects I have used stereostimuli phase separation. It was accomplished alternately switching stimuli for the left and the right eye with the liquid crystal goggles – controllable light shutters switching in time with the display frame rate. The even PC frame sequence displays stimuli for stimulating the right eye and the odd sequence – for stimulating the left eye. The alteration of sequences is sequential and quick in order not to destroy the perception mechanism of binocular vision. Such stereo image separation forms compulsory conditions so that both images – the clear and the blurred one reach the brain and possibly are not suppressed at once.

During tests of the binocular vision for individuals who have a reduced visual acuity (amblyopia or cataract), the lack of stereovision very often is diagnosed because it is not found using the clinical tests. Clinical tests also have different ways of determining the stereothreshold in range from 15 to 500 arc sec. In the *Titmus* test the image of the fly is produced with about 3000 arc sec disparity, but using this test we cannot obtain reliable results about the existence of stereovision as there are people who do not understand the test correctly. Usually the stereotests are used to determine amblyopia, anisometropia or aniseikonia, which can destroy the binocular functions of vision, including stereopsis. However, the methods used to determine and distinguish the optical and neural causes of the destruction of perception are not found yet. Researchers try to determine the criteria for aniseikonia destroying the stereovision and reducing the stereoacuity. The relations between the degrees of monocular or binocular amblyopia and the changes in the quality of stereovision are looked for.

In our stereovision study stereotests the random-dot stereopair was demonstrated on the computer screen. The left and right eye stereostimuli were separated using liquid crystal goggles synchronized with the even and odd PC screen frame sequence. It gives a possibility to demonstrate a clear stimulus for the amblyopic eye that project a blurred image to our brain. For the eye with good vision the stimulus is blurred already on the PC screen. Thus stimuli, when they reach the brain, are equally blurred and eventually they might create at least coarse stereovision for an amblyopic subject.

At induced anisometropia I have observed tendency that the decrease of stereoacuity depends on the eye refraction (hypermetropia, myopia). One reason of such difference could be the loss of accommodation process in hypermetropic eye to create clear image on the retina. In the mild myopic anisometropia, the more myopic eye can sometimes be used for near work and the less myopic eye for distance, either eye having a clear retinal image. In myopic anisometropia subject do not use accommodation, and our brain always chooses the easier way to see something.

*Rutstein & Corliss* (1999) showed results that higher degrees of anisometropia generally cause deeper amblyopia and poorer levels of binocularity for hyperopes, but not for myopes. The retina of the more ametropic eye in hypermetropic anisometropia rarely receives a clear image. If the difference between the optical powers of eyes is +2.7D (hypermetropic conditions) and -6.2D (myopic conditions) than it would be big risks to develop amblyopia in childhood.

Another explanation of these cases could be found in the retina of the eye. *Cheng et al.* (2003) have investigated different types of aberration and sizes in myopic, emmetropic and hypermetropic eyes. The obtained results show that the numerical value of all the aberrations is equal at high degree of myopia (above 6.00 D) and hypermetropia (up to 3.00 D). Considering the obtained data on the stimuli average of modulation depth for blurring with optical lenses (see Table 4.1), then here we do not see great changes which could possibly influence the stereothreshold. The main criteria to form the stereovision is the quality of image on the retina and how this stimulus is sent along the vision canals to the brain where it is further processed and, sequently, the stereosense is or is not formed.

Stereovision is the highest level in the hierarchy of binocular vision. The formation of stereosense occurs in the primary vision cortex. And how that happens, - we have only guesses, explanations, algorithms and models – cooperative disparity model, phase and energy disparity models (*Julesz* 1974; *Marr & Poggio* 1976; *Poggio & Poggio* 1984; *Ohzawa et al.* 1997; *Cumming & DeAngelis* 2001; *Grossberg & Howe* 2003). What can influence the stereovision? First, these are factors, which destroy the primary levels of binocular vision: concerning the eye – anisometropia, aniseikonia, squinting, congenital cataract and glaucoma, pathologies of the retina. Binocular vision functions at anisometropia, squint and amblyopia are most widely studied. As the main reasons the following are mentioned: visual acuity, the contrastsensitivity, the anomalous retinal correspondence, which is most often formed in the case of squint (*Lovasik & Szymkiw* 1985; *Goodwin & Romano* 1985; *Holopigian et al.* 1986; *Stathacopoulos et al.* 1993; *Brooks et al.* 1996; *Rutstein & Corliss* 1999; *Lubkin et al.* 1999; *Lee & Isenberg* 2003; *Harwerth et al.* 2003). Second, the changes could happen in stereovision system, called stereoblindness. *Richards* (1970, 1971) concluded that perceived depth depends on the pooling of inputs from three classes of tuned disparity detectors. One class is tuned to crossed disparities, one to uncrossed disparities, and one to zero disparities. He also concluded that some people lack either the crossed or uncrossed disparity detectors and consequently fail to detect either crossed or uncrossed disparities.

In clinics doctor devotes usually no more than 1-2 minutes to assess stereovision. If the subject does not recognize various stereostimuli during this period of time the test is interrupted. In clinics such procedure is considered to be sufficient to prove the presence or absence of stereovision. Actually the negative test according to such procedure leaves over the answer. Most likely subjects do have stereovision that can be revealed under special conditions helping them to identify stereostimuli. In the case of amblyopia this time mostly is not enough to make sure conclusions about the presence of stereovision. Ophthalmologists and optometrists prescribe a number of exercises for treatments of amblyopia in childhood. Also liquid crystal goggles are applied in vision practice for children with disturbances of binocular vision to stabilize and develop it (*Bahn et al.* 2001). If no practicing was done in childhood or it was ineffective, the visual acuity does not improve and remains unchanged for the rest of life.

One aim of my research was to investigate the influence of induced anisometropia on the quality of stereovision and to assess the prognosis to obtain the coarse stereovision at high degrees of anisometropic amblyopia. Further we liked to create conditions to facilitate provoking of stereovision for individuals with amblyopia, and for those failed in diagnosis of stereovision with the clinical stereotests.

Possibly also amblyopic subjects have stereovision, however they yet cannot give an affirmative answer looking on stereostimuli of the standard clinical tests due to the lack of experience and the restricted test time. A special test developed by us displaying random-dot stereostimuli on a computer screen, first of all allowed to produce a blurred stimulus also for the well seeing eye. Thus two blurred images of the same size reach the brain, and perhaps they are perceived in our brain as more similar thus diminishing one eye dominance. Using the liquid crystal shutters it is possible to stimulate the amblyopic eye at least for some moment, i.e. eye alone sees the stimulus and this information reach the primary visual cortex. Such conditions could make the brain to receive both eye images and to fuse them without suppression to form stereo sensation. A patient with amblyopia needs a longer time to “control” the sensor fusion mechanism in the process of stereovision, however thereafter he is capable to see the hidden depth image. Going on with looking at the stereostimuli even with great disparities subjects needed long adaptation time (at least 20-30 seconds) until they saw the stereo image. A difference in the ease to recognize stereostimuli exists also for normal subjects. Thus time needed to see crossed disparity images is shorter as compared with uncrossed disparity stimuli (*Birch & Gwiazda* 1982; *Landers & Cormack* 1997; *Lam et al.* 2002). Authors also have mentioned that comparing stereoacuity for such cases, the stereoacuity by crossed disparity was better as compared with uncrossed disparity.

After the amblyopic patients for the first time affirmed their depth sense while applying the random-dot stereotest as described above, the stereovision was assessed also by clinical tests. To ease at the beginning the clinical stereotest – we held the TNO test much closer to eyes than it is prescribed (increasing the disparity values). Besides the longer adaptation period than during the clinical vision test was needed.

It was found out in the additional study that for three subjects with amblyopia the stereovision was obtained and the stereothreshold decreased if the well seeing eye is covered with a light filter of three times smaller light transparency. In case of real amblyopia the stereothreshold is higher if colour filters are with equal light transparency.

The developed equipment should be allowed to help subjects having a manifest difference in both eye visual acuities to see at first the random dot stereograms and to train them afterwards. The only requirement – the subject should have at least weak binocular

vision. Unification of both eye stimuli responses through blurring of the good eye stimulus or decreasing of the neural response by higher optical density filters in front of the better seeing eye turn out to be factors to facilitate inducing of stereopsis.

It is found out experimentally that it is possible to train even in a considerably short time period (20-30 minutes while the experiment goes on) and to improve stereovision.

Sometimes we met problems with the subjects facing these types of tests for the first time. Such subjects failed to see the stereo image at once and had difficulties with the idea of the test, which could influence the results of the experiment – to raise the stereothreshold and to increase the dispersion of results. As another disadvantage of the experiment we could mention the long time period needed – a series of 40 measurements took about 20 minutes – the time period when the subject had to concentrate on the computer monitor.

Similar to the colour contrast tests it is important to add that advantages and disadvantages of each method must be known. In this case it is stated that using light filters the colour contrast threshold at different stereodisparities can be determined at much higher values than using liquid crystal glasses. However using light filters the range of certain colour can be distinguished more precisely. This cannot be achieved on the monitor. If the formation of stereovision at different changes of colour contrast is further studied, then the intensity of phosphors for each colour must be well established and balanced with the intensity of the other colour so that the brain could receive the light stimuli of the same luminance but the question about the perception of different colours at the formation of stereovision remains current.

The measured values of the threshold for each subject were individual. Besides for some subjects the dispersion of the determined thresholds is very high and the values can differ up to three times, using the method of constant stimuli and method of limits. Also summing up the results of all subjects no essential differences are found between the types of disparity. In our experiments no looking limits were introduced in the test thus the subject could compensate one type of disparity with another disparity.

With the present methods we can determine the values of thresholds using two different psycho-physical methods – the method of limits and the method of constant stimulus. The obtained colour contrast thresholds at different stereodisparities differ in the case of the black white stereotest and the blue red test. It can be explained with the displacement of colour receptors on the retina and separate colour and disparity canals existing in the brains. How does it really analyze the disparity of colour tests? Most probably it is the black and white contrast channel (luminance) in which the colours are transformed greyscale level. Then such a contrast will be like the black one and the thresholds of stereovision will be larger.

At the end I remind about an interesting discovery that would be important in practice. If the subject's stereothreshold is assessed using the TNO test in the near for patients trying to apply monocularly +0.50 D and sequentially -0.50 D overcorrection looking for changes of the stereothreshold. We have discovered in our experiments that for a half of subjects that decreased the stereothreshold. Perhaps it is because stereo images are observed for about half an hour and actually that it was a short training, which improved the quality of stereovision.

At the end I would like to conclude that the three developed methods could be used in the studies of stereovision and binocular vision simulating the cataract, amblyopia and uncorrected anisometropia. It can be seen from the experimental results that in the case of

uncorrected hypermetropic anisometropia the stereothreshold is lower than in the case of uncorrected myopic anisometropia. Also for people with uncorrected hypermetropic anisometropia amblyopia is more often observed than for those with uncorrected myopic anisometropia. During studies a tendency was observed that at induced cataract and/or amblyopia the stereothreshold increases faster if the vision conditions are made worse for the leading eye.

## *Conclusions*

- The techniques are developed for the estimation of stereothreshold in conditions when one eye retinal image quality is artificially decreased:
  - using monocular defocus to simulate uncorrected anisometropia together with the inducing of small aniseikonia, aniso-accommodation and blurring;
  - one eye occluding with controllable light scattering obstacles to investigate stereovision in induced cataract conditions (PLZT ceramics and polymer dispersive liquid crystals PDLC have been found as good smart materials to build optical phantoms to simulate different cataract stages);
  - direct blurring of stimuli on PC screen for stereostimuli separation using liquid crystal shutters, allowing to study stereovision's (as well for achromatic as for chromatic stimuli) characteristics for induced amblyopia and cataract, thus avoiding anisometropia and aniseikonia contribution to determine stereothreshold changes;
  - the last technique proves to be worthwhile for the formation of the stereosense and training of stereovision;
  - the conversion table is created for comparison of stimuli features in the different methods of stereothreshold detection.
- Experimental results showed that estimated stereothreshold in conditions of induced uncorrected hyperopic anisometropia is higher as the stereothreshold measured in conditions of the induced myopic anisometropia. It is established that blurring is the main factor for the changes of stereothreshold for subjects with real amblyopia in hyperopic anisometropia.
- In cases when the quality of one eye retinal image is artificially lowered, the stereothreshold increase follows the linear relationship  $k = \frac{\Delta \log y}{\Delta x}$ , where  $y$  – stereothreshold (arc sec),  $x$  – parameter that characterizing the degree of stimuli blurring or contrast decreases,  $k$  – the sensitivity coefficient of stereovision (depending on subject's age, initial stereovision threshold, a.o. factors).
- It is determined that dependences of stereothreshold for subjects with amblyopia or cataract and with difference in both eye visual acuity are on the same level as that measured for another subjects for whom approximately same difference if amblyopia, cataract and uncorrected anisometropia were induced artificially.
- In the experiment the developed equipment should be allowed to help subjects having a manifest difference in both eye visual acuities to see at first the random dot stereograms and to train them afterwards. Unification of both eye stimuli responses through blurring of the good eye stimulus or decreasing of the neural response by higher optical density filters in front of the better seeing eye turn out to be factors to facilitate inducing of stereopsis.
- In this stereovision studies *ca.* 50% of subjects manifest the decrease of stereothreshold after longer stereovision assessment and together with small monocular overcorrection.

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