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Influence of Physiological Factors on Stereopsis

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1 Abstract

A good stereopsis (depth perception) is needed in everyday life, regardless whether a person is a professional driver or chef. Good estimation of distance, and of what is further and what closer, could mean the difference between a crushed and a whole car or between a bloody and a healthy finger. The main theme of this Master thesis is detect and quantify major factors in depth perception. Do the younger estimate the depth better than the older; do they have better depth perception with greater or smaller pupil distance; does depth perception depend on gender; what happens with stereopsis when vision is fogged by +0,5 and +1,0 D? These are the questions dealt with in this Master thesis.

To answer these questions measurements were made on 51 subjects (mean age 45,0 +/- 13,32 years) of whom 25 were women, mean age 45,5 +/-13,55 years (12 with PD<62 mm, mean and 13 with PD>66 mm) and 26 men, mean age 44,4 +/- 13,34 years (13 with PD<62 mm and, 13 with PD >66 mm). Each of these four groups was further divided by age (one in range 20 to 35 years and second in range 50 to 65 years).

The measurements were made with a few assumptions. The first assumption was that stereopsis is in direct correlation with visual acuity, the second assumption was that persons with bigger interpupillar distance have better stereopsis, and the third assumption was that with age the stereopsis ability decreases.

The measurements were done with modified Frisby–Davis test expanded from four geometrical shapes to twenty-five circles. The stereopsis was measured with full refractive correction at 4,5 and 3,0 meters. Later, stereopsis was measured with fogging with +0,5 and +1,0 D at the 4,5 and 3,0 meter distances.

Statistically there is no correlation (or very weak) between stereopsis and the visual acuity for whole group of 51 test persons, but if only young test persons are taken in consideration, the correlation becomes significant, $r(20)=0,566$, $p=0,009$ at 4,5 m and $r(20)=0,456$, $p=0,043$ at 3,0 m and that matches the assumption. Stereopsis is in no or weak positive correlation with pupil distance $r(51)=0,059$, $p=0,679$, which is in total contrast to the assumption. Stereopsis is in positive correlation with age at 4,5 meters measuring distance, $r(51)=0,371$, $p=0,007$, which corresponds to assumption. In addition, stereopsis is better in females than in males by 32,5%.

Based on the results it can be concluded that the stereopsis is in negative correlation with age, in positive correlation with visual acuity, females have better stereopsis than males and statistically, the correlation between stereopsis and pupil distance (PD) has not been proved. The most important conclusion is that the decreased visual acuity brings significant fall of stereopsis. A deficit in refraction of -0,50 D decreases stereo acuity by about 90% (nearly 2x) and a deficit of -1,0 D decreases stereo acuity by about 220% (about 3x).

Keywords: Stereopsis, stereo acuity, depth perception, pupil distance (PD), visual acuity (VA).

2 Introduction

Stereopsis, also known as depth perception, is the highest form of binocular vision. Perception of environment, in which people work and live, is of great importance. Estimation of what is closer and what further can be of vital importance. The process of stereo image inside human brain includes several factors, some of which are measurable and some not. The purpose of this study is to determine to what extent the factors influencing stereopsis are measurable.

In order to be perceived as an image with impression of all three dimensions of space, stereo image produced in brain must pass its vision path without disruption. All media through which light beam passes after entering the eye and before falling on photoreceptors must be transparent so that the image created on the retina would be of good quality. Furthermore, the first photoreceptors in creating the image must be of sufficient density and without image-degrading mutations.

Photochemistry is the next step in conversion of light energy into visual signal. It means that nerve impulses which are passing through optic nerve, chiasm, optic tract, lateral geniculate body, optic radiation come to visual cortex in occipital lobe of the brain where the image is formed and where by combining two images depth perception is formed.

If any part of visual pathway was not properly formed during childhood or if it was disrupted in an injury or disease depth perception can be either compromised or non-existent which leads to monocular cues being the only means for perception of space.

3 Organisation of thesis realization

The main goal of this master thesis is to prove which anatomical and physiological factors influence stereopsis more and which less with the assumption that better visual acuity brings better space perception. Another assumption is made that bigger pupil distance (PD) results in better stereopsis. The third assumption is that with age the stereopsis ability decreases since retina loses specific amount of its receptors through years together with its visual acuity and consequently loses depth perception.

Organisation of thesis realization is heading that way. Exclusively people with visual acuity higher than 1,0 were chosen for the test in order to eliminate the possibility of dealing with factors which could influence the results, such as diseases. First, half of the chosen test persons had small pupil distance (PD) and the other half big regarding the third assumption all test persons were categorised by age. Besides these divisions, half of the test persons chosen were males and half females. The most important condition the test persons had to satisfy was depth perception measured with random dot test on LCD tester. All test persons unable to see the picture on random dot test were eliminated from further examination.

When selecting the test for stereopsis, important factors were both precision and brevity because all test persons were chosen directly from standard optometric practice. First reason for this is the fact that each test person was a volunteer and they cannot keep their concentration for a long time and secondly too long examination would be too much to ask from clients.

In order to achieve the above-mentioned requirements of brevity, it was necessary to construct a specific new test, which enables those requirements to be satisfied. All other standard machines used to measure depth perception were very time consuming and therefore could not be used in this examination.

4 Theoretical consideration

4.1 Visual pathway

Creating a binocular image in the brain begins with eyes (Figure 1). The optical system of the eye (cornea, aqueous humour, lens, vitreous) creates an image on the retina. That image converts the electromagnetic energy of the light to chemical and then to electrical energy. This transformation happens in the photoreceptors of the retina. Visual processing continues with transduction signals through the optic nerve, chiasm crossing and entering the lateral geniculate nucleus, then through optic radiation it reaches primary visual cortex (V1).[1]

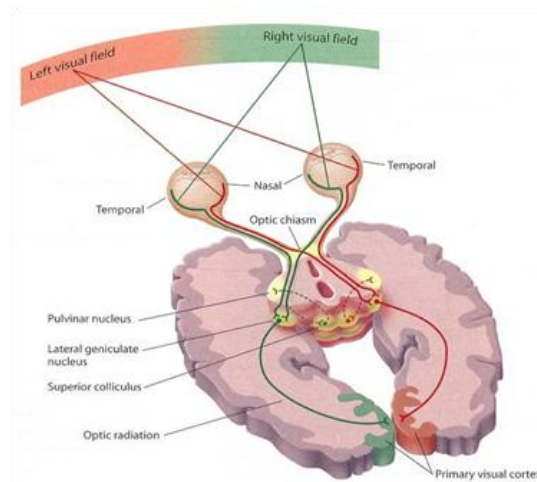


Figure 1: Visual Pathway

How can image quality in a particular part of the visual pathway be evaluated? To measure the reduced sharpness, the resolution of a particular part of the same common denominator, we need a unit of measure by which we can trace individual parts separately, as well as the result, which is the max stereoscopic resolution or stereopsis. Ultimately, spatial perception is influenced by many factors of which the first optics of the eye.

Grating acuity in cycles per degree is the best way to determine how good the optical system of the eye is. The standard optotypes for visual acuity measurement have different shapes and some are more recognizable than the others and to avoid that, grating acuity is more convenient to determine the threshold of the optical system and retina of the eye. That is why shape independent gratings in cycles per degree are the most convenient way to determine the maximum ability of the optical system of the eye.[2]

The main requirement of picture quality on the retina is the transparency of all media, which the light is passing through. Cornea, aqueous humour, lens and vitreous are not allowed to have any opacities or deformations (e.g., cataract, edema, hemorrhages) and on other hand, eyes must have full refractive correction. To perceive best depth perception, the picture on the retina must be the best possible.

4.2 Grating acuity (resolution acuity)

Grating acuity, or sometimes called resolution acuity, can be measured with gratings with three properties: spatial frequency, contrast and orientation. Spatial frequency relates to a number of pairs of black and white stripes per centimetre or per degree. This can vary depending on the distance from the eye and it is better to express spatial frequency in cycles per degree because it is not dependable on distance. Contrast can vary between 0 and 100%, but for grating acuity, measurement is maximum contrast of 100%. Third property is orientation of the stripes and the examinee has to say not only if they can see gratings but also orientation of gratings.[2]

There are two types of gratings, sinusoidal and square wave gratings.

Sinusoidal wave gratings

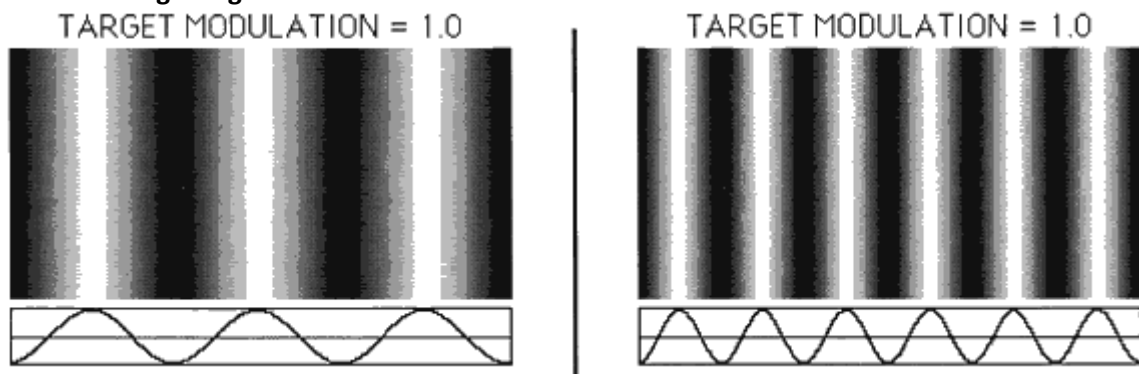


Figure 2: Sinusoidal wave gratings

Square wave gratings

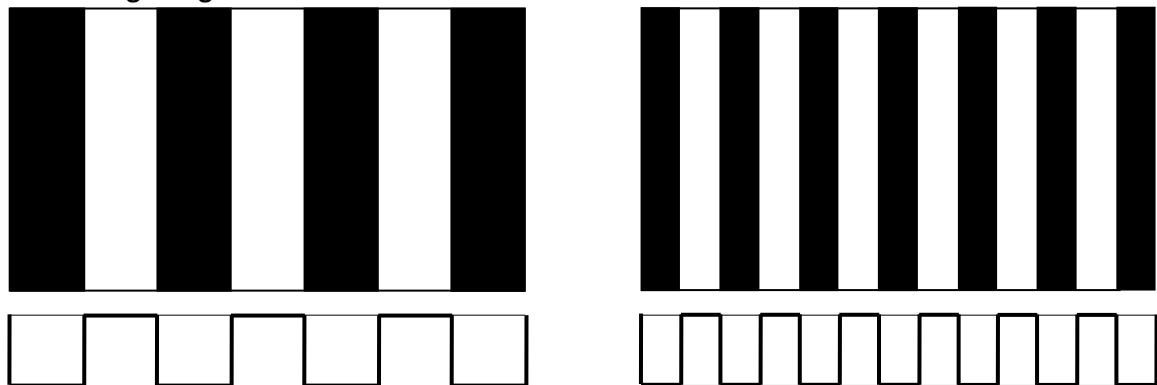


Figure 3: Square wave gratings

Grating acuity is determined with square wave gratings and the grating acuity measurement set consists of seven cards with different gratings (from $\frac{1}{2}$ to 32 cycles per cm) and one gray field.[3]

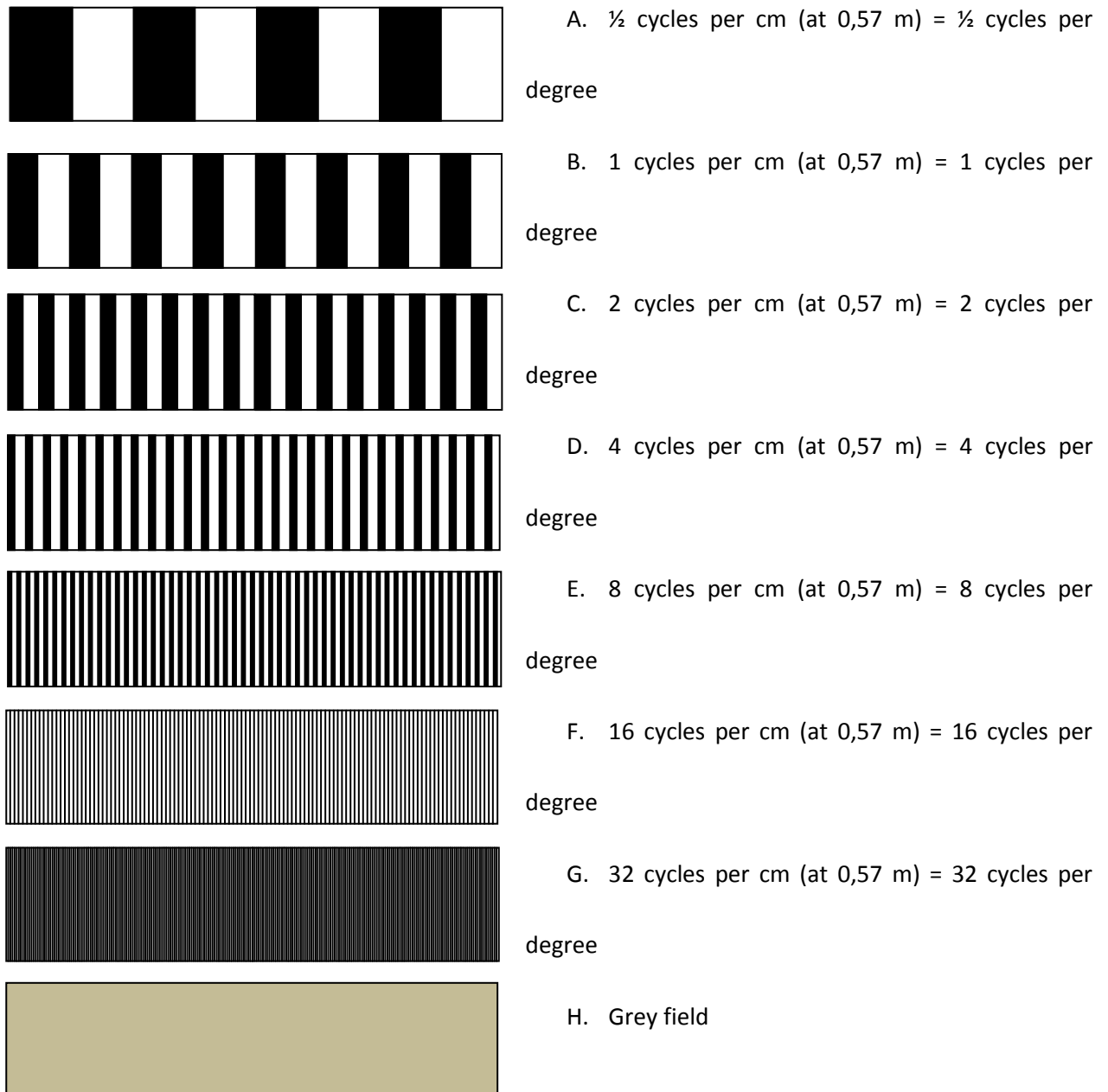


Figure 4: Grating acuity cards

G sample of 32 cycles per cm seen at distance of 0,57 m is grating acuity of 32 cycles/degree, but if seen at 1,07 m grating acuity is 60 cycles per degree.

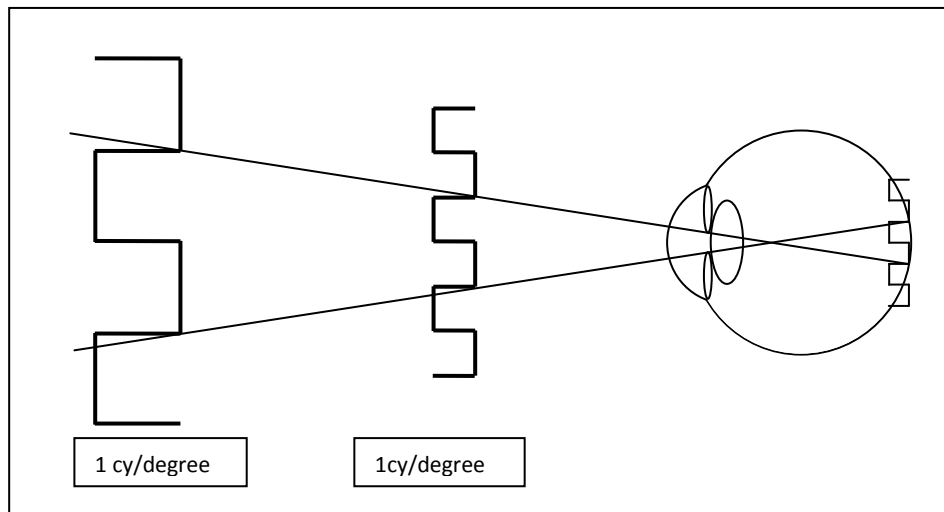


Figure 5: The same grating acuity gives gratings on different distances

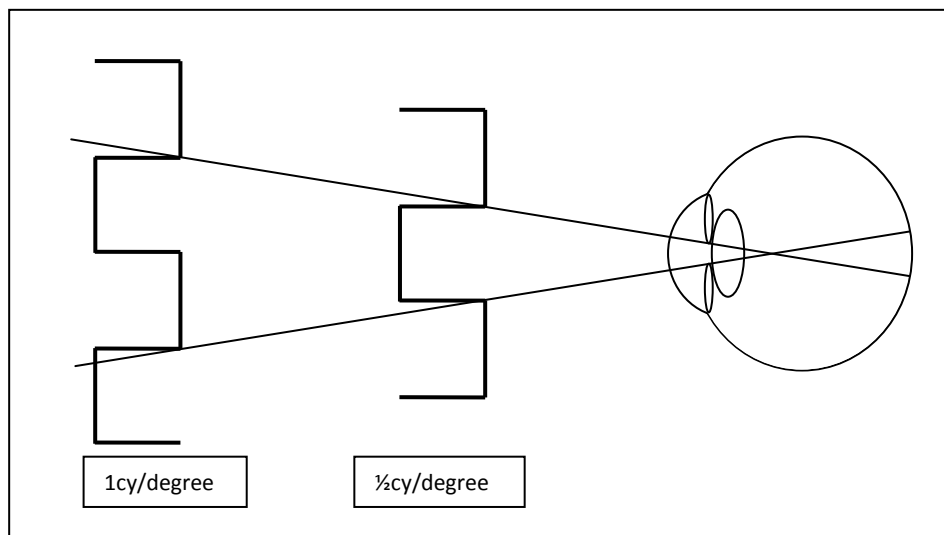


Figure 6: Different grating acuity gives the same gratings on different distances

Once we have the units of measurement, we can ask, what would grating acuity be for the best optical system of the eye? Under the best conditions, in the best young eyes, grating acuity is just about 60 cy/cm, since there are 60 minutes of arc in one degree, the best visual acuity is about 1 cycle per minute of arc which corresponds with Minimum Angle of Resolution (MAR) for normal vision. That is, the finest grating you can resolve (if you have excellent eyes) contains about 60 black and 60 white stripes in angle of 1 degree. In Figure 4, this is the spatial frequency of grating E at 4,28 meters, grating F at 2,14 meters, or grating G at 1,07 meter.[2]

4.2.1 Density of human retinal photoreceptors

When this perfect picture of 60 cycles per degree reaches the retina, the next question is how dense gratings can retina receive. Remember that each foveal cone subtends an angle of about 30" with another cone or two cones per minute of arc. Centre of the receptive field of a foveal ganglion cell is connected to only a single cone, and LGN cells are connected to single ganglion cells. To make a higher-level channel that responds optimally to a 60 cy/deg vertical grating, the higher-level neuron could

receive alternating excitatory and inhibitory input from closely spaced vertical rows of cells, each row only one cell wide.

To make a cortical neuron tuned to one/half that spatial frequency (30 cy/deg), every second cone must be turned on/stimulated, that leads us to maximum grating acuity of 30 cy/degree. Each photoreceptor absorbs only the quanta of light that arrive to photoreceptor's location. However, photoreceptors sums signal arising and that why maximal grating acuity becomes 60 cy/deg.[2]

4.2.2 Other forms of visual acuity

Other forms of visual acuity can also provide useful information regarding the limitation of spatial vision. One of them is **minimum detectable acuity** and refers to the smallest object that can be seen. If we take a thin line on white paper and we increase the distance of viewing until it is barely detectable, this is the minimum detectable acuity and it can be considered to be equivalent to detectable threshold. Due to optical imperfection of the eye the line is not in perfect focus on the retina, its image takes form of a spread line. The threshold for this spread line on retina is about one arcsec, although the density of photoreceptors is about 30 arcsec.[4]

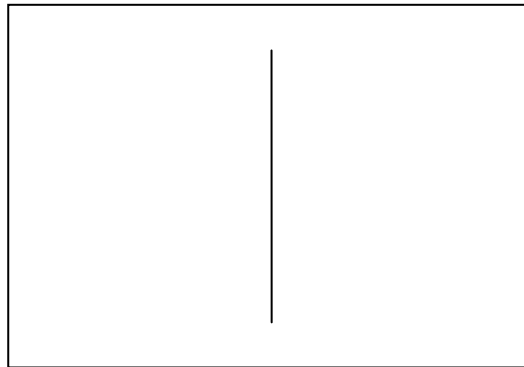


Figure 7: Pattern for measuring minimum detectable acuity

The final type of hyper acuity is **vernier acuity**. The ability to sense different direction or small shift of one line in relation to another (also for dots) is called vernier acuity. The threshold for vernier acuity is, like minimum detectable acuity, also very low and it is about 3 arcsec. This low threshold is related to the visual system's ability to average luminance information across space and get sense of direction.[4]

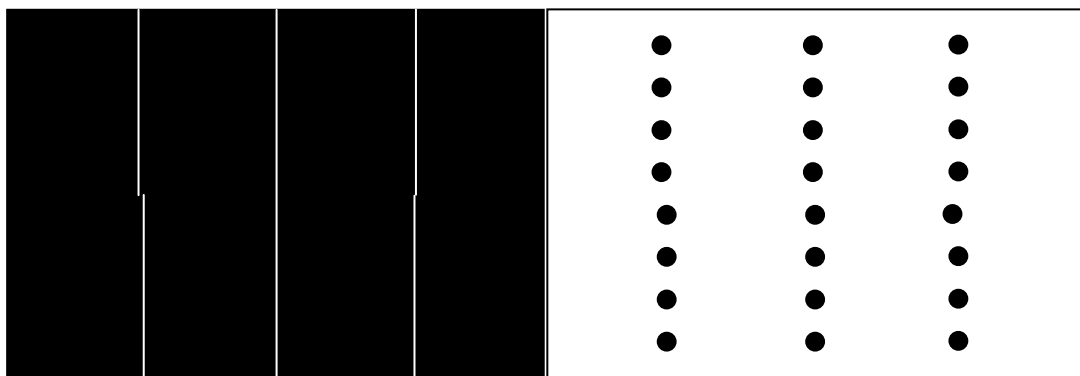


Figure 8: Vernier acuity

4.3 Binocular disparity

Stereoscopic vision may be defined as the ability to perceive the distance of objects based on visual information available only to an observer with two eyes. Because two eyes are separated horizontally, they receive disparate views of object at different distances. The field of horizontal retinal disparities combined with the information about directions of the gaze of two eyes (convergence) provides precise, quantitative information about the distance of the objects from the observer.

If eyes fixate an object at a given distance (bifoveal fixation), an image of it will fall on the fovea in each eye and there will be no binocular disparity between the images. If the object (not fixating object) is moved closer to the observer, the change in depth may be signalled in two ways, as a result of binocular disparity or by change in convergence.

If an object is placed at a distance other than fixation distance, there will be a binocular disparity between the images on the retinas. This can be interpreted by the observer as separation in depth of the object from the point of convergence. When the object is in front of this point, lines of sight of the monocular images intersect in front of convergence giving rise to a crossed disparity. If the object is moved away from the observer, the lines of sight cross beyond the convergence distance, and the disparity is described as uncrossed.[5]

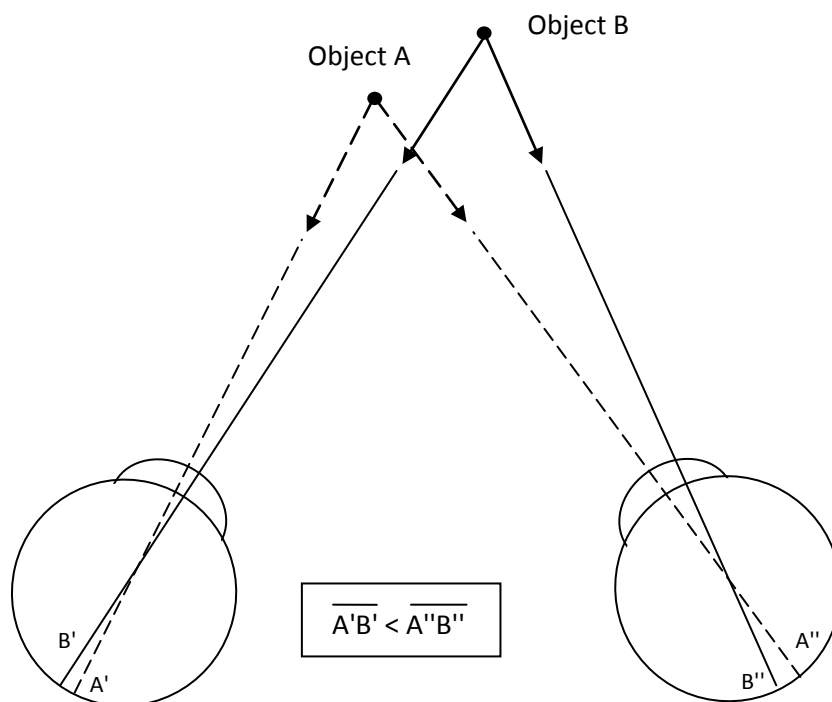


Figure 9: Retinal disparity

4.4 Precision of stereoscopic localization

Under normal conditions, most observers with no ocular abnormalities can discriminate a depth difference that produces a relative disparity of only about 5 to 10 arcsec (0,0014-0,0028 degrees). The best values reported in the literature have been obtained by method of constant stimuli with test with two vertical rods (Howard-Dolman test) and they go to nearly to 2 arcsec.[5]

Since stereopsis is a three-dimensional sense, it is degraded as the test is moved away from the horopter without changing the visual direction. This degradation is exponentially proportional to the disparity from the horopter over a range of horizontal eccentricities.

4.5 Depth perception – monocular depth cues

In absence of binocular cues, we can rely on monocular cues, which are not so precise. Monocular cues are the ones that are obtained from the 2D image of only one eye. These include the following.[6]

4.5.1 Occlusion

When one object is hidden fully or partially, this hidden (occluded) object is considered to be farther away, behind the object which is covering it (occluding object). Figure 10 illustrates occlusion.

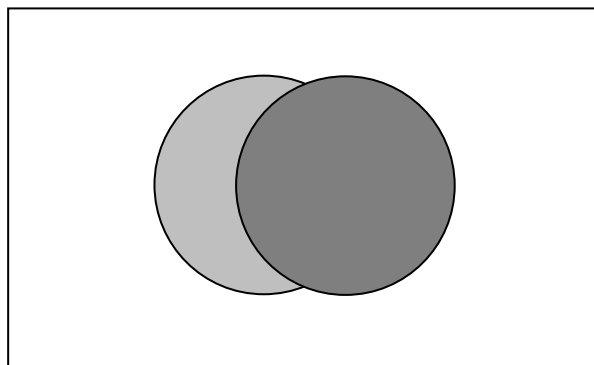


Figure 10: Occlusion cue

4.5.2 Relative cues

The second cue is that of relative height. The objects that are farther away have higher bases in the image as shown in Figure 11. The three men in this figure are perceived at different depths and the man with feet higher up in the image appears farther away. However, note the perception is entirely different for the clouds. The clouds with highest base appear to be closest and they seem to be at greater depth as the height of their bases decreases. The objects, which are above the horizon, look closer if their bases are higher.



Figure 11: Relative in height cues

4.5.3 Shadows

Figure 12 shows as an example where the shadows provide very important depth cues. In this case, the cylinders seem to be in same distance but with the presence of the shadows, we can tell that the right cylinder is closer to us.

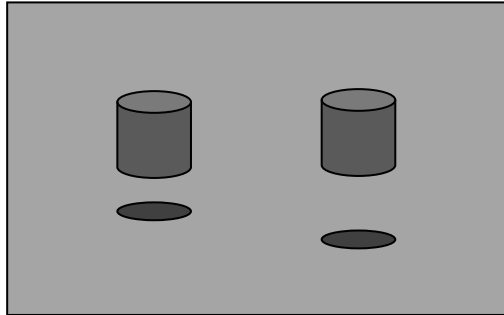


Figure 12: Cylinders with shadows as a depth cues

Also in figure 13, four left circles seem to be convex and four right circles seem to be concave only because of shadows.

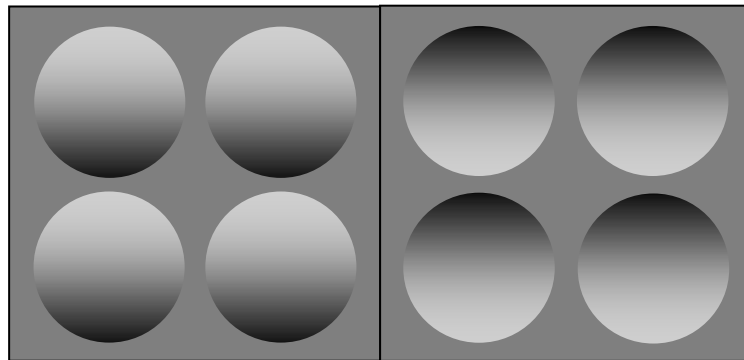


Figure 13: Convex and concave circles with shadows as a depth cues

4.5.4 Relative size

If objects are equal in size, one that is farther away will take up less of the field of view than the closer one. This is called the relative size cue as illustrated in figure 14 where amongst three tennis balls the middle one looks closer. This depends on our ability to recognize that all tennis balls have the same size.



Figure 14: Tennis balls and relative size cue

4.5.5 Familiar size

Our knowledge of sizes of objects can affect our perception. This is called the cues of familiar size. For example, our familiarity with the sizes of the different types of coins is important in perceiving the depth of the array of dimes and quarters in figure 15. Under normal lighting conditions, someone can perceived the twenty cents coin to be closer than the one-euro and the one-euro to be closer than the two-euro coin.



Figure 15: Familiar size cues.

4.5.6 Atmospheric perspective

Atmospheric perspective makes us see distant objects as blurred as shown in figure 16. We look at objects through atmosphere, which has suspended dust and water particles in the air. Light from distant objects needs to traverse more such particles. Thus very little light from those objects reaches our eye and we can perceive high frequencies with so less light. So, we tend to see distant objects as blurred.



Figure 16: Atmospheric perspective cues.

4.5.7 Linear perspective and texture gradient

Parallel lines in the environment that are not parallel to the retinal image plane do not remain parallel in the 2D image. With depth the distance between such lines become smaller and smaller and they seem to vanish in infinity. This is the basis of projective geometry. This linear perspective helps us give depth cues. Texture surface in particular shows such a gradient due to linear perspective that provides additional cues about the depth of scenes, as shown in Figure 17.



Figure 17: Linear perspective cue

4.5.8 Movement Produced Cues

We have considered only stationary images and stationary head but if head is moving side to side, we have changed viewpoints (Figure 18). These movements cause motion parallax by which nearby objects seem to move faster than the distant objects and this is an important depth cue. If we travel in the train, the closer objects moves faster than objects in the distance. If the rails have no curves, the Moon apparently does not move.

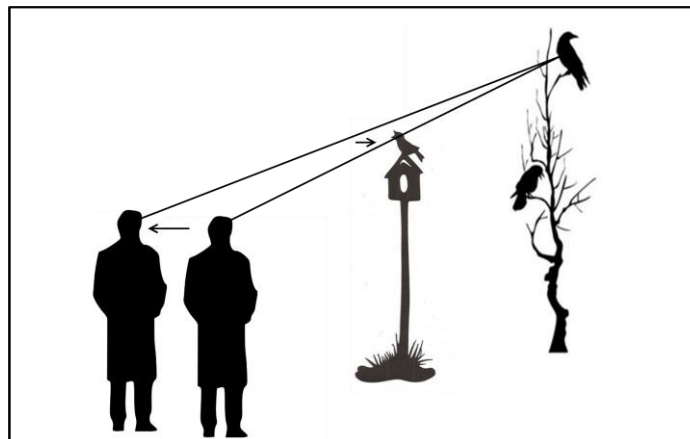


Figure 18: Movement produced cues

One important point to note here is that monocular cues do not provide absolute information about depth, only relative depth with respect to other objects in the environment.

5 Materials and method

5.1 Available stereo acuity tests

When the realization of this thesis was considered none of the available tests satisfied the requirements of precision and quick measurements. That is why I decided to develop a new one which will meet my criteria. Howard-Dolman stereo test and Frisby-Davis stereo test (NFD 2) were taken into consideration.[7]

5.1.1 Howard-Dolman test

Old test for stereo acuity measurements named Howard-Dolman, after its inventors, is a very precise device with two rods, which has excluded all monocular cues for depth perception (Figure 19). There are no shadows, no relative cues, no perspective cue, only binocular cues and care should be taken of head movement cue.



Figure 19: Howard-Dolman test

There are two ways how to use this device. The first is with two strings and the observer has to adjust a moveable rod on the place where he sees that they are in the same plane in relation to him. The disadvantage of this method is that the observer can pull one string to the obvious place where he can see that this rod is in front of the other and then with another string he can move in the opposite direction until he can see that rod is now a bit behind the fixed rod. When the observer finds the range, he can put the rod in the middle of that range. This method is very fast but you can trick the device and get false results.

Second way to use this device is a predetermined arrangement of two rods. The rod separation vary and are 9, 6, 4, 2 and 1 cm and in front can be left or right rod (Table 1). The observer says which rod is in front and has to be right for at least three out of four times and after that smaller separation can be presented. In table 1 separation in arcsec and in centimetres can be seen and order of presentation.

Separation Distance (cm)	Stereo acuity (arcsec)	Presentation: Rod in Front
9	30,94	R,L,L,R
6	20,63	L,R,L,R
4	13,73	L,L,R,R
2	6,88	R,L,R,L
1	3,44	R,L,L,R

Table 1: Howard-Dolman test rod separation with stereo acuity

The disadvantage of this method is that it is time inefficient and the observer has a 50% chance to guess the right answer. For one level of stereo acuity testing total chance to randomly guess is 12,5%, which is quite high for such a test.

5.1.2 Frisby–Davis test (NFD 2)

The Frisby-Davis test works in a little bit different way than Howard-Dolman test. The testing distance is at 3, 4 and 6 meters and instead of two rods, there are four different geometrical shapes. Stereo acuity

range is between 50 and 5 arcsec with 5 arcsec steps at 6 meters. The observer needs to have 4 out of 5 right answers after that he can go to smaller stereo acuity. All monocular depth cues have been excluded and the observer must be warned not to move head.[7]

Stereo acuity at 6 m	Stereo acuity at 4 m	Stereo acuity at 3 m
50''	115''	200''
45	100	180
40	90	160
35	80	140
30	70	120
25	55	100
20	45	80
15	35	60
10	25	40
5	10	20

Table 2: Frisby-Davis test stereo acuity for different distance

Chance to randomly guess, is relatively small, only 25% in one trial and in total for one level of stereo acuity it is less than 1% (0,39%). The only problem with this stereo acuity test is that it is very time inefficient.



Figure 20: Frisby-Davis test (upper view and front view)

5.2 Development of Stereopsis test

5.2.1 Criteria for development

The main criterion for developing stereo acuity test is time. New developed test must be very low time consuming. The second criterion was the precision of device with no monocular cues. The idea was to build a device, which is like computer stereo acuity test but without polarization filters. Binocular cues must be physical, like in real life because only such can be as precise as required. Some observers who have solid depth perception have problems with tests, which work with polarizing filters.

Frisby-Davis test has only one disadvantage, it is time inefficient. To make it much faster we have to put five rows of geometrical shapes, and to make it even faster the whole device must have two sides, one with bigger separation and one with smaller.

Modified Frisby-Davis test is shown in figure 21.

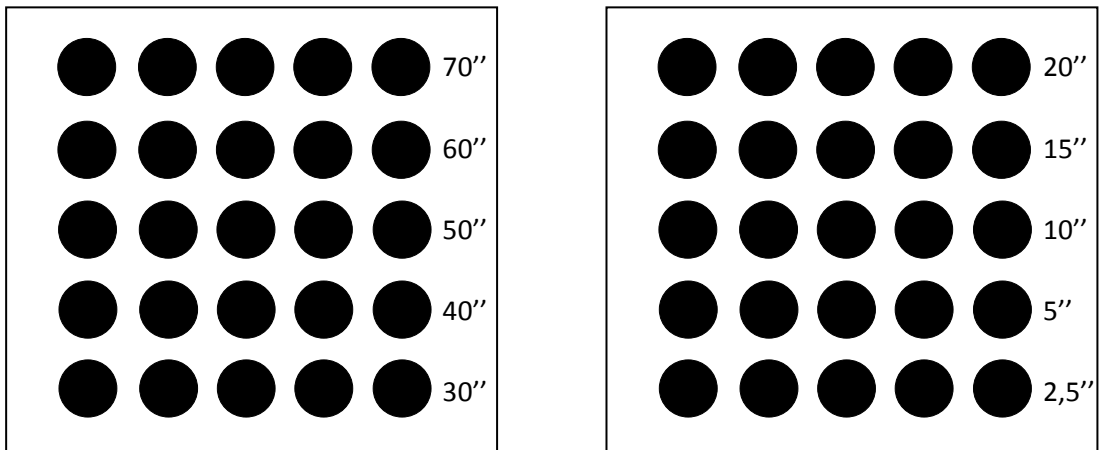


Figure 21: Two sides of modified stereo test

5.2.2 Stereo acuity test calculations

Stereopsis or depth perception is the ability to perceive space in three dimensions. Stereo acuity is actually a minimum difference in distance, so it can be recognized that one object is a little bit in front of the other. It is measurable in degrees or in smaller units like minute of arc (arc minute, arcmin) and second of arc (arc second, arcsec).

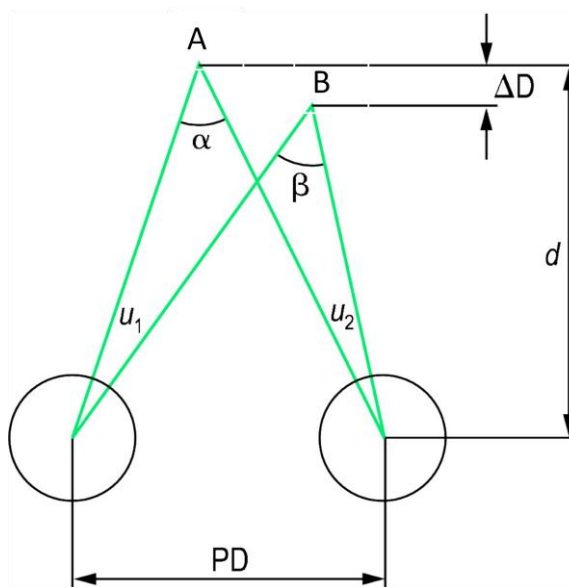


Figure 22: Stereopsis Δu

If we are fixating one object **A** with angle α and at the same time, we are aware that object **B** is not in the same plane with object **A** (Figure 22). This can be expressed with a simple equation 1:

$$\Delta u = u_1 - u_2 = \beta - \alpha$$

Equation 1: Stereopsis

In addition, we can calculate what distance between planes **A** and **B** makes the given difference in angles (Equation 2).

$$\Delta d = C \cdot \Delta u \cdot d^2 / (PD + d \cdot \Delta u)$$

Equation 2: Target separation

For example if we have $d = 4500$ mm, $PD = 64$ mm and we want to know distance (Δd) between planes on which object A and object B are for stereo acuity of 10 arcsec. When we put all data in to equation 2, we will get the result $\Delta d = 15,3$ mm.

For the same calculation, we can take a differential calculus (Equation 3):

$$\Delta d = \Delta u \cdot d^2 / C \cdot PD$$

Equation 3: Differential calculus of target separation

In table 3 there are stereo acuity separation for 4,5 and 3,0 meter view distance.

Stereo acuity (arcsec)	Δd (mm) for 4,5 m observing distance	Δd (mm) for 3,0 m observing distance
2,5	3,8	1,7
5	7,7	3,4
10	15,3	6,8
15	22,9	10,2
20	30,5	13,6
30	45,6	20,3
40	60,5	27,0
50	75,4	33,7
60	90,2	40,4
70	104,9	47,0

Table 3: Stereo acuity and planes separation between two circles

5.2.3 Device construction

A newly developed device must be fast, precise and with no monocular cues, it must have a maximal contrast between targets and background. A black circle is taken for geometrical shape and the background is light silver. To eliminate all reflexes both surfaces have to be mat and to eliminate all shadows diffused lights are added. To make the whole measurement process even faster the device will have two equal sides. One side with the measurement range 70 to 30 arcsec and the other side with range 20 to 2,5 arcsec. Each row has only one separation distance (Figure 23).

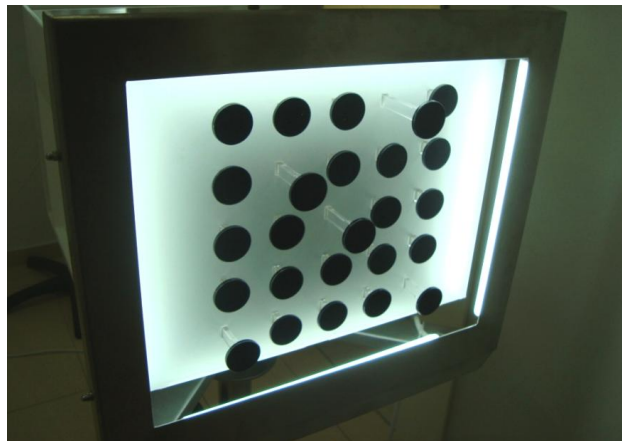


Figure 23: Stereo acuity testing device

To eliminate any possible monocular depth perception cue the observer must have his/hers head in chin rest and then the test is presented. This is also the procedure when the arrangement is changing between two testing. No monocular cues, because only pure binocular stereopsis results are wanted (Figure 24).



Figure 24: Test person with her head in chin rest

5.3 Pupil distance measurement

In measurements, the precision is required and for pupil distance measurements, the same criteria were applied. Of all available methods and tools none was precise enough that can be rely on and that why new method is necessary to introduce.

5.3.1 Tools

Every digital PD measuring device producer states that their product is the one and the others are not so precise. They all are comparing their sophisticated devices with manual PD meters and because of that, I did little research with to me available PD measuring devices (Figure 25 and 26).



Figure 25: Devices for PD measuring (PD-82, PM-600, Speedy-k)

Shin-Nippon model PD-82, Nidek PM-600, Automatic refracto-keratometer Nikon Speedy-K, Rodenstock ImpressionIST 3 and Oculus UB 4 trial frame were used in measurements.

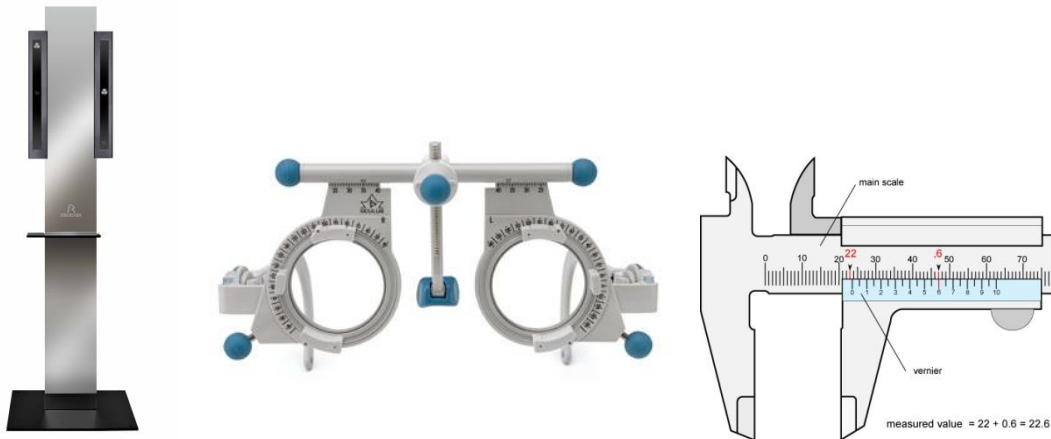


Figure 26: Devices for PD measuring (ImpressionIST 3, Oculus UB 4, vernier calliper)

Oculus UB 4 trial frame was not used with crosses but with two vertical slits (Figure 27). Each slit was shortened with adhesive tape but on opposite sides. One on the upper and another on the lower side but middle parts were left uncovered so that the target can be fixated with both eyes. Upper side of left slit and lower part of the right slit, through which can be seen only monocular, test person has to adjust with screw both monocular pictures to be in one line on vernier acuity principle (Figure 28).

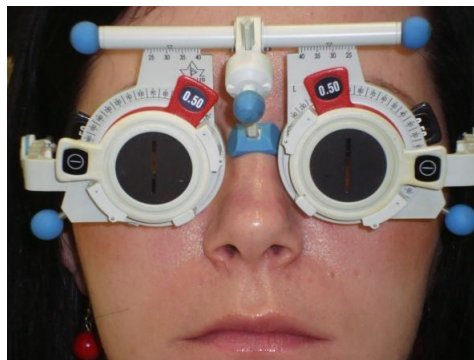


Figure 27: Slits in trial frame

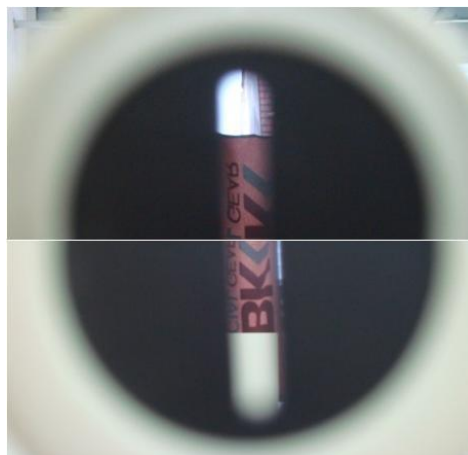


Figure 28: Test persons view through both slits in trial frame

Distance between two slits was measured with vernier calliper. After three measurements, the average was taken for pupil distance.

5.3.2 Precision of the devices

Precision of each pupil distance-measuring device is questionable but precision of the scale of each instrument is 1 mm for Nikon Speedy K, handheld manual PD meters have scales with 0,5 mm step and 0,1 mm step have both Rodenstock ImpressionIST 3 and Oculus UB 4 (vernier calliper).

NAME	GENDER	AGE	2 SLITS	RODENSTOCK	2 SLITS - ROD	PD 82	2 SLITS - PD 82	PM 600	2 SLITS - PM 600	NIKON	2 SLITS - NIKON
BA	F	65	57,5	57,9	0,4	56,0	-1,5	55,5	-2,0	56,0	-1,5
AS	F	32	58,4	59,2	0,8	57,5	-0,9	58,0	-0,4	58,0	-0,4
GF	M	52	61,3	62,1	0,8	61,0	-0,3	60,5	-0,8	60,0	-1,3
NB	M	50	61,3	62,2	0,9	60,5	-0,8	61,0	-0,3	61,0	-0,3
TZ	M	60	61,9	63,8	1,9	61,0	-0,9	61,5	-0,4	61,0	-0,9
MA	F	24	61,3	62,5	1,2	60,5	-0,8	61,0	-0,3	61,0	-1,3
PM	M	33	66,2	67,5	1,3	66,0	-0,2	65,5	-0,7	65,0	-1,2
MV	F	50	66,7	68,5	1,8	65,5	-1,2	65,0	-1,7	65,0	-1,7
BA	F	31	67,8	68,7	0,9	67,0	-0,8	66,5	-1,3	66,0	-1,8
MI	F	34	69,1	69,6	0,5	67,5	-1,6	67,5	-1,6	67,0	-2,1
MR	F	54	67,9	69,9	2,0	68,0	0,1	67,0	-0,9	68,0	0,1
JV	F	54	69,0	70,2	1,2	68,0	-1,0	68,5	-0,5	68,0	-1,0
SB	F	50	69,8	72,0	2,2	69,0	-0,8	68,5	-1,3	69,0	-0,8
PD	F	56	68,1	69,2	1,1	67,0	-1,1	66,5	-1,6	66,0	-2,1
AVERAGE:			64,88	66,09	1,21	64,04	-0,84	63,89	-0,99	63,71	-1,16

Table 4: Different devices result comparison

In this measurement comparison, we can see that automatic refractometer and both manual PD meters on average give similar results to some extent. In case of future use of these devices the recommendation is to add 1 mm to each amount. The case is similar with Rodenstock ImpressionIST 3 but in the opposite direction PD 0,5 mm should be subtracted of each ½.

Manual PD meters measure the distance between reflexes on both eyes and this seems to be a logical approach, but in reality, they usually underestimate results. On the other side Rodenstock ImpressionIST 3 does not work with reflex on cornea but with distance centre to centre of the irises principle (or we do not know how to use it properly?).

PD measurement principle with trial frame and two slits basically is the best way but it is very time consuming with some persons and you must repeat it several times to be sure that the result is accurate.

Maybe in future, if someone has the opportunity and wish to develop such a device in Oculus two slits principle, but in an objective way, it could be a very precise usable device.

5.4 Stereo acuity measurements

All stereo acuity measurements have to be done on fully corrected test persons, so before stereopsis measurement starts refraction correction has to be done and visual acuity is measured for full

correction and for additional +0,50 and +1,0 D. Now, the fully corrected test person is taken to the room prepared for testing. The space for testing is divided with room door with a purpose to be open when everything is ready for measuring and when the test person has head in chinrest (Figure 29).

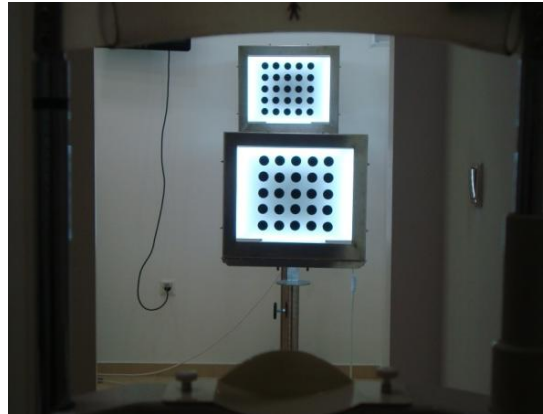


Figure 29: View from test person perspective

Test persons are not chosen randomly but they have to have certain characteristics. Only those who match these criteria were called from our archive. Final qualification was made at the end of refraction procedure when the person was tested on a random dot test. If the test person can recognize object he/she was qualified for further stereopsis measurement.

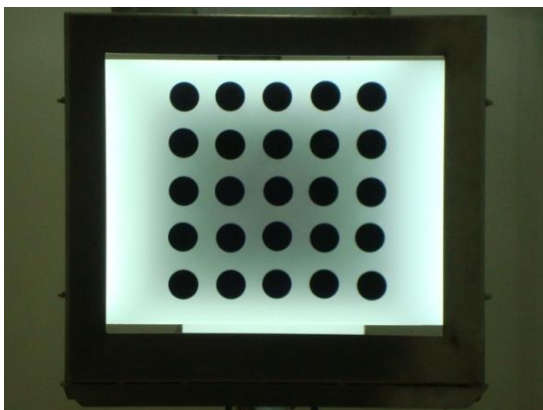


Figure 30: Stereo acuity test view at front

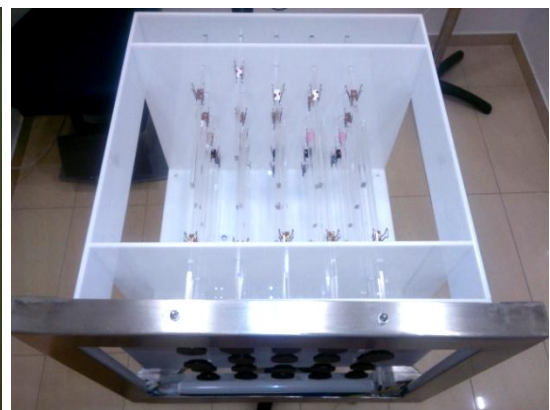


Figure 31: Stereo acuity test-upper view

The whole measurement procedure was done by the same protocol. The distances (3 and 4,5 meters), with full correction and also with Add of +0,5 and +1,0 D, number of trials and the arrangement of circles which are closer to the test person are the same. Before the measurements begin, a brief explanation about what is required from the test person and a onetime demonstration is done. A test person puts his head in the chin rest, the door is opened and the test person has to say, beginning with the upper row of circles at 4,5-meter distance, which circle is closer to her/him. Then the same is done on 3-meter distance.

Every answer is recorded on the protocol sheet (Figure 32).

Surname: _____		Date: _____		Gender: <input type="checkbox"/> F <input type="checkbox"/> M	
Name: _____		PD: _____ mm.		Date of birth: _____	
Refraction with full correction:	EYE	SPH	Cyl	AX	Vcc
	O.D.				
	O.S.				
<div>4,5 M</div> <div>70 – 30" 20-2,5"</div> <div>70" 20" 15" 10" 5" 2,5"</div> <div>60" 50" 40" 30"</div> <div>3,0 M</div> <div>70 – 30" 20-2,5"</div> <div>70" 20" 15" 10" 5" 2,5"</div> <div>60" 50" 40" 30"</div>					
Refraction with +0,5 D fogging:	EYE	SPH + 0,5 D	Cyl	AX	Vcc
	O.D.				
	O.S.				
<div>4,5 M</div> <div>70 – 30" 20-2,5"</div> <div>70" 20" 15" 10" 5" 2,5"</div> <div>60" 50" 40" 30"</div> <div>3,0 M</div> <div>70 – 30" 20-2,5"</div> <div>70" 20" 15" 10" 5" 2,5"</div> <div>60" 50" 40" 30"</div>					
Refraction with +1,0 D fogging:	EYE	SPH + 1,0 D	Cyl	AX	Vcc
	O.D.				
	O.S.				
<div>4,5 M</div> <div>70 – 30" 20-2,5"</div> <div>70" 20" 15" 10" 5" 2,5"</div> <div>60" 50" 40" 30"</div> <div>3,0 M</div> <div>70 – 30" 20-2,5"</div> <div>70" 20" 15" 10" 5" 2,5"</div> <div>60" 50" 40" 30"</div>					

Figure 32: Stereopsis test protocol sheet

Measurements started with 70 to 30 arcsec side, if all five rows are recognized correctly without hesitation testing continues on 20 to 2,5 arcsec side. For testing with full distance correction, it is expected that the range of measurement will be 20 to 2,5 arcsec, but we started with a larger separation as an introduction to the test. If a test person was not able to reach stereo acuity of 30 arcsec than all measurements were done on the 70 to 30 arcsec range (side).

If the test person has had consistent answers for each different measurement (2x with full correction on 4,5 and 3 meters and 4x with add on 4,5 and 3 meters= 6x in total) three measurements are enough, but if hesitating, the test person gets an additional fourth.

For each of six categories average of three or four measurements was taken as a stereo acuity result and noted in the results table 5.

6 Results

Complete results are presented in table 5.

No.	Patient	Gender	Age	Pupil Distance (mm)	Visual Acuity (VA)			STEREOPSIS (arcsec)					
					max VA (MAR)	with +0,5 D Add (MAR)	with +1,0 D Add (MAR)	max VA @ 4,5 m	max VA @ 3,0 m	VA with +0,5 D Add @ 4,5 m	VA with +0,5 D Add @ 3,0 m	VA with +1,0 D Add @ 4,5 m	VA with +1,0 D Add @ 3,0 m
1	AA	M	34	60,5	0,862	1,042	1,852	15,0	11,7	18,3	15,0	30,0	20,0
2	AM	F	62	61,5	0,893	1,316	2,632	10,0	10,0	20,0	20,0	50,0	40,0
3	AS	F	32	58,4	0,725	1,000	1,429	3,3	8,3	10,0	13,3	20,0	20,0
4	BA	F	31	67,8	0,758	1,042	1,515	10,0	20,0	23,3	23,3	30,0	30,0
5	BA	F	65	57,5	0,926	1,163	1,613	23,3	26,7	36,7	40,0	56,7	66,7
6	BF	M	63	66,5	0,862	1,042	1,389	10,0	10,0	40,0	30,0	70,0	36,7
7	BI	M	51	67,0	0,758	1,250	2,273	15,0	15,0	40,0	30,0	50,0	40,0
8	BI	M	54	70,5	0,962	1,136	1,429	13,3	16,7	40,0	30,0	50,0	40,0
9	BM	F	52	61,4	0,758	0,926	1,282	7,5	10,0	17,5	15,0	25,0	20,0
10	BM	F	25	57,0	0,862	1,220	1,667	10,0	9,2	10,0	17,5	13,3	18,3
11	BN	F	30	62,0	0,667	0,833	1,471	5,0	5,0	15,0	15,0	50,0	30,0
12	BS	F	27	66,2	0,862	1,190	1,667	8,3	10,0	10,0	12,5	26,7	20,0
13	BZ	M	61	66,5	0,862	1,111	1,471	10,0	10,0	17,5	12,5	43,3	43,3
14	CI	M	33	58,0	0,833	1,042	1,429	5,0	5,0	7,5	7,5	12,5	16,7
15	CZ	M	56	68,0	0,926	1,389	2,500	10,0	12,5	26,7	25,0	50,0	40,0
16	DA	M	26	70,7	0,667	1,020	1,471	15,0	18,3	30,0	33,3	40,0	40,0
17	DF	F	51	60,0	0,833	1,220	1,786	12,5	20,0	33,3	30,0	30,0	40,0
18	DM	M	31	59,5	0,926	1,250	2,000	30,0	35,0	46,7	35,0	40,0	56,7
19	DR	F	53	67,0	0,862	1,087	1,429	6,7	7,5	20,0	20,0	30,0	30,0
20	EM	M	50	72,5	0,833	1,316	2,083	23,3	26,7	30,0	40,0	50,0	55,0
21	EN	M	23	59,0	0,667	0,862	1,471	7,5	7,5	15,0	15,0	45,0	35,0
22	FD	M	33	67,0	0,694	1,020	1,667	10,0	15,0	15,0	10,0	20,0	30,0
23	GF	M	52	61,3	0,694	0,893	1,471	4,2	4,2	12,5	7,5	15,0	10,0
24	GS	F	26	54,0	0,794	1,190	1,923	6,7	11,7	15,0	25,0	20,0	30,0
25	HK	M	28	73,0	0,667	0,862	2,174	7,5	5,0	12,5	12,5	45,0	45,0
26	HN	F	50	71,0	0,893	1,020	1,316	7,5	10,0	20,0	25,0	36,7	30,0
27	JV	F	54	69,0	0,893	1,316	1,923	12,5	5,8	16,7	15,0	56,7	30,0
28	KB	M	51	72,0	0,694	1,000	1,724	17,5	22,5	50,0	43,3	53,3	50,0
29	KJ	F	52	67,0	0,758	1,042	1,429	10,0	7,5	15,0	18,3	43,3	46,7
30	KR	F	53	62,0	0,725	1,000	1,316	25,0	30,0	40,0	40,0	56,7	63,3
31	LV	F	29	67,5	0,667	0,893	1,042	5,0	7,5	10,0	10,0	15,0	15,0
32	MI	F	34	69,1	0,667	0,833	1,667	2,5	2,5	5,0	7,5	21,7	23,3
33	MR	F	54	67,9	0,758	1,042	1,429	4,2	6,7	5,0	10,0	15,0	12,5
34	MV	F	50	66,7	0,862	1,042	1,786	5,0	5,0	5,0	6,7	15,0	15,0
35	NB	M	50	61,3	0,667	1,136	1,667	20,0	25,0	35,0	35,0	46,7	40,0
36	NI	M	56	67,5	0,926	1,087	1,471	30,0	40,0	46,7	60,0	63,3	66,7
37	PD	F	56	67,9	0,758	0,926	1,351	25,0	35,0	50,0	55,0	65,0	70,0
38	PJ	M	55	61,8	0,833	1,111	1,786	17,5	16,7	40,0	36,7	70,0	70,0
39	PM	M	33	66,2	0,725	0,893	1,515	6,7	7,5	11,7	10,0	20,0	16,7
40	PM	F	58	57,5	0,862	1,064	1,724	26,7	26,7	40,0	35,0	50,0	45,0
41	SB	M	50	60,0	0,758	1,042	1,316	9,2	8,3	16,7	10,0	20,0	15,0
42	SB	F	50	69,8	0,926	1,316	1,786	10,0	15,0	20,0	18,3	30,0	25,0
43	SM	F	65	66,9	0,833	1,087	1,724	11,7	15,0	20,0	20,0	40,0	45,0
44	ST	M	31	60,5	0,725	0,893	1,042	2,5	5,0	7,5	7,5	17,5	12,5
45	SV	F	54	62,0	0,694	1,042	1,282	20,0	25,0	30,0	40,0	55,0	65,0
46	SV	M	27	61,0	0,725	1,000	1,667	10,0	16,7	20,0	25,0	56,7	60,0
47	TI	M	56	59,0	0,758	1,000	1,351	13,3	13,3	30,0	20,0	50,0	46,7
48	TI	M	27	66,5	0,862	1,087	1,724	10,0	11,7	15,0	16,7	63,3	43,3
49	TN	F	25	59,0	0,833	1,220	1,786	15,0	15,0	30,0	17,5	60,0	30,0
50	TZ	M	60	61,9	0,694	1,163	2,083	20,0	20,0	25,0	25,0	30,0	30,0
51	UA	M	64	62,1	0,694	0,926	1,351	17,5	20,0	30,0	50,0	60,0	63,3
AVERAGE:			45,0	64,23	0,79	1,07	1,63	12,42	14,60	23,47	23,38	39,67	36,93
STDEV			13,317	4,68	0,09	0,14	0,32	7,11	8,80	12,63	13,00	16,90	16,88
MAX			65	73,0	1,0	1,4	2,6	30,0	40,0	50,0	60,0	70,0	70,0
MIN			23	54,0	0,7	0,8	1,0	2,5	2,5	5,0	6,7	12,5	10,0

Table 5: Measurement results

6.1 Stereopsis in correlation with maximal visual acuity

6.1.1 Stereopsis measured at distance of 4,5 meters with full refractive correction

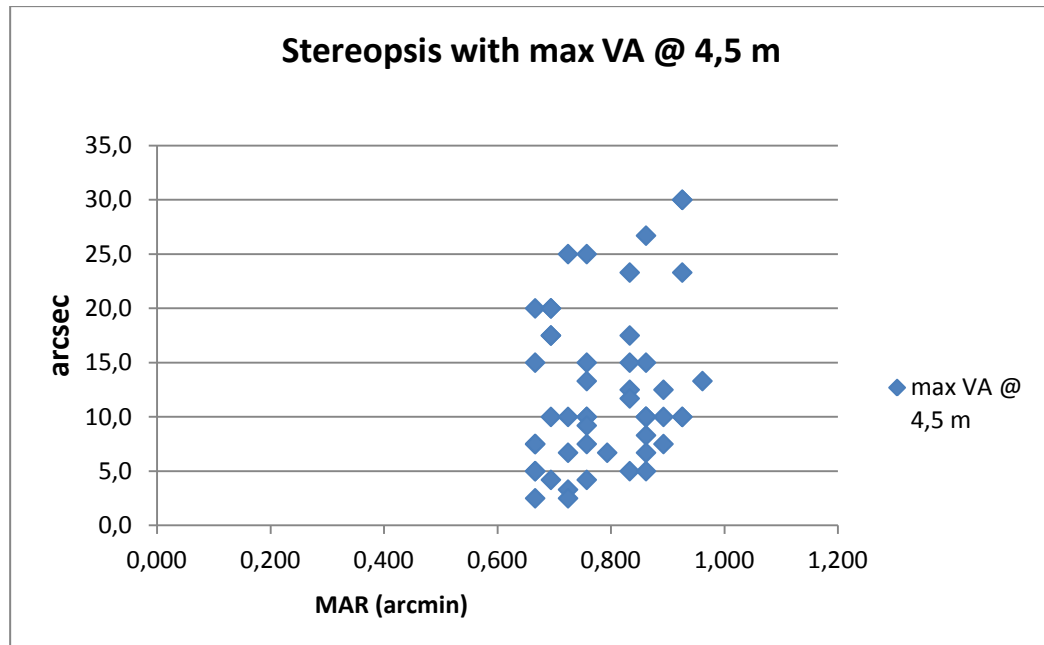


Figure 33: Stereopsis measured at distance of 4,5 meters

There is a weak positive correlation between the visual acuity with full refractive correction and the stereopsis at 4,5 meters measuring distance, $r(51)=0,231$, $p=0,103$.

6.1.2 Stereopsis measured at distance of 3,0 meters with full refractive correction

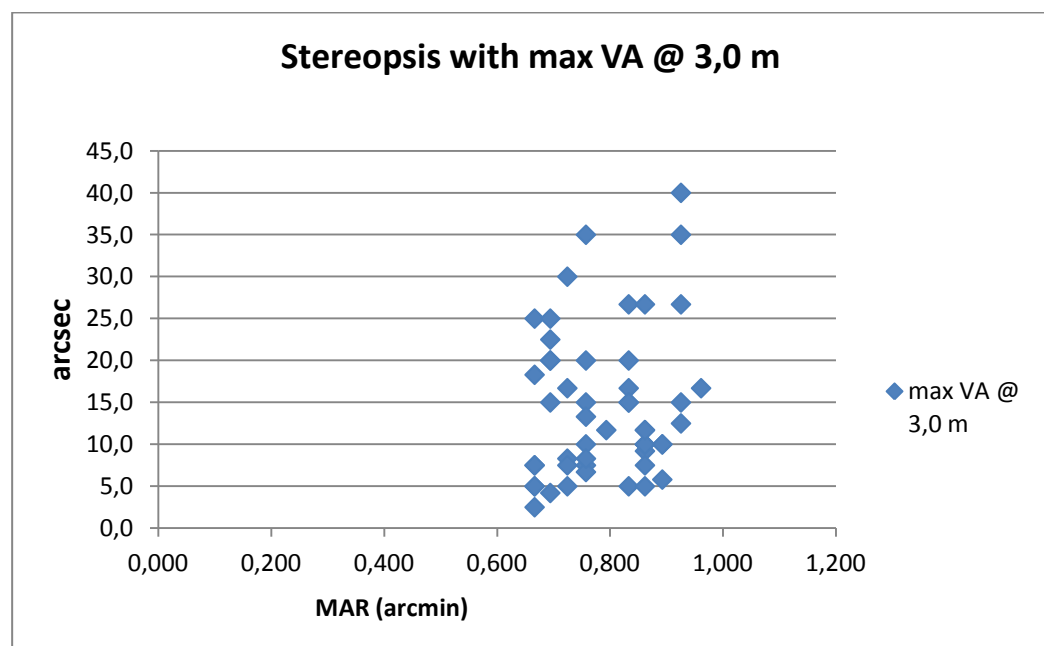


Figure 34: Stereopsis measured at distance of 3,0 meters

There is no or negligible positive correlation between the visual acuity with full refractive correction and the stereopsis at 3,0 meters measuring distance, $r(51)=0,173$, $p=0,224$.

6.1.3 Stereopsis measured at distance of 4,5 meters with +0,50 D fogging

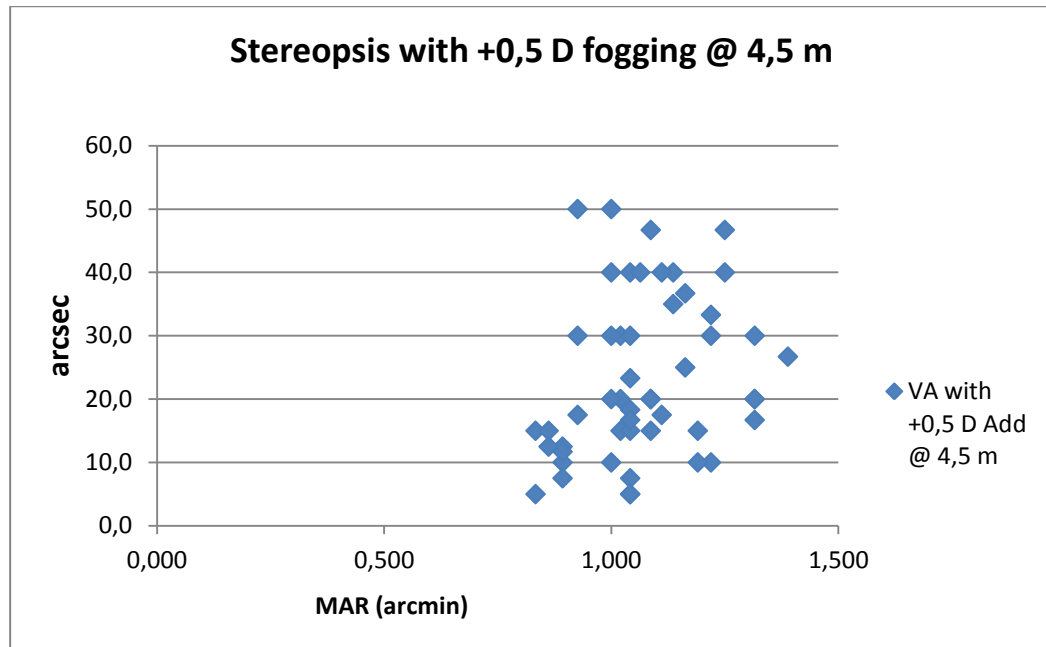


Figure 35: Stereopsis measured at distance of 4,5 meters with +0,50 D fogging

6.1.4 Stereopsis measured at distance of 3,0 meters with +0,50 D fogging

There is a weak positive correlation between the visual acuity fogged with +0,5 D and the stereopsis at 4,5 meters measuring distance, $r(51)=0,261$, $p=0,064$.

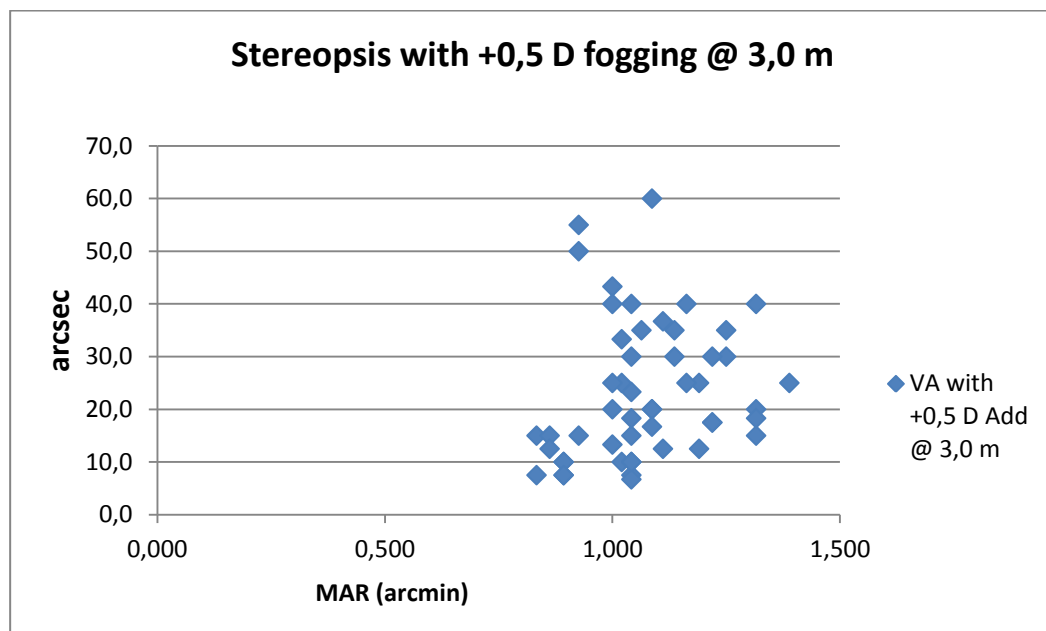


Figure 36: Stereopsis measured at distance of 4,5 meters with +0,50 D fogging

There is a weak positive correlation between the visual acuity fogged with +0,5 D and the stereopsis at 3,0 meters measuring distance, $r(51)=0,197$, $p=0,167$.

6.1.5 Stereopsis measured at distance of 4,5 meters with +1,0 D fogging

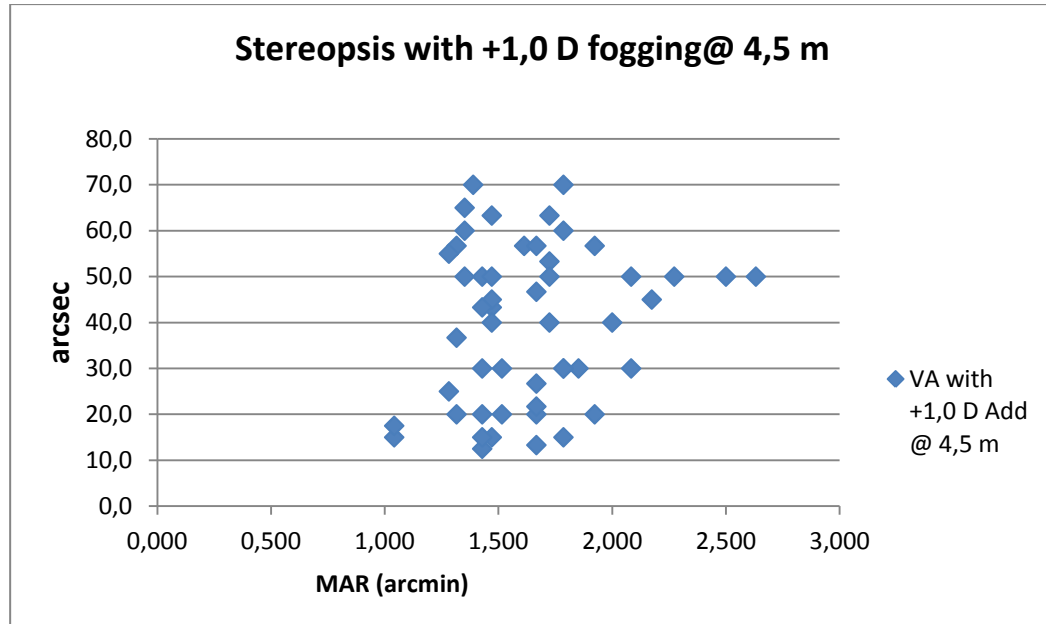


Figure 37: Stereopsis measured at distance of 4,5 meters with +1,0 D fogging

6.1.6 Stereopsis measured at distance of 3,0 meters with +1,0 D fogging

There is no or negligible positive correlation between the visual acuity fogged with +1,0 D and the stereopsis at 4,5 meters measuring distance, $r(51)=0,179$, $p=0,210$.

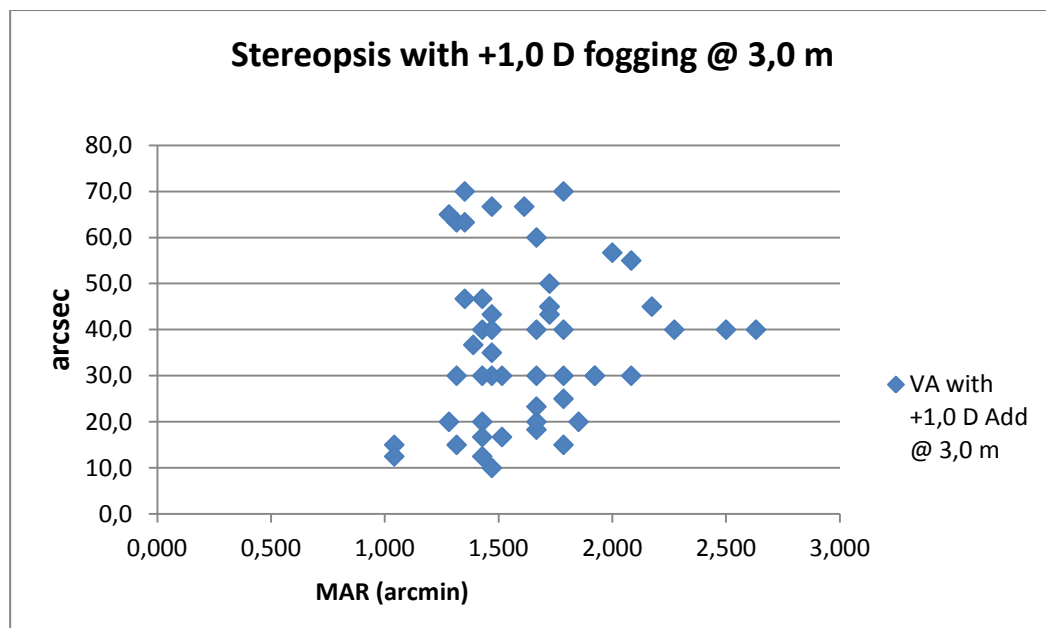


Figure 38: Stereopsis measured at distance of 3,0 meters with +1,0 D fogging

There is no or negligible positive correlation between the visual acuity fogged with +1,0 D and the stereopsis at 3,0 meters measuring distance, $r(51)=0,131$, $p=0,361$.

6.1.7 Stereopsis of two groups sorted by VA

When 51 test persons are divided in two groups, the first with visual acuity in range of 1,5 and 1,26 (MAR 0,67–0,79) and the second group with VA in the range 1,2 and 1,04 (MAR 0,83–0,96) and average results of each group are compared we get a more obvious correlation. A group with better average of visual acuity (VA) has better average of stereo acuity.

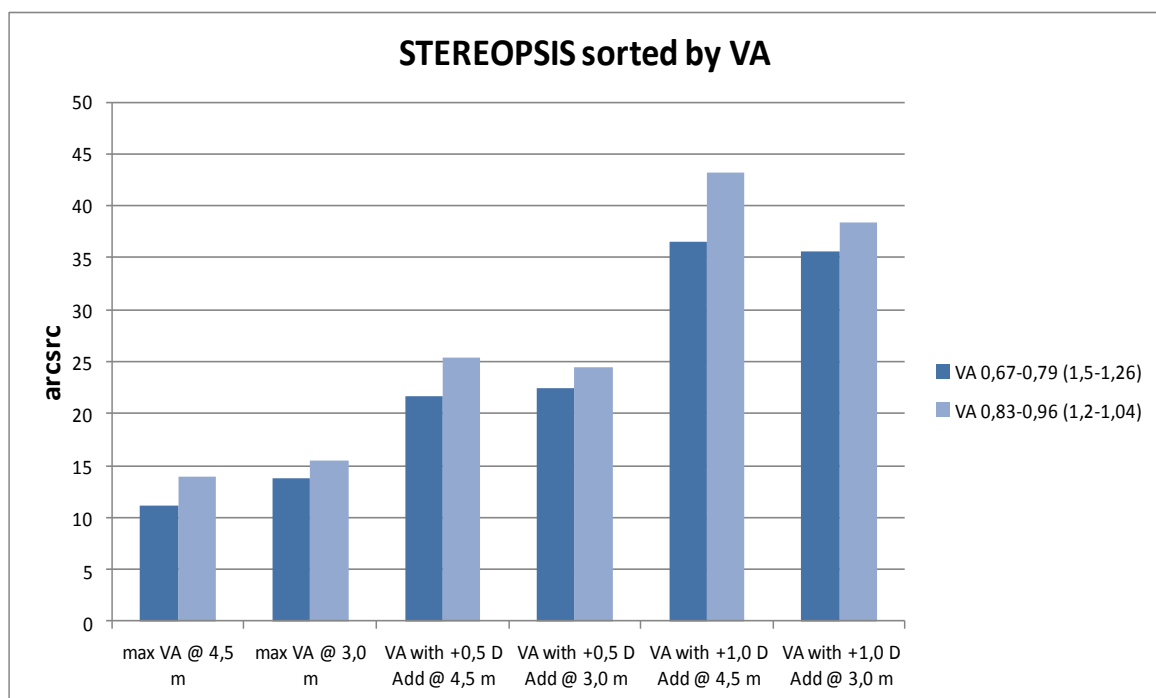


Figure 39: Stereopsis of two groups sorted by VA

Average of the stereopsis is better in the group with better visual acuity between 8,2 and 24,9%.

6.1.8 Stereopsis in correlation with visual acuity at 4,5 m distance with full refractive correction only at young test persons

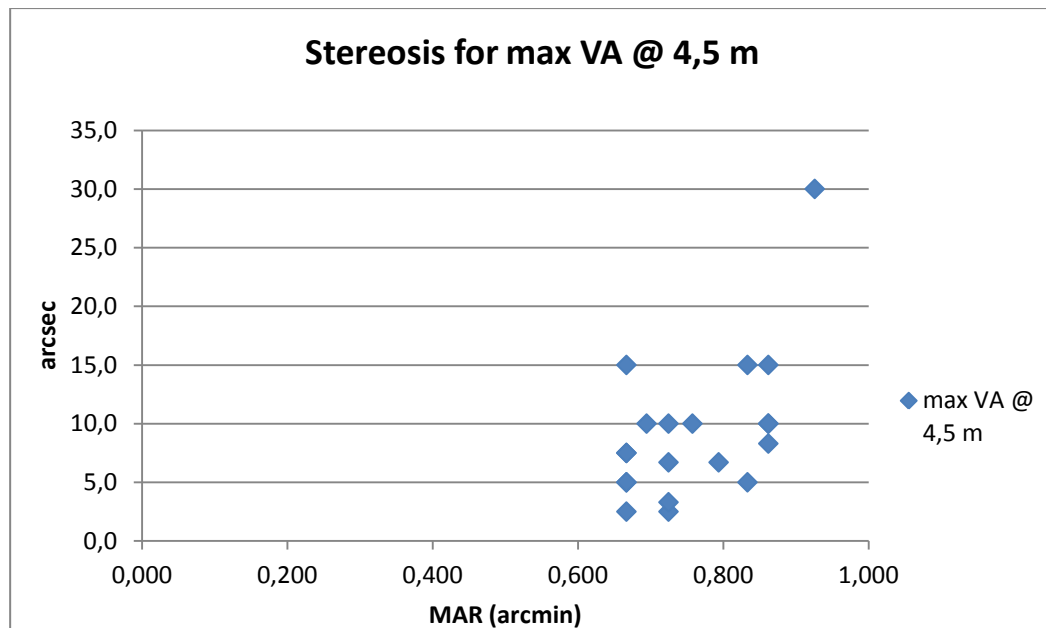


Figure 40: Stereopsis at 4,5 m in correlation with visual acuity by young group

Excluding older test persons who have good visual acuity but decreased stereo acuity because of age, positive correlation becomes significant ($r(20)=0,566$, $p=0,009$ at 4,5 meters).

6.1.9 Stereopsis in correlation with visual acuity at 3,0 m distance with full refractive correction only at young test persons

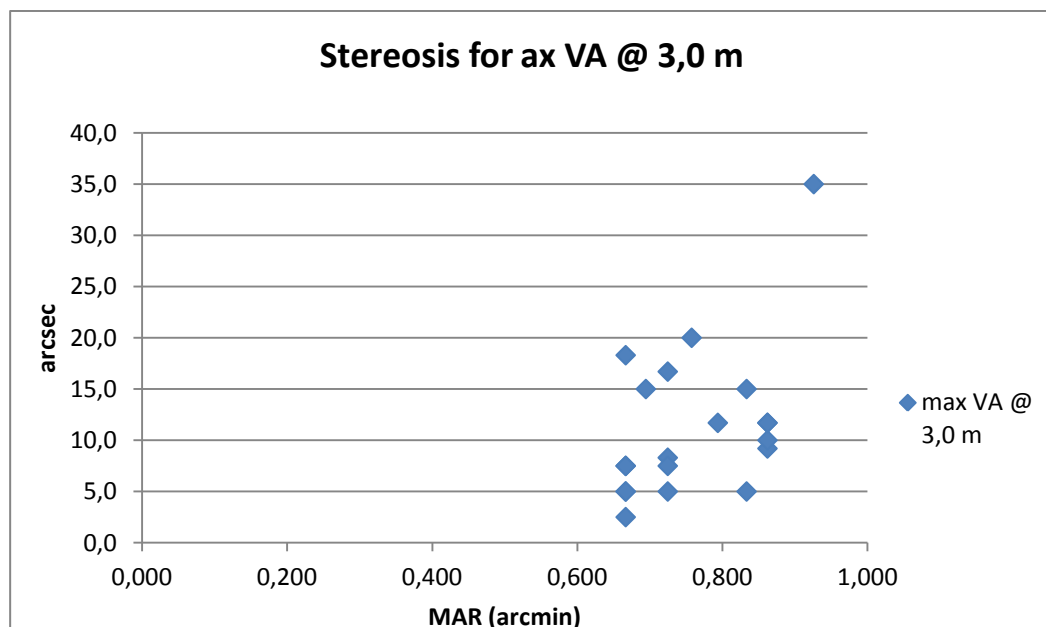


Figure 41: Stereopsis at 4,5 m in correlation with visual acuity by young group

Stereopsis is in positive correlation with visual acuity at younger test persons at 3,0 meter distance ($r(20)=0,456$, $p=0,043$) and that matches the assumption of this work.

6.2 Stereopsis sorted by pupil distance

6.2.1 Stereopsis and pupil distance with max VA at 4,5 meters

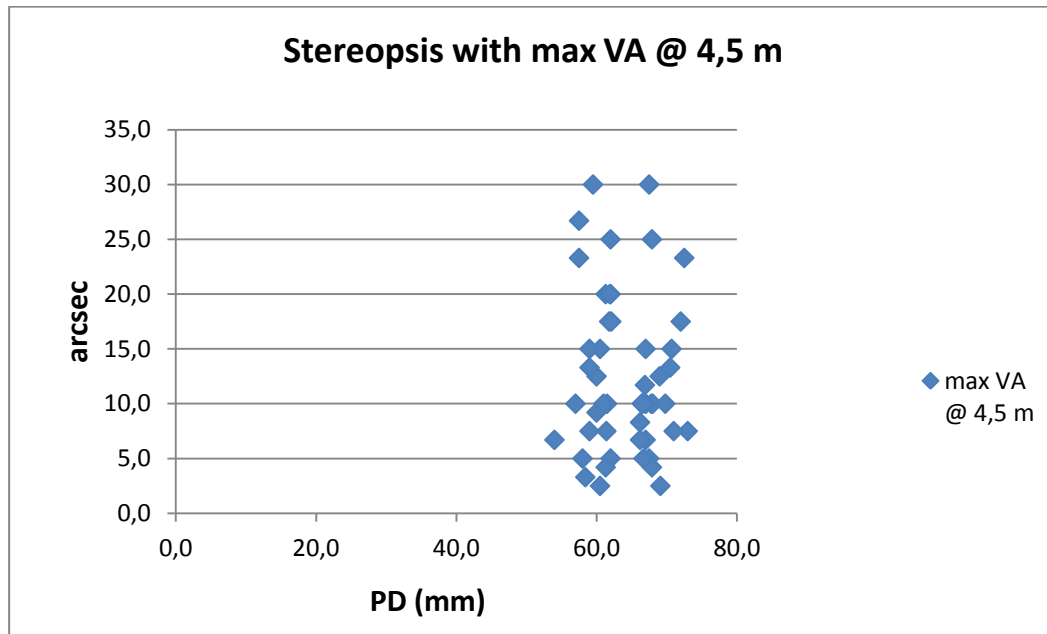


Figure 42: Stereopsis sorted by pupil distance with full refractive correction at 4,5 m

There is no correlation between stereopsis and pupil distance by visual acuity with full refractive correction at 4,5 meters measuring distance, $r(51)=0,059$, $p=0,679$.

6.2.2 Stereopsis and pupil distance with max VA at 3,0 meters

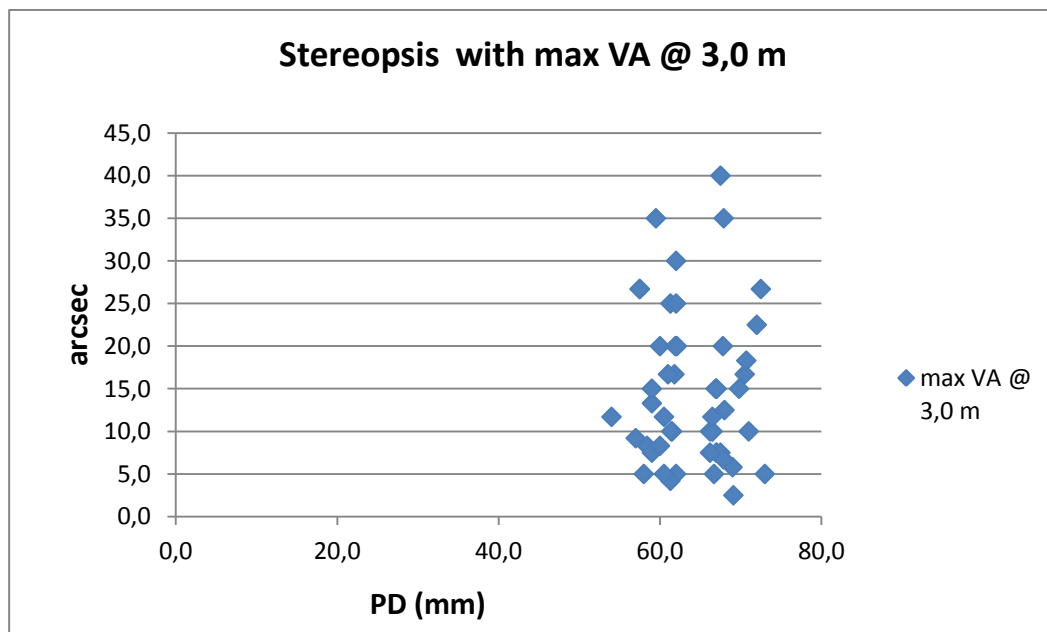


Figure 43: Stereopsis sorted by pupil distance with max VA at 3,0 meters

There is no correlation between stereopsis and pupil distance by visual acuity with full refractive correction at 3,0 meters measuring distance, $r(51)=0,027$, $p=0,849$.

6.2.3 Stereopsis and pupil distance with VA fogged with +0,5 D at 4,5 meters

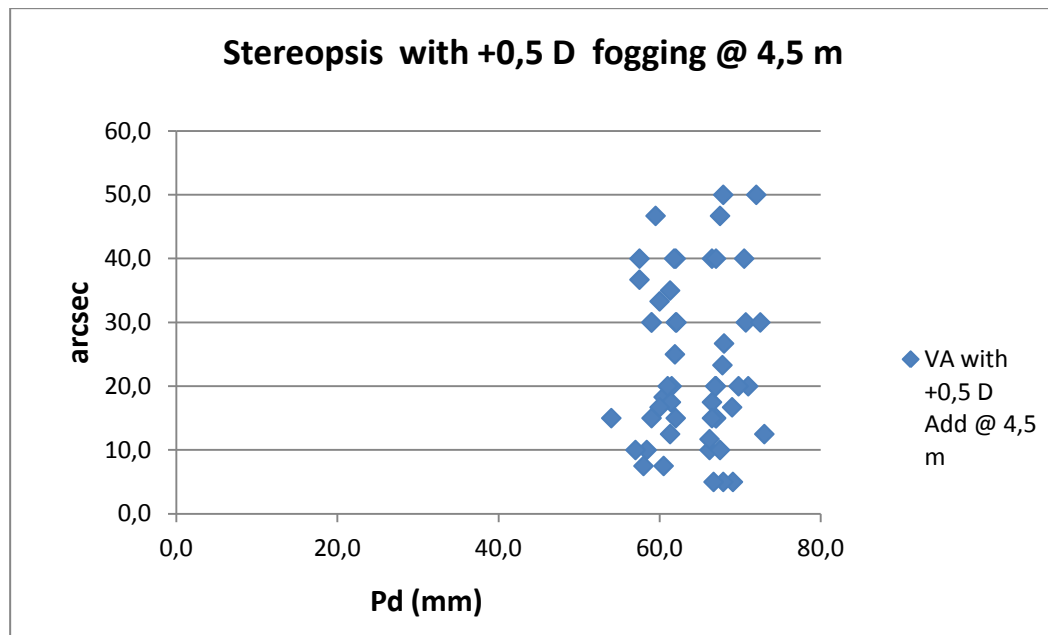


Figure 44: Stereopsis sorted by pupil distance with VA fogged with +0,5 D at 4,5 meters

There is no correlation between stereopsis and pupil distance by the visual acuity fogged with +0,5 D at 4,5 meters measuring distance, $r(51)=0,049$, $p=0,734$.

6.2.4 Stereopsis and pupil distance with VA fogged with +0,5 D at 3,0 meters

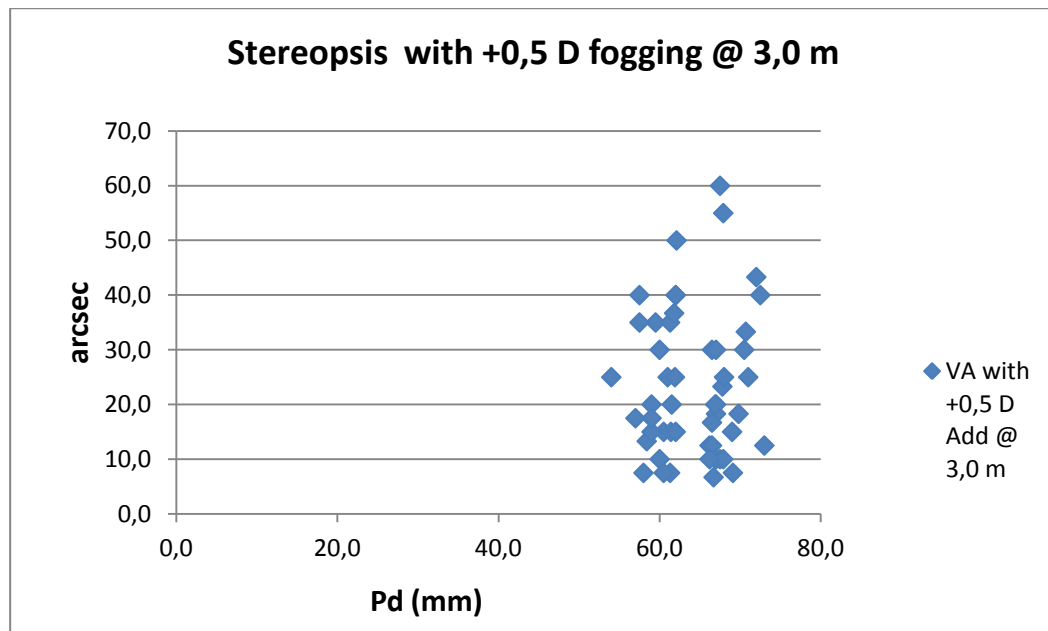


Figure 45: Stereopsis and pupil distance with VA fogged with +0,5 D at 3,0 meters

There is no correlation between stereopsis and pupil distance by the visual acuity fogged with +0,5 D and the stereopsis at 3,0 meters measuring distance, $r(51)=0,062$, $p=0,663$.

6.2.5 Stereopsis and pupil distance with VA fogged with +1,0 D at 4,5 meters

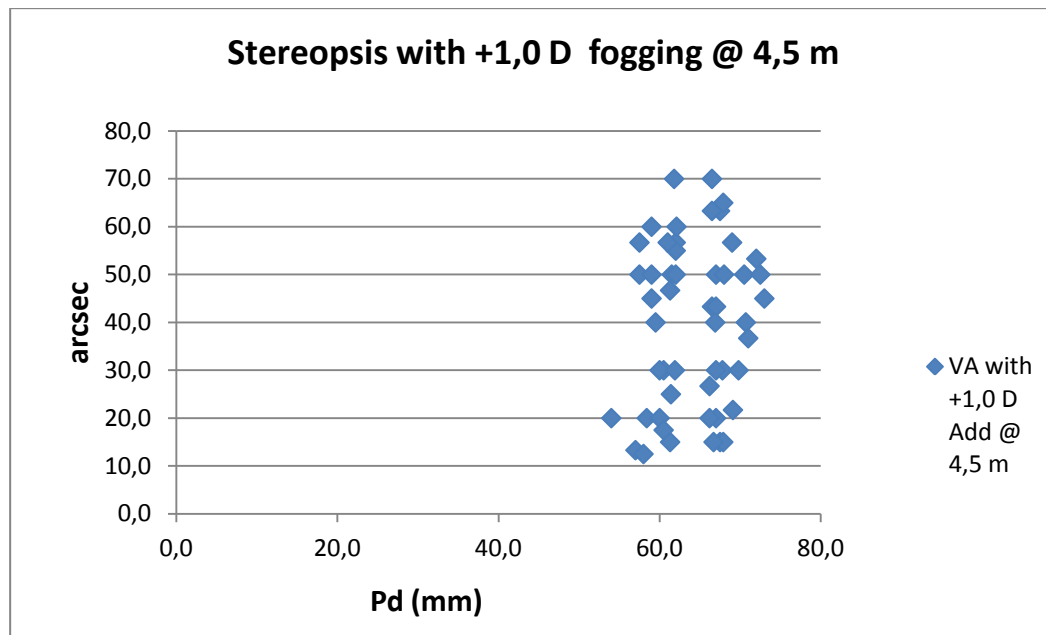


Figure 46: Stereopsis and pupil distance with VA fogged with +1,0 D at 4,5 meters

There is no or negligible correlation between the pupil distance by the visual acuity fogged with +1,0 D and the stereopsis at 4,5 meters measuring distance, $r(51)=0,138$, $p=0,333$.

6.2.6 Stereopsis and pupil distance with VA fogged with +1,0 D at 3,0 meters

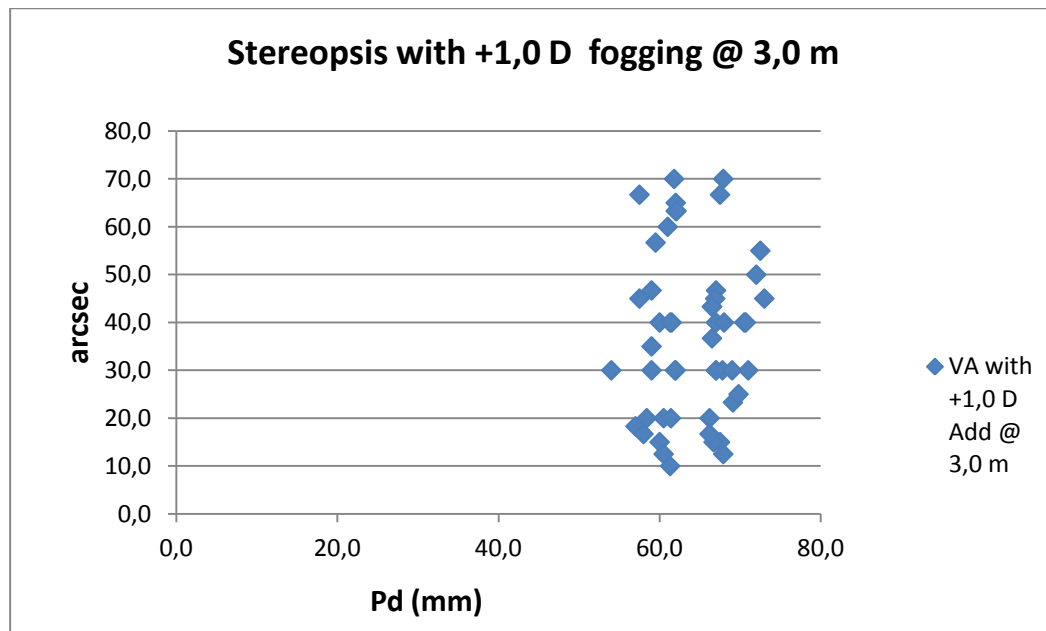


Figure 47: Stereopsis and pupil distance with VA fogged with +1,0 D at 3,0 meters

There is no or negligible correlation between the pupil distance by the visual acuity fogged with +1,0 D and the stereopsis at 3,0 meters measuring distance, $r(51)=0,058$, $p=0,688$.

6.2.7 Stereopsis of two groups sorted by pupil distance

However, if 51 test persons are divided into two groups, the first with pupil distance smaller than 62,1 mm and the second group with pupil distance bigger than 66 mm and the average results of each group are compared, it can be seen that the group with bigger average of pupil distance has better stereo acuity.

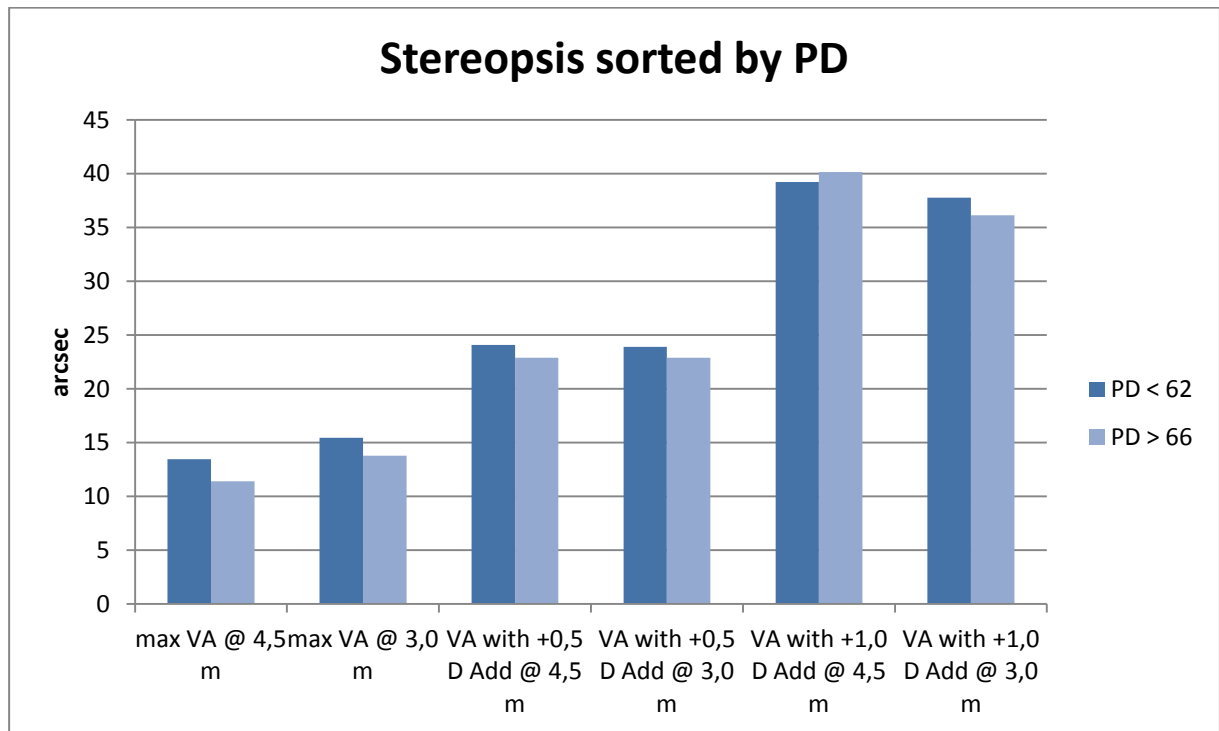


Figure 48: Stereopsis sorted by PD

Stereopsis is better in the group with bigger pupil distance.

6.3 Stereopsis in correlation with age

6.3.1 Stereopsis sorted by age with full refractive correction at 4,5 meters

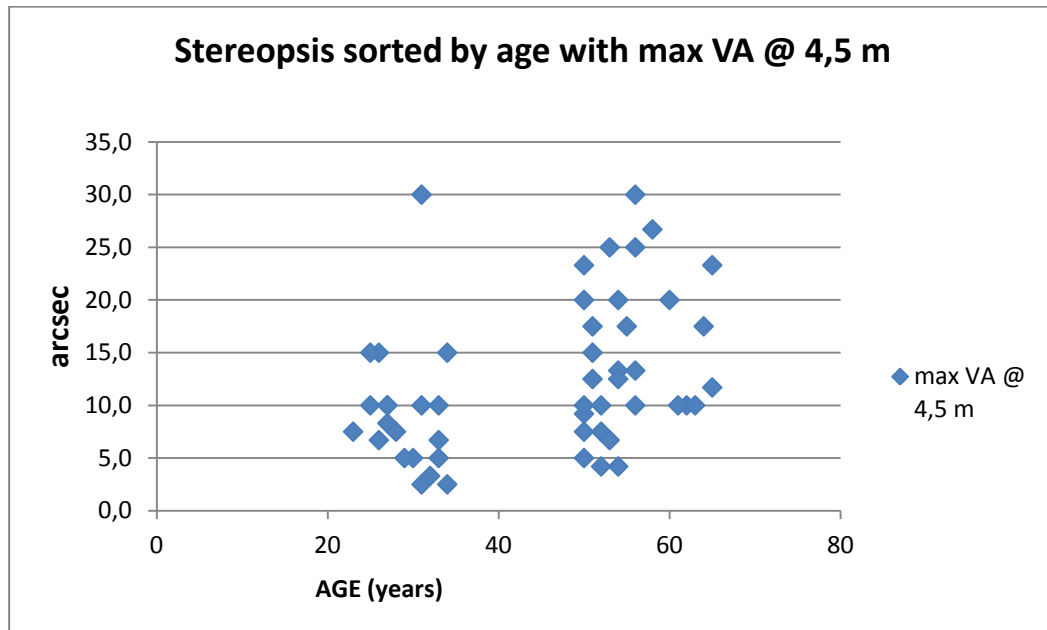


Figure 49: Stereopsis sorted by age with full refractive correction at 4,5 meters measuring distance

There is a moderate positive correlation between stereopsis and age by visual acuity with full refractive correction at 4,5 meters measuring distance, $r(51)=0,371$, $p=0,007$.

6.3.2 Stereopsis sorted by age with full refractive correction at 3,0 meters

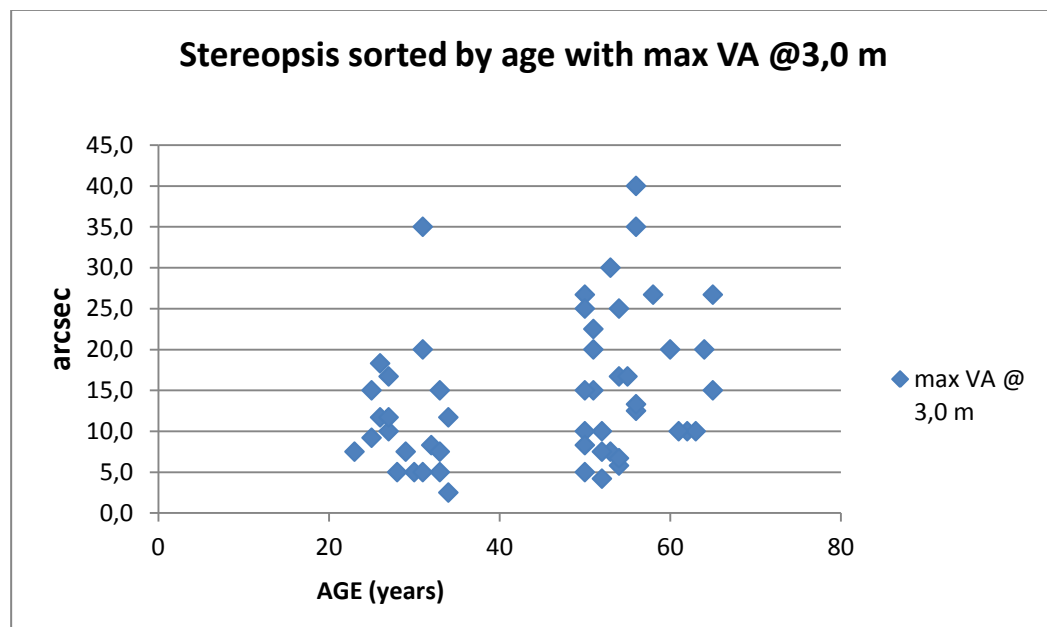


Figure 50: Stereopsis sorted by age with full refractive correction at 3,0 meters

There is a moderate positive correlation between stereopsis and age by visual acuity with full refractive correction at 3,0 meters measuring distance, $r(51)=0,299$, $p=0,033$.

6.3.3 Stereopsis sorted by age with +0,5 D add at 4,5 meters

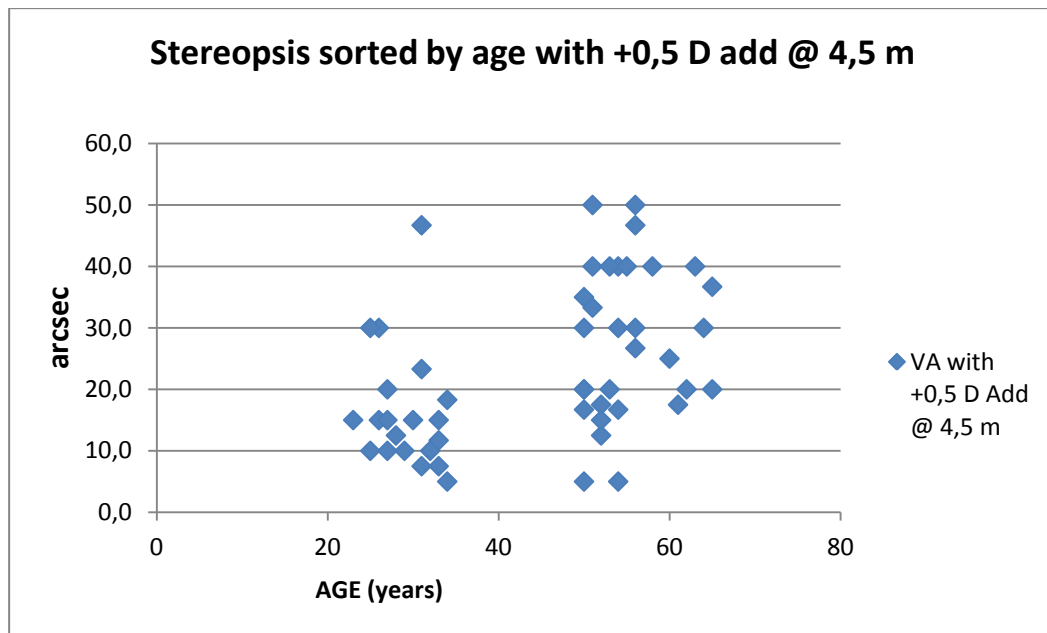


Figure 51: Stereopsis sorted by age with +0,5 D add at 4,5 meters

There is a strong positive correlation between stereopsis and age by visual acuity fogged with +0,5 D at 4,5 meters measuring distance, $r(51)=0,442$, $p=0,001$.

6.3.4 Stereopsis sorted by age with +0,5 D add at 3,0 meters



Figure 52: Stereopsis sorted by age with +0,5 D add at 3,0 meters

There is a strong positive correlation between stereopsis and age by visual acuity fogged with +0,5 D at 3,0 meters measuring distance, $r(51)=0,427$, $p=0,0018$.

6.3.5 Stereopsis sorted by age with +1,0 D add at 4,5 meters

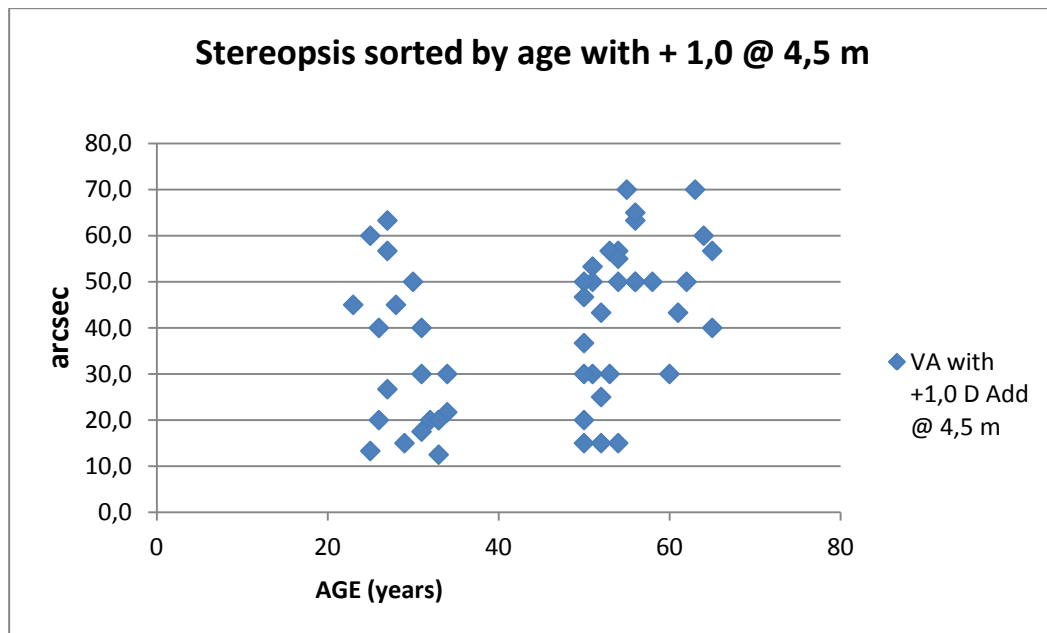


Figure 53: Stereopsis sorted by age with +1,0 D add at 4,5 meters

There is a moderate positive correlation between stereopsis and age by visual acuity fogged with +1,0 D at 4,5 meters measuring distance, $r(51)=0,370$, $p=0,007$.

6.3.6 Stereopsis sorted by age with +1,0 D add at 3,0 meters

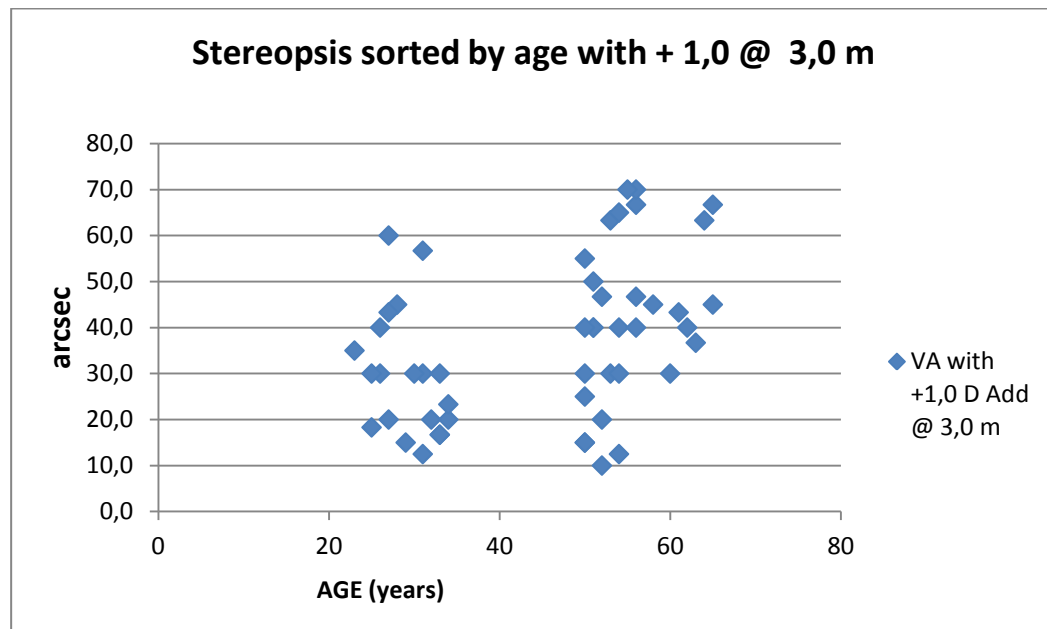


Figure 54: Stereopsis sorted by age with +1,0 D add at 3,0 meters

There is a moderate positive correlation between stereopsis and age by visual acuity fogged with +1,0 D at 4,5 meters measuring distance, $r(51)=0,384$, $p=0,005$.

6.3.7 Stereopsis of two groups sorted by age

At the beginning of the study, test persons were divided by age into two groups, in the first they were aged between 20 to 35 years and in the second between 50 and 65 years and when averages of stereopsis measurements of each group were compared, a significant correlation was found (Figure 53).

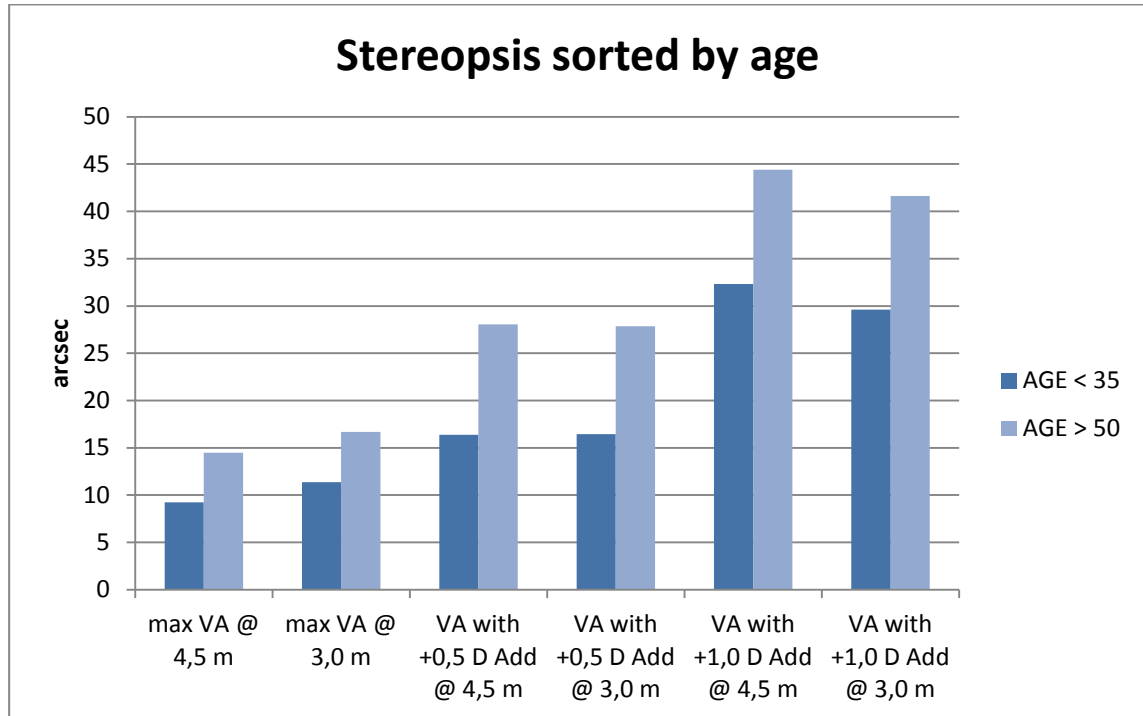


Figure 55: Stereopsis of two groups sorted by age

When stereopsis results are sorted by age it can be seen that the younger group has better stereo acuity at 4,5 meters by 36,05% and at 3,0 meter measuring distance, by 31,74%. Also, with fogged vision for +0,5 D the younger group has better stereo acuity at 4,5 meters by 41,61% and by 40,91% at 3,0 meter distance. The case is similar with fogged vision with +1,0 D at 4,5 m the younger group is better by 27,19% and by 28,86% at 3,0 m distance.

6.4 Stereopsis in correlation with gender

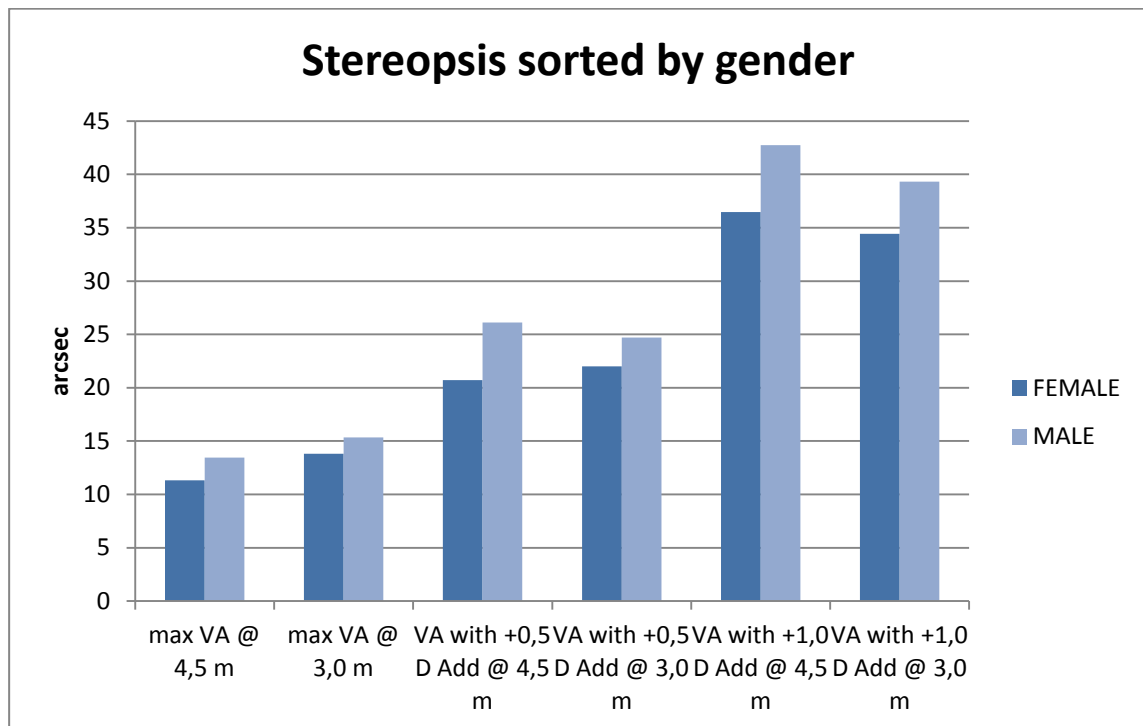


Figure 56: Stereopsis in correlation with gender

Female test persons have better stereopsis than male test persons by 15,79% at 4,5 m and by 10,12% at 3,0 m with full refractive correction. Females have also better stereopsis with decreased visual acuity with +0,5 D by 20,77% at 4,5 m and by 10,99% at 3,0 m distance. The case is similar with decreased vision at 4,5 m by 14,69% and at 3,0 m by 12,46% (Figure 54).

6.5 Stereopsis sorted by gender and age

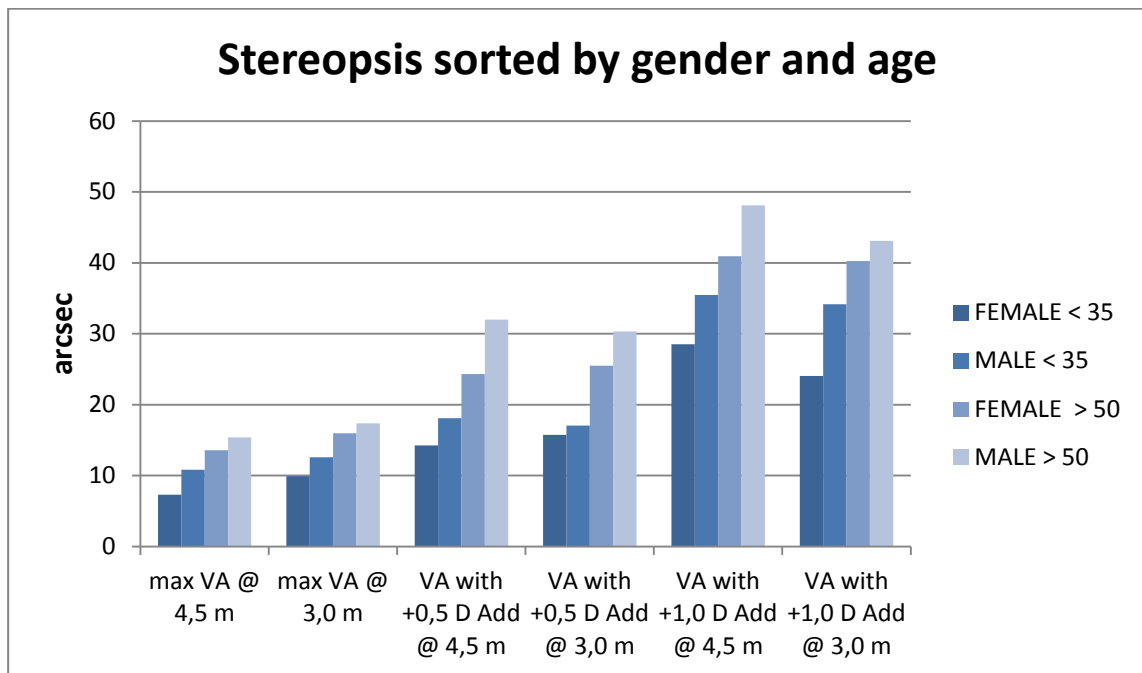


Figure 57: Stereopsis sorted by gender and age

Stereopsis compared in percentage between genders sorted by age.

%	STEREOPSIS (arcsec)					
	max VA @ 4,5 m	max VA @ 3,0 m	VA with +0,5 D Add @ 4,5 m	VA with +0,5 D Add @ 3,0 m	VA with +1,0 D Add @ 4,5 m	VA with +1,0 D Add @ 3,0 m
FEMALE < 35	100,0	100,0	100,0	100,0	100,0	100,0
MALE < 35	148,2	126,9	127,0	108,3	124,3	142,0
FEMALE > 50	186,0	161,4	170,6	162,2	143,6	167,3
MALE > 50	210,5	175,5	224,5	192,8	168,7	179,1

Table 6: Stereopsis compared in percentage between genders sorted by age

6.6 Stereopsis sorted by gender, age and pupil distance

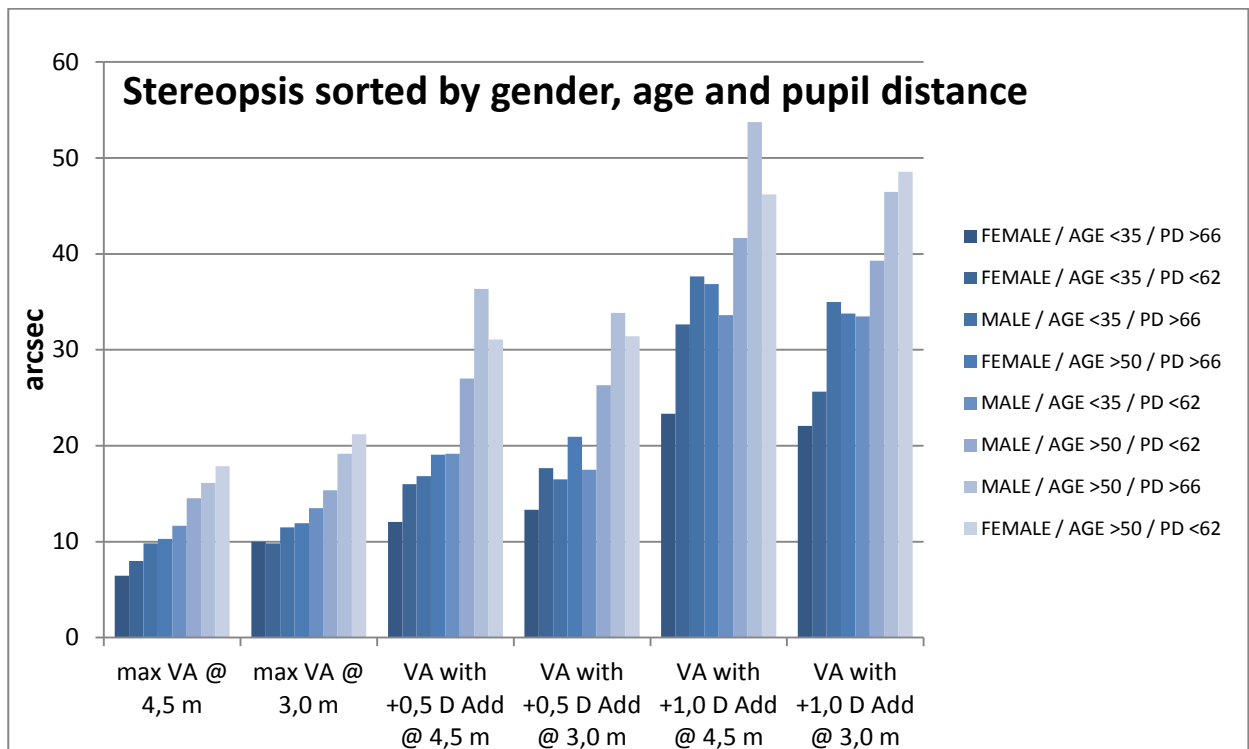


Figure 58: Stereopsis sorted by gender, age and pupil distance

Stereopsis results are sorted by gender, age and pupil distance in the way that the best result of the groups at 4,5 meter distance (female, age<35, PD>66) are 100% and other results are in percent relation with that group (Table 7).

%	STEREOPSIS (arcsec)					
	max VA @ 4,5 m	max VA @ 3,0 m	VA with +0,5 D Add @ 4,5 m	VA with +0,5 D Add @ 3,0 m	VA with +1,0 D Add @ 4,5 m	VA with +1,0 D Add @ 3,0 m
FEMALE / AGE <35 / PD >66	100,00	100,00	100,00	100,00	100,00	100,00
FEMALE / AGE <35 / PD <62	124,03	98,40	132,51	132,53	139,87	116,24
MALE / AGE <35 / PD >66	152,56	115,00	139,46	123,83	161,28	158,55
FEMALE / AGE >50 / PD >66	159,52	119,44	157,99	157,01	157,84	153,11
MALE / AGE <35 / PD <62	180,88	134,83	158,73	131,33	143,97	151,68
MALE / AGE >50 / PD <62	225,25	153,57	223,84	197,48	178,46	177,96
MALE / AGE >50 / PD >66	250,19	191,75	301,14	254,03	230,14	210,48
FEMALE / AGE >50 / PD <62	276,85	212,00	257,32	235,86	197,86	220,03

Table 7: Percent relation between groups sorted by gender, age and PD

6.7 Stereopsis compared at 4,5 and 3,0 meter distances

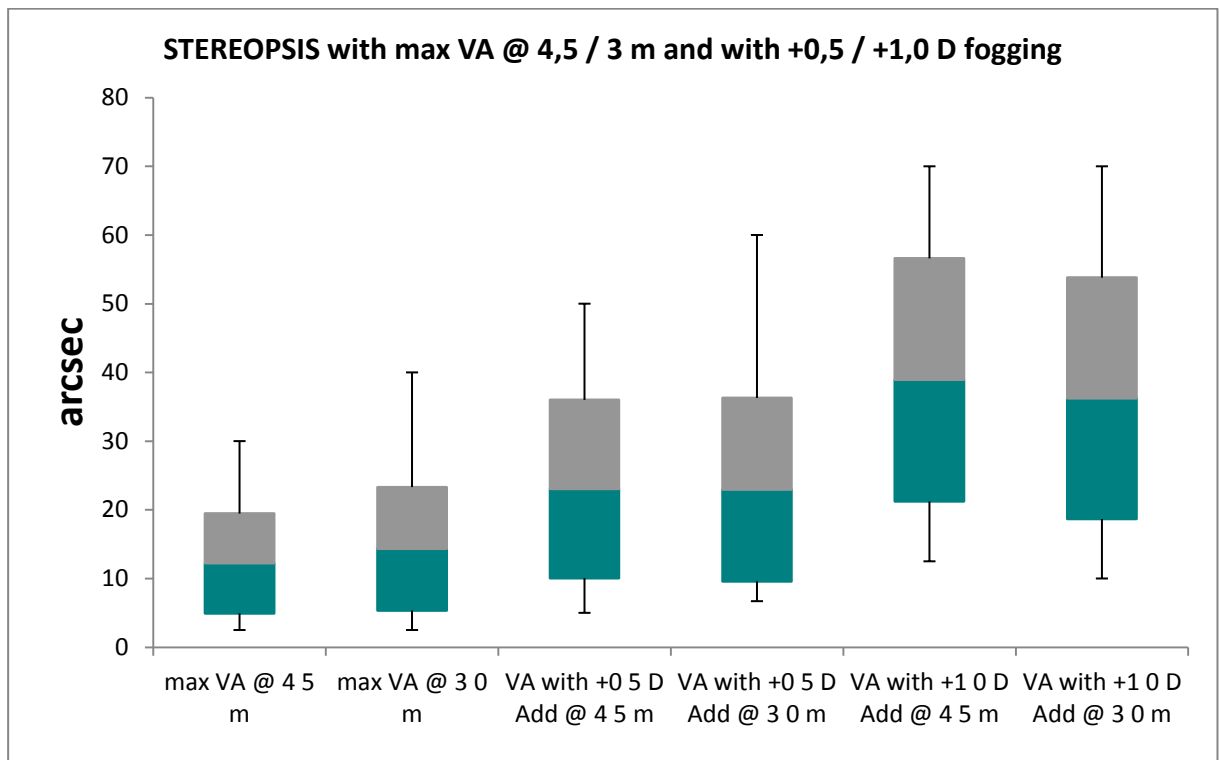


Figure 59: Stereopsis compared at 4,5 and 3,0 meter distances

There is a very strong correlation between stereopsis measured at 4,5 and 3,0 meters, $r(51)=0,935$, $p=0,000$. Results of stereopsis measurements varied through test. Results with full correction were better at 4,5 m than 3,0 m measuring distance, than with +0,5 D fogged vision, stereopsis became more-less equal and then fogged with +1,0 D stereopsis at 3,0 meters were better.

How can this turn be explained?

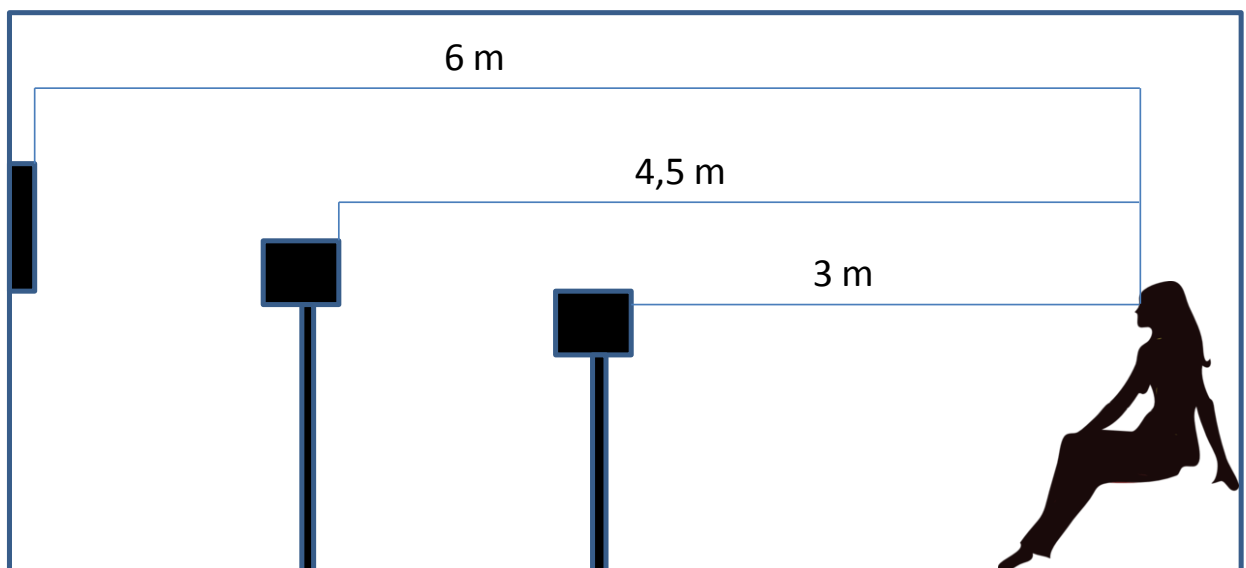


Figure 60: Refractive correction at 6 meters and stereopsis measurements at 4,5 and 3,0 meters

Stereopsis measurements started with full correction at 4,5 and 3,0 m distance. At that point refractive correction was closer to 4,5 m than to 3,0 m distance, so it can be presumed that stereopsis results are better at 4,5 m because it was closer to refractive distance. When the correction was fogged with +0,5 D, refractive plane was moved from 6 m to 2,7 -2,0 meters. Two meters is $1/0,5=2,0$ m. However, why 2,7 m? Some test persons were not totally corrected, maybe it was -0,12 D too much at 6 meters and full correction was at infinity. This -0,12 D makes fogging with +0,5 D actually +0,37 and that explains 2,7 m. With this fogging (+0,37 to +0,5 D) the plane of refraction was closer to 3,0 m stereopsis measuring distance, so results became better at 3,0 than 4,5 m or about the same (Figure 58).

Based on the theory of vergence, when fogged with +1,0 D, then the refractive plane is much closer to 3,0 m than to 4,5 m measurement distance and then at 3,0 m stereopsis results become better. This theory has base if we forget about accommodation.

6.8 Multiple regression

Regression is a measure of the relation between the mean value of one variable and corresponding values of other variables.

	Age	Pupil Distance (mm)	max VA (MAR)	with +0,5 D Add (MAR)	with +1,0 D Add (MAR)	max VA @ 4,5 m	max VA @ 3,0 m	VA with +0,5 D Add @ 4,5 m	VA with +0,5 D Add @ 3,0 m	VA with +1,0 D Add @ 4,5 m
Pupil Distance (mm)	0,137									
max VA (MAR)	0,305	0,026								
with +0,5 D Add (MAR)	0,250	-0,006	0,689							
with +1,0 D Add (MAR)	0,069	0,083	0,312	0,655						
max VA @ 4,5 m	0,371	-0,059	0,231	0,320	0,169					
max VA @ 3,0 m	0,299	-0,027	0,173	0,257	0,065	0,935				
VA with +0,5 D Add @ 4,5 m	0,442	0,049	0,217	0,261	0,116	0,844	0,836			
VA with +0,5 D Add @ 3,0 m	0,427	0,062	0,140	0,197	0,045	0,844	0,883	0,879		
VA with +1,0 D Add @ 4,5 m	0,370	0,138	0,189	0,179	0,179	0,607	0,523	0,718	0,688	
VA with +1,0 D Add @ 3,0 m	0,384	0,058	0,112	0,144	0,131	0,760	0,752	0,755	0,838	0,826

Table 8: Multiple regression

Interpretation of Pearson's r		
>0,70	Very strong positive relationship	
0,40 - 0,69	Strong positive relationship	
0,30 - 0,39	Moderate positive relationship	
0,20 - 0,29	Weak positive relationship	
0,01 - 0,19	No or negligible relationship	

Table 9: Interpretation of Pearson's correlation

7 Discussion

This study has tried to prove the possible existence of the correlation between stereopsis and some anatomical and physiological factors. If we recall the three assumptions from the beginning of this study, we can analyse each of them.

7.1 Correlation of stereopsis and visual acuity

When we talk about how visual acuity influences stereopsis, we have to consider two different things. One is that stereopsis of a subject decreases if visual acuity decreases. When fully corrected, both visual acuity and stereo acuity increase again. Another correlation between stereopsis and visual acuity is among different subjects. A subject with better visual acuity has more chance to have better stereopsis. Both of these correlations were proved in this work.

It could be said that the first assumption, that stereopsis is in direct correlation with visual acuity, was proved, may be with weak correlation but it was proved. It does not mean that if someone has better visual acuity that he will automatically have better stereopsis, but in general subjects with better visual acuity usually have better stereopsis.

In the paper, "Correlation between Refractive Error and Stereoacuity", the authors Farvardin Mohsen, Farvardin Majid, Eghtedari M. did research with purpose to assess the correlation between refractive error and stereo acuity in school children.

Their result was that the correction of refractive error with spectacles resulted in improved stereo acuity to normal values in all types of refractive errors except anisometropia.[8]

In previous paper, the authors came to the same conclusion, but in the opposite direction. In the paper, they measured stereopsis before and after refractive correction, while in this study test persons were first fully corrected and then fogged for the same amount of plus power. While their results must be scattered, the results from this study are less scattered.

When comparing the two groups of test persons, it can be seen that a small difference in visual acuity gives little difference in stereo acuity, but when the subject's visual acuity decreases dramatically, stereo acuity also decrease significantly, and these are conclusions of the authors Mohsen et al..

7.2 Correlation of stereopsis and pupil distance

The second assumption, that people with bigger inter pupil distance have better stereopsis, was statistically not proved but when average of two groups of test persons were compared, one with $PD < 62$ mm and second with $PD > 66$ mm, the group with $PD > 66$ mm has better stereopsis average by 18%. Theoretically, the same conclusion should be reached. When stereopsis equation is analysed, separation of two objects is in reciprocal correlation with pupil distance, so conclusion should be the same, bigger PD should give better stereopsis. If we calculate the difference in stereopsis between two groups of test persons, average $PD = 68,4$ mm, for group $PD > 66$ and average $PD = 59,9$ mm, for group $PD < 62$ mm we can see that theoretically the first group must be better by 14,2%.

Group of authors, Danial Shafiee, Ali Reza Jafari, Ali Akbar Shafiee in the article, "Correlation between Interpupillary Distance and stereo acuity", have found that the correlation is positive, that means people with smaller PD have better stereopsis. Their conclusion is diametrically opposite to the conclusion of this study but both, the article and the study, agree that female test persons have better stereopsis.

7.3 Correlation of stereopsis and age

The third assumption is that with age the stereopsis ability decreases since retina loses a specific amount of its receptors through years, together with its visual acuity and consequently loses depth perception. This study can confirm a decreased visual acuity in the older age group (mean age=55,1 years) by 31,7 – 36,1 % in comparison with the younger age group (mean age= 29,3 years).

L. Garnham, J.J. Sloper, in their work "Effect of age on adult stereoacuity as measured by different types of stereotest", published their results in the British Journal of Ophthalmology, 90 (2006), pp. 91–95, Stereo acuity was measured in 60 normal subjects aged 17-83 years, using TNO, Titmus, Frisby near, and Frisby-Davis distance stereo tests. The conclusion was that stereo acuity measured by all tests showed a mild decline with age ($p<0.001$) for all tests.[9]

In the article "Change of Stereo acuity with Aging in Normal Eyes" the authors, Se-Youp Lee, MD, Nam-Kyun Koo, MD, found the correlation of stereopsis with age. Their conclusion was that both near and distance stereopsis decreased with increasing age. They divided 80 normal individuals into 8 groups (7-10,11-20, 21-30 and so on to 70-80). They concluded that stereopsis decreased after the age of 50.[10]

7.4 Correlation of stereopsis and gender

Although this was not the assumption at the beginning of this study, it was found that females have a much better stereopsis than males. It depends on the age but young (under 35) females have better stereo acuity by 32,5% than males of the same age.

A group of authors, Danial Shafiee, Ali Reza Jafari, Ali Akbar Shafiee in the article, "Correlation between Interpupillary Distance and stereo acuity", also found that females have better stereopsis by 25,6% than males (males 10,26 arcsec vs females 7,63 arcsec with $p=0,015$).[11]

7.5 The functional significance of stereopsis

The importance of stereopsis in everyday life is a part of general knowledge. For children it is very important to develop the stereopsis ability at a very early age because the lack of this ability could lead to the lack of coordination and other functions. Very often, a dysfunction of a child's stereopsis is acknowledged too late because the symptoms are mistaken for clumsiness. During their childhood, these children are unable to do the simplest activities such as ball play. Later on, these children are often rejected by others. By their choice of profession, these people are often limited in broadness of their options because for most work places good stereopsis is required. The whole life of an individual is full of similar experiences. People with underdeveloped stereopsis lack many life experiences only because of the lack of awareness of consequences of such conditions. When is the lack of stereopsis most often discovered? When a child starts school or even later. Since a lot can be done to eliminate

causes of this disability and ensure the proper development for each child, all children should be tested for stereopsis disability at a very early age (hopefully before the age of three). For testing one's stereopsis, no advanced equipment is needed but some basic stereo tests such as Lang test, Frisby test, and Titmus test or any similar. If a child passes the test appropriate for their age, it means that they have developed stereopsis and that stereopsis will most likely develop normally, while the children who do not pass the test must take other optometric tests to determine the cause of stereopsis underdevelopment. Once the cause is eliminated, the child has once again the chance to develop a proper stereopsis ability.

8 Conclusion

The most important conclusion of this master thesis is that the decreased visual acuity brings significant fall of stereopsis. A deficit in refraction of $-0,50$ D decreases stereo acuity by about 90% (nearly 2x) and a deficit of $-1,0$ D decreases stereo acuity by about 220% (about 3x). Therefore, it is important to control vision refraction of our clients more frequently and have the best possible correction in glasses or contact lenses, especially if a person is involved in work which requires good stereopsis. Clients are not aware that old eyeglasses with old prescription decrease their stereopsis and they should be instructed to pay more attention to this.

It is very important to monitor children's stereopsis development and start testing not later than the age of three when emmetropization is usually finished. It is our responsibility as optometrists, to check child's stereopsis development on regular basis and take action if some deviations are detected.

Further conclusions are that females have better stereopsis than males, younger people have better stereopsis than older, and also people with better visual acuity have better stereopsis.

Next important conclusion is that pupil distance has no statistically significant influence on stereopsis but to be sure, a similar test should be done on a bigger homogenous group of test persons. My suggestion is young females with different pupil distances and high visual acuity.

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