HELSINKI UNIVERSITY OF TECHNOLOGY

Faculty of Electronics, Communications and Automation

Anni Kuusinen

Human stereopsis, stereoacuity and a web-based test for assessing stereo threshold

Master's Thesis
August 6th 2009

Supervisor: Timo Korhonen, adjunct professor, Dr.Sc.(Tech.)
Instructor: Jukka Häkkinen, adjunct professor, Ph.D.

HELSINKI UNIVERSITY OF TECHNOLOGY
Faculty of Electronics, Communications and Automation

ABSTRACT OF
MASTER'S THESIS

Author: Anni Kuusinen		
Title of the Thesis: Human stereopsis, stereoacuity and a web-based test for assessing stereo threshold		
Date: August 6th, 2009	Language: English	Number of pages: 95
Professorship: Human factors in communications design		Professorship code: S274-3
Supervisor: Timo Korhonen, adjunct professor, Dr.Sc.(Tech.)		
Instructor: Jukka Häkkinen, adjunct professor, Ph.D.		

This study is a contribution to develop an easily attainable web-based stereo vision test that can be used to assess stereo threshold of a person. An extensive review of human binocular depth perception, measurement of stereoacuity, stereoscopic systems and stereo vision tests was produced and a prototype of a web-based stereo vision test was designed and implemented. Stereo threshold of twenty participants were assessed using two versions of the implemented Web Stereo Tests and, for comparison, the TNO and the Titmus Stereo Tests. Based on the theoretical knowledge and the test results the prototype was evaluated, special requirements for the web-based approach were determined and outlines for further development were constructed.

Further experiments to validate the reliability of the test should be conducted before it can be delivered in the Internet. This requires expert knowledge on both human visual system and underlying technologies. A color and luminance calibration feature and a user interface should also be designed and added to the application. This study includes a comprehensive review of the theories and technologies underlying the automatic measurement of stereoacuity. It was also proved in this study that it is possible to design a web-based stereo vision test using currently available technologies.

Keywords:

stereo vision test, web-based method, stereo threshold, stereoacuity, global stereopsis, anaglyph, random-dot stereogram, binocular vision, depth perception, stereoscope

TEKNILLINEN KORKEAKOULU
Elektroniikan, tietoliikenteen ja automaation tiedekunta

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä:
Anni Kuusinen

Työn nimi:
Stereonäön tarkkuus ja webbipohjaisen stereokynnystestin kehittäminen

Päivämäärä: 6.8.2009	Kieli: englanti	Sivumäärä: 95

Professuuri: Tietoliikenteen käyttäjäkeskeinen tuotekehitys	Professuurin koodi: S274-3

Työn valvoja:
Dosentti, TkT Timo Korhonen

Työn ohjaaja:
Dosentti, PsT, Jukka Häkkinen

Tämä työ on osa kehitysprosessia, jonka tarkoituksena on kehittää helposti saavutettavissa oleva webbipohjainen stereonäkötesti, jolla voidaan arvioida henkilön stereonäkökynnys. Työssä tuotettiin kattava katsaus ihmisen stereonäöstä, stereotarkkuuden mittaamisesta, stereoskoopeista sekä stereonäkötesteistä. Lisäksi suunniteltiin ja toteutettiin prototyyppi webbipohjaiseen teknologiaan perustuvasta stereonäkötestistä. Toteutetun Web stereotestin kahta eri versiota testattiin käytännössä kahdenkymmenen koehenkilön kanssa. Testituloksia verrattiin TNO ja Titmus stereonäkötestien tuloksiin. Teoriatiedon sekä testausten perusteella testin prototyyppi arvioitiin, webbipohjaisen lähestymistavan asettamat vaatimukset määritettiin ja testin jatkokehitystarpeet hahmoteltiin.

Ennen testin webbijakelua tarvitaan lisäkokeita sen luotettavuuden varmistamiseksi. Tämä vaatii syvällistä asiantuntemusta sekä ihmisen näköjärjestelmästä että käytettävissä olevista teknologioista. Webbipohjaisuus vaatii myös riittävän tasoisen värien ja luminanssin kalibrointitoiminnallisuuden liittämisen testiin sekä käyttöliittymän kehittämisen testin ympärille. Tässä työssä tuotettiin laaja yhteenveto stereotarkkuuden automaattiseen mittaamiseen liittyvistä teorioista ja teknologioista, sekä osoitettiin webbipohjaisen stereonäkötestin kehittämisen olevan mahdollista nykyisin käytettävissä olevilla teknologioilla.

Avainsanat:
stereonäkötesti, webbipohjainen menetelmä, stereonäkökynnys, stereonäön tarkkuus, anaglyfi, kohinakuvastereogrammi, syvyysaistimus, stereonäkö, stereoskooppi

Acknowledgements

I would like to thank the Finnish Institute of Occupational Health for providing facilities to develop and experiment the stereo vision test. I also wish to thank my supervisor, Adj. Professor Timo Korhonen, for his help and encouragement to convert this work to a thesis.

Special thanks belong to my instructor, Adj. Professor Jukka Häkkinen, whose comprehensive knowledge of stereo vision, professional attitude and great investment of time and patience were critical for this work. In addition, I would like to express my gratitude to the participants of the empirical research activities, and to all the other people who helped me in various ways during this study.

My sincere thanks go also to my friends for bringing joy to my life during the study years, and to my family for supporting and encouraging me throughout my studies.

Finally, I want to thank Jani for all his love, understanding and support.

Nummela, August 6th 2009

Anni Kuusinen

Table of contents:

APPENDICES:

Symbols

η	horizontal binocular disparity
α_{left}	horizontal angle between the monocular visual directions of the target and the fixation point in the left eye
α_{right}	horizontal angle between the monocular visual directions of the target and the fixation point in the right eye
Δd	depth difference between two objects
Δs	horizontal separation of the stimulus picture elements at the display
Δb	horizontal separation of the background picture elements at the display
d	viewing distance
a	interpupillary distance

Abbreviations

3D	three-dimensional
LCD	liquid crystal display
HMD	head-mounted display
VRD	virtual retinal display
arc sec	seconds of arc
′′ arc	seconds of arc
arc min	minutes of arc
′ arc	minutes of arc
TNO	the TNO Stereo Test
Titmus	the Titmus Stereo Test
Web-P	the Web Stereo Test using Pac-Man figure as a stimulus
Web-L	the Web Stereo Test using Landolt-C figure as a stimulus
L_{min}	lowest disparity value which the participant perceived correctly during the Web-L Stereo Test
P_{min}	lowest disparity value which the participant perceived correctly during the Web-P Stereo Test
L_{2min}	lowest disparity value, which the participant perceived correctly twice during the Web-L Stereo Test
P_{2min}	lowest disparity value, which the participant perceived correctly twice during the Web-P Stereo Test

Key concepts

The following list includes the definitions of the key concepts of the thesis in an alphabetical order.

anaglyph:

Anaglyph represents two superimposed images of mutually exclusive colors which can be viewed through color filter glasses to separate the right and left eye's views from each other. (see chapter 2.3.2)

binocular vision:

Binocular vision represents an ability to use two eyes that can co-operate to work as a team. (see chapter 2.1.2)

crossed disparity:

Objects lying inside the horopter have crossed disparity. (see chapter 2.1.4.2)

cyclopean depth perception:

Cyclopean depth perception is produced merely by binocular depth cues. (see chapter 2.3.4)

fixation point:

In geometrical terms, the fixation point is the point in space where the visual axes intersect (Howard and Rogers, 1995).

global stereopsis:

Global stereopsis is a phenomenon where the visual system performs an overall disparity computation to match the portions in the disparate images of the two eyes and to combine the images into a single three-dimensional view. (see chapter 2.3.4)

horizontal binocular disparity:

Horizontal binocular disparity represents the horizontal angular difference between the monocular visual directions of the target in the two eyes. (see chapter 2.1.4.2)

horopter:

Horopter represents the locations in space that stimulate corresponding points on both of the retinae at a given fixation of the eyes. (see chapter 2.1.4.1)

interpupillary distance:

Distance between the two pupils. (see chapter 2.1.2)

local stereopsis:

Local stereopsis is a phenomenon where the visual system matches corresponding, monocularly visible, contours in the disparate images of the two eyes into alignment and combines these images into a single three-dimensional view.

monocular depth cues:

Monocular depth cues are cues to depth which can be perceived with only one eye, i.e. monocularly. (see chapter 2.1.1.1)

random-dot stereogram:

Random-dot stereograms are random-dot noise images where you can perceive figures in depth when the right and left eye's views are separated from each other. (see chapter 2.3.4)

stereoacuity:

Stereoacuity represents our ability to perceive small horizontal binocular disparities as a difference in depth. (see chapter 2.2.1)

stereo pair:

Stereo pair represents two images of the same target from slightly different horizontal points of view. (see chapter 2.3.1)

stereo threshold:

Stereo threshold represents a depth discrimination threshold, that is, the smallest angular disparity value that we can still perceive as a difference in depth. (see chapter 2.2.1)

stereogram:

Stereograms are two-dimensional images where you can perceive the illusion of depth when the right and left eye's views are separated from each other. (see chapter 2.3.4)

stereopsis:

Stereopsis is a process where the visual system compares the images of both eyes to produce sense of depth. (see chapter 2.1.3)

stereoscope:

Stereoscope is a device that takes advantage of the phenomenon of stereopsis by presenting a separate image of a stereo pair to each eye. (see chapter 2.3.1)

uncrossed disparity:

Objects lying outside the horopter have uncrossed disparity. (see chapter 2.1.4.2)

vergence movements:

In vergence movements the eyes converge or diverge, that is, move the pupils nearer or further from each other to point the eyes to the same object at a particular distance.

visual axis:

The axis from the object of regard to the fovea is called visual axis.

visual direction:

Visual direction represents a two-dimensional localization of an object in the visual field. (see chapter 2.1.4.1)

1 Introduction

1.1 Motivation of the study

Due to the recent development in display technologies 3D user interfaces and -applications are announcing their arrival both in the entertainment and in professional use. However, few usability studies have been done concerning 3D technologies. How do these technologies serve people with different properties? There are also professions where depth perception is essential like, for example, a surgeon, ophthalmologist, ice hockey player or crane operator. How important is binocular vision in practicing these professions? This study, for its part, brings us closer to the answers of these questions by enlightening the properties of human stereo vision and by offering a web-based method to assess stereo threshold.

There are differences in binocular vision between individuals. Stereoacuity is an important indicator of stereopsis and it can be measured by defining stereo threshold of a person. At present, mostly manual and quite expensive stereo vision tests are available to measure stereo threshold. Although a few automatic stereo vision tests exist, there are no easily attainable web-based stereo vision tests at the moment. An easily attainable test is a test that does not require expensive additional equipment from the user and is easily available. There should be an easily attainable method to measure stereo threshold and to collect norm data on stereoacuity. This would be beneficial in studying the effects of stereoacuity on completing work tasks or on using 3D user interfaces. Since computers, fast internet connections and web-based technologies have become common at offices and homes, a web-based stereo vision test would be easily attainable for a large number of users. A web-based stereo vision test would enable stereoacuity norms based on enormous amounts of data and statistical analysis to understand human capabilities in binocular depth perception.

1.2 Objectives

This study is a contribution to develop an easily attainable web-based stereo vision test that can be used to assess stereo threshold of a person. The objectives were to collect theoretical information related to the assessment of stereo threshold, and to design and implement the first prototype of a stereo vision test using web-based technology. The stereo threshold values of a sample of observers were going to be collected with the implemented prototype and, for comparison, with some commonly used stereo vision tests. On the base of the theoretical knowledge and the test results the plan was to evaluate the prototype, to determine special requirements for the web-based approach and to construct outlines for further development of the test.

1.3 Framework of the study

The prototype of the Web Stereo Test was developed for the Finnish Institute of Occupational Health where the general goal was to create a comprehensive pack of vision tests that could be delivered in the Internet for everyone who needs it. A web-based stereo vision test could, for example, be applicable to promote occupational health issues, to choose suitable people or tools for tasks requiring depth perception or to develop and test 3D applications.

1.4 Organization of the study

The structure of the thesis is illustrated in Figure 1 below. The motivation, objectives and framework of the study as well as the description of the contents are presented in chapter 1. Chapter 2 deals with the theoretical information and concepts concerning the assessment of stereo threshold. Binocular depth perception as a part of human visual system is reviewed emphasizing the attributes that contribute to stereoacuity. Stereoscopic systems, stereograms and stereo vision tests are also discussed. The technical design and realization of the prototype is described in chapter 3 as well as the testing of the prototype and the analysis of the test results. In chapter 4 the results and the methods of the study are discussed. On the base of the theoretical knowledge and the test results, the prototype is evaluated, special requirements for the web-based approach are determined and outlines for further development are constructed. The applicability and the future of the implemented stereo test are also discussed. Conclusions are made in chapter 5.

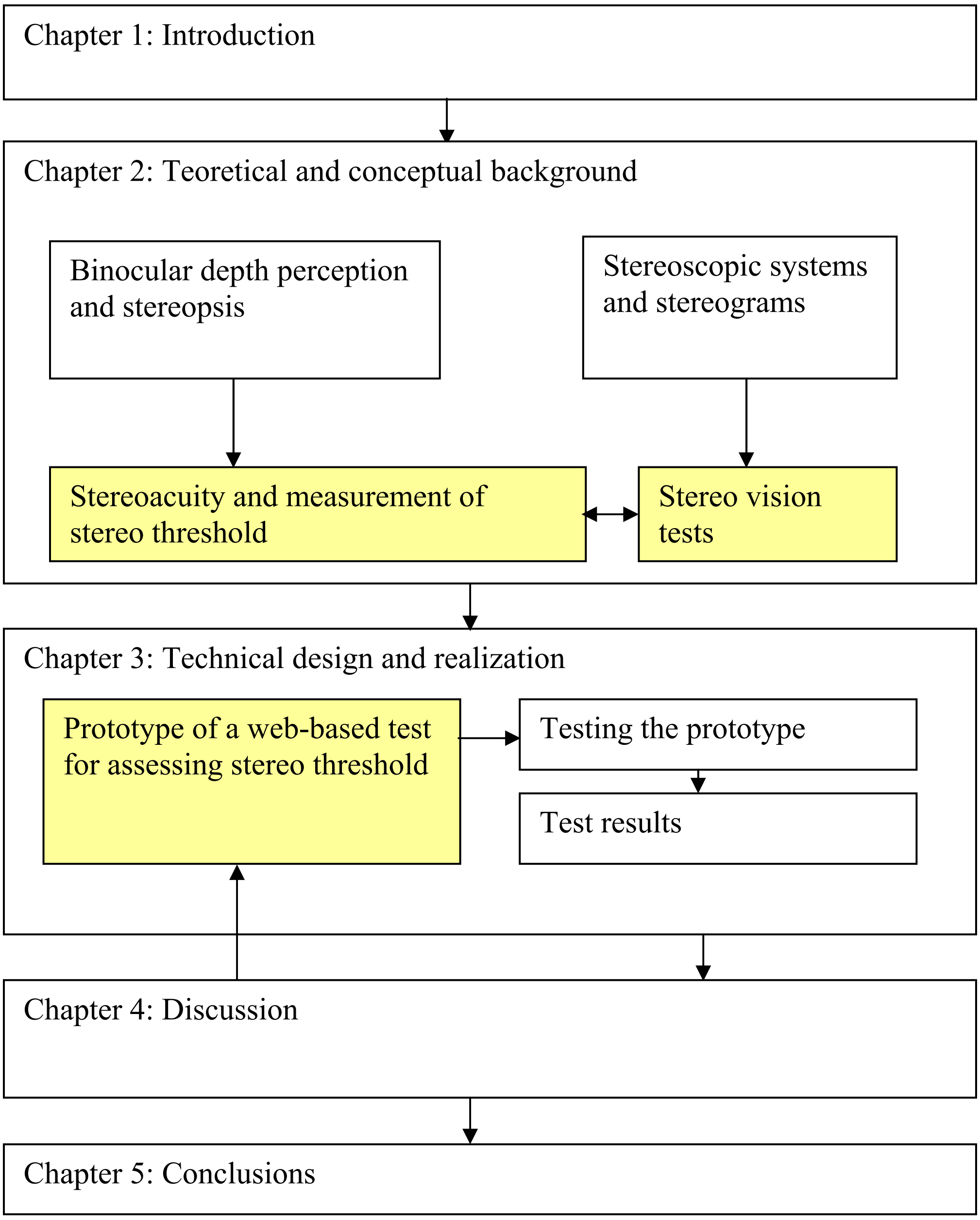


Figure 1. The structure of the thesis. The key subjects are colored in yellow.

2 Theoretical and conceptual background

The essential concepts and theory on the ground of this study are presented in this chapter. Binocular depth perception as a part of the human visual system is reviewed in chapter 2.1. Stereoacuity and measurement of stereo threshold are discussed in more detail in chapter 2.2. Stereoscopic systems and stereo vision tests are discussed in chapters 2.3 and 2.4.

2.1 Binocular depth perception and stereopsis

In this chapter, the essential concepts of binocular depth perception are presented. Factors of stereoacuity are discussed in more detail in chapter 2.2.

2.1.1 Depth perception

We could not manage without depth perception. It is necessary in everyday tasks, such as navigating through our environment, noticing abrupt edges, grasping for objects and distinguishing them from the surroundings. Many everyday tasks would be impossible without depth perception.

Depth perception is a relative measure. We are very poor in telling absolute distances for the objects. Hence, our depth perception is optimized to judge if an object is in front of, behind or at the same distance as another object.

2.1.1.1 Monocular cues to depth

Most of the everyday tasks requiring depth perception are well possible with only one eye, i.e. monocularly, by analyzing monocular depth cues. Monocular cues to depth include pictorial cues such as the size of the retinal image, linear perspective, texture gradients, aerial perspective, occlusions, position and shading as well as non pictorial cues such as accommodation, motion parallax, deletion or accretion from motion and structure from motion. Vergence eye movements, that are the inward eye movements while focusing on an object, are also a weak cue to depth. Other senses, such as hearing, sense of touch or even a sense of smell may help in judging depth.

2.1.2 Binocular vision

Worth classified (1921) three phases of binocular vision: simultaneous perception, fusion and stereopsis. Fusion is a process where the visual system combines the two views in both of the eyes into a unified perception of the scene enabling us to see singly. Fusion is divided in motor fusion and sensory fusion. The movement of the eyes to turn the visual axes of each eye toward the fixation point is known as motor fusion. Motor fusion is a prerequisite for sensory fusion. Sensory fusion is a cognitive process by which the visual cortex combines the visual data from the two eyes into a single percept. Although the information about the eye-of-origin is lost to conscious perception, the visual system still has some access to it. It is the processing of the monocular data that gives us stereopsis. Sensory fusion and stereopsis are parallel processes that cannot be distinguished clearly from each other.

For the fusion to be successful, the outer contours or low spatial frequency components of the images should be similar. If the images differ too much from each other, rivalry is introduced and the images are processed sequentially. The visual system must find corresponding points on the images to be able to calculate the disparities between them. It is probably done by detecting similar contours emerging from the contrasts of brightness and color in each image. The exact mechanisms by which sensory fusion is accomplished are not totally understood yet. The correspondence problem is one of the most active research areas in binocular vision.

2.1.3 Stereopsis

Although we are able to determine depth somewhat monocularly, the most accurate depth perception, a phenomenon called stereopsis, is only possible with binocular vision, i.e., using two eyes that can co-operate to work as a team. Stereopsis is possible in a field of about 120 degrees where the two eyes have common field of view, as illustrated in Figure 2. In a horizontal plane the human visual field is about 180 degrees in extent. The visual field extends upward approximately 80° and downward about 75°.

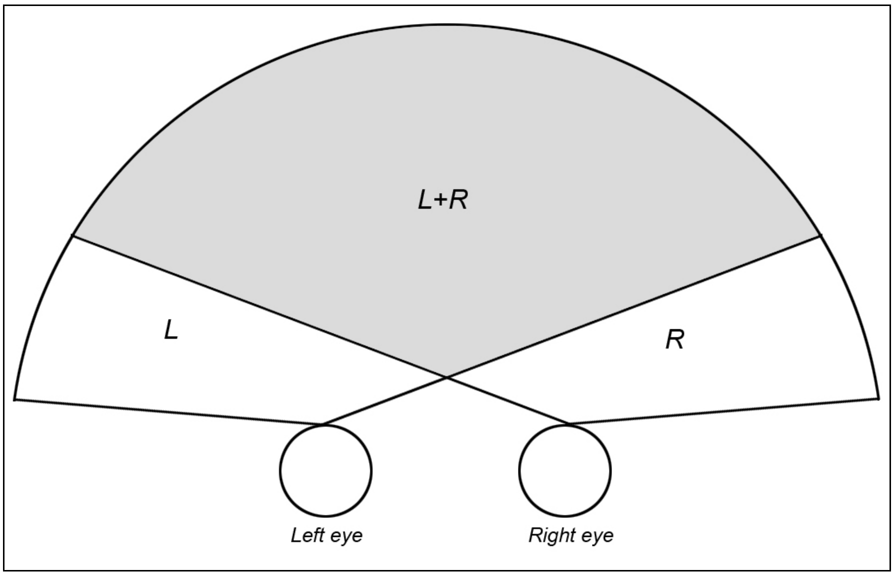


Figure 2. Human visual field. The white areas L and R stand for the monocular fields of view. The grey area L+R illustrates the binocular filed of view.

Stereopsis is a process where the visual system compares the images of both eyes to produce sense of depth. Our eyes are separated by 63 +/- 3 mm in average (Murphy and Laskin, 1990; Bogren et al., 1986) and thus receive a slightly different view of the scene. It is the subtle differences between the images in each eye that produce stereopsis. Interpupillary distance is defined as the distance between the two pupils and it is very stable among races. In the equations of this study, letter a is used to symbolize the interpupillary distance. Horizontal binocular disparity (see chapter 2.1.4.2) serves as the main cue to depth in stereopsis. In addition, half-occlusion processing (Häkkinen, 2007) and vertical binocular disparities (Rogers and Bradshaw, 1992) have significant effects on stereoscopic perception.

Stereopsis makes the human depth perception extremely accurate. It is advantageous when we have to move quickly in the surroundings or to catch and move objects accurately. It is needed in many sports and professional tasks. Surgeons, for example, need fine hand-eye coordination. In addition, the use of some 3D displays or 3D user interfaces require stereopsis.

2.1.4 Horizontal binocular disparity and the correspondence of the two retinae

As mentioned above, it is the horizontal binocular disparity that gives rise to the perception of stereoscopic depth or stereopsis. This chapter enlightens the concept of horizontal binocular disparity.

2.1.4.1 Corresponding retinal points and the horopter

Binocular depth perception is based on the correspondence of the two retinae. Each visual neuron on the retina encodes a unique visual direction associated with it. Visual direction represents a two-dimensional localization of an object in the visual field. For every point on the other eye's binocular portion of the retina there is a corresponding point on the other eye's retina whose visual direction is identical. Especially the two foveae are corresponding points.

Horopter is used to explain how corresponding points are arranged in the human visual system. Horopter represents the locations in space that stimulate corresponding points on both of the retinae at a given fixation of the eyes. It can be thought as the zero point for the relative depth perception. The measured horopter varies with the fixation point and with the observer. The Vieth-Müller circle, which is illustrated in Figure 3, is a geometrical model and simplification of the horopter. This model assumes that the corresponding points in each eye are displaced evenly at the same angular eccentricity from their respective foveae. This prediction is not precisely true but is very near to the shape of the horopter at the proximity of the fixation point.

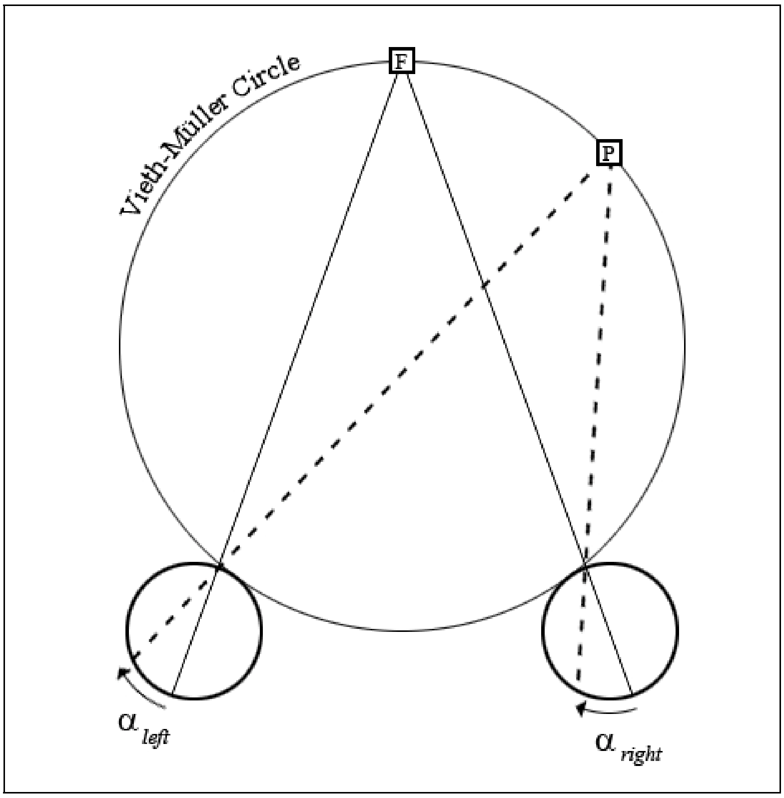


Figure 3. The Vieth-Müller circle is a good approximation of the horopter at the proximity of the fixation point. The angle between the horizontal visual directions of the target *P* and the fixation point *F* in the left eye is denoted by α_{left} and the corresponding angle in the right eye by α_{right}. For all the targets lying on the Vieth-Müller Circle $\alpha_{left} = \alpha_{right}$.

2.1.4.2 Horizontal binocular disparity

Targets that stimulate corresponding retinal points are perceived as being at the same distance than the fixation point. If the images of an object on the two retinae differ in position in relation to the corresponding points they are said to have binocular disparity. A horizontal difference in locations of the images is called horizontal binocular disparity and vertical difference is called vertical binocular disparity. The horizontal binocular disparity η is defined as a horizontal difference in the monocular visual directions of the target in the left and right eye as shown in Equation 1 below.

Equation 1. Horizontal binocular disparity

$$\eta = \alpha_{left} - \alpha_{right}$$

The horizontal angle between the monocular visual directions of the target and the fixation point in one eye is denoted by symbol α. If we look at the eyes from above, then positive angles of α are counted in a clockwise direction and negative angles in an opposite direction. For an illustration of the angles α_{left} and α_{right} see Figure 3 in the previous chapter 2.1.4.1. For the accuracy of human stereo vision units as small as seconds of arc are normally used to describe horizontal binocular disparities. For more information about small angular units and their notations, see Appendix A.

Horizontal binocular disparity is classified as crossed and uncrossed disparity. The sign of the angle η is positive for the crossed disparity and negative for the uncrossed disparity. An object is perceived to be closer than the fixation point if its images on the retinae have crossed disparity, whereas an object is perceived to be farther away than the fixation point if its images have uncrossed disparity. In geometrical terms objects lying outside the horopter have uncrossed disparity and objects lying inside the horopter have crossed disparity.

2.1.4.3 Effects of the magnitude of horizontal binocular disparity

According to the magnitude of the disparity, some of the objects off the horopter are seen in double while some of them are seen singly but in different depth. The area of single vision or haplopia determines the range of disparities of the images that can be fused or seen as single. Small disparities that fall within this area produce single perception of the target while images with larger disparities produce double vision or diplopia. Besides enabling stereopsis, this is advantageous to the visual system by allowing for some drift or imprecision in eye movements, such as micro drifts and tremors that occur during fixation, without the introduction of diplopia. Similarly, it compensates the potentially adverse effects of fixation disparity.

Horizontal binocular disparities that fall within the area of single vision give rise to the robust perception of depth in direct proportion to the magnitude of the disparity: the larger the disparity the greater the perceived distance in relation to the fixation point. This is called quantitative stereopsis. In the area of double vision the linear relationship between the magnitude of depth perception and the magnitude of disparity breaks down (Ware, 2000; Ware et al., 1998; Richards and Kaye, 1974; Richards, 1971). However, up to disparities of about 1000′ arc in extend, that is about 17 degrees, we can still tell if an object is closer than or farther than the fixation point (Westheimer and Tanzman, 1956; Ogle, 1952). This is called an area of qualitative stereopsis. Beyond the upper disparity limit, objects are simply seen as double but disparity no longer evokes a percept of depth.

2.2 Stereoacuity and measurement of stereo threshold

This chapter covers the concepts of stereoacuity and stereo threshold. Measurement of stereo threshold and the attributes that contribute to stereoacuity are discussed in more detail.

2.2.1 Stereoacuity and stereo threshold

Stereoacuity represents our capability to perceive small horizontal binocular disparities as a difference in depth. It is often denoted by the Greek symbol δ, σ or η. In this study, symbol η is used. The better the stereoacuity is the smaller disparities rise the perception of depth. Stereo threshold represents a depth discrimination threshold, that is, the smallest horizontal disparity value that we can still perceive as a difference in depth.

Stereo threshold also defines a geometric limit for the furthest possible distance to discriminate depth differences. This limit can be calculated geometrically as a distance of a point whose vergence angle equals stereo threshold. Beyond this limit all the objects seem to be at a same distance in relation to the fixation point. From the distances of 800 m to 1300 m stereopsis doesn't exist because the disparity becomes too small to be discriminated by the receptive cells at the retina. The depth perception disappears, for example, while watching ground from an airplane.

2.2.2 The role of stereoacuity

Even though stereoacuity is one of the indicators of stereopsis, you can not assume that better stereoacuity always means better stereopsis. For example, some individuals have problems on observing accurately certain disparity areas such as crossed or uncrossed disparity. Other individuals can have depth perception bias that causes over or under estimation of the depth perception and thus affects stereoacuity. In this case the person does not perform well in depth matching tasks even if he had good stereoacuity. Thus, it depends on the task at hand, how important it is to have well performing stereopsis and how disturbing certain kinds of defects on stereopsis are. Besides, in daily life people usually deal with larger disparities than their stereo threshold. Even stereo-blind persons can perform quite well in daily life using monocular cues to depth.

2.2.3 Stereoacuity norms

The human visual system is very sensitive to differences in depth and under optimal testing conditions stereo threshold values as small as 1,8 seconds of arc and 2 seconds of arc have been reported (Cöltekin, 2006; Harwerth and Boltz, 1979). This threshold is actually smaller than the smallest receptive fields on the retina suggesting very progressive signal processing in the visual system. In fact, stereopsis provides the best discrimination thresholds of the human visual system: the binocular thresholds via disparity are smaller than any other measurable thresholds of visual acuity even if we compare them with the other hyper acuities like, for example, with vernier thresholds. Andersen and Weymouth (1923) measured stereo thresholds of 4 to 5 seconds of arc.

Even if the stereoacuity varies with the person and with the method used, the stereo thresholds measured under optimal testing conditions normally stay under 10´´ arc (Harwerth and Boltz, 1979). In practical situations we are not capable of detecting so small disparities. Practical stereo threshold is normally from 20 to 40 seconds of arc. Diner and Fender (1993) suggests 20´´ arc as a working limit. 95% of the population has 40´´ arc or better stereopsis, which is thus considered as the limit of normal stereoacuity (Steinman et al., 2000). Therefore, most clinical tests of stereopsis measure disparities only down to 40´´ arc. These tests are not used to quantify a stereoacuity threshold but to screen for poor stereopsis and binocular problems. Stereo thresholds based on binocular disparity are about 20 times better than monocular thresholds for depth perception. For this reason, monocular cues have hardly any effect on the perception of the smallest disparities.

2.2.4 Measuring stereo threshold

Stereo threshold is usually expressed as a disparity angle, which is calculated in relation to the Vieth-Müller circle as described in chapter 2.1.4.2. This is geometric, not retinal, disparity and is used to produce comparable data. However, at the proximity of the fixation point, the Vieth-Müller circle is very near the horopter.

Equation 2 below shows a simple expression for angular disparity in terms of distances. This equation can be derived geometrically from the definition of disparity in Equation 1 (see chapter 2.1.4.2). For the derivation see Howard and Rogers (1995).

Equation 2. Angular disparity in terms of distances in radians

$$|\eta| \approx \frac{a\Delta d}{d^2}$$

The variables of the above equation are illustrated in Figure 4. On the equation, η stands for the angular stereoscopic disparity in radians, a for the interpupillary distance of the observer, d for the fixation distance and Δd for the depth difference between the two objects.

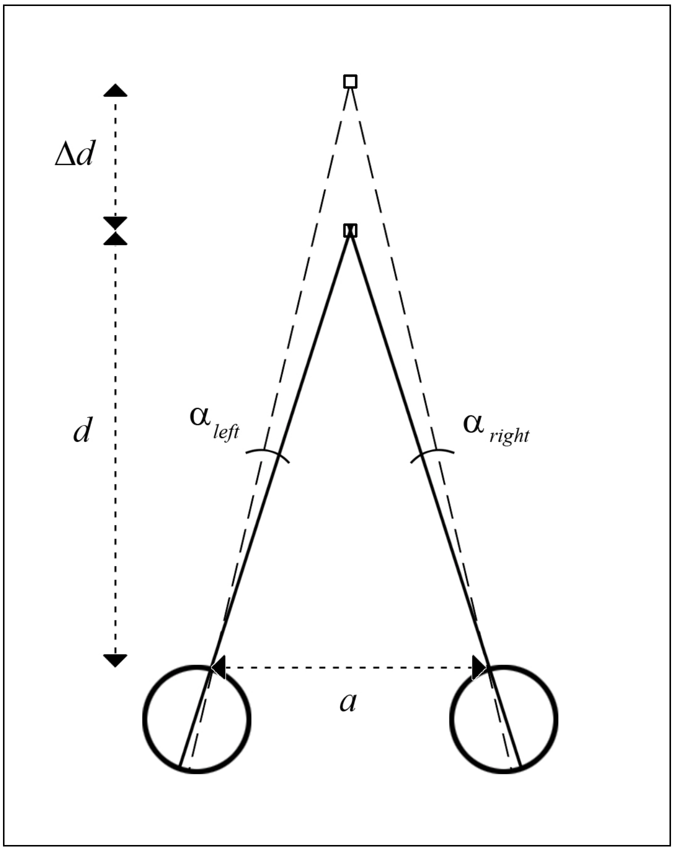


Figure 4. An illustration of the variables in Equation 2. An approximation of the angular disparity can be expressed in terms of the depth difference *Δd,* the distance *d* from the observer to the fixation point and the interpupillary distance *a.* On the other hand, the angular disparity η is defined by the angles α_{left} and α_{right}.

Equation 2 gives a good insight of the relation of the disparity to depth difference and distance even though it is an approximate expression. This equation holds true only if the convergence is symmetrical, the convergence angle is small and the depth difference *Δd* is small in relation to the distance *d*. This is assumed to be the case in most stereoacuity tests.

It follows from this expression that the larger the interpupillary distance is the larger is the perceived disparity at a given depth difference. You can also see from the expression that the disparity produced by a disparate object is inversely proportional to the square of the distance of the fixation point. This means that if you increase the distance to the fixation point from 1 meter to 100 meters you need to increase the depth difference 10 000 fold to retain the disparity. Therefore, we are much more accurate on detecting depth differences at near than at far distances as can be seen in Figure 5 below.

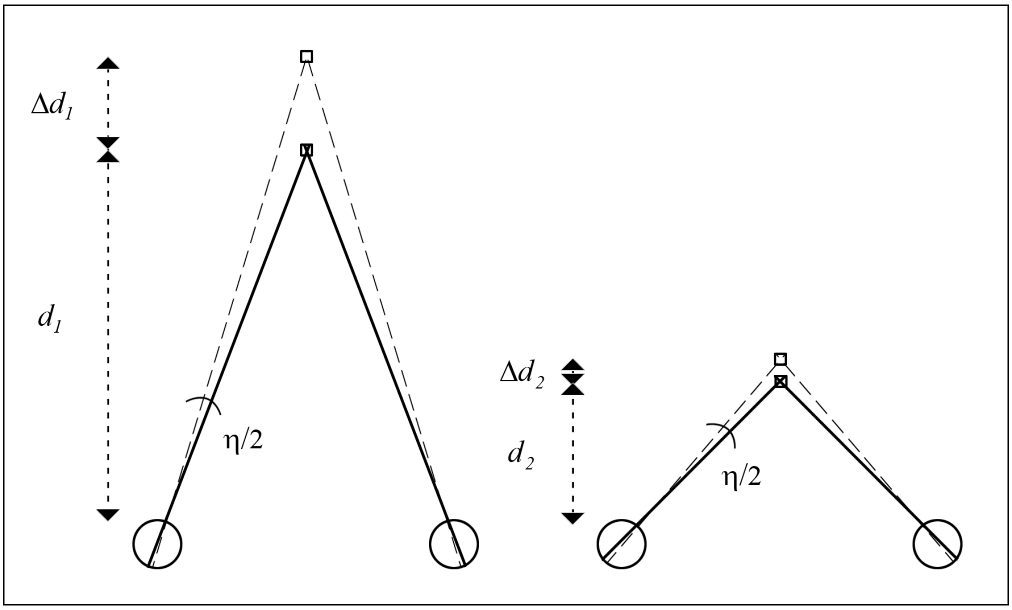


Figure 5. At a given disparity η and interpupillary distance, the depth difference Δd between the two objects decreases remarkably when the distance d from the observer to the fixation point is decreased. The depth difference between two disparate objects is directly proportional to the square of the distance of the fixation point.

2.2.5 Depth constancy

Equation 2 and Figure 5 illustrate well that the absolute depth difference cannot be determined merely on the basis of the disparity information. Thus, the object's perceived disparity has to be scaled based on the fixation distance. The ability to make accurate judgments of relative depth at different absolute distances is known as depth constancy. Depth constancy can be achieved only if the viewer registers the absolute distance of an object correctly. However, the human visual system is not very accurate in judging absolute distances, as discussed in chapter 2.1. Even so, some information about the absolute distance can be derived from signals associated with convergence, vertical disparities, accommodation, familiar size cues, linear perspective, motion parallax, observer's translational velocity or other depth cues (Ono et al., 1986; Sedgewick, 1986; Nakayama, 1985; Foley, 1980). Hence, it depends on the situation and the cues available, how accurate judgments we are able to make of the absolute distance.

2.2.6 Attributes of stereoacuity

In addition to the binocular vision of the observer stereoacuity is affected by many other attributes defined by testing conditions. These attributes have to be taken into consideration while planning tests for measuring stereo threshold. In order to get comparable data of binocular vision the properties that contribute to stereoacuity should remain constant in the test for all observers. In this chapter, different attributes affecting stereoacuity are presented.

2.2.6.1 Interpupillary distance

In natural viewing conditions, the larger the interpupillary distance is the larger is the perceived disparity at a given depth difference, as can bee concluded from Equation 2 in chapter 2.2.4. However, it can be derived geometrically, that the reverse is true in the case of stereo displays. The smaller is the interpupillary distance the larger is the perceived depth difference at a given horizontal separation of the images at the display.

2.2.6.2 Fixation disparity

The fixation disparity will affect stereo threshold by displacing the horopter off the intended fixation target (Cole and Boisvert, 1974). People with significant fixation disparities will have less tolerance for disparity changes in either side of the fixation point (Jiménex et al., 2000). The effect depends on the type of the fixation disparity. If the horopter is, for example, displaced too far back from the intended fixation plane because of an exo disparity, the person will reach the limit of Panum's area when presented with only a small amount of crossed disparity.

2.2.6.3 Heterophoria

According to the studies by Lam et al. (2002), heterophoria have an adverse effect on stereoacuity. They discovered that esophoria deteriorates stereoacuity more than exophoria while orthophoric testees achieved the smallest stereo thresholds. In their study both crossed and uncrossed stereoacuities were measured at distance. Shippman and Cohen (1983) observed in their investigations that the effect of heterophoria on stereoacuity depends on the type of disparity while Saladin (1995) states that it depends on the type of the heterophoria.

2.2.6.4 Visual acuity

"The relationship between visual acuity and stereoacuity has been well documented: as binocular visual acuity increases, stereoacuity improves" (Kirschen et al., 1999).

2.2.6.5 Practice

Thresholds of stereovision tend to decrease on practice (Fendick and Westheimer, 1983). Effect of practice is most evident when using complex stimuli such as random dot stereograms (see chapter 2.3.4) (Julesz, 1960).

2.2.6.6 Cognitive factors

Cognitive processing, that is, learned concepts affect on depth perception. All the Finnish testees, for example, know that one euro coin is smaller than a tennis ball. If the coin seems to be bigger in the image, it is usually considered to be nearer, even though the depth perception through stereopsis refers to the opposite interpretation. However, these factors are of less importance while dealing with the smallest stereo threshold values and with more general figures.

2.2.6.7 Luminance

Luminance is one, although not very strong (Geib and Baumann, 1990), factor on our ability to detect disparity. The weaker the luminance is the more difficult it is to perceive depth (Berry et al., 1950). It is because in a dimmer light only rod cells, which have smaller resolution than cone cells, are stimulated at the retina. Stereopsis can be reduced remarkably in scotopic adaptation (Livingstone and Hubel, 1994; Graham, 1965).

2.2.6.8 Color

The color of the stereoscopic stimulus may also contribute to stereoacuity. The depth of the blue targets stimulating blue cone cells is most difficult to perceive (Pennington, 1970). This is because the blue cone cells have larger receptive fields and weaker contrast sensitivity than red and green cone cells (Gringberg and Williams, 1985). In addition, there is a very low density of blue cone cells at the central fovea. In the development of species, sensing blue light is an older mechanism than sensing other colors, and it first developed on nocturnal animals.

A perception of depth can be produced using different colors even without a real depth difference. This phenomenon is called chromostereopsis. For example, a red stimulus on a blue background seems to stand out on a different depth level from its background. This happens because different wavelengths diffract differently on the lens.

2.2.6.9 Exposure duration of the stimulus

Exposure duration, that is, how long the testees are allowed to see the stimulus, have an effect on the acuity of depth perception. We are most sensitive to depth on long exposure durations. Even if we are able to perceive depth on very short exposure durations, say in a fraction of a second, stereo threshold values are higher on them (Ogle and Weil, 1958). Very small disparities near the threshold take longer to be detected than larger ones (Tyler, 1991). Producing depth perception may take also longer on persons who have weak stereo vision.

2.2.6.10 Asynchronous visual information

When asynchronous images are shown to each eye, stereopsis is interrupted only after the time interval exceeds 1/10 s (Ross and Hogben, 1974) or 1/15 s (Steinman et al., 2000). This property is utilized on liquid crystal goggles, which are discussed more in chapter 2.3.3.4. In the case of a moving stimulus, a temporal disparity is produced if the images in both eyes are asynchronous. It is discussed more in chapter 2.2.6.15.

2.2.6.11 The eccentricity of the target

The location of the target in the field of view, or retinal eccentricity, has influence on the stereoacuity. That is because the receptive fields have different resolution in different locations of the retina. The resolution of the visual system has an important role in detecting small disparities, that is, in detecting how far the images in each eye are from each other. Hence, the best stereoacuity values are achieved with targets reflected near the fovea, where the receptive fields are smallest (Harris et al., 1997). We are less sensitive in binocular disparity at the eccentric field of view (Rawlings and Shipley, 1969).

2.2.6.12 Contrast and blur

Depth perception through stereopsis is degraded remarkably near the threshold of contrast vision, where the contrast of the target has most influence on stereoacuity. However, only a small accretion in contrast improves greatly one’s sensitivity in depth (Cormack et al., 1991). Even if we are poor in detecting depth differences near the contrast threshold, we are capable of telling the sign of the depth as long as the contrast of the images in both of the eyes is still visible (Simmons, 1998). Moderate contrast values have reported to produce lowest stereo thresholds, since too high a contrast may also deteriorate depth perception (Geib and Baumann, 1990). Stereoacuity suffers if the images in each eye differ in contrast (Halpern and Blake, 1988; Westheimer and McKee, 1980 a; Lit, 1968). This is due to the inhibition of the image of lower contrast in the visual system (Legge, 1979) and the different spatial frequencies of the images in the eyes (see chapter 2.2.6.13).

Blur or defocus decreases the contrast of the image and, thereby, may have an adverse effect on depth perception. Blur and defocus also removes high spatial frequencies from the images. Thus stereoacuity tolerates binocular blur better than spatial resolution, that is, one’s ability to distinguish high frequency spatial changes in the image. Blur has a greater influence on stereoacuity if it is monocular (Halpern and Blake, 1988; Westheimer and McKee, 1980 a; Lit, 1968).

2.2.6.13 Differences in the images of the eyes

Generally speaking, the differences in whatever visual factors to each eye, excluding disparity, deteriorate stereoacuity. These factors may be, for example, different contrast (Halpern and Blake, 1988; Westheimer and McKee, 1980 a), color, spatial frequency (Schor et al, 1984), luminance or orientation of the target in the images of each eye.

2.2.6.14 Eye movements

Stereoacuity is better if the person is able to do eye movements without having to fixate into the same point all the time. The microsaccades and drifting eye movements, which happen during the fixation, have no effect in stereoacuity.

2.2.6.15 Movement of the target

Dynamic stereoacuity can be measured with moving stimulus. Dynamic and static stereoacuity correlate only weakly with each other (Zinn and Solomon, 1985). Usually vision tests measure only static stereoacuity, yet it is sometimes meaningful to measure dynamic stereoacuity.

We are more sensitive in perceiving horizontal movement than movement in depth, or stereo motion, for it is more difficult to detect an image that is moving in horizontally opposite directions at the retinas of the two eyes. This phenomenon is also called stereo movement suppression (Tyler, 1971). Looming is an only movement in depth we are able to perceive even moderately well. A target oscillating in depth has an adverse effect on dynamic stereoacuity threshold if the oscillating frequency exceeds 1Hz (Schor et al., 1983).

Our visual system tolerates horizontal movement quite well. The target may move horizontally even two to three degrees per second without affecting on stereoacuity even though resolution acuity gets much worse due to horizontal movement. Stereoacuity is a hyperacuity like vernier acuity, and all hyperacuities are very tolerant of horizontal movement. Actually, stereoacuity may be even better when eye movements are present.

The best known and most investigated stereo phenomenon of moving targets is the Pulfrich effect. Carl Pulfrich (1922) reported his finding according to which a target oscillating in a frontal plane was perceived as having an elliptical path when the view of the other eye of the person was filtered by a neutral density filter. Pulfrich explained this phenomenon by the dimmer filtered image being processed slower in the visual system than the unfiltered image. Hence, in the visual system, this time difference produces disparity which is perceived as depth difference.

Therefore the pendulum is perceived as moving from one depth level to another on the elliptical path while it is oscillating.

2.2.6.16 Sign of disparity

The sign of the disparity may impact on stereo threshold values. According to Steinman et al. (2000), most of us have from two to three times better stereoacuity for crossed disparity than for uncrossed disparity. The experiments of Lam et al. (2002) support this conclusion even if in their study, the difference is not that significant and depends on the type of the phoria of the testee. According to the studies of Shippman and Cohen (1983) the type of the disparity is an essential factor if the testees have heterophoria. They found that esophoric testees had a tendency to better crossed stereoacuity while exophoric testees perceived uncrossed disparities better. Most clinical tests of stereopsis measure sensitivity only to crossed disparity.

2.2.6.17 The image type

The image type of the target has an influence on stereo perception. For example, when random dot stereograms are used, processing of the depth information takes from 0,5 to 1 seconds longer (Harwerth and Rawlings, 1977) and the stereo threshold values achieved are higher than when using simple line stereograms. This phenomenon may be related to the characteristics of perceiving spatial frequency (see chapter 2.2.6.18). As a rule, a person performing well on a global stereopsis test will perform acceptably well on a local stereopsis test, but the reverse is not true (Saladin, 2005; Schor, 1991). The differences between global and local stereopsis are assumed to be physiological (Harwerth and Rawlings, 1977).

2.2.6.18 Spatial frequency and the crowding effect

Stereoacuity as well as visual acuity is affected by crowding effect, a phenomenon in which higher stereo thresholds are introduced when the stimuli are closely spaced laterally. The best stereoacuity values are achieved when the horizontal distance between the targets stays between 15 to 50 minutes of arc. This is to say that stereoacuity also suffers if the targets are set laterally too far from each other (Westheimer and McKee, 1979). However, these results are gained by using simple line stereograms and thus cannot be directly applied to random dot stereograms. Stereoacuity may also suffer from other objects situated near the stimuli. The effect of flanking objects has been investigated by line stereograms where the reference line is accompanied with lines of similar orientation and depth plane.

These phenomena can be explained by spatial frequency processing in our visual system. The spatial processing fields overlap if the horizontal distance between the targets is too small. The visual system inhibits the areas just beside the stimulus signal for making the signal clearer. The inhibition area of the other stimulus deteriorates the signal of the other stimulus when two targets are near each other. This may also explain the higher stereo threshold values achieved by random dot stereograms by comparison with line stereograms.

2.2.6.19 A nearby feature on another depth plane

Nearby objects in another depth plane may introduce distortion in depth perception by causing "depth attraction" or "depth repulsion" effects (Stevenson et al., 1991). When disparate stimuli are closely spaced laterally the different disparity values are averaged in the visual system and depth attraction occurs. Depth repulsion is present at larger lateral separations between the stimuli.

2.2.6.20 Prolonged exposure to a given disparity

Prolonged exposure to a given disparity may cause depth aftereffects (Mitchell and Baker, 1973; Blakemore and Julesz, 1971), as is the case in contrast vision. Depth aftereffects bias your percept of depth. This can be explained by the adaptation or fatigue of the disparity processing channels (Schumer and Ganz, 1979).

2.2.6.21 The size of the target

The size of the target affects our ability to detect small disparities. Stereoacuity gets worse with larger targets. This may be explained by the fact that they activate a larger number of spatial frequency channels. Larger targets also extend more on the area of lower resolution at the retina.

2.2.6.22 Standing disparity

Stereo thresholds are higher if we try to detect depth difference in a situation where the reference target also has disparity (Badcock and Schor, 1985; Ogle, 1953). In this situation the reference target is said to have standing disparity. Stereo threshold values grow exponentially in relation to the standing disparity. As we can detect small depth differences most easily near the horopter, the best stereoacuity values are achieved when the reference target has no disparity, that is, it is situated on the horopter.

2.2.6.23 Consistency of the depth cues

Depth cues that are in conflict with each other deteriorate the perception of depth. The sensation of depth is always a sum of the depth cues.

2.2.6.24 Depth constancy

Depth constancy is discussed more in chapter 2.2.5. Failing of the depth constancy can bias the depth perception.

2.2.6.25 Viewing distance

Stereoacuity is reduced with larger viewing distances. Ocular deviation, i.e., the departure of the visual axis of one eye from the point of fixation, has a greater effect on distance than on near stereopsis (Rutstein et al., 1994). Distance stereopsis is highly sensitive to small refractive error changes, heterophoria and strabismus or visual acuity (Rutstein and Corliss, 2000).

2.3 Stereoscopic systems and stereograms

In this chapter, stereoscopic methods are compared and their applicability to a web-based stereo test use is discussed. Anaglyphic and random-dot stereogram methods used in this study are described in more detail.

2.3.1 Stereoscope and stereo pair

Stereoscope is defined as a device that takes advantage of the phenomenon of stereopsis by presenting a separate image of a stereo pair to each eye. Stereo pair represents two images of the same target from slightly different horizontal points of view. When viewed through a stereoscope, the two images fuse into a single, three-dimensional image. In an ordinary two-dimensional picture the disparity information has been lost making binocular depth perception from them impossible.

2.3.2 Anaglyphs

Color filtering is one method for separating the left and right eye's view. In anaglyphic technique two images of mutually exclusive colors are superimposed and viewed through color filter glasses so that the other color is filtered by one lens but not by the other and vice versa. Using stereo pairs in this way a stereo effect can be created in the image. Figure 6 below shows inexpensive color filter glasses with cardboard frames.

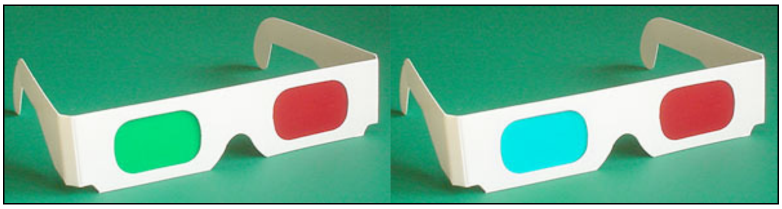


Figure 6. Red-green and red-cyan filter glasses for anaglyphic viewing. The image is from: http://www.assistpoint.co.uk/3d_glasses_red_green_with_arms.html [accessed 4 Dec 2008].

Red-green or red-cyan color combinations are most common in anaglyphic stereo images but other combinations of colors can also be used. However, attention must be paid on choosing the colors since crosstalk and ghosting effects may occur if the filters do not wholly eliminate the view meant for the opposite eye (McAllister, 2002). Crosstalk occurs if the image meant for the other eye is partially or part of the time visible to the fellow eye. In this case the image may appear blurred or a double image may be produced, a phenomenon also known as ghosting. (Linde, 2003; McAllister, 2002) Inter-ocular contrast may also deteriorate stereo perception (Halpern and Blake, 1988; Westheimer and McKee, 1980 a; Lit, 1968). See Figure 7 below for an example of an anaglyphic photograph.

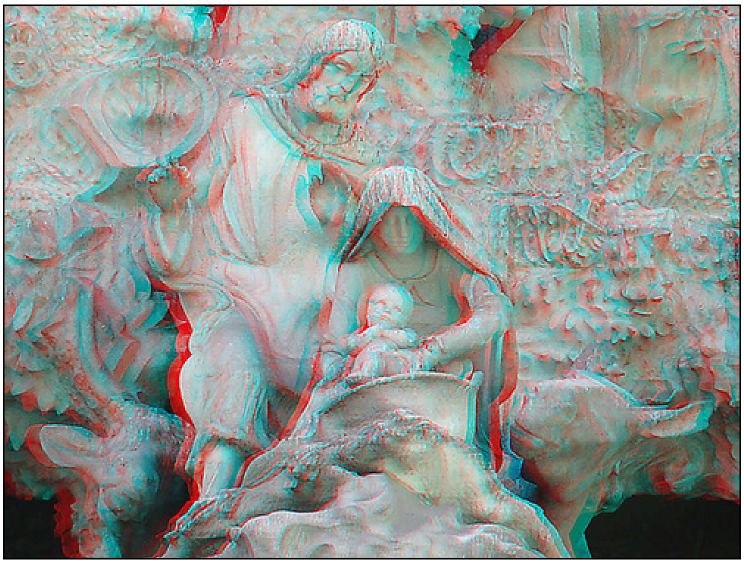


Figure 7. An anaglyphic photograph from: http://farm1.static.flickr.com/150/450652013_987ba2ec95.jpg?v=0 [accessed 4 Dec 2008]. If you have a color print of this thesis try to view this 3D photograph through red-cyan glasses the red filter in front of your left eye.

Anaglyphic method is commonly used in clinical tests for binocular vision because it does not require expensive equipment and anaglyphic images are easy to observe. Anaglyphs are often applied to random-dot stereograms (see chapter 2.3.4) when there is a need to eliminate monocular depth cues. A downside of anaglyphic method is that full color stereo images can not be created (Huk, 1999) and the color filters reduce the luminance level of the image.

In this study, anaglyphic method is used to implement the web-based stereo vision test (see chapter 3.1) since it is suitable for a web-based approach and does not require expensive additional equipment from the user. Inexpensive color filter glasses, as seen in Figure 6, are easily available. The anaglyphic method enables small enough disparities in the stereo images when viewed on a basic consumer display, since it does not halve the image resolution. Hence, the test requirement of being easily attainable is best achieved with this method.

2.3.3 Other methods for separation

In addition to the anaglyphic technique there are several other methods to separate the right and left eye's views from each other. These methods are compared in this chapter and their applicability to a web-based stereo test use is discussed.

2.3.3.1 Mirror stereoscopes

Reflecting mirror stereoscopes, for example, can be used to measure stereoacuity since the targets can be placed at very distant positions so that the disparities in the images are small. This method, however, is quite large and cumbersome to use and is not a reasonable choice for a web-based test. Wheatstone's reflecting mirror stereoscope is illustrated in Figure 8 below.

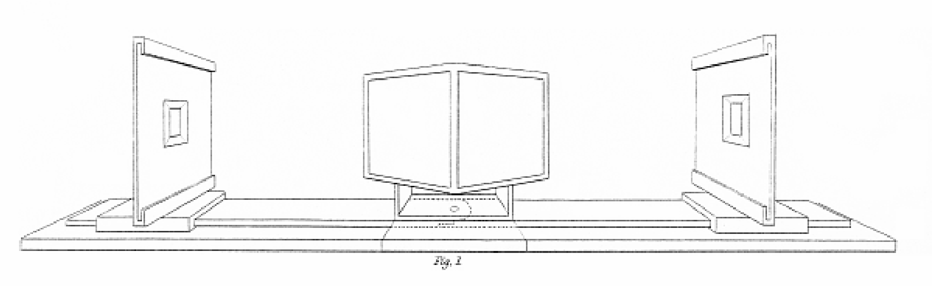


Figure 8. Wheatstone's reflecting mirror stereoscope (Wheatstone, 1852). Wheatstone's actual stereoscope is preserved at the Science Museum in London.

2.3.3.2 Lenticular stereoscopes

Lenticular stereoscope is a more compact device which enables far accommodation of the eyes for near pictures. Some modifications of the lenticular stereoscope are reported to be excellent for binocular vision testing (Saladin, 2005; Anapolle, 1957). These instruments are able to measure very small disparities. Since the high cost of them they are mainly used by professionals.

2.3.3.3 Vectographs

Polarization of light can also be used to separate the left and right eye's view. Vectographs are used in many clinical tests for binocular vision. One of the most famous tests using this technique is the Titmus Stereo Test (see chapter 2.4.4), which is used as a comparison test in this study. One downside of using linear polarization method in stereo vision tests is that the image disappears if you tilt your head. With circular polarization this effect is diminished, but it is not commonly used in manual stereo vision tests. Other downsides include deterioration of the resolution, contrast and clarity of the image. However, manual stereo vision tests using this method allow wide visual field, are fairly inexpensive and easy to use. To view an automatic stereo vision test with this method would require stereoscopic display utilizing polarization technique from the user. New displays utilizing circular polarization and interlacing of the stereopair have recently appeared and they might increase the relevance of this display type in the stereo display market.

2.3.3.4 Shutter glasses

Some of the liquid crystal shutter glasses are quite affordable at the moment. With shutter glasses high quality images can be produced but the visual field is restricted. With adequate display technology and synchronization accuracy, shutter glasses could be used to view web-based stereo vision tests. However, the refresh rate of most of the consumer displays of today is still inadequate to produce unflickering stereo images time-sequentially. This is a major constraint in stereo test use since flickering disrupts stereopsis near the stereo threshold. In addition, most of the LCD displays have been reported to be unusable for 3D viewing with shutter glasses due to their image update method or pixel response rate (Woods et al., 2006). With these displays cross-talk and ghosting effects deteriorate the image. Figure 9 below shows an example of liquid crystal shutter glasses.

Figure 9. Liquid crystal shutter glasses from: http://www.vrlogic.com/html/shutter_glasses.html [accessed 4 Dec 2008].

2.3.3.5 Head-mounted displays and virtual retinal displays

Head-mounted displays, abbreviated as HMD, are displays worn on the head (see Figure 10 and Figure 11). HMDs basically consist of an image source, optics and a supporting device. Virtual retinal displays, abbreviated as VRD, use low power laser beams to project the image straight at the retina of the user.

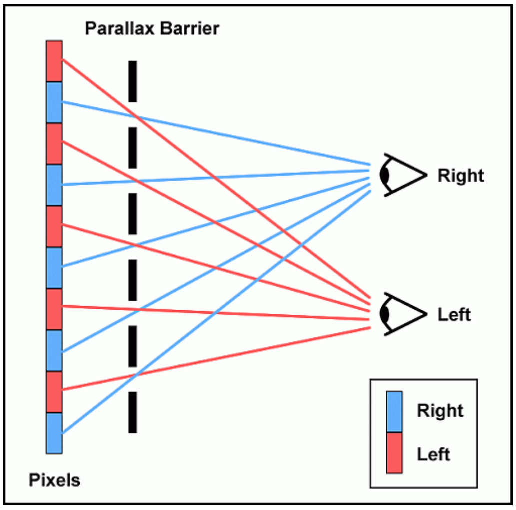
The advantages of the HMDs and the VRDs include a wide visual field and the ability to fully separate the right and left eye's view. In addition, window violation does not occur with these technologies (Linde, 2003). In window violation, the depth effect collapses if the edge of the screen appears to occlude the displayed object and occlusion overrides the stereo depth information. The major advantage of virtual retinal displays compared to others is that they produce much brighter image than screen based displays and thus they can also be used in daylight. (Isdale, 1998; Tidwell et al., 1995) The adverse symptoms experienced by some users limit the use of the HMDs. Since high resolution is required for measuring stereoacuity, both HMDs and VRDs would be an expensive choice. For an example of the relationship between the HMD resolution and price, see Figure 10 and Figure 11 below.

Figure 10. An example of a head-mounted display with a resolution of 640 * 480 pixels. According to the internet store in: http://www.vrealities.com/i-3d.html, where the image is from [accessed 10 Dec 2008], this device "represents a breakthrough in an affordable 3D capable Head Mounted Displays". It is sold for $ 225 that is about 175 €.

Figure 11. An example of a head-mounted display with a resolution of 1280 * 1024 pixels per eye. The prize is $ 23 900 that is about 18 500 €. The image is from: http://www.vrealities.com/nvisorsx.html [accessed 10 Dec 2008].

2.3.3.6 Autostereoscopic displays

Parallax display is the most common type of autostereoscopic display. Parallax displays emit light of varying intensity in different directions and thus different images can be displayed to the left and the right eye. Parallax displays can be implemented, for example, using parallax barrier- or lenticular sheet methods (see Figure 12 and Figure 13) (Halle, 1997). The parallax barriers weaken the luminance of the image but they are easier to adjust to the viewing angle than the lenticular sheets. In both of these methods the horizontal resolution of the image is halved which restricts the stereo test use of them. Other disadvantages include the restrictions in the viewing angle and the high cost of the equipment required. On the contrary, a goggle-free viewing would be an advantage.



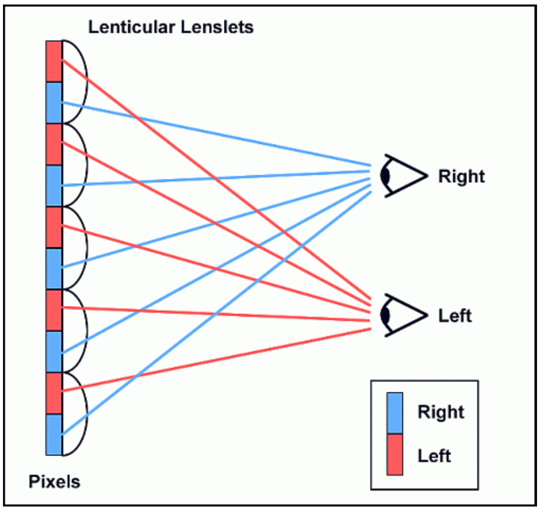


Figure 12. Illustration of the parallax barrier method seen from abowe. The image is from: http://www.reviewspring.com/3d-lcd-monitors-a80.php [accessed 4 Dec 2008].

Figure 13. Illustration of the lenticular sheet method seen from abowe. The image is from: http://www.reviewspring.com/3d-lcd-monitors-a80.php [accessed 4 Dec 2008].

2.3.3.7 Volumetric displays

Volumetric displays are an attempt to create natural-like viewing conditions of an image of a target. These displays allow natural ocular accommodation but are poor in creating occlusion effects. This is a major constraint that limits the use of these displays. Also images, that change their appearance when the viewing angle changes, can be called volumetric displays. Holograms are an example of these techniques. However, they have restrictions in the range of viewpoints.

2.3.4 Random-dot stereograms and cyclopean depth perception

Stereograms are two-dimensional images where you can perceive the illusion of depth when the right and left eye’s views are separated from each other. Random-dot stereograms are stereograms created using random-dot noise. By the invention of random-dot stereograms Béla Julesz showed that binocular disparity alone can create depth perception (Julesz, 1960).

Random-dot stereograms are created by generating two similar random-dot images and by shifting a part of the other image horizontally thus introducing binocular disparity into the image pair. The two images are then presented separately to different eyes. When viewed monocularly, both of the images just look like a pattern of random dots with no apparent form. When viewed binocularly, the visual system is able to fuse the two images and to perceive the disparate figure in the image. This kind of overall disparity computation between the images of the two eyes is called global stereopsis. For an example of a random-dot stereogram see Figure 19 in chapter 3.1.3.

With random-dot stereograms properties of stereopsis can be measured in a purely cyclopean domain, that is, no monocular cues are available. Therefore this method is used in many common stereo vision tests as, for example, in the TNO Stereo Test (see chapter 2.4.3). The TNO Stereo Test is used in this study as a comparison test. When assessing stereo threshold using computer screens, the main restriction so far has been the low resolution of the displays. The recent development in display technologies has, however, brought new possibilities to utilize random-dot stereograms on computer screens. This enables the implementation of automatic and cyclopean stereo vision tests. Random-dot stereogram method was applied in this study to prevent monocular cues from appearing in the anaglyphic images.

2.3.5 Other types of stereograms

Other types of stereograms are compared and their applicability to stereo test use is discussed in this chapter.

2.3.5.1 Line stereograms

Line stereograms are typically used when carefully controlled stimulus conditions are needed. Binocular disparities even smaller than the resolution limit of the eye have been measured with line stereograms. However, with larger disparities there are clear monocular cues in the relative differences between the positions of the lines. Therefore, line stereograms are best used for measurement of subthreshold disparities.

2.3.5.2 Autostereograms

The advantage of autostereograms is that there is no need for an optical equipment to see depth in them. However, this method would not be suitable for stereo test use since some people are not able to attain free fusion (McAllister, 2002). Viewing autostereograms also causes eye strain. For an example of a random-dot autostereogram, see Figure 14 below.

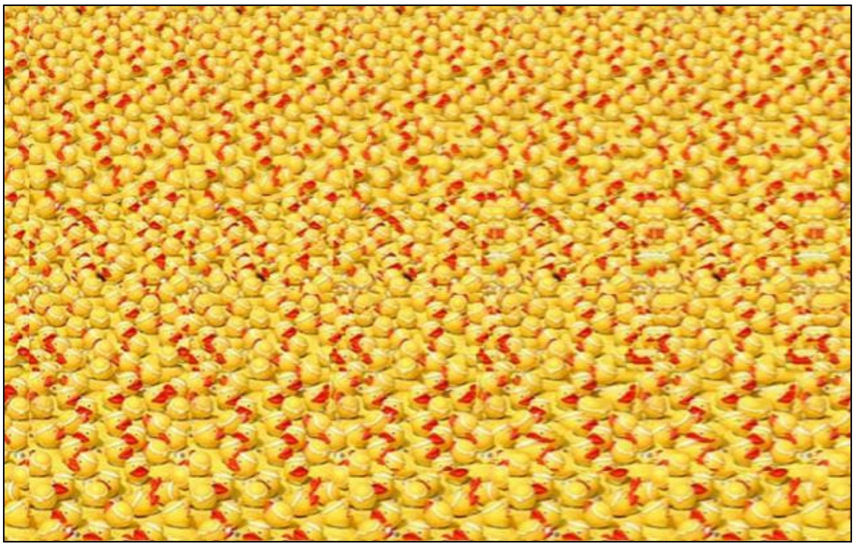


Figure 14. Can you see the duck in this random-dot autostereogram? The image is from : http://www.magicmazes.fusiveweb.co.uk/Magic Eye/tabid/496011/Default.aspx [accessed 4 Dec 2008].

2.4 Stereo vision tests

This chapter is a review of different types of stereo vision tests. The TNO and the Titmus Stereo Vision Tests, which are used as comparison tests in this study, are described in more detail.

2.4.1 Stereo vision tests based on actual depth

The earliest stereo vision tests were mechanical rod tests based on assessing actual depth, such as Helmholtz Three-Rod Test and its more well-known modification Howard-Dolman Test (Pearlman, 1969; Howard, 1919). In the Helmholtz Three-Rod test three rods are set in line in front of the testee. The two outer rods are fixed to an equal distance from the observer and the central rod can be moved forward or backward by the testee. The testee is requested to move the central rod closer to the fixed rods so that (s)he can not notice the difference in the depth of the rods anymore. The stereo threshold of the testee is then determined by measuring the depth difference between the central rod and the fixed rods.

The Howard-Dolman Test (see Figure 15) is a commercial version of the rod test. Only two rods are used where one is fixed and another is moved. The stereo threshold is determined identically with the Helmholtz method. In the Howard-Dolman Test, monocular depth cues are reduced by using a window through which the testee can only see the central parts of the rods. The Howard-Dolman Test is commonly used as a comparison test (Reading, 1983).

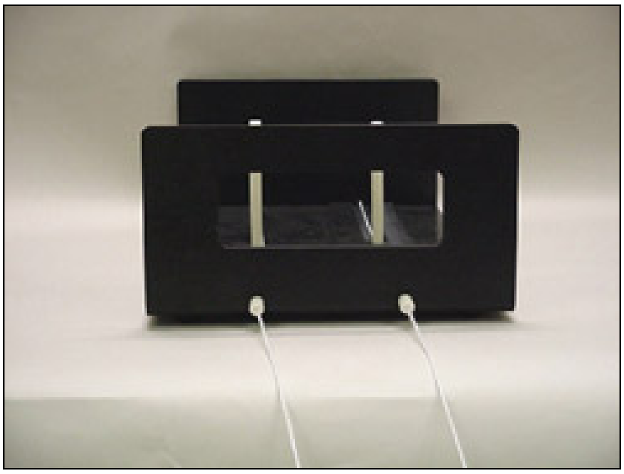


Figure 15. Howard Dolman type test from: http://www.bernell.com/product/2013/11 [accessed 4 Dec 2008].

With mechanical tests, low stereo threshold results (2-15 arc sec) are gained (Saladin, 2005; Pearlman, 1969). However, the tests contain several monocular cues that are difficult to eliminate. Different versions of the rod tests have been developed to eliminate the monocular cues. For instance, strips of different widths were used in the Verhoeff Stereopter-test to disturb the monocular cue caused by relative size. (Pearlman, 1969) Also lightning, atmospheric perspective, linear perspective, accommodation and motion parallax generate monocular cues in these methods. Mechanical stereo vision tests are relatively bulky and time-consuming. They also require very accurate motor skills from the testee as a response indicator (Saladin, 2005).

2.4.2 Stereoscopic stereo vision tests

Due to their clumsiness, the stereo vision tests measuring actual depth have mainly been replaced by tests using stereo images. These tests can be classified into local and global stereopsis tests according to the type of stereopsis that they measure. Another classification can be done between manual and automatic tests. Manual tests are based on printed stereo images while automatic tests utilize computers for image generation and test data collection. The latter classification is used in this chapter.

2.4.2.1 Manual tests

The most commonly used stereo vision tests for screening stereopsis or stereo vision anomalies are manual stereoscopic tests, such as the TNO- (Lee and McIntyre, 1996), the Titmus- (Saladin, 2005; Lee and McIntyre, 1996; Pearlman, 1969; Wirt, 1947), the Randot- (Lee and McIntyre, 1996), the Random dot E- (Reinecke and Simons, 1974), the Lang- (Lee and McIntyre, 1996), the Frisby- (Saladin, 1998) and the Keystone Multi- (Anapolle, 1957) stereo vision tests. In the Keystone Multi-Stereo Test Brewster-type binocular is used to view the stereoscopic target. In the TNO Stereo Vision Test red-green filter glasses are used. Polarizing filter glasses are used in the Titmus-, Randot- and Random dot E tests. The Frisby- and the Lang stereo vision tests are autostereoscopic, so no glasses or other viewing devices are required. The TNO-, Randot-, Random dot E- and Frisby stereo vision tests measure global stereopsis, while the Keystone Multi-, Titmus- and Lang stereo vision tests measure local stereopsis.

Most of the manual stereo vision tests are rather used for screening purposes than for to measure stereo threshold or stereoacuity. However, the TNO-, Frisby and Keystone Multi-Stereo Tests as well as the Howard-Dolman peg test may be applied to assess stereoacuity (Saladin, 2005; Lee and McIntyre, 1996; Pearlman, 1969). The TNO Stereo Vision Test was chosen as a comparison test in this study since it measures global stereopsis and is applicable on assessing stereoacuity, like the Web Stereo Test developed in this work. The Titmus Stereo Vision Test, which is a screening test for measuring local stereopsis, is used as another comparison test in order to get a different type of comparison. The TNO- and the Titmus Stereo Vision Tests are described in more detail in chapter 2.4.

2.4.2.2 Automatic tests

A few automatic stereo vision tests have been developed but they have not become very popular. Screen properties, which are often difficult to control, have a significant effect on them. So it can be quite difficult to ensure comparable results with different screens. Screen resolution has also been a limiting factor. In addition, automatic stereo vision tests often require expensive equipment.

Possibly the most well known automatic stereo vision test is the Freiburg Stereoacuity Test (Bach et al., 2001). In this test, time-sequential stereo pairs are viewed through liquid crystal shutter glasses which enable 60 Hz frequency to each eye. The stimulus consists of a frame around a vertical bar and the task is to decide whether the bar is in front of or behind the frame level. This resembles the three-rod test stimulus setting. The special feature of the Freiburg Stereoacuity Test is the ability to generate disparities as low as 1 arc sec with low resolution screen (resolution: 800 px * 600 px size: 36 cm * 27 cm) and a reasonable viewing distance (4,5 m). This is achieved by using anti-aliasing, which enables narrower shifts than the width of a pixel. This method would be extremely difficult to use with random-dot stimuli. In the Freiburg Stereoacuity Test, other methods, such as changing the horizontal position of the bar randomly, are used to reduce monocular cues.

Hoffmann and Menozzi (1999) have created a PC-based stereo vision test which measures global stereopsis with random-dot stereograms. The test stimuli and the test procedure resemble the TNO Stereo Vision Test. The researchers used a viewing distance of 2 meters and a screen where the pixel width was 0,28 mm. The pixel width combined width this viewing distance limited the lowest possible disparity to 29 arc sec. The authors concluded that a computer-based assessment of stereopsis could use anaglyphic method.

Moussa et al. (2003) developed a dynamic computer-based stereo vision test "The Moving Dynamic Random Dot Stereosize test: MDRS". In this test a horizontally moving anaglyphic random-dot stimulus is observed by the testee. The variable, though, is not the disparity but the size of the stimulus. The disparity remains constant 616 arc sec, while the target size varies from 11° to 0,13°. The target moves to a random direction across the screen and the response can be observed from the eye movements of the testee. Therefore, the MDRS test can be used with young children and individuals with communication difficulties. According to the authors this test is suitable for screening visual anomalies.

Stereo vision testing has also been tried with autostereoscopic displays. Breyer et al. (2006) presented random-dot stimuli to testees on an autostereoscopic display. According to them autostereoscopic displays can be useful while testing small children, who do not necessarily want to wear glasses. However, current autostereoscopic displays require limiting of the horizontal head movements, so a head support needs to be used. In this test the stimulus figure is a circle with a crossed-disparity of 0,34°. The figure is positioned in one of the four different locations at the screen and the response was observed from the eye movements of the testee. According to the authors this test allows objective assessment of stereopsis in children older than three years.

A web-based stereo vision test is an automatic stereo vision test which is based on web-based technologies so that the test can be used or shared over the Internet. An easily attainable test is a test that does not require expensive additional equipment and is easily available. The commonly used stereo vision tests are relatively expensive and difficult to get. They cost usually hundreds of euros or more and are often available only through postal order. Especially the applicability of the manual tests is often limited. If a new variation of a test is required either a totally new test or an extension of the test needs to be purchased. Over the last decades, computers, fast internet connections and web-based technologies have become common at offices and homes. Due to the developments in display technologies, screen resolution is not anymore a major obstacle for automatic stereo vision tests. So, today a web-based stereo vision test would be easily attainable for large number of users. However, easily attainable web-based stereo vision tests are not currently available. The test described in this thesis is the first prototype of a stereo vision test that uses exclusively web-based technologies and that does not require expensive additional equipment.

2.4.3 The TNO Stereo Vision Test

The TNO Stereo Vision Test (see Figure 16) consists of seven plates and a pair of red-green filter glasses. Anaglyphic random-dot images are used to eliminate monocular cues. The test was originally planned for screening pre-school children of age 2,5-5 years for defects of binocular vision, but it is also suitable for testing adults. Richmond Products, Inc. sells the test for $ 295 (approximately 231 €) (Richmond Products Inc., n.d.) and Sussex Vision International Ltd. for £135 (approximately 168 €) (Sussex Vision International Ltd., n.d.).

Figure 16. The TNO Stereo Vision Test (Richmond Products Inc., n.d.)

The first plates contain both monocularly and binocularly visible targets. These can be used to study coarse stereopsis and to teach the testee to observe stereo images. These plates are especially used while testing children. Plates five to seven can be used for the exact determination of stereoscopic sensitivity. The TNO Stereo Vision Test has become widely used since it is a practical test that is very easy to use.

In the empirical part of this study, the TNO plates five to seven are used as a comparison test. Each plate contains four random-dot images. A Pac-Man shape, which is a disc with a missing sector, is used as a stimulus figure (see Figure 17 below). The testee views the images at a distance of 40 cm through red-green filter glasses and is asked the direction of each of the missing sectors. There are two images of each of the six different disparity values and the scale is logarithmic. The test begins with the two images of the largest disparity value (480 arc sec). For the rest of the images the disparity values are halved from the previous value until the disparity of 15 arc sec is reached (240, 120, 60, 30, 15 arc sec). The images have crossed disparity but this can be changed to uncrossed disparity either by turning the plates or the classes. (Richmond Products Inc., 2009)

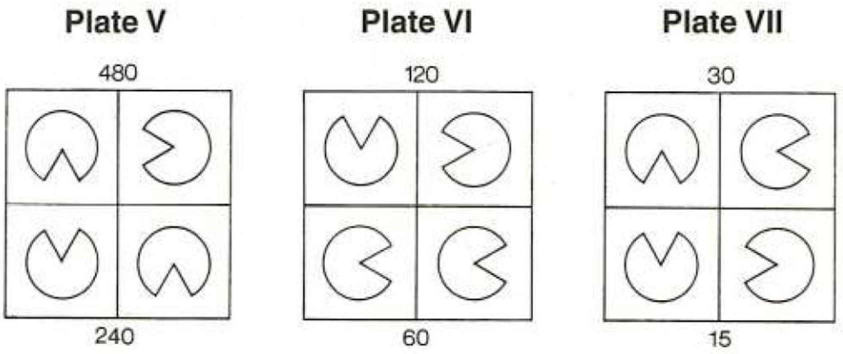


Figure 17. The stimulus figures in the TNO Stereo Test plates five to seven. The numbers represent the disparity values in the images. (Richmond Products Inc., 2009).

2.4.4 The Titmus Stereo Vision Test

The multiple names it has been given tells about the popularity of the Titmus Stereo Vision Test. These names are, for example: ”Titmus Stereo Vision Test”, “ Titmus Stereo Test”, “ Wirt Stereo Test”, “ Wirt Fly Test”, “ Titmus Fly Test”, “Stereo Fly Test”. In this study “Titmus Stereo Test” or shortly “Titmus” is used. In the Titmus Stereo Vision Test the left and right eye images are dissociated by polarization technique, so polarization filter glasses are needed. This test consists of three parts: the Titmus Stereo Fly, the Titmus Animal Test and the Titmus Circle Test (see Figure 18 below) (Pearlman, 1969). The Titmus Circle Test part is also called Wirt Rings (Saladin, 2005). In this study it is called Circle Test. The Circle Test part of the Titmus Stereo Vision Test is used in this study for comparison, so it is discussed in more detail below. Sussex Vision International Ltd. sells the Titmus stereo vision test for £135 (approximately 168 €) (Sussex Vision International Ltd., n.d.) and School Kids Healthcare division of Emergency Medical Products sells it for $ 158,95 (n.124 €) (School Kids Healthcare, n.d.).

The Stereo Fly part is a full page sized stereoscopic image of a fly. The binocular disparity in this image is 3500 arc sec from the recommended viewing distance of 40 cm. This stereoscopic photograph is quite dramatic and has been noticed to be disturbing for small children (Lee and McIntyre, 1996). The Animal Test part contains three series of animal pictures where the binocular disparity varies between 400 arc sec to 100 arc sec. The Circle Test part contains nine diamond formed figures with four circles in each. One of the four circles appears to pop out while seen binocularly. The testee is asked to choose the circle with disparity. The binocular disparities range from 800 arc sec to 40 arc sec (800, 400, 200, 140, 100, 80, 60, 50 and 40 arc sec). The Circle Test portion of the Titmus Stereo Vision Test is the most popular stereopsis test in the United States (Saladin, 2005), because it is compact, done from close distance and easy to store, transport, administer and score. This test is mainly used for screening binocular, oculomotor or refractive problems at near. The disadvantages of this test are a number of monocular cues and inability to measure low disparities. In addition, the testee has only one chance to select the correct circle at each depth level, and the polarization technique decreases the resolution and contrast and makes the images slightly blurred.

Figure 18. The three portions of the Titmus Stereo Vision Test and its polarization filter glasses. The portion in the upper left corner is the Circle Test. The image is from: http://www.southerncreative.co.uk/clients/keeler/Wirt-Stereo-Fly-Test-210.htm [accessed 4 Dec 2008].

3 Technical design and realization

This chapter describes the technical design, realization and the testing of the prototype. The technical design and realization are described in chapter 3.1 while chapter 3.2 deals with the testing of the prototype. Chapter 3.3 presents the results of the testing.

3.1 Prototype of a web-based test for assessing stereo threshold

This chapter describes the realization of the prototype from the three most important points of view: stereo test properties, graphics of the test and the test program.

3.1.1 Objectives

The main objective is to design and implement the first prototype of an easily attainable stereo vision test that can be used to assess the stereo threshold of a person. For the definition of easy attainability, see chapter 1.1. The test should find the threshold of the person in a reasonable reliability. In addition, the test should be cyclopic, repeatable, quick and easy to use and easily modifiable for different purposes.

3.1.2 Test requirements

Since a web-based stereo vision test would be easily attainable for a large number of users, as already discussed in the introduction of this study (see chapter 1.1), the prototype will be created using web-based technology. The test program will also be kept lightweight so that the test will work on a basic consumer computer. To ensure an easy availability and a low-cost use of it, the stereo test will be implemented using anaglyph method: color filter glasses are well available and inexpensive. An easy adjustment of the colors will be important to enable the use of the anaglyphic stereo test on different displays. The stereo test will be designed on the basis of the manual TNO Stereo Test with some modifications making advantage of the digitalization. It will, for example, iteratively find the threshold with a staircase procedure to possibly produce more accurate results. Random-dot stereogram method is used to eliminate monocular depth cues. The learning factor will be diminished by using random variation on the stimuli. To be easily modifiable, the test will be parameterized so that its colors, stimulus size or type, measuring accuracy and measuring reliability can be easily configured.

3.1.3 Properties of the Web Stereo Test

The idea of the widely used manual TNO Stereo Test (see chapter 2.4.3) was partly adapted to develop a prototype of a web-based stereo test called “the Web Stereo Test”. Both of the tests use cyclopic random-dot stereograms as a stimulus and the red-green anaglyphic technique to dissociate the images in each eye. Two different stimulus types were used in the Web Stereo Test, the other one of which is the same as in the TNO Stereo Test. The processes of the tests also resemble each other as stimulus figures with different separations are showed and the responses of the testee are analyzed to determine the stereo threshold.

The user requirements for the Web Stereo Test are red-green filter glasses, a display with minimum resolution of 800 * 600 pixels, and a computer that can run Macromedia Flash-programs. The Flash-player can be downloaded and installed on www.adobe.com (Adobe Systems Inc., 2008). The Web Stereo Test is viewed through the red-green glasses green filter in front of the right eye. The random-dot picture has a constant size of 800 px width and 600 px height. The program window size can freely be adjusted. If it is larger than the random-dot picture the yellow background is increased, otherwise, the random-dot picture is cropped.

Two versions of the Web Stereo Test were implemented with two different stimulus types having a shape of the Pac-Man and the Landolt-C figures (see Figure 21 and Figure 22 in chapter 3.1.4.2). The diameters of these stimuli are 371 px each and they are shown in 4 different alignments during the test. Figure 19 below presents a random-dot anaglyph of the Web Stereo Test program.

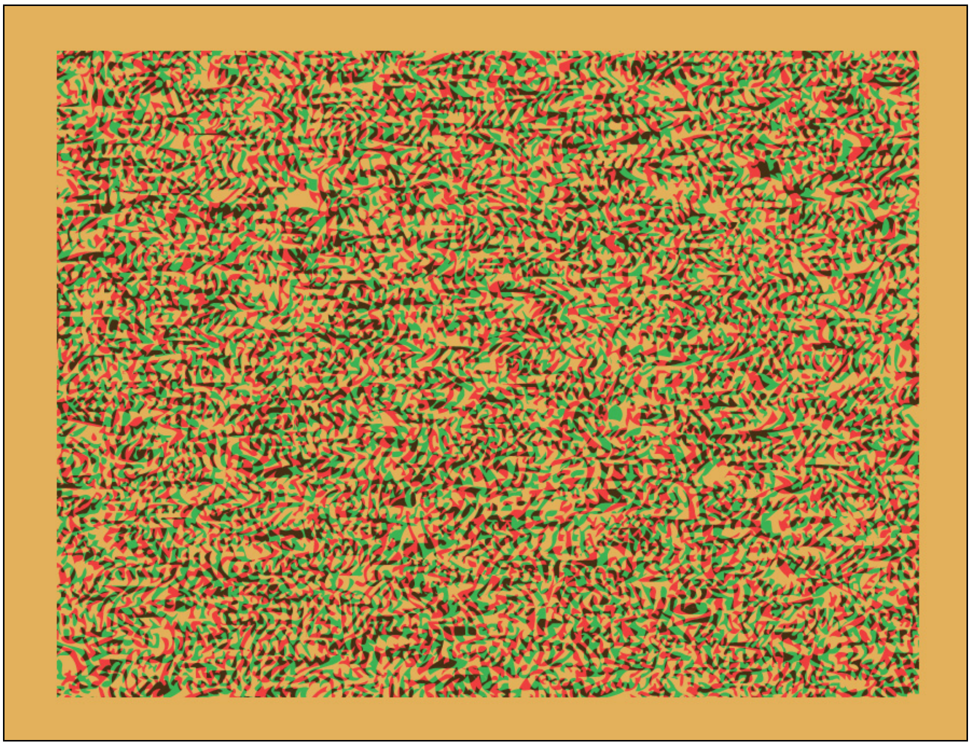


Figure 19. An example of the random-dot anaglyph of the Web Stereo Test. If you look at this stereogram through red-green filter glasses with the green filter in front of your right eye you can see a figure popping out of it, provided that you have a color print of this thesis. Stereo blind people, though, are not able to perceive depth effect in random-dot stereograms.

To prevent monocular cues from appearing through the colors, the background noise is separated by 10 pixels producing crossed disparity. The stimuli have from 1 to 12 px separation of crossed disparity. The corresponding binocular disparity angles depend on the pixel width, viewing distance and the interpupillary distance as can be seen in Equation 3 in chapter 3.3.2. For example, with pixel width of about 0,29 mm, interpupillary distance of 63 mm and the viewing distance of 303 cm, the scale of the measurable stereo thresholds is 20-240 arc sec, while with the 404 cm viewing distance it is 15-180 arc sec. The prototype of the Web Stereo Test gives the stereo threshold of the testee in pixels. The binocular disparity angle can then be calculated by the Equation 3. A fixation image was shown between the target images to lock the fixation to a same vergence position before each image. It is a line stereogram having a plus-sign shaped figure that is open at the centre (see Figure 23 in chapter 3.1.4.2). It is situated at the same depth plane with the background noise and it is visible for 250 ms at a time. The purpose of the fixation image is to keep the focus in the direction of the stimulus and to restore vergence between the stimuli so as to prevent depth cues from motion in depth from appearing.

The Web Stereo Test is controlled by keyboard keys w, s, a and q. The corresponding alignments for the Pac-Man figure are up, right, down and left and for the Landolt-C figure up-right, down-right, down-left and up-left. The program does not respond to the press of any other key. The program is executed once at the boot up. At first the stimulus with highest binocular disparity angle is shown. Its alignment is determined randomly. The program then waits until one of the control keys is pressed and as a respond shows the fixation image for 250 ms. Thereafter, a new randomly aligned stimulus is represented having binocular disparity angle determined by the staircase procedure (see chapter 3.1.5.1). This is continued until the staircase procedure allows the test to end. At this point the test result in pixels appears on the screen along with a report of the test just performed. The report contains the information whether the answer to a certain binocular disparity value was right or wrong during the test.

3.1.4 Graphics of the Web Stereo Test

3.1.4.1 Noise images for random dot stereograms

Random-dot picture elements (see Figure 20 below) were included in the program. Generating random-dot noise during the program run would slow it down more than desirable. The random-dot picture elements were also vectorized to achieve stimuli that can be scaled in size without losses in image quality. Thus the Web Stereo Test may easily be modified to a suitable size, while viewing it from different distances.

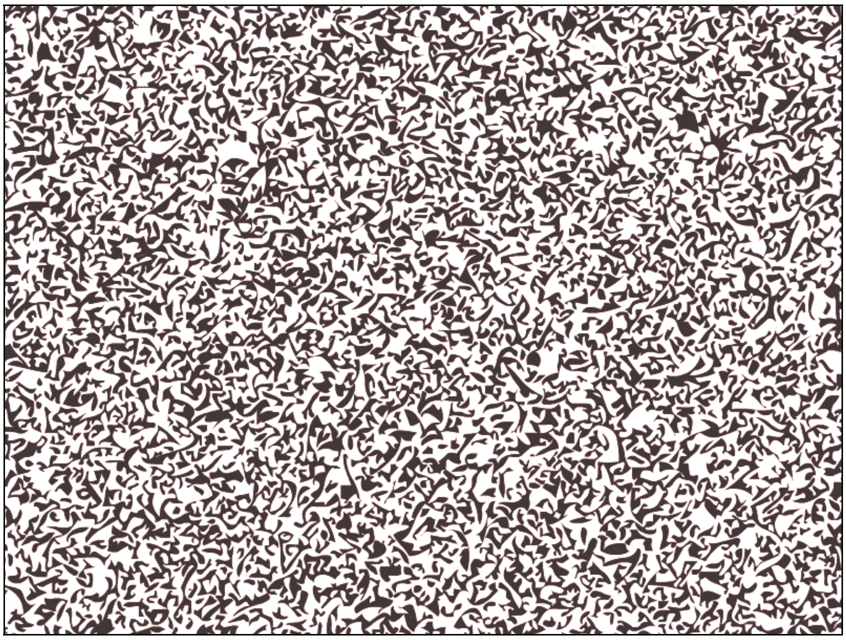


Figure 20. The vectorized random-dot noise used in the Web Stereo Test program.

The objective in generating the random-dot noise was that the discrete colored areas in the noise should be visible from several meters away to allow the visual system to combine the pictures from both eyes. At the same time they should be small enough to maintain the edges of the stereo figure clear. Too large areas could disturb the perception of the stereo image and make it appear blurry. The shape and the size of the colored areas should also be random. The objectives were reached by combining groups of dots in a fully random noise and by vectorizing the result. The vectorized random-dot noise was generated by Adobe Photoshop 6.0 and Adobe Illustrator CS2. The anaglyphic stereograms were generated using monochromatic picture elements as described in chapter 3.1.5.3.

The program includes green and red versions of the noise element described above. In addition, a sum color noise element was created for each separation of the red and the green noise elements. In the sum noise element, all the superimposed points of the green and the red noise with a certain separation are colored with the sum color. This calculation requires enormous amounts of processing capacity and is thus not performed during the program run. Thirteen sum color elements are included according to the amount of the different separations used in the program.

3.1.4.2 Stimulus figure masks and the fixation image

In the Web Stereo Test, a cyclopean stimulus figure is distinguished from the background noise to different depth planes. Because the next stimulus alignment is selected randomly and there are four possible alignments per stimulus figure, there should be 48 random-dot stereograms to cover each of the 12 depth planes. To reduce the required number of the picture elements in the program the stimulus figures were created by using masks as described in chapter 3.1.5.3. With this method, any shape aligned in any direction may be transformed into a random-dot stereogram in this program. Only the masks of the shape are needed. The two different stimuli used in the two versions of the Web Stereo Test program are Landolt-C and Pac-Man stimulus figures. The shapes of the stimuli are illustrated in Figure 21 and Figure 22 below. The figure masks were created using Adobe Illustrator CS2.

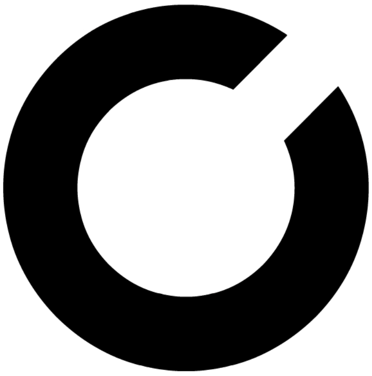


Figure 21. The shape of the Landolt-C stimulus.

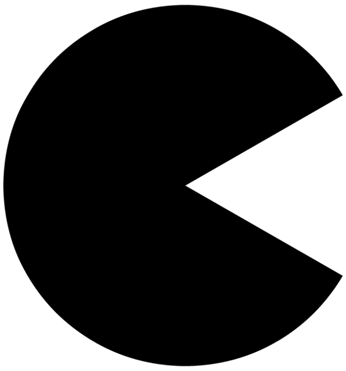


Figure 22. The shape of the Pac-Man stimulus.

The Landolt-C figure has a shape of a ring missing one tiny section. The Landolt-C stimulus figure mask were formed using ISO-standard for that figure (ISO 8596:1994), that is, the width of the circumference and the width of the missing section in the circumference are both fifth of the diameter length of the figure. In this case, the diameter was 371 px which follows the golden mean in relation to the background noise height (600 px). The Landolt-C figure has four possible alignments in the Web Stereo Test wherein the missing section is directed either to up-right, down-right, down-left or up-left.

The Pac-Man figure is a pie-like circle with a missing section of 60 degrees. This figure is also used as a stimulus in the TNO Stereo Test. In the Web Stereo Test, its diameter is 371 px in length being coherent with the Landolt-C figure diameter. In this work, the figure is called Pac-Man according to a computer game creature invented by Japanese Toru Iwatani in 1980. His computer game made the figure well-known all around the world. The Pac-Man figure has four possible alignments in the Web Stereo Test wherein the missing section in the circle is directed either to up, right, down or left.

Figure 23 below illustrates the fixation image used in the program. The fixation image is an anaglyphic line stereogram with a plus-sign shaped figure.

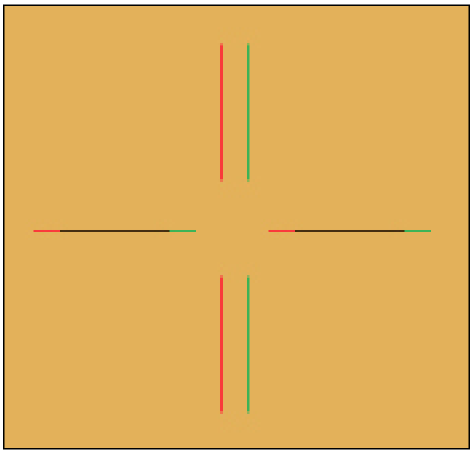


Figure 23. The fixation lock image.

The height and width of the plus-sign is 138 px with a 50 times 50 px open area at the centre. It is situated at the same depth plane with the background noise and it is shown for 250 ms between the stimuli.

3.1.4.3 Defining colors of the anaglyph

The anaglyph colors on the LCD (LG1910B 19´´) were adjusted to the Zeiss (West Germany) red-green filter glasses which are inexpensive glasses with a cardboard frame. The same display and filter glasses were also used on the testing of the Web Stereo Test.

Four colors were defined: stimulus colors red and green, sum color and a background color. The objectives were as follows:

1. The green filter does not transmit red color but transmits green color.
2. The red filter does not transmit green color but transmits red color.
3. The sum color is transmitted by neither of the filters.
4. The background color is transmitted by both of the filters with the same luminance levels, and it is perceived similarly with the transmitted stimulus colors.
5. The transmitted colors have a moderate luminance.

In the ideal case, the absorbed colors would seem black through the absorbing filters, in which case, the sum color could also be plain black. The transmitted colors would have same luminance levels and their luminance would be moderate. Both too low and too high a contrast disrupts stereoacuity (Geib and Baumann, 1990). However, this was not possible with the filter glasses in use. A compromise had to be found between the objectives by optimizing the colors. Contrast has strongest effect on stereoacuity if the images in each eye differ in contrast (Halpern and Blake, 1988; Westheimer and McKee, 1980 a). Therefore, along with an adequate separation of the left and right images, attention was paid to minimize the interpupillary contrast while still keeping the contrast of a single image high enough.

A color fading method was used to adjust the colors. This means adjusting the stimulus colors while seeing through the filter glasses until they fade and disappear through the absorbing filter and until the luminance levels are as desired through both of the filters. The requirements mentioned above could not be met adjusting the luminance levels of the plain colors red (#ff0000), green (#00ff00) and yellow (#ffff00) on the LCD. Using these color conditions the green color was totally merged into the background and the red color was perceived as black while seen through the green filter, which was just as desired. However, the red filter distinguished the red color from the background and the green color was not fully absorbed.

As a result, RGB-colors red (#f93b3b), green (#3cb456), sum (#452f12) and background (#e3b15b) in hexadecimals were selected. The selected colors were mixtures, where a slight amount of green and blue light was added to the red stimulus color as well as a slight amount of red and blue light were added to the green stimulus color. These colors were not fully eliminated by the absorbing filter but they produced most congruent luminance through the transmitting filter. The effects of the color leaking were minimized by selecting a dark brown sum color instead of black and by using a mixed yellow color for the background instead of plain yellow.

3.1.5 The Web Stereo Test program

3.1.5.1 Programming language

The program (see program code in Appendix B) was created using Macromedia Flash MX action script. To run the program a user needs Adobe Flash player which can be downloaded on www.adobe.com (Adobe Systems Inc., 2008) for free. Flash technology was selected because it can be seen as a web standard in expressing multimedia content.

3.1.5.2 Stereo threshold with an adaptive staircase procedure

A forced-choice adaptive “1 up 3 down”- staircase procedure with a constant step size was used to define the stereo threshold. The procedure is based on the psychometric function typical of experiments of this type (Wetherill and Levitt, 1965). The threshold is calculated by averaging eight reversal values of the sequence if it is not saturated to a certain value. According to Wetherill and Levitt, this procedure defines the disparity that the testee is able to perceive correctly in a probability of 79,4 %. They recommend using eight or more reversals on the calculation for a reliable estimate. Eight reversals were used to calculate the threshold as a compromise between the reliability of the test results and the time required to complete the test. Wetherill and Levitt also introduce a procedure to choose the starting level of the algorithm which is used in this program. A detailed description of the procedure is provided below.

The Web Stereo Test program is started by showing the stereogram with largest binocular disparity. The separation of the stereo pair is decreased by 1 px until the first wrong answer occurs. A wrong answer always increases the separation by 1 px except when the separation already is at the maximum level. In this case, the binocular disparity of the images remains intact. If the first wrong answer has occurred, the separation is decreased by 1 px only after three successive right answers. Other right answers do not change the binocular disparity of the images. The minimum separation is not changed after a right answer.

Every local maximum and minimum value in the binocular disparity function is counted during the procedure. If the stereo threshold of the testee lies within the binocular disparity scale of the program, the test reaches its end after eight reversals in the binocular disparity function, and the stereo threshold value is determined as an average of these reversal values.

If the stereo threshold of the testee does not lie within the binocular disparity scale of the program, the stereo threshold is saturated into the extreme binocular disparity value, either the maximum or the minimum value. For this case, there is an algorithm in the program that tests if the binocular disparity of the stereogram has stayed constant after nine successive answers. If so, the program ends and the extreme binocular disparity value is determined as the stereo threshold. This is the case, for example, when the testee has reached the smallest binocular disparity and is able to tell the correct direction of the stimulus for eight times successively. In the report of the results shown at the end of the program, it can be seen if the threshold was saturated.

3.1.5.3 Generation of the stereograms

Figure 24 below shows the principle of constructing the stereograms in the Web Stereo Test program.

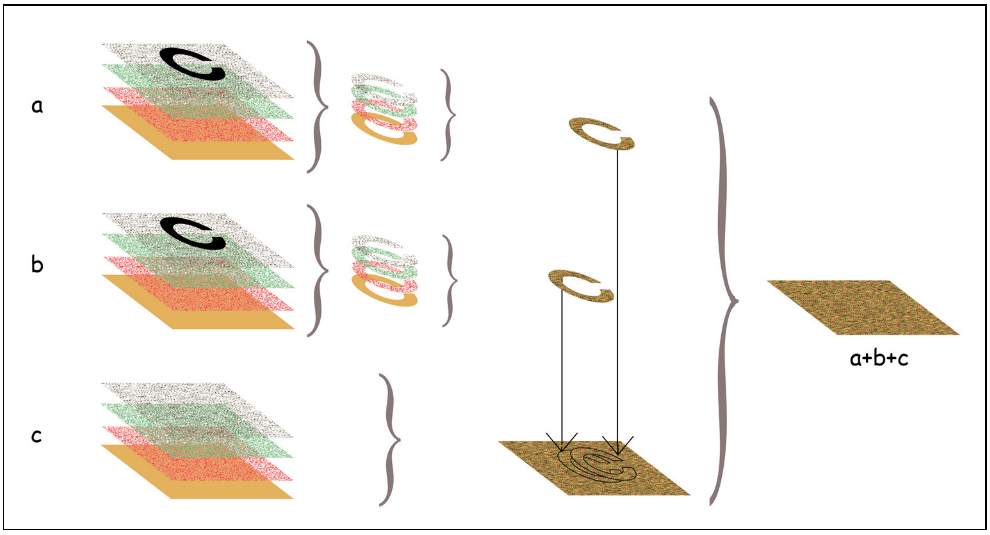


Figure 24. The principle of constructing the stereograms in the Web Stereo Test program. The three series illustrate the generation of each of the three picture elements a, b and c. In the whole image a + b + c the opaque elements are laid one upon the other so that the element a is uppermost and the element c is undermost as shown in the figure.

The stereograms were created by using masks of the stimulus figures. Masks are uniform colored shapes that can be used to cut pictures below them in Flash programming. The elucidation of the stereogram construction in Figure 24 uses Landolt-C stimulus mask to cut the random-dot noise layers below it. The stereogram consists of three image components a, b and c as seen in Figure 24. The undermost layer in each of the three components is uniformly yellow. Above it, there is a red and partly transparent noise image layer and a similar green noise image layer. The sum colored and partly transparent noise image is the topmost color layer in each component. A different sum color noise is used for each separation of the green and red noise elements. According to the disparity, the stimulus figure masks of the components a and b have horizontally separated positions and the green noise layer in the component a is shifted to the right. The red noise elements have a fixed position. The half-occlusion area in the green noise of the stereogram is filled with a mirror image of the green noise element to prevent blurry edges in the perception of the stimulus (component b in Figure 24). A part of the green noise in the background (component c) is occluded by the shifted stimulus element (component a) that creates the half-occlusion area in the red noise of the stereogram.

3.2 Testing the prototype

This chapter describes how the prototype was tested. The test conditions as well as the conduction of the tests are covered. The Web Stereo Test using Landolt-C figure as a stimulus is called the Web-L Stereo Test and the other version using Pac-Man stimulus is called the Web-P Stereo Test.

3.2.1 Objectives

The main objective of the testing is to collect stereo threshold values of a sample of observers with the implemented prototype and, for comparison, with some commonly used stereo vision tests. Other objectives are to collect relevant information of the participants as well as to study their experiences during the tests. In addition, the program will be tested through the Internet on a basic consumer computer. The purpose of the testing is to test the program functionalities in practice and to figure out how the prototype should be developed further to make it a valid test for stereopsis that can be delivered in the Internet.

3.2.2 Pilot tests

A pilot test of the prototype was conducted with 10 participants. The objective of the pilot test was mainly to assure that the prototype works well enough to be tested. It also gave important experience in conducting the tests. Thus, the testing of the prototype was planned on the base of the pilot test. Changes were made in the Web Stereo Test program during the pilot test. Another stimulus figure (Pac-Man figure) was added into the program to get information about the impact of the stimulus figure on the results.

3.2.3 Conduction of the tests

Stereoacuity of 20 participants was assessed using the Web-L Stereo Test, the Web-P Stereo Test, the TNO Stereo Test and the Titmus Stereo Test. For more information about the TNO- and Titmus Stereo Tests see chapters 2.4.3 and 2.4.4. Each participant also filled two different questionnaires. The results of the Web-L and the Web-P Stereo Tests were compared to the results of the TNO and the Titmus Stereo Tests. There were no other criterions in choosing the participants except that they should see with their both eyes. Only artificial light was used during the tests. The windows of the test room were covered with blackout curtains to control the illumination of the room.

The participant answered first to the questions of the pre-questionnaire. Then, the stereoacuity of the participant was assessed using the two different Web Stereo Tests, after which the participant filled a post-questionnaire. Lastly, the stereoacuity was assessed using the TNO Stereo Test and the Titmus Stereo Test, respectively.

3.2.3.1 Pre-questionnaire

The participants were asked the pre-questions at the beginning. The test controller wrote the answers in the pre-questionnaire form, which was also used to store the answers during the manual stereo tests. The purpose of the pre-questions was to collect basic information of the participants that may have an effect on the stereo test results. The age, gender, and use of lenses for vision correction were asked as well as the type of the lenses and the reason for the vision correction if existent. The pre-questionnaire can be seen in Appendix C.

3.2.3.2 Assessment of stereoacuity using the Web-L and the Web-P Stereo Tests

Stereoacuity was assessed using the Web-L Stereo and the Web-P Stereo Test. Figure 25 and Figure 26 show the testing conditions for the Web Stereo Tests. Half of the participants did the Web-L Stereo Test first and the other half did the Web-P Stereo Tests first. This arrangement was used to be able to differentiate between the effects of the practice and the stimulus figure when analyzing the results.

Figure 25. Testing conditions for the Web Stereo Tests.

Figure 26. The chair with a head rest in a fixed location.

The 19´´ LG L1910B LCD display was used to present the Web Stereo Test stimuli. The resolution was 1280 px * 1024 px the pixel with being 0,2944 mm. The participant saw the stimuli through the Zeiss (West Germany) red-green filter glasses which are inexpensive glasses with a cardboard frame. The green filter was in front of the right eye.

The distance and the gaze direction of the participant were kept unchanged by the help of a chair in a fixed location and a head rest in it (see Figure 26). The participant viewed the first stimulus of the highest binocular disparity at the viewing distance of 404 cm. If the participant was not able to perceive the direction of this stimulus correctly the viewing distance was changed to 303 cm. Otherwise, the first distance setting was used. These distance values were selected because they produce whole numbers for the binocular disparity of the stimuli in seconds of arc. The smallest binocular disparity of the Web Stereo Test viewed at the distance of 404 cm also corresponds to the smallest binocular disparity of the TNO Stereo Test viewed at the distance of 40 cm.

The binocular disparities of the Web Stereo Test stimuli viewed at the distance of 404 cm range from 15´´ to 180´´ arc. Correspondingly, the disparities range from 20´´ to 240´´ arc while viewed at the distance of 303 cm. The minimum binocular disparity step of the Web Stereo Test corresponds to 15´´ arc at the far viewing distance and to 20´´ arc at the near viewing distance. Since the stereo threshold value is counted by averaging as described in chapter 3.1.5.1, the scale of the results is continuous. The participant was asked to tell the direction of the missing section in the figure. The directions were up, right, down, or left for the Web-P Stereo Test or up-right, down-right, down-left, or up-left for the Web-L Stereo Test. If the participant did not perceive the stereo stimulus, he or she was asked to guess one of the four alternatives. The test controller used the keyboard controls according to the answers of the participant. At the end of the test, the test controller stored the test result and the report of the test offered by the program.

3.2.3.3 Post-questionnaire

The participant filled a post-questionnaire. The purpose of the post-questionnaire was to study the experiences of the participants during the tests. They were also asked opinions on the different stimulus types. The post-questions were modulated on the basis of the SSQ-questionnaire (Kennedy et al., 1993) which is used for studying stimulator sickness symptoms related to the use of 3D applications.

The questionnaire includes 13 questions related to the simulator sickness symptoms: dizzy eyes closed, dizzy eyes open, general discomfort, fatigue, headache, eye strain, difficulties accommodating, nausea, difficulty focusing, difficulty concentrating, blurred vision, flicker in light, flicker in color. Concerning these matters the participants answered either none, mild, moderate or strong by checking one of the four checkboxes beside the question. At the end of the questionnaire, there are 4 extra questions with a free text field. The participants were given a possibility to write free comments about their previous answers and to comment about any other matters that may have caused discomfort during the test. They were also asked to write their opinions about which one of the stimulus types they liked better and which one of them was easiest to perceive. The post-questionnaire can be seen in Appendix D.

3.2.3.4 Assessment of stereoacuity using the comparison tests

The TNO and the Titmus Stereo Tests are commonly used manual stereo vision tests (see chapters 2.4.3 and 2.4.4). The TNO Stereo Test assesses global stereopsis and is used for screening purposes as well as to define stereo thresholds. On the contrary, local stereopsis is assessed with the Titmus Stereo Test which is mostly used for screening purposes. The binocular disparity scale of the TNO Stereo Test plates V to VII is logarithmic: the next disparity halves the previous one. The maximum binocular disparity value is 480´´ arc while the minimum is 15´´ arc viewed at the distance of 40 cm. The scale of the TNO Stereo Test results is the same than the scale of the binocular stimulus disparities in the test. The binocular disparities of the Titmus Circle Test range from 800´´ to 40´´ arc. The disparities are: 800, 400, 200, 140, 100, 80, 60, 50 and 40 seconds of arc. These values are also the possible results of the Titmus circle test.

The stereoacuity of the participant was assessed using the plates V to VII of the TNO Stereo Test at the standard viewing distance of 40 cm. A head rest was used to fix the viewing distance. The test plates were set parallel to the face of the participant. Figure 27 below illustrates the testing conditions for the TNO Stereo Test. The participant viewed the TNO plates through the red-green filter glasses of the test. The green filter was in front of the right eye. The test controller laid each of the test plates in front of the participant one after the other. The test controller asked the participant to tell the direction of the missing sector of each of the four stimuli on the plate and stored the answers in the pre-questionnaire form (see Appendix C). The possible directions were up, right, down, and left. The participant was asked to guess one of the four possible directions if (s)he could not perceive the stereo effect. Beginning with the test plate of largest binocular disparities, the test was run through regardless of the correctness of the answers. The smallest disparity perceived correctly twice in succession were chosen as the result of the test.

Figure 27. The testing conditions for the TNO Stereo Test.

Figure 28. The testing conditions for the Titmus Stereo Test.

The stereoacuity of the participant was assessed using the Circle Test portion of the Titmus Stereo Test at the standard viewing distance of 40 cm. A head rest was used to fix the viewing distance. The test plates were set parallel to the face of the participant. The testing condition for the Titmus Stereo Test is illustrated in Figure 28. The stimuli of the Titmus Stereo Test were viewed through the Polaroid glasses of the test. The test controller asked the location of the popping up circle of each of the stimuli and stored the answers in the pre-questionnaire form (see Appendix C). The possible locations were up, right, down, and left. The participant was asked to guess one of the four possible locations if (s)he could not perceive the stereo effect. The test was run through regardless of the correctness of the answers. The disparity perceived correctly before the fist wrong answer were chosen as the result of the test.

3.2.4 Tests through the Internet

The Web Stereo Tests were also tested through the Internet on a basic computer having 0,5 GB of RAM and 1,3 GHz processor. The download speed of the internet connection was 1 M b/s. Both versions of the Web Stereo Tests were tested by two participants while the fluency of the test run was observed. The same anaglyphic filter glasses were used than in the other parts of the testing.

3.3 Test results

In this chapter, the results of the testing of the prototype are presented. The Web Stereo Test results are compared to the TNO and the Titmus Stereo Test results. The results of the questionnaires are also analyzed.

3.3.1 Participants and the realized test distances

The tests were administered to 20 participants whose ages were between 22 to 56 years. The average age of the participants was 37 years and the age median was 35 years. There were 8 male and 12 female participants. 17 participants used lenses for vision correction. The information about the type of the lenses and the reason for the vision correction was not achieved since the participants could not answer to these questions.

Eight of the participants could not perceive the stimulus of the largest binocular disparity from the distance of 404 cm. Six of them was tested using the viewing distance of 303 cm. Two of them could not complete the Web Stereo Tests since they did not perceive the easiest stimulus from the nearer distance either.

3.3.2 Conversion of the Web Stereo Test results

The prototype of the Web Stereo Test represents the stereo threshold results in pixels based on the separations of the stimuli. To compare the results with those of the TNO and the Titmus Stereo Tests they had to be converted into angular binocular disparities. The angular binocular disparity depends on the conditions of the test, such as the viewing distance, interpupillary distance, display size, and display resolution. Hence, the results were converted into seconds of arc by using Equation 3.

The Equation 3 was derived for this purpose because the equations for similar purposes found in literature were all based on the rounded Equation 2 (see chapter 2.2.4) which has limitations. Since the calculation was conducted by a computer an exact formula was preferred. Equation 3 can be used to calculate the angular binocular disparity based on the horizontal separations of the image for any random-dot stereogram. This equation can also be applied to the upcoming user interface of the Web Stereo Test in the matter of representing the results to the user.

Equation 3. The angular binocular disparity of the target at the stereo display

$$\eta = 2\left(\arctan\frac{a + \Delta s}{2d} - \arctan\frac{a + \Delta b}{2d} \right)$$

In the above equation, η stands for the angular binocular disparity of the stereo stimulus, a for the interpupillary distance of the observer, d for the viewing distance, Δs for the horizontal separation of the stimulus picture elements at the display, and Δb for the horizontal separation of the background picture elements at the display. The sign of the separation value Δs or Δb is positive if it produces crossed disparity in relation to the display plane and negative if it produces uncrossed disparity in relation to the display plane. The sign of the binocular disparity η is positive if the stimulus figure has crossed disparity, and negative if the stimulus figure has uncrossed disparity, in relation to the background of the image. The variables of the equation are illustrated in Figure 29 below.

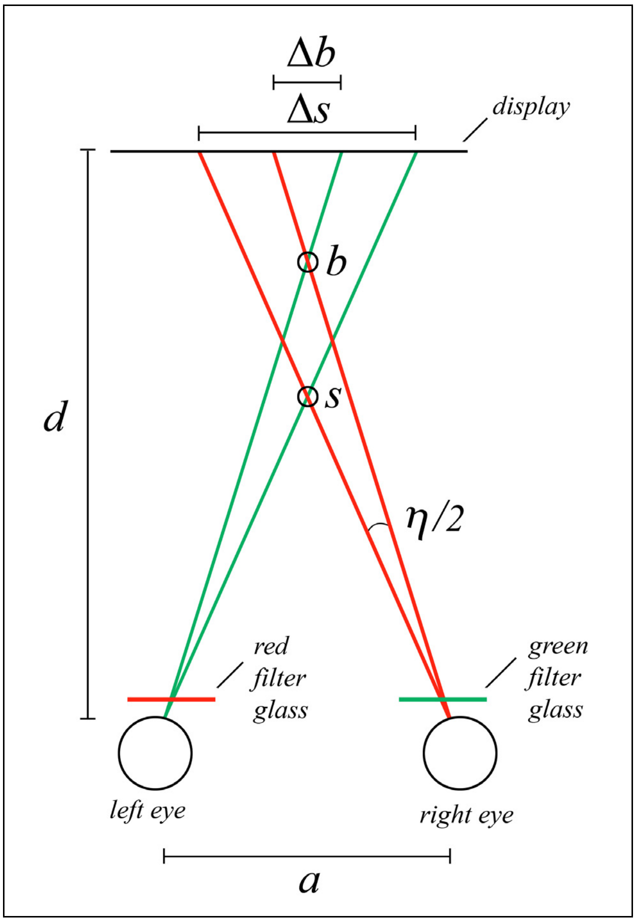


Figure 29. The angular binocular disparity of the target at the stereo display. Illustration of the variables in Equation 3. The two eyes see the points s and b in a slightly different points of view through the red and green filters due to the horizontal separations Δs and Δb of the points on the display plane. η represents the perceived binocular disparity of the points at the distance d while a stands for the interpupillary distance of the observer.

In this study, an average interpupillary distance of 63 mm was used. The background noise had a constant horizontal separation of 10 px producing crossed disparity. Hence, Δb had a constant value of 2,944 mm. The horizontal separation of the stimulus figures varied between 1 to 12 px and, thus, depending on the stereo threshold of the participant, Δs had a value between 3,2384 mm to 6,4768 mm. The distance d was either 303 cm or 404 cm depending on the test settings for the participant.

3.3.3 Comparison of the stereo vision test results

Results from the Web-L (Web Stereo Test with Landolt-C stimulus), the Web-P (Web Stereo Test with Pac-Man stimulus), the TNO and the Titmus Stereo Tests were compared to each other. The main focus was on comparing the Web-L and the Web-P Stereo Test results with the TNO Stereo Test results. The precision of the Titmus Stereo Test was low compared to the other tests so there was only minimal usage of the Titmus Stereo Test results. The lowest possible stereo threshold value with the Titmus Stereo Test was 40 arc sec. Only two of the nineteen participants failed to achieve the best possible threshold from this test. Also the majority of thresholds from other tests were below 40 arc sec.

3.3.3.1 Stereo threshold levels

The stereo thresholds of the participants with different stereo vision tests are illustrated in Figure 30. Participants 1, 5, 6, 7, 12, 13, 15 and 19 could not perceive the Web Stereo Test stimulus of the largest binocular disparity from the distance of 404 cm. Therefore, they viewed the Web Stereo Tests from the viewing distance of 303 cm. Participants 7 and 13 could not complete the Web Stereo Tests since they did not perceive the easiest stimulus from the nearer distance either. However, participant 7 could complete the TNO and Titmus Stereo Tests.

Based on Figure 30 the TNO Stereo Test seems to give lower thresholds than the other tests. The lowest threshold measured, that is 15 arc sec, was achieved by 32% of the participants with the TNO Stereo Test, by 22% of the participants with the Web-P Stereo Test and by 6% of the participants with the Web-L Stereo Test. The lowest personal stereo threshold was gained with the TNO Stereo Test by 42% of the participants, with the Web-P by 33% and with the Titmus by 16%. Nobody got their lowest personal stereo threshold with the Web-L Stereo Test.

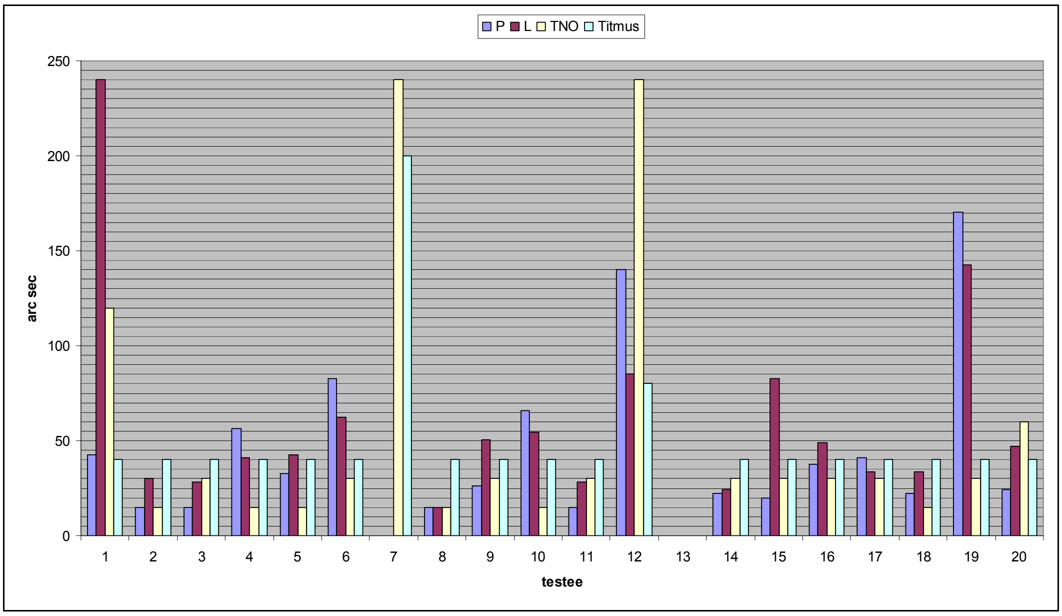


Figure 30. Stereo thresholds with the Web-P, the Web-L, the TNO and the Titmus Stereo Tests. Bar height indicates the stereo threshold in arc seconds, the color indicates the test type as illustrated above the figure, and the value at x-axis indicates the testee id. Testees 1, 5, 6, 7, 12, 13, 15 and 19 viewed the Web Stereo Tests from the nearer distance of 303 cm.

Mean values and standard errors of the stereo thresholds using different stereo vision tests are illustrated in Figure 31. Outliers were removed from the test data based on the 95% significance criteria. Also based on this analysis the TNO Stereo Test gave lower stereo thresholds than the Web-L or the Web-P Stereo Tests. The Web-P Stereo Test gave lower stereo thresholds than the Web-L Stereo Test. However, none of these differences were statistically significant.

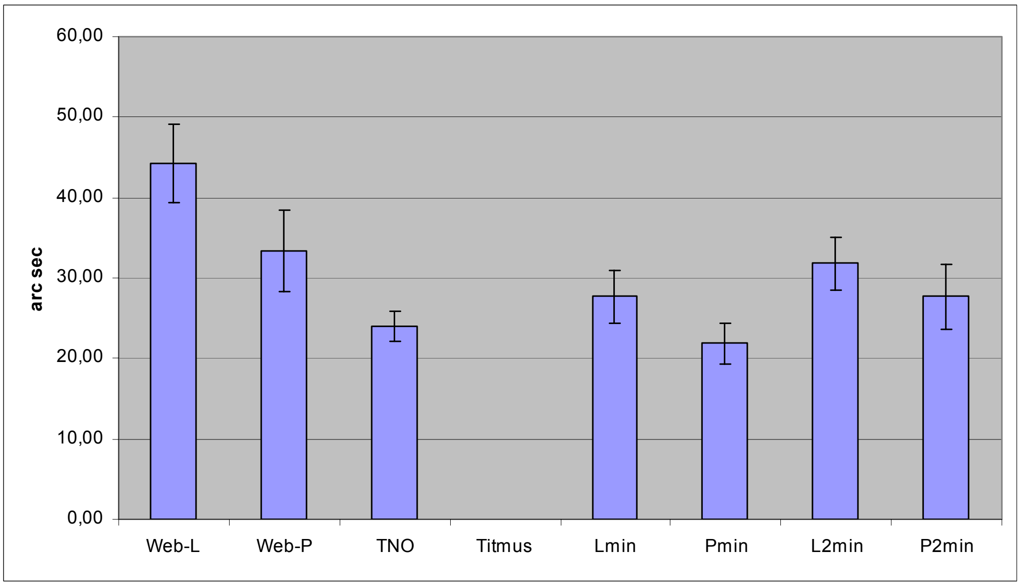


Figure 31. Mean values and standard errors of the stereo vision test results. Bar height indicates the average stereo threshold in arc seconds from each type of test (standard error intervals included). Before the analysis outliers were removed from the test data based on the 95% significance criteria. In the Titmus Stereo Test all data, in the Web-L Stereo Test two outliers (240, 143), in the Web-P Stereo Test two outliers (170, 140), in the TNO Stereo Test four outliers (240, 240, 120, 60), in L_{min} test one outlier (80), in P_{min} test two outliers (140, 60), in L_{2min} test one outlier (120) and in P_{2min} test one outlier (140) was removed. For the notations L_{min}, P_{min}, L_{2min} and P_{2min} see chapter 3.3.3.4.

Table 1 contains the paired comparison of the stereo vision test results. It shows the fraction of the users who got lower, equal or higher stereo thresholds with one test compared to the other. This table shows that the TNO and the Web-P Stereo Tests give lower thresholds than the Web-L or the Titmus Stereo Tests. The highest thresholds were got from the Web-L Stereo Tests. Due to the low sample size the results are only suggestive.

Table 1. Paired comparison of the stereo vision test results. The columns indicate the test pair to be compared. The rows include the frequencies of the participants based on the different comparison rules. All the results were rounded to the closest integer values before the comparison. N represents the number of the participants.

	Web-P vs. TNO	Web-L vs. TNO	Web-P vs. Titmus	Web-L vs. Titmus	Web-P vs. Web-L	TNO vs. Titmus	L_{2min} vs. TNO	P_{2min} vs. TNO	P_{min} vs. Titmus	L_{min} vs. Titmus	L_{min} vs. TNO	P_{min} vs. TNO
> (%)	44,44	66,67	38,89	61,11	33,33	21,05	38,89	27,78	11,11	16,67	27,78	22,22
= (%)	11,11	5,56	0,00	0,00	5,56	0,00	33,33	27,78	5,56	5,56	33,33	27,78
< (%)	44,44	27,78	61,11	38,89	61,11	78,95	27,78	44,44	83,33	77,78	38,89	50,00
N	18	18	18	18	18	19	18	18	18	18	18	18

The highest individual stereo thresholds were gained from the Web-L and the TNO Stereo Tests as illustrated in Figure 30. The highest threshold with the Web-L Stereo Test was 240 arc sec (one participant), with the TNO Stereo Test 240 arc sec (two participants), with the Titmus Stereo Test 200 arc sec (one participant) and with the Web-P Stereo Test 170 arc sec (one participant). In the case of the TNO and the Web-L Stereo Tests the high thresholds are significantly different from the other threshold results of the participant. This implies that these users had difficulties to learn these particular types of tests.

3.3.3.2 Correlations of the stereo vision tests

Correlations of the stereo thresholds from the different tests are presented in Table 2. In Table 3 the paired correlations are classified according to their significance level. Most of the corresponding correlation plots are illustrated in figures from Figure 32 to Figure 42. According to Table 1, Figure 32 and Figure 33 the plot between the TNO and the Web-P is more symmetrical than the plot between the TNO and the Web-L. The Web-P Stereo Test also produces more identical results with the TNO Stereo Test than the Web-L Stereo Test. This would suggest that the Web-P Stereo Test corresponds better with the TNO Stereo Test than the Web-L Stereo Test. However, the correlation between the Web-L and the TNO ($p=0,0500$) is stronger than between the Web-P and the TNO ($p=0,2976$) (Table 2, Figure 32, Figure 33). Figure 32 and Figure 33 show that few high threshold points strongly affect the correlation and that most of the plot points are clustered around low threshold values. Due to the small sample size no definitive conclusions can be made based on the correlations.

Table 2. Spearman correlation coefficients and the p-values between stereo vision test results (N=18). The Titmus Stereo Test results are not included due to the low precision of the results. Shaded values do not correlate significantly. For the notations L_{min}, P_{min}, L_{2min} and P_{2min} see chapter 3.3.3.4.

	TNO	**Web-L**	**Web-P**	**L_{2min}**	**P_{2min}**	**L_{min}**	**P_{min}**
TNO	1.00000 --------	0.46832 0.0500	0.25989 0.2976	0.39162 0.1080	0.19484 0.4385	0.41956 0.0830	0.19726 0.4327
Web-L	0.46832 0.0500	1.00000 --------	0.74442 0.0004	0.70367 0.0011	0.73673 0.0005	0.77894 0.0001	0.63648 0.0045
Web-P	0.25989 0.2976	0.74442 0.0004	1.00000 --------	0.78099 0.0001	0.91543 <.0001	0.73659 0.0005	0.75401 0.0003
L_{2min}	0.39162 0.1080	0.70367 0.0011	0.78099 0.0001	1.00000 --------	0.73777 0.0005	0.84442 <.0001	0.61262 0.0069
P_{2min}	0.19484 0.4385	0.73673 0.0005	0.91543 <.0001	0.73777 0.0005	1.00000 --------	0.70507 0.0011	0.82686 <.0001
L_{min}	0.41956 0.0830	0.77894 0.0001	0.73659 0.0005	0.84442 <.0001	0.70507 0.0011	1.00000 --------	0.65653 0.0031
P_{min}	0.19726 0.4327	0.63648 0.0045	0.75401 0.0003	0.61262 0.0069	0.82686 <.0001	0.65653 0.0031	1.00000 --------

Table 3. Correlations between stereo vision test results classified by their significance.

Statistically extremely significant ($p<0{,}0001$):	**Statistically highly significant ($0{,}0001 \leq p<0{,}0100$):**	**Statistically significant ($0{,}0100 \leq p \leq 0{,}0500$):**	**Not significant ($p>0{,}0500$):**
Web-P, P_{2min} ($p<0{,}0001$)	Web-P, Web-L ($p=0{,}0004$)	Web-L, TNO ($p=0{,}0500$)	Web-P, TNO ($p=0{,}2976$)
L_{min}, L_{2min} ($p<0{,}0001$)	L_{2min}, Web-L ($p=0{,}0011$)		P_{min}, TNO ($p=0{,}4327$)
P_{min}, P_{2min} ($p<0{,}0001$)	P_{2min}, Web-L ($p=0{,}0005$)		L_{min}, TNO ($p=0{,}0830$)
	L_{min}, Web-L ($p=0{,}0001$)		P_{2min}, TNO ($p=0{,}4385$)
	P_{min}, Web-L ($p=0{,}0045$)		L_{2min}, TNO ($p=0{,}1080$)
	L_{2min}, Web-P ($p=0{,}0001$)		
	L_{min}, Web-P ($p=0{,}0005$)		
	P_{min}, Web-P ($p=0{,}0003$)		
	P_{2min}, L_{2min} ($p=0{,}0005$)		
	P_{min}, L_{2min} ($p=0{,}0069$)		
	L_{min}, P_{2min} ($p=0{,}0011$)		
	P_{min}, L_{min} ($p=0{,}0031$)		

The Web-L and the Web-P Stereo Tests correlate highly significantly with each other ($p=0{,}0004$) as seen in Table 2 and in Figure 36. This implies that the Web Stereo Tests works technically well. Also all the Web Stereo Tests using different threshold determination procedures correlate either extremely significantly or highly significantly with each others (Table 2 and figures from Figure 37 to

Figure 42). This points that procedures and stimulus figures affect the results systematically.

Correlation plots of the TNO Stereo Test against the Web-P and the Web-L Stereo Tests:

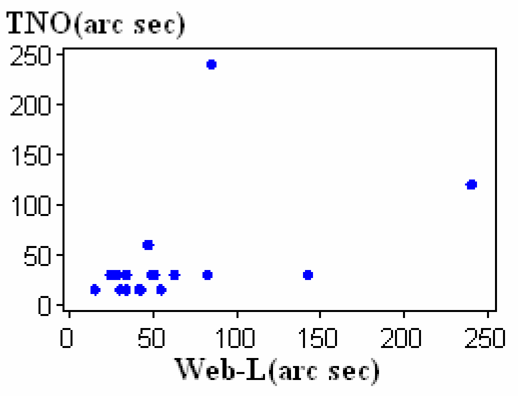


Figure 32. Correlation between the Web-L Stereo Test and the TNO Stereo Test.

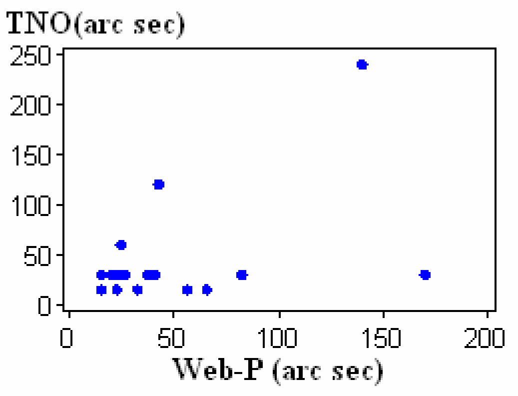


Figure 33. Correlation between the Web-P Stereo Test and the TNO Stereo Test.

Correlation plots of the TNO Stereo Test against the P_{2min} and the L_{2min} tests (for the notations P_{2min} or L_{2min} see chapter 3.3.3.4):

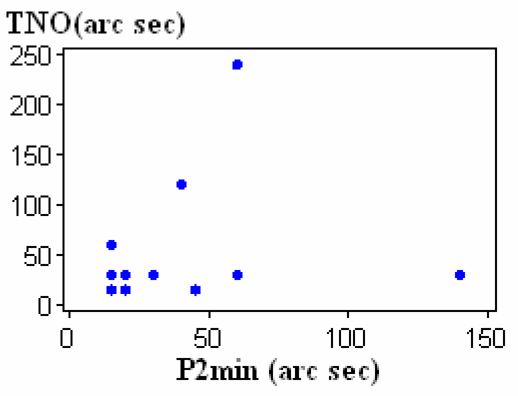


Figure 34. Correlation between the P_{2min} test and the TNO Stereo Test.

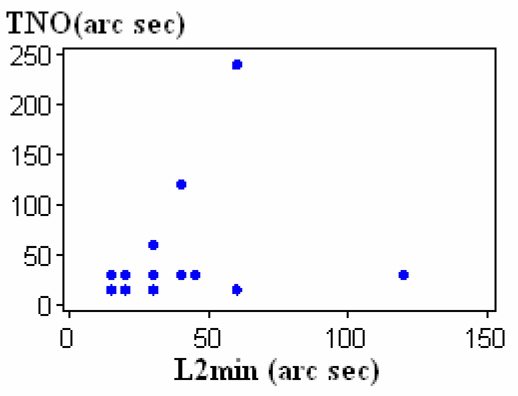
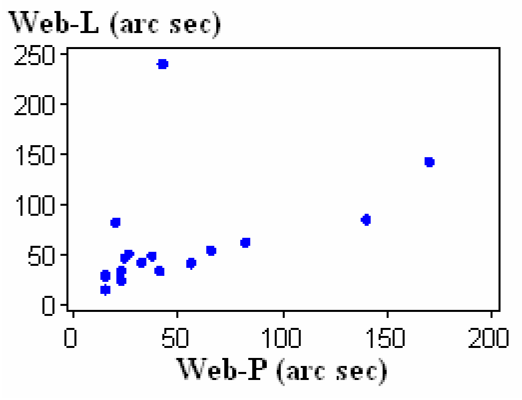


Figure 35. Correlation between the L_{2min} test and the TNO Stereo Test.

Correlation plots between the different versions of the Web Stereo Tests:



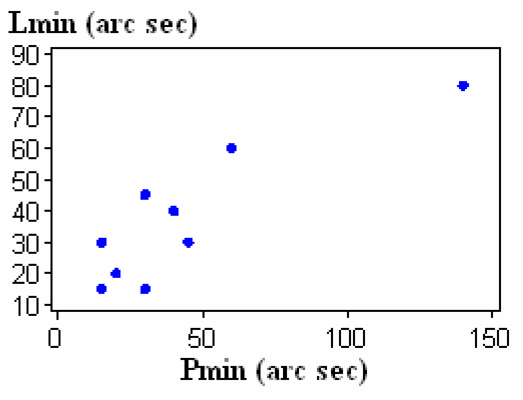
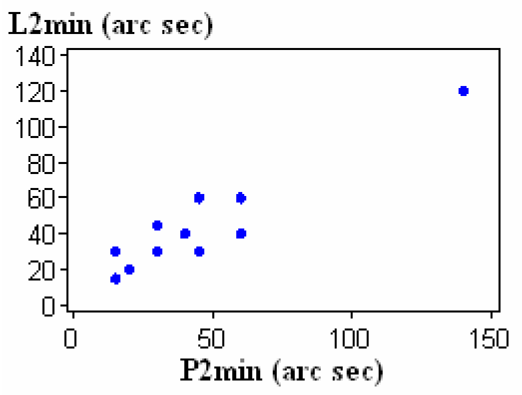


Figure 36. Correlation between the Web-L test and the Web-P Stereo Test.

Figure 37. Correlation between the L_{min} test and the P_{min} test.



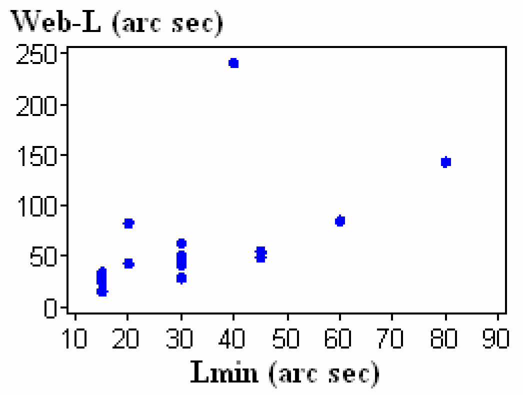
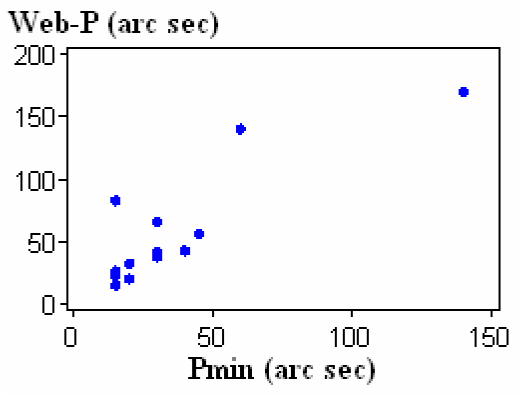


Figure 38. Correlation between the L_{2min} test and the P_{2min} test.

Figure 39. Correlation between the Web-L Stereo Test and the L_{min} test.



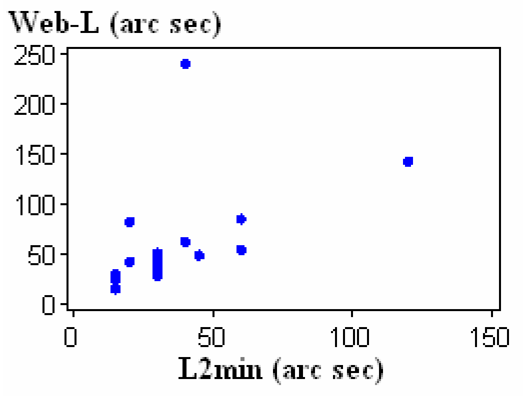


Figure 40. Correlation between the Web-P Stereo Test and the P_{min} test.

Figure 41. Correlation between the Web-L Stereo Test and the L_{2min} test.

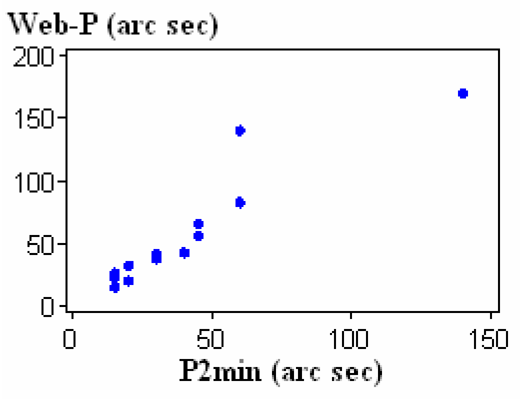


Figure 42. Correlation between the Web-P Stereo Test and the P2min test

3.3.3.3 Differences in accuracy and stability of the tests

It can be seen from the correlation plots in Figure 32 and Figure 33 that the TNO Stereo Test is more stable and gives lower threshold values than the Web Stereo Tests. As can be seen in Figure 31 there was also less variance in the TNO Stereo Test results than in the Web-P or the Web-L Stereo Test results.

3.3.3.4 Effects of the threshold determination procedures

In order to outline the effects of the different threshold determination algorithms to the results, the individual responses during the tests were also analyzed and results called P_{min}, P_{2min}, L_{min} and L_{2min} were determined. P_{min} result was the lowest disparity value, which the participant perceived correctly during the Web-P Stereo Test. P_{2min} was the lowest disparity value, which the participant perceived correctly twice during the Web-P Stereo Test. L_{min} and L_{2min} are the corresponding results using the Web-L Stereo Test. In the TNO Stereo Test the stereo threshold was the lowest disparity value, which the participant perceived correctly twice during the test. The easing of the algorithm of the Web Stereo Tests seems to move the test results closer to the TNO Stereo Test results as can be seen in Figure 31.

Table 1 illustrate that when stereo threshold was determined according to the eased algorithms of the Web Stereo Tests, there were more identical results with the TNO Stereo Test (P_{min} 28%, L_{min} 33%, P_{2min} 28%, L_{2min} 33%, Web-P 11% and Web-L 6%). 39% of the participants got higher threshold with L_{2min} than with the TNO Stereo Test while the percentage for the Web-L Stereo Test was 67%. This suggests that L_{2min} procedure corresponds better with the TNO Stereo Test than the Web-L Stereo Test. However, P_{min}, P_{2min}, L_{min} and L_{2min} do not correlate significantly with the TNO while the Web-L does (Table 2, Figure 34, Figure 35, Figure 32). According to Table 1, P_{2min} procedure gives lower threshold values than the TNO while the Web-P results are evenly distributed around the TNO results. However, the sample size is too small to get statistically significant results about the effects of the threshold determination procedures. In addition, P_{2min} and L_{2min} procedures are not directly comparable with the procedure used in the TNO test since there are other differences between these procedures such as the performance time, number of stimuli and successiveness of the correct answers.

3.3.3.5 Effects of the testing order and the viewing distance on stereo test results

If the Web-L Stereo Test was conducted before the Web-P Stereo Test the results were poorer than if it was conducted after the Web-P Stereo Test. Also the participants who performed the Web Stereo Tests from a nearer distance got poorer results from the TNO Stereo Test. However, neither of these results was statistically significant.

3.3.4 Subjective results of the Web Stereo Tests

3.3.4.1 Discomfort experienced by the participants

The post-questionnaire data is summarized in Table 4, Table 5 and Table 6 and in Figure 43, Figure 44 and Figure 45. The questions in the post-questionnaire have been grouped into five clusters that have been analyzed in Table 4 and in Figure 43. The eye-related symptoms is the only cluster where the rounded average of the results was above zero, so its individual questions has been analyzed separately in Table 5 and in Figure 44. All the questions have been individually summarized in Table 6 and in Figure 45. From the eye-related symptoms the participants experienced some eye strain, difficulties accommodating, difficulties focusing and blurred vision but no headache. Some of the participants also experienced slight general discomfort and fatigue.

Table 4. Mean values and standard errors of the numeric post-questionnaire data by clusters. Scale: 0=none, 1=mild, 2=moderate, 3=strong.

Cluster:	Mean by cluster:	Mean rounded to nearest whole number:	Standard errors by clusters:	N
Dizziness (questions 1,2):	0,16	0 = “none”	0,06	38
Discomfort (questions 3,4,10):	0,25	0 = “none”	0,06	57
Eye-related symptoms (questions 5,6,7,9,11):	0,56	1 = “mild”	0,08	95
Nausea (question 8):	0,00	0 = “none”	0,00	19
Flickering (questions 12,13):	0,11	0 = “none”	0,05	38

Table 5. Mean values and standard errors of the “eye-related symptoms” cluster. Scale: 0=none, 1=mild, 2=moderate, 3=strong.

Question number:	Question:	Mean:	Mean rounded to nearest whole number:	Standard error:
5	Did you experience headache during the test?	0,00	0 = “none”	0,00
6	Did you experience eye strain?	0,53	1 = “mild”	0,14
7	Did you have difficulties in accommodating your eyes to the figures?	0,95	1 = “mild”	0,19
9	Did you have difficulties in focusing on the figures?	0,63	1 = “mild”	0,17
11	Did you see the figures blurred?	0,68	1 = “mild”	0,19

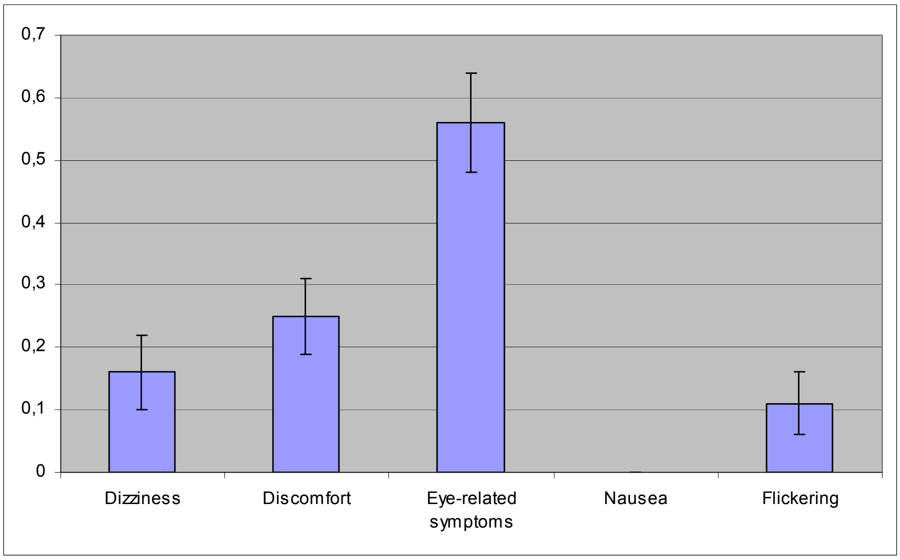


Figure 43. Mean values and standard errors of the numeric post-questionnaire data by clusters. Scale: 0=none, 1=mild, 2=moderate, 3=strong.

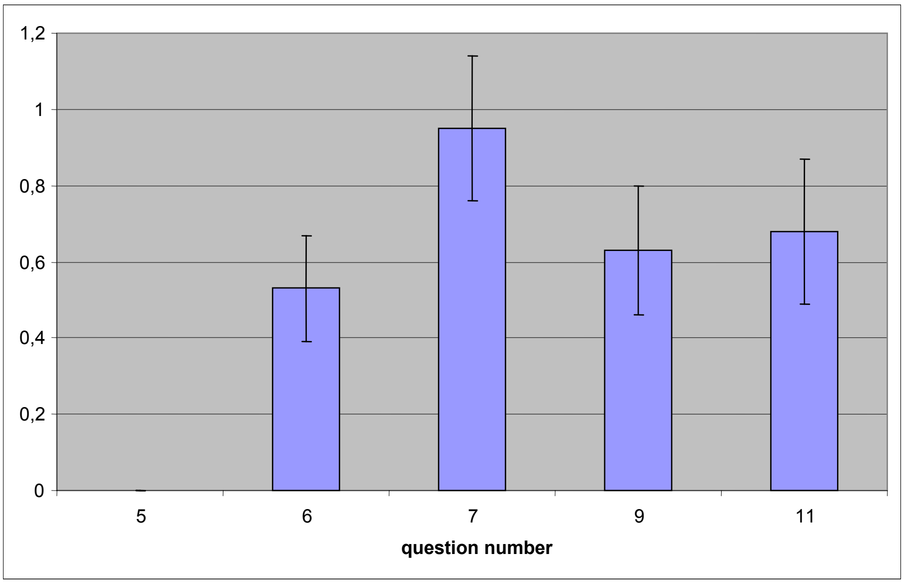


Figure 44. Mean values and standard errors of the eye-related symptoms cluster. Scale: 0=none, 1=mild, 2=moderate, 3=strong. For the questions related to the question numbers on the x-axis, see Table 5.

Table 6. Mean values and standard errors of the numeric post-questionnaire data. Scale: 0=none, 1=mild, 2=moderate, 3=strong.

Question number:	Question:	Mean (N=19):	Standard error:
1	Do you now feel dizziness eyes closed?	0,16	0,09
2	Do you now feel dizziness eyes opened?	0,16	0,09
3	Did you experience discomfort during the test?	0,37	0,14
4	Did you experience fatigue after the test?	0,21	0,1
5	Did you experience headache during the test?	0,00	0,00
6	Did the test strain your eyes?	0,53	0,14
7	Did you have difficulties in accommodating your eyes to the figures?	0,95	0,19
8	Did you experience nausea during the test?	0,00	0,00
9	Did you have difficulties in focusing on the figures?	0,63	0,17
10	Did you have difficulties in concentrating during the test?	0,16	0,09
11	Did you see the figures blurred?	0,68	0,19
12	Did you notice distracting flicker in light?	0,11	0,07
13	Did you notice distracting flicker in color?	0,11	0,07

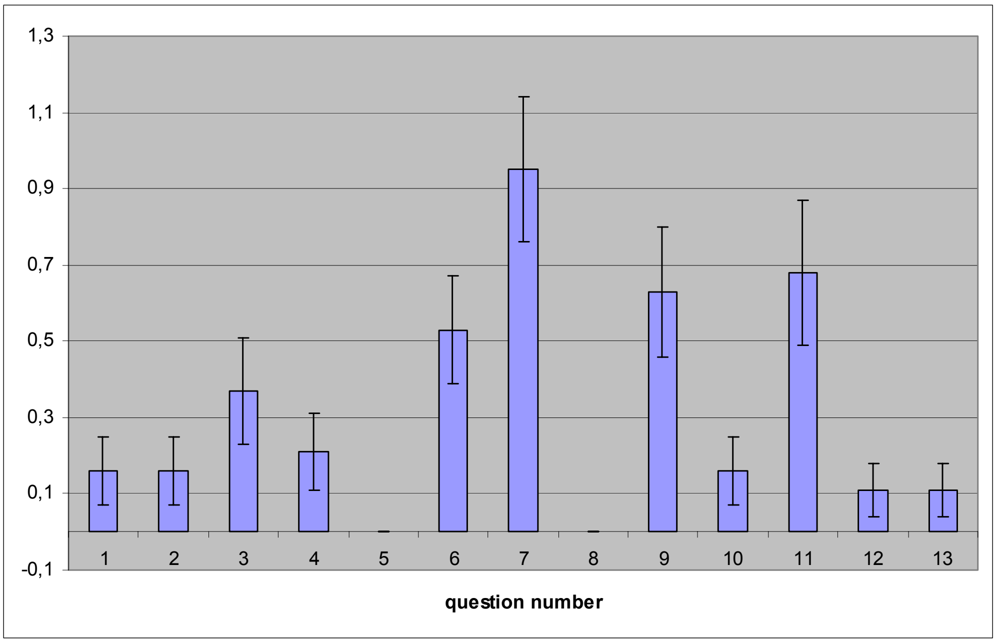


Figure 45. Mean values and standard errors of the numeric post-questionnaire data. Scale: 0=none, 1=mild, 2=moderate, 3=strong. For the questions related to the question numbers on the x-axis, see Table 6.

3.3.4.2 Comparison of the test stimuli

The participants were asked about the effect of the stimulus figure on the easiness and the pleasantness of the Web Stereo Test completion. The results are described in Table 7. 80 % of the participants considered the Pac-Man figure easier. 13% of the participants thought that the Landolt-C figure was easier and 7% did not notice a difference in easiness. Five of the twenty participants did not answer to this question. In average, Pac-Man and Landolt-C figures were considered equally pleasant by the participants (Table 7). Eight participants did not answer to this question.

Table 7. Comparison of the test stimuli by easiness and pleasantness. The percentages are rounded to the nearest whole number. "No difference" row indicates those who did not see difference between the stimuli. "No answer" indicates those who did not answer to this question.

	Easier % (N=15)	**More pleasant %** (N=12)
Pac-Man	80	42
Landolt-C	13	42
No difference	7	17
No answer (N=20)	25	40

3.3.5 Results of the tests through the Internet

Both versions of the Web Stereo Tests functioned fluently on the basic computer and through the basic internet connection used in the test. Latencies in the program run did not occur. The stereo effect was clear and ghosting effect was not observed even if color calibration was not done before the test.

4 Discussion

In this chapter, the realization and the results of the study are discussed and compared to the objectives. On the base of the theoretical knowledge and the test results, further development of the prototype and special requirements for the web-based approach are outlined. The future and the applicability of the Web Stereo Test are also figured.

4.1 The main results of the testing

Technically, the Web Stereo Test functioned faultlessly and the test was quick and easy to use. The results were logical and reasonable and the stereo effect in the images was clear and sharp without ghost images. Only very little discomfort related to simulator sickness symptoms were experienced by the participants during the Web Stereo Tests. Both versions of the Web Stereo Tests correlated statistically highly significantly with each other (p=0,0004) but the correlation with the TNO Stereo Test was rather low: the Web-L results correlated statistically significantly (p=0,0500) while the Web-P results did not have a significant correlation (p=0,2976) with the TNO results. The TNO Stereo Test appeared to be more stable and to give lower threshold values than the Web Stereo Tests. The stimulus figure as well as the procedure used to determine the stereo threshold seemed to have a clear effect on the test results. However, due to the small sample size, the results are only suggestive. Further investigations should be conducted to ensure the reliability of the Web Stereo Test results. The factors that may cause the differences on the results are discussed in chapter 4.3 below. These factors could be further analyzed by unifying the properties of the tests and changing one factor at a time.

4.2 Discussion of the testing

The Titmus Stereo Vision Test was not a suitable comparison test for the Web Stereo Test. It measures disparities only down to 40´´ arc while most of the participants had better stereopsis. For this reason, the Titmus Stereo Vision Test had to be dropped out of the correlation analysis and some other comparisons. The

Titmus Stereo Test also uses a different method for separation. The TNO Stereo Vision Test was more suitable for comparison purposes. At the recommended viewing distance its minimum stereo disparity is 15´´ arc which corresponds to the minimum stereo disparity of the Web Stereo Test at the distance used on the testing. Even so, the comparability of the TNO Stereo Vision Test with the Web Stereo Tests is also weakened by multiple differences on the implementation of the tests like, for example, the procedure used to determine the stereo threshold, image size, viewing distance, light source, colors, scale distribution, disparity of the background and the properties of the noise.

The visual acuity of the participants have an effect on stereoacuity (Kirschen et al., 1999) which may affect the results as the stereo vision tests were viewed from different distances. In addition, fixation disparity (Jiménex et al., 2000; Cole and Boisvert, 1974) and heterophoria (Lam et al., 2002; Saladin, 1995; Shippman and Cohen, 1983) affect stereoacuity and may have an effect on the results. Thus, the participants should be tested for the visual acuity, fixation disparity and heterophoria from distance and near to explore if these properties have an effect on the results. These factors were not taken into consideration in the preliminary testing of the prototype. In addition, special attention should be paid to lightning conditions since both luminance and adaptation to light affect stereo vision (Livingstone and Hubel, 1994; Graham, 1965). The weaker the luminance is the more difficult it is to perceive small differences in depth (Berry et al., 1950). Differences between the lightning conditions of the tests may deteriorate depth perception on a certain test. Even if the interior light in the test room was constant during the different tests, the lightning on the manual and automatic test images may have differed from each other. The cardboard images were merely illuminated by the surrounding room light while the screen served as a light source itself. The luminance levels should, thus, be measured through the filter glasses separately for every test.

4.3 Factors affecting the Web Stereo Test and its further development

The critical targets for development include the addition of the color calibration feature (see chapter 4.3.1) and the user interface (see chapter 4.3.2) as well as the validation of the results (see chapter 4.1). These are also prerequisites for delivering the Web Stereo Test in the Internet. The critical targets for development are discussed more in this chapter as well as the other targets for development. The factors affecting the Web Stereo Test and the comparison results are also analyzed.

4.3.1 Adjustment of colors and luminance

A major challenge in developing a web-based stereo vision test is that it would be used on different displays by different people. The differences in the available color filter glasses should also be taken into consideration while using an anaglyphic test. Hence, a reliable color calibration feature is needed to ensure valid results when the Web Stereo Test is used through the Internet. An easy adjustment of the colors was set as a requirement for the prototype to enable an addition of a color calibration feature in it in the future. Each stereo image is thus a combination of single colored picture elements. During the program run, these elements are dynamically combined to form stereo images with certain disparity values. One of the main research subjects in developing a color calibration feature would be to define a sufficient level of calibration of the colors and luminance and to investigate whether it could be achieved with visual estimation. The calibration feature could then be based on visual similarity assessment so that the user adjusts the color or luminance to fulfill certain picture criteria. If a reliable color calibration feature based on visual estimation can be developed, the Web Stereo Test could be used through the Internet on different displays. Otherwise, the use of the test would be limited only to locations where proper calibration tools are available.

The aim in the color adjustment is not only to fully separate the left and right eye's images but also to ensure that the luminance levels in both images are similar. Stereoacuity suffers if the images in each eye differ in contrast (Halpern and Blake, 1988; Westheimer and McKee, 1980 a; Lit, 1968). In addition, monocular contrast should be maintained sufficient, since both too low or too high a contrast disrupts stereoacuity (Geib and Baumann, 1990). The optimization of the colors of the prototype was done visually since there were not suitable tools available. A screen adjustment, that would perfectly fulfill the requirements with the filter glasses in use, could not be found; some compromises had to be done between the color leakage and the interpupillary contrast. However, the stereo stimulus distinguished clearly and sharply in the resulting images and ghosting effect was not observed.

The filtering properties of the glasses may also have an effect on the available optimization level of the color adjustment. Because of the web-based approach, the glasses should be optimal to a wide variety of screens and luminance ranges. Therefore, a comparison of different filter glasses would be beneficial. A red-green combination of the colors is probably preferable, since the blue cone cells have larger receptive fields and weaker contrast sensitivity than the red and green cone cells (Gringberg and Williams, 1985). In the other hand, a cyan-red color combination would utilize all the color channels of the screen and thus maximize the luminance.

4.3.2 User interface

To be sure that different people are able to use the Web Stereo Test correctly and get comparable results with it, the user interface of the test should be further developed and evaluated with the users. Actually, the color calibration feature, which is discussed more in chapter 4.3.1 above, can be considered as a target for the user interface development. Other essential targets include developments in the user assistance and in presenting and managing of the results. The Web Stereo Test have been designed so that it can be easily modified to different purposes by changing the parameter values of the program code. Thus, it would be useful to embed those possibilities in the user interface too.

4.3.3 Viewing distance

The Web Stereo Tests were viewed from different distances than the TNO and the Titmus Stereo Tests, which may have an effect on the comparison results. Since distance stereopsis is highly sensitive to ocular deviations, visual acuities and refractive error changes (Rutstein and Corliss, 2000), these factors should be taken into consideration while comparing tests from different distances. Stereopsis is usually reduced with larger viewing distances. This suggests that the viewing distance may contribute to the higher threshold values with the Web Stereo Tests. However, it does not explain the higher threshold values of the Web-L Stereo Test compared to the Web-P Stereo Test, which may be more affected by the differences of the stimulus type as discussed in chapter 4.3.5.

4.3.4 Random-dot noise

In the Web Stereo Test, the same random-dot noise was used for all stereograms which may have an adverse, and maybe systematic, effect on the test results. For example, a larger color area at the edge of the stimulus figure may disturb the perception of a certain alignment of the stimulus (Beard and Ahumada, 1998). However, it would be too computing intensive to generate the individual random-dot noise elements, and especially to calculate the overlapping areas of the two differently positioned noise elements, during the runtime. The problem could be minimized by using a few different noise elements randomly in the program. This approach would minimize the systematic error but would not compromise the performance of the program. Different kinds of random-dot noise were used in the TNO and in the Web Stereo Tests. The properties of the noise could affect the results. It might be a good idea to investigate how different kinds of random-dot noises affect the test results, and to select the noise type with most desirable effects.

4.3.5 Stimulus type

Based on the Web Stereo Test results the stimulus figure has a clear effect on the stereo threshold. Using Landolt-C figure the threshold values were higher than when using Pac-Man figure, even if the figures are identical in diameter. Also the subjective results support this interpretation: most of the participants commented that the test using Pac-Man stimulus was easier. Landolt-C figure was experimented as an alternative stimulus since it is commonly used in other vision tests. However, it may not be suitable for random-dot stereograms, probably because the part of the figure that indicates the direction is relatively small and may be difficult to distinguish. This effect is amplified by the small size of the Web Stereo Test stimuli from the test distance. The missing sector in the Pac-Man figure is significantly larger and thus easier to perceive. This may explain the worse results and user feedback for Landolt-C figure.

4.3.6 Size of the stimuli

The size of the stimulus affects the stereo threshold. The visual angle of the Web Stereo Test stimulus figure is 2,06° from the viewing distance of 303 cm and 1,55° from 404 cm, while in the TNO Stereo Test it is 8,5° from the standard viewing distance of 40 cm. The parts of the stimuli indicating the direction are even smaller. The difference in the size of the stimulus figures degrades the comparability of the TNO and the Web Stereo Tests. Usually, stereoacuity gets worse with larger targets extending more on the area of lower resolution at the retina. However, if the stimulus figure is too small, visual acuity may become a limiting factor in perceiving details of the figure. This may have caused higher threshold values in the Web Stereo Tests especially with the Landolt-C stimulus.

In the prototype, the random-dot image elements as well as the stimulus figure masks were created using vector graphics to ensure the scalability of the test images to different sizes without a loss of precision. Since the stereograms are dynamically generated using distinct picture elements, the relative size of the stimulus figure can be adjusted separately. Hence, it would be easy to improve the prototype by a feature that automatically scales the size of the stimuli based on the viewing distance. This would ensure identical visual angles from different distances.

4.3.7 Sign and size of the binocular disparity

Since the image shift for the background disparity in the Web Stereo Test is constant ten pixels, the disparity angle varies with different viewing distances or screen resolutions. Because the disparities of the stimulus figure change in the same proportion, this may not have adverse effects. A possible difference in the background disparities of the Web Stereo Test and the TNO Stereo Test may, however, degrade the comparability of these tests. Information about the disparity of the background noise in the TNO Stereo Test was not available.

Studies suggest that most of the people have better stereoacuity for crossed than for uncrossed disparity (Lam et al., 2002; Steinman et al., 2000). Therefore, the Web Stereo Test measures sensitivity to crossed disparity, as well as does the TNO Stereo Test and most of the other clinical stereo vision tests. To avoid monocular depth cues in cyclopic random-dot stereograms, there have to be disparity also in the background noise. Since large disparities have been reported to cause eye strain and simulator sickness (Ware, 2004; Linde, 2003), smallest possible background disparity was preferred. Therefore, crossed disparity was selected for the background noise too. With small uncrossed disparities in the background noise, monocular cues would appear when the stimulus reaches screen surface level. Since eye movements were allowed, standing disparity, that is, a disparity of the reference target, do not affect the stereo threshold values. The effects of the background disparity, and possible other ways of determining it, could be a subject for further research.

4.3.8 Procedure for determining the threshold

On the basis of the test results, the procedure used to determine the stereo threshold affect the threshold values. The criterions for determining the stereo threshold were stricter in the Web Stereo Test than in the TNO or the Titmus Stereo Tests. The easing of the algorithm (P_{min}, P_{2min}, L_{min} and L_{2min}) moved the Web Stereo Test results closer to the TNO Stereo Test results. This suggests that the differences in the algorithms could explain at least part of the differences in the results of the TNO and the Web Stereo Tests.

In the TNO Stereo Test two correct answers and in the Titmus Stereo Test even one correct answer for a certain disparity was adequate to determine that disparity as a stereo threshold of the participant. The procedure used in the Web Stereo Test minimizes the effect of guessing by iterating the disparity that the participant is able to perceive correctly in a probability of 79,4 %. Due to the differences in the procedures, the scale distribution is also different in these tests. The scale of the TNO Stereo Test is discrete while in the Web Stereo Tests it is continuous. This may have an effect to the stability of the test results.

The completion of the Web Stereo Test is more time consuming than the completion of the TNO Stereo Test because of the differences in the procedures. The participants completed the TNO plates V to VII in a few minutes and the Titmus Circle test in even shorter time, while the Web Stereo Test required up to ten minutes depending on the progress of the procedure and the response times of the participant. This may have led to the deterioration of the participants' ability to concentrate in the Web Stereo Test causing higher thresholds. The ability to distinguish random-dot stereo stimulus requires concentration and time from the user especially near the threshold value (Chung and Berbaum, 1984; Westheimer and McKee, 1980 b).

Even if the Web Stereo Tests were more difficult, an adaptive staircase procedure might result in more reliable stereo threshold values than the procedures used in the TNO or in the Titmus Stereo Tests. The effects of the procedure could be studied further and different procedures could be examined to optimize the reliability of the results and the time required to complete the Web Stereo Test.

4.3.9 Method for separation

There are several methods that could be used to view a web-based stereo vision test like methods utilizing polarization of light, parallax displays, shutter glasses or head-mounted displays. However, there are constraints in using the polarizing or parallax methods to assess stereo threshold. Since those methods halve the horizontal resolution of the stereo image, either the viewing distance should be impractically long or the screen resolution should be higher than those in the contemporary displays. If the image resolution in this study had been halved, a viewing distance of eight meters would have been needed to present a binocular disparity of 15´´ arc. In addition, these methods require special equipment that is quite expensive at the moment. This would conflict with the original goal of creating an easily accessible stereo test.

Since high resolution is required for measuring stereoacuity, head-mounted displays would be an expensive choice too. However, some of the shutter glasses are quite affordable at the moment. The prize of the cheapest shutter glasses is no more than 50-100 euros which is quite inexpensive when comparing to the prize of about 300 euros of the TNO Stereo Test, as an example (Richmond Products Inc., n.d.). While using shutter glasses the main problem is still the refresh rate of the displays. There are, however, divergent opinions about an adequate refresh rate. According to Ross and Hogben (1974) a frequency of 10 Hz and according to Steinman et al. (2000) a frequency of 15 Hz is enough to form a unified 3D perception of the stereo image that is presented time sequentially. However, such low frequencies cause flickering in the images disrupting stereopsis near the stereo threshold. The flickering can be noticed even when using shutter glasses with displays having the industry minimum of 60 Hz or 75 Hz as a refresh rate. Since the refresh rate of the image for one eye is halved while time-sequential method is used for separation, the adequate frequency for an unflickering 3D image would be twice the industry minimum, that is, 120 Hz or 150 Hz. Only few and expensive displays are available with such refresh rates. In addition, most of the LCD displays have been reported to be unusable for 3D viewing with shutter glasses due to their image update method or pixel response rate (Woods et al., 2006). They produce cross-talk and thus ghosting in the stereo images.

Since display technologies are improving rapidly towards the demands of 3D applications, shutter glasses may soon be a better choice for viewing web-based stereo vision test than the anaglyphic method. With adequate display technology and synchronization accuracy, shutter glasses would offer full separation between the left and right eye images, and there would be no need for a complicated color and luminance calibration. Until then, anaglyphic method best meets the requirements set for the Web Stereo Test.

4.4 Were the objectives met?

The objectives were met because a prototype of a web-based stereo vision test was designed and implemented and theoretical information was collected to develop the test. Two versions of the Web Stereo Test with different stimuli were completed. According to the objectives and the test requirements, the Web Stereo Test is a lightweight web-based program so it can be used through the Internet. It can also be easily modified for different purposes by configuring parameters such as colors, stimulus size or stimulus type, measuring accuracy and measuring reliability. The learning factor is diminished by using random variation on the stimuli. The staircase procedure used in the Web Stereo Test program iteratively finds the disparity that the participant is able to perceive in a probability of 79,4 %. Since it is implemented using anaglyphic random-dot stereograms it is cyclopic and does not require expensive special equipment from the user. It is also quick and easy to use. Stereo threshold of twenty participants were assessed with both versions of the Web Stereo Tests, the TNO Stereo Test and the Titmus Stereo Test to compare the results. Based on the theoretical knowledge and the test results the prototype was evaluated, special requirements for the web-based approach were determined and outlines for further development were constructed.

4.5 Future and applicability of the Web Stereo Test

Because of its modifiability the Web Stereo Test can be used to explore the factors affecting binocular depth perception by changing the parameter values in the program. After the validation of the results and the addition of the color calibration feature and the user interface the Web Stereo Test can be delivered in the Internet for assessing stereo threshold. It would be easy to collect norm data on stereo vision with a web-based stereo vision test. This would also enable statistical analysis to understand human capabilities in binocular depth perception. The Web Stereo Test could, for example, be applicable to promote occupational health issues, to choose suitable people or tools for tasks requiring depth perception or to develop and test 3D applications. Since it is easily scalable, the Web Stereo Test can also be used to assess stereo threshold at far distances.

5 Conclusions

In this study, an extensive review of human binocular depth perception, measurement of stereoacuity, stereoscopic systems and stereo vision tests was produced and a prototype of a web-based stereo vision test was designed and implemented. Stereo threshold of twenty participants were assessed using two versions of the implemented Web Stereo Tests and, for comparison, the TNO- and the Titmus Stereo Tests.

The Web Stereo Test is a lightweight web-based program using anaglyphic random-dot stereograms so it does not require expensive special equipment from the user. It is also modifiable so that its parameters such as colors, stimulus size or stimulus type, measuring accuracy and measuring reliability can be easily configured. The learning factor is diminished by using random variation on the stimuli. The staircase procedure used in the program iteratively finds the disparity that the participant is able to perceive in the probability of 79,4 %.

Based on the theoretical knowledge and the test results, the prototype was evaluated, special requirements for the web-based approach were determined and outlines for further development were constructed. Further experiments to validate the reliability of the test should be conducted before it can be delivered in the Internet. This requires expert knowledge on both human visual system and underlying technologies. A color and luminance calibration feature and a user interface should also be added to the application.

This study includes a comprehensive review of the theories and technologies underlying the automatic measurement of stereoacuity. It was also proved in this study that it is possible to design a web-based stereo vision test using currently available technologies. It would be beneficial to further develop the test since an automatic and easily attainable stereo vision test would bring several advantages in comparison with the stereo vision tests available at present.

References

Adobe Systems Inc. (2008) *Adobe Flash Player* [online] Adobe Systems Inc., Available from: http://www.adobe.com/products/flashplayer/ [Accessed 3 Dec 2008].

Anapolle, L. (1957) "An evaluation of stereopsis tests", *American journal of optometry and archives of American Academy of Optometry,* vol. 34, no. 6, pp. 310-319.

Andersen, E.E. and Weymouth, F.W. (1923) "Visual perception and the retinal mosaic: I. Retinal mean local sign—an explanation of the fineness of binocular perception of distance", *American Journal of Physiology,* vol. 64, no. 3, pp. 561-594.

Bach, M., Schmitt, C., Kromeier, M. and Kommerell, G. (2001) "The Freiburh stereoacuity test: automatic measurement of stereo threshold", *Graefe's archive for clinical and experimental ophthalmology,* vol. 239, pp. 562-566.

Badcock, D. and Schor, C.M. (1985) "Depth-increment detection function for individual spatial channels", *Journal of the optical society of America, A,* vol. 2, no. 7, pp. 1211-1216.

Beard, B.L. and Ahumada, A.J. (1998) "A technique to extract relevant image features for visual tasks", *SPIE proceedings series,* vol. 3299, pp. 79-85.

Berry, R.N., Riggs, L.A. and Duncan, C.P. (1950) "The relation of vernier and depth discriminations to field brightness", *Journal of Experimental Psychology,* vol. 40, no. 3, pp. 349-354.

Blakemore, C. and Julesz, B. (1971) "Stereoscopic depth aftereffect produced without monocular cues", *Science,* vol. 171, no. 3968, pp. 286-288.

Bogren, H.G., Franti, C.E. and Wilmarth, S.S. (1986) “Normal variations of the position of the eye in the orbit”, *Ophthalmology*, vol. 93, no. 8, pp. 1072-1077.

Breyer, A., Jiang, X., Rütsche, A. and Mojon, D.S. (2006) "A new 3D monitor-based random-dot stereotest for children", *Investigative Ophthalmology & Visual Science,* vol. 47, no. 11, pp. 4842-4846.

Chung, C.S. and Berbaum (1984) “Form and depth in global stereopsis”, *Journal of experimental psychology. Human perception and performance*, vol. 10, no. 2, pp. 258-275.

Cole, R.G. and Boisvert, R.P. (1974) "Effect of fixation disparity on stereoacuity", *Am. J. Optom.,* vol. 51, pp. 206-213.

Cöltekin, A. (2006) *Foveation for 3D visualization and stereo imaging*, Ph.D. thesis, Helsinki University of Technology.

Cormack, L.K., Stevenson, S.B. and Schor, C.M. (1991) "Interocular correlation, luminance contrast and cyclopean processing", *Vision research,* vol. 31, no. 12, pp. 2195-2207.

Diner, D.B. and Fender, D.H. (1993), *Human Engineering in Stereoscopic Display Devices,* Plenum Press.

Fendick, M. and Westheimer, G. (1983) "Effects of practice and the separation of test targets on foveal and peripheral stereoacuity", *Vision Research,* vol. 23, no. 2, pp. 145-150.

Foley, J.M. (1980) "Binocular distance perception", *Psychological Review,* vol. 87, pp. 411-434.

Geib, T. and Baumann, C. (1990) "Effect of luminance and contrast on stereoscopic acuity", *Graefe's archive for clinical and experimental ophthalmology,* vol. 228, no. 4, pp. 310-315.

Graham, C.H. (1965) “Visual space perception” in *Vision and visual perception,* eds. C.H. Graham, Wiley, New York, pp. 839–845.

Häkkinen, J. (2007) *Half-occlusion processing in stereoscopic vision*, Ph.D. thesis, University of Helsinki.

Halle, M. (1997) "Autostereoscopic displays and computer graphics", *Computer Graphics, ACM SIGGRAPH,* vol. 31, no. 2, pp. 58-62.

Halpern, D.L. and Blake, R.R. (1988) "How contrast affects stereoacuity", *Perception,* vol. 17, no. 4, pp. 483-495.

Harris, J.M., McKee, S.P. and Smallman, H.S. (1997) "Fine-scale processing in human binocular stereopsis", *Journal of the Optical Society of America A,* vol. 14, no. 8, pp. 1673-1683.

Harwerth, R.S. and Rawlings, S.C. (1977) "Viewing time and stereoscopic threshold with random-dot stereograms", *American journal of optometry,* vol. 54, no. 7, pp. 452-457.

Harwerth, R.S. and Boltz, R.L. (1979) "Stereopsis in monkeys using random dot stereograms: The effect of viewing duration", *Vision Research,* vol. 19, no. 9, pp. 985-991.

Hoffmann, A. and Menozzi, M. (1999) "Applying anaglyphs for the assessment of stereopsis to a PC-based screening system", *Displays,* vol. 20, no. 1, pp. 31-38.

Howard, H.J. (1919) "A test for the judgment of distance", *Transactions of the American Ophthalmological Society,* vol. 17, pp. 195-235.

Howard, I.P. and Rogers, B.J. (1995) *Binocular vision and stereopsis,* Oxford university press, New York.

Huk, A. (1999) *Seeing in 3D* - Lecture notes [online] Department of Psychology, Stanford University, Stanford, Available from: http://www-psych.stanford.edu/~lera/psych115s/notes/lecture8/ [Accessed 12 Nov 2008].

Isdale, J. (1998) *Technology Review: Head Mounted Displays*, VR News.

ISO 8596:1994 (1994) *Ophthalmic optics - Visual acuity testing - Standard optotype and its presentation*, International Organization for Standardization, 4p.

Julesz, B. (1960) "Binocular depth perception of computer generated patterns", *The Bell System Technical Journal,* vol. 39, no. 5, pp. 1125-1162.

Kennedy, R.S., Lane, N.E., Berbaum, K.S. and Lilienthal, M.G. (1993) "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness", *Journal of Aviation Psychology,* vol. 3, no. 3, pp. 203-220.

Kirschen, D.G., Hung, C.C. and Nakano, T.R. (1999) “Comparison of suppression, stereoacuity, and interocular differences in visual acuity in monovision and acuvue bifocal contact lenses”, *Optometry and vision science*, vol. 76, no. 12, pp. 832-837.

Lam, A.K.C., Tse, P., Choy, E. and Chung, M. (2002) “Crossed and uncrossed stereoacuity at distance and the effect from heterophoria”, *Opthalmic and physiological optics*, vol. 22, no. 3, pp. 189-193.

Lee, J. and McIntyre, A. (1996) "Clinical tests for binocular vision", *Eye,* vol. 10, pp. 282-285.

Legge, E.G. (1979) "Spatial frequency masking in human vision: binocular interactions", *Journal of the optical society of America,* vol. 69, no. 6, pp. 838-847.

Linde, I. (2003) *Space-variant perceptual image compression for gaze-contingent stereoscopic displays*, Ph.D. thesis, Anglia Polytechnic University, UK.

Lit, A. (1968) "Presentation of experimental data", *Journal of the American optometric association,* vol. 39, no. 12, pp. 1098-1099.

Livingstone, M.S. and Hubel, D.H. (1994) “Stereopsis and positional acuity under dark adaptation”, *Vision Research,* vol. 34, no.4, pp. 799-802.

McAllister, D.F. (2002) ”3D displays” in *Wiley Encyclopedia on Imaging*, Wiley, New York, pp. 1327-1344.

Mitchell, D.E. and Baker, A.G. (1973) "Stereoscopic aftereffects: Evidence for disparity-specific neurones in the human visual system", *Vision Research,* vol. 13, no. 12, pp. 2273-2288.

Moussa, M.A., Leat, S.J. and Faubert, J. (2003) "The moving dynamic random dot stereosize test: validity and repeatability", *Journal of pediatric ophthalmology and strabismus,* vol. 40, no. 6, pp. 341-348.

Murphy, W.K. and Laskin, D.M. (1990) "Intercanthal and interpupillary distance in the black population", *Oral surgery, oral medicine, and oral pathology*, vol. 69, no. 6, pp. 676-680.

Nakayama, K. (1985) "Biological image motion processing: A review", *Vision Research,* vol. 25, no. 5, pp. 625-660.

Ogle, K.N. (1953) "On the limits of stereoscopic vision", *Journal of experimental psychology,* vol. 44, no. 4, pp. 253-259.

Ogle, K.N. and Weil, M.P. (1958) "Stereoscopic Vision and the Duration of the Stimulus", *AMA Archives of Ophthalmology,* vol. 59, no. 1, pp. 4-17.

Ogle, K.N. (1952) "Disparity Limits of Stereopsis", *Ama Archives of Ophthalmology,* vol. 48, no. 1, pp. 50-60.

Ono, M.E., Rivest, J. and Ono, H. (1986) "Depth perception as a function of motion parallax and absolute-distance information", *Journal of Experimental Psychology,* vol. 12, no. 3, pp. 331-337.

Pearlman, J.T. (1969) "Stereoscopic vision testing: A review", *The American orthoptic journal,* vol. 19, pp. 78-86.

Pennington, J. (1970) "The Effect of wavelength on stereoacuity", *American journal of optometry and archives of American Academy of Optometry,* vol. 47, no. 4, pp. 288-294.

Pulfrich, C. (1922) "Die Stereoskopie im Dienste der isochromen und heterochromen Photometrie", *Naturwissenschaften,* vol. 10, no. 27, pp. 596-601.

Rawlings, S.C. and Shipley, T. (1969) "Stereoscopic acuity and horizontal angular distance from fixation", *Journal of the Optical Society of America,* vol. 59, no. 8, pp. 991-993.

Reading, R.W. (1983) *Binocular vision: Foundations and applications,* Butterworth Publishers, Boston.

Reinecke, R.D. and Simons, K. (1974) "A new stereoscopic test for amblyopia screening", *American journal of ophthalmology,* vol. 78, pp. 714-721.

Richards, W. (1971) "Anomalous Stereoscopic Depth Perception", *Journal of the Optical Society of America,* vol. 61, no. 3, pp. 410.

Richards, W. and Kaye, M.G. (1974) "Local versus global stereopsis: Two mechanisms?", *Vision Research,* vol. 14, no. 12, pp. 1345-1347.

Richmond Products Inc. (2009) *TNO test for stereoscopic vision: manual,* Richmond Products Inc.

Richmond Products Inc. (n.d.) *TNO Stereo Test* - product information [online] Richmond Products Inc., Available from: http://www.richmondproducts.com/884%20TNOStereotests.aspx [Accessed 23 Feb 2009].

Rogers, B.J. and Bradshaw, M.F. (1992) "Differential perspective effects in binocular stereopsis and motion parallax", *Investigative ophthalmology and visual science,* vol. 33, no. 4, pp. 1333.

Ross, J. and Hogben, J.H. (1974) "Short-term memory in stereopsis", *Vision Research,* vol. 14, pp. 1195-1201.

Rutstein, R.P. and Corliss, D.A. (2000) “Distance stereopsis as a screening device”, *Optometry and vision science*, vol 77, no. 3, pp. 135-139.

Rutstein, R.P., Fuhr, P. and Schaafsma, A. (1994) “Distance stereopsis in orthophores, heterophores and intermitted strabismics”, *Optometry and vision science*, vol. 71, no. 7, pp. 415-421.

Saladin, J.J. (2005) "Stereopsis from a performance perspective", *Optometry and vision science,* vol. 82, no. 3, pp. 186-205.

Saladin, J.J. (1998) "Phorometry and stereopsis" in *Borish's clinical refraction*, eds. W.J. Benjamin and I.M. Borish, WB Saunders, Philadelphia, pp. 724-773.

Saladin, J.J. (1995) “Effects of heterophoria on stereopsis”, *Optometry and vision science*, vol. 72, no. 7, pp. 487-492.

School Kids Healthcare (n.d.) *Stereo Fly* [online] School Kids Healthcare division of Emergency Medical Products Inc., Waukesha, WI, USA, Available from: http://www.schoolkidshealthcare.com/product/574.html [Accessed 4 Nov 2008].

Schor, C.M. (1991) "Binocular sensory disorders" in *Binocular vision*, ed. D. Regan, CRC press, Boca Raton, pp. 179-223.

Schor, C.M., Wood, I. and Ogawa, J. (1984) "Binocular sensory fusion is limited by spatial resolution", *Vision research,* vol. 24, no. 7, pp. 661-665.

Schor, C.M. (1983) "Fixation disparity and vergence adaptation" in *Vergence Eye Movements: Basic and Clinical Aspects*, eds. C.M. Schor and K.J. Ciuffreda, Butterworths, London, pp. 465-516.

Schumer, R. and Ganz, L. (1979) "Independent stereoscopic channels for different extents of spatial pooling", *Vision Research,* vol. 19, no. 12, pp. 1303-1314.

Sedgewick, H.A. (1986) "Space perception" in *Handbook of human perception and performance*, eds. K.R. Boff, L. Kaufman and J.P. Thomas, Wiley, New York.

Shippman, S. and Cohen, K.R. (1983) “Relationship of Heterophoria to Stereopsis”, *Archives of ophthalmology*, vol. 101, no. 4, pp. 609-610.

Simmons, D.R. (1998) "The minimum contrast requirements for stereopsis", *Perception,* vol. 27, no. 11, pp. 1333-1343.

Steinman, S.B., Steinman, B.A. and Garzia, R.P. (2000) *Foundations of Binocular Vision: a Clinical Perspective,* McGraw-Hill Medical, New York, 368p.

Stevenson, S.B., Cormack, L.K. and Schor, C.M. (1991) "Depth attraction and repulsion in random dot stereograms", *Vision Research,* vol. 31, no. 5, pp. 805-813.

Sussex Vision International Ltd. (n.d.) *Sussex Vision* [online] Sussex Vision International Ltd., Lancing, West Sussex, UK, Available from: http://www.sussexvision.co.uk [Accessed 4 Nov 2008].

Tidwell, M., Johnston, R.S., Melville, D. and Furness, T.A. (1995) "The Virtual Retinal Display-A Retinal Scanning Imaging System", *Proceedings of Virtual Reality World '95*, pp. 325-333.

Tyler, C.W. (1991) "Cyclopean vision" in *Vision and Visual Dysfunction*, ed. D. Regan, Macmillan, London.

Tyler, C.W. (1971) "Stereoscopic depth movement: two eyes less sensitive than one", *Science,* vol. 174, no. 4012, pp. 958-961.

Ware, C. (2004) *Information Visualization: Perception for Design,* 2nd edn, Morgan Kaufmann.

Ware, C. (2000) *Information Visualization - Perception for Design,* 1st edn, Academic Press, Morgan Kaufmann Publishers.

Ware, C., Gobrecht, C. and Paton, M.A. (1998) "Dynamic Adjustment of Stereo Display Parameters", *IEEE Transactions on Systems, Man and Cybernetics - Part A,* vol. 28, no. 1, pp. 56-65.

Westheimer, G. and McKee, S.P. (1980 a) "Stereoscopic acuity with defocused and spatially filtered retinal images", *Journal of Optical society of America,* vol. 70, no. 7, pp. 772-778.

Westheimer, G. and McKee, S.P. (1980 b) “Stereogram design for testing local stereopsis”, *Investigative Ophthalmology & Visual Science*, vol. 19, no. 7, pp. 802-809.

Westheimer, G. and McKee, S.P. (1979) "What prior uniocular processing is necessary for stereopsis?", *Investigative Ophthalmology & Visual Science,* vol. 18, no. 6, pp. 614-621.

Westheimer, G. and Tanzman, I.J. (1956) "Qualitative Depth Localization with Diplopic Images", *Journal of the Optical Society of America,* vol. 46, no. 2, pp. 116-117.

Wetherill, G.B. and Levitt, H. (1965) "Sequential estimation of points on a psychometric function", *The British journal of mathematical and statistical psychology,* vol. 18, no. 1, pp. 1-10.

Wheatstone, C. (1852) "Contributions to the physiology of vision. Part the second. On some remarkable and hitherto unobserved phenomena of binocular vision", *Philosophical Transactions of the Royal Society of London,* vol. 142, pp. 1-17.

Wirt, S.E. (1947) "A new near-point stereopsis test", *The Optometric weekly,* vol. 58, pp. 647-649.

Woods, A.J., Rourke, T. and Yuen, K.L. (2006) "The compatibility of consumer displays with time-sequential stereoscopic 3D visualisation", *Proceedings of the K-IDS Three-Dimensional Display Workshop 2006*, pp. 7-10.

Worth, C.A. (1921) *Squint - Its Cause, Pathology and Treatment,* 5th edn, P. Blakiston's Son and Co., Philadelphia.

Zinn, W.J. and Solomon, H. (1985) "A comparison of static and dynamic stereoacuity", *Journal of the American optometric association,* vol. 56, no. 9, pp. 712-715.

Appendix A: Angular units

When we speak about the size of an area on a circular retina, we usually use angular units. For the accuracy of our visual system units as small as seconds of arc are used. Second of arc is a unit of angular distance equal to a 60th of an arc minute, while minute of arc is equal to a 60th of a degree.

Alternative notations:

1 second of arc:	*1 arc second*	*1 arc sec*	*1′′ arc*
1 minute of arc:	*1 arc minute*	*1 arc min*	*1′ arc*

Appendix B: The program code

```
onLoad = function(){

// variables:
//--------------------------------------------------------------------------------
// stereo test properties:
    _global.keyCodes = new Array(87,83,65,81);
    _global.dismax = 12;
    _global.levelmax = 24;
    _global.turnPointsMax=8;
    _global.successLimit=3;
    _global.maxStatic = 9;

// measures of the graphical elements of the movie:
    _global.mw = 371;
    _global.nw = 800;
    _global.nh = 600;
    _global.gw = 900;
    _global.sw = Stage.width;
    _global.sh = Stage.height;

// indicators of the state of the test:
    _global.firstWrongOccurred = false;
    _global.slope = "down";
    _global.success = 0;
    _global.rn = 0;
    _global.dir = keyCodes[0];
    _global.dis = 12;
    _global.disparities = new Array();
    _global.answers = new Array();
```

```
    _global.threshold = 12;
    _global.index = 0;
    _global.changePoints = 0;
    _global.th = 0;

// text variables:
    _global.welcome = "Tervetuloa Web-stereotestin protoon! Katso kuvaa
         punaviherlaseilla, vihreä linssi oikean silmän edessä. \nNäetkö kuvion?
        Mihin suuntaan kuvion aukko osoittaa? Vastausnäppäimet w, s, a ja q
        \nVastaavat suunnat ovat: ylös/yläoikealle, oikealle/alaoikealle,
        alas/alavasemmalle ja vasemmalle/ylävasemmalle.";
    _global.controlkey = "Vastausnäppäimet ovat w, s, a ja q ja niitä vastaavat
         suunnat ovat: ylös/yläoikealle, oikealle/alaoikealle, alas/alavasemmalle ja
        \nvasemmalle/ylävasemmalle. Mihin suuntaan kuvion aukko osoittaa? Paina
        jotakin vastausnäppäintä.";
    _global.txtformat = new TextFormat();
    _global.txtformat.size = 15;
    _global.txtfield_h = 60;

// listeners:
//-------------------------------------------------------------------------------------
keyListener = new Object();
Key.addListener(keyListener);



// functions - for graphics:
//-------------------------------------------------------------------------------------
_global.generateC = function() {// generates the stimulus figure on the stage
    //sum layer:
        _root.attachMovie("C"+rn,"CmaskS",levelmax);
        CmaskS._x=(sw/2-mw/2)+dis;
        CmaskS._y=(sh/2-mw/2);
```

```
    _root.attachMovie("sum_gbr"+dis+"_rbl10","Csum",levelmax-1);
    Csum._x = (sw/2-nw/2);
    Csum._y = (sh/2-nh/2);
    Csum.setMask(CmaskS);
// green layer:
    _root.attachMovie("C"+rn,"CmaskG",levelmax-2);
    CmaskG._x=(sw/2-mw/2)+dis;
    CmaskG._y=(sh/2-mw/2);
    _root.attachMovie("green_wide","Cgreen",levelmax-3);
    Cgreen._x = (sw/2-gw/2)+dis;
    Cgreen._y = (sh/2-nh/2);
    Cgreen.setMask(CmaskG);
// red layer:
    _root.attachMovie("C"+rn,"CmaskR",levelmax-4);
    CmaskR._x=(sw/2-mw/2)+dis;
    CmaskR._y=(sh/2-mw/2);
    _root.attachMovie("red_rbl10","Cred",levelmax-5);
    Cred._x = (sw/2-nw/2);
    Cred._y = (sh/2-nh/2);
    Cred.setMask(CmaskR);
// background layer:
    _root.attachMovie("C"+rn,"CmaskBG",levelmax-6);
    CmaskBG._x=(sw/2-mw/2)+dis;
    CmaskBG._y=(sh/2-mw/2);
    _root.attachMovie("background","Cbg",levelmax-7);
    Cbg._x = (sw/2-nw/2);
    Cbg._y = (sh/2-nh/2);
    Cbg.setMask(CmaskBG);
}
```

```
_global.generateRemains = function() {
    // generates noise in the area revealed by the shift of the stimulus figure
    //sum layer:
        _root.attachMovie("C"+rn,"RmaskS",levelmax-8);
        RmaskS._x=(sw/2-mw/2);
        RmaskS._y=(sh/2-mw/2);
        _root.attachMovie("sum_gmirror_rbl10","Rsum",levelmax-9);
        Rsum._x = (sw/2-nw/2);
        Rsum._y = (sh/2-nh/2);
        Rsum.setMask(RmaskS);
    // green layer:
        _root.attachMovie("C"+rn,"RmaskG",levelmax-10);
        RmaskG._x=(sw/2-mw/2);
        RmaskG._y=(sh/2-mw/2);
        _root.attachMovie("green_mirror","Rgreen",levelmax-11);
        Rgreen._x = (sw/2-nw/2);
        Rgreen._y = (sh/2-nh/2);
        Rgreen.setMask(RmaskG);
    // red layer:
        _root.attachMovie("C"+rn,"RmaskR",levelmax-12);
        RmaskR._x=(sw/2-mw/2);
        RmaskR._y=(sh/2-mw/2);
        _root.attachMovie("red_rbl10","Rred",levelmax-13);
        Rred._x = (sw/2-nw/2);
        Rred._y = (sh/2-nh/2);
        Rred.setMask(RmaskR);
    // background layer:
        _root.attachMovie("C"+rn,"RmaskBG",levelmax-14);
        RmaskBG._x = ((mw/2)+((ww/2)-mw));
        RmaskBG._y = (mw/2)+((wh/2)-mw);
        RmaskBG._x = (sw/2-mw/2);
        RmaskBG._y = (sh/2-mw/2);
```

```
        _root.attachMovie("background","Rbg",levelmax-15);
        Rbg._x = (sw/2-nw/2);
        Rbg._y = (sh/2-nh/2);
        Rbg.setMask(RmaskBG);
    }

_global.generateBackground = function() {// generates background noise
    //sum layer:
        _root.attachMovie("sum_gbr0_rbl10","Bsum",levelmax-17);
        Bsum._x = (sw/2-nw/2);
        Bsum._y = (sh/2-nh/2);
    // green layer:
        _root.attachMovie("green_wide","Bgreen",levelmax-18);
        Bgreen._x = (sw/2-gw/2);
        Bgreen._y = (sh/2-nh/2);
        _root.attachMovie("bg_mask","BmaskG",levelmax-19);
        BmaskG._x = (sw/2-nw/2);
        BmaskG._y = (sh/2-nh/2);
        Bgreen.setMask(BmaskG);
    // red layer:
        _root.attachMovie("red_rbl10","Bred",levelmax-21);
        Bred._x = (sw/2-nw/2);
        Bred._y = (sh/2-nh/2);
    // background layer:
        _root.attachMovie("background","Bbg",levelmax-23);
        Bbg._x = (sw/2-nw/2);
        Bbg._y = (sh/2-nh/2);
    }

_global.createPlus = function(){// creates the 3D plus sign
    _root.attachMovie("background","plusbg",levelmax+1);
    plusbg._x = (sw/2-nw/2);
```

```
    plusbg._y = (sh/2-nh/2);
    _root.attachMovie("plus_green","plusgreen",levelmax+2);
    var a = plusgreen._width;
    var b = plusgreen._height;
    plusgreen._x = (sw/2-a/2)+10;
    plusgreen._y = (sh/2-b/2);
    _root.attachMovie("plus_red","plusred",levelmax+3);
    var c = plusred._width;
    var d = plusred._height;
    plusred._x = (sw/2-c/2);
    plusred._y = (sh/2-d/2);
    _root.attachMovie("plus_sum_r0_gr10","plussum",levelmax+4);
    var e = plussum._width;
    var f = plussum._height;
    plussum._x = (sw/2+e/2)-125;
    plussum._y = (sh/2-f/2)+1;
    }

_global.removePlus = function(){// removes the plus sign
    plusbg.removeMovieClip();
    plusgreen.removeMovieClip();
    plusred.removeMovieClip();
    plussum.removeMovieClip();
    }

_global.generateStimulus = function() {// generates the 3D stimulus
    rn = Math.floor(4*Math.random());
    dir = keyCodes[rn];
    generateC();
    generateRemains();
    generateBackground();
    }
```

```
_global.showPlus = function(){// shows the plus sign for a moment
    gotoAndPlay(2);
    }

_global.emptyBackground = function(){ // empties the background
    _root.attachMovie("background","end",levelmax+5);
    end._x = sw/2-nw/2;
    end._y = sh/2-nh/2;
    }

// functions – for procedures:
//--------------------------------------------------------------------------------
_global.isRight = function() {
    // returns true if the pressed key corresponds the direction of the stimulus
    if (Key.getCode() == dir) {
        return true;
        }
    else return false;
    }

_global.isValid = function(){
    // checks if the key pressed is one of the control keys
    c=Key.getCode();
    if(c==keyCodes[0]||c==keyCodes[1]||c==keyCodes[2]||c==keyCodes[3]){
        return true;
        }
    else return false;
    }
```

```
_global.isStatic = function(){
    // checks if the disparity has stayed constant after ‘maxStatic’ successive
    // answers
    if(index >= maxStatic-1){
        for(i=index-1; i > index-maxStatic; i--){
            if(disparities[i]!= disparities[index]){
                return false;
                }
            }
        threshold = disparities[index];
        return true;
        }
    }

_global.nextDisparity = function(){
    // sets a new disparity value in ‘dis’ if this is a reversal
    if(answers[index] == 0 && dis < dismax){dis+=1;}
    else if (answers[index] == 1 && !firstWrongOccurred && dis > 1){
        dis-=1;
        }
    else if (answers[index] == 1 && success==successLimit && dis > 1){
        dis-=1;
        success = 0;
        }
    }


// program script:
//--------------------------------------------------------------------------------
    Stage.scaleMode = "noScale"; // sets the scalability of the stage
    dis=dismax;
    generateStimulus(); // generates the first stimulus
```

```
_root.createTextField("txt",levelmax+6,sw/2-nw/2,sh/2-nh/2-
    txtfield_h,800,630);
txt.setNewTextFormat(txtformat);
txt.text = welcome;
keyListener.onKeyUp = function () { //event handler
if (isValid()){          // requires a press of one of the control keys
    disparities[index]=dis;
    if (isRight()){ // if the answer is correct...
        answers[index] = 1;// 1 represents a correct answer
        if(firstWrongOccurred){success += 1}
            // counts the number of correct successive answers
        if(success==successLimit && slope == "up"){
             // recognizes a reversal
            changePoints += 1;
            th += dis;
            slope ="down";
            threshold = th/changePoints;  // defines a new threshold value
            }
        }
    else { // if the answer is incorrect...
        answers[index] = 0; // 0 represents an incorrect answer
        firstWrongOccurred = true;
        success = 0;
        if (slope == "down"){// recognizes a reversal
            changePoints += 1;
            th += dis;
            slope = "up";
            threshold = th/changePoints; // defines a new threshold value
            }
        }
    if(changePoints == turnPointsMax || isStatic()){//if the test ends...
        emptyBackground();
```

```
            txt.text = String("Testi päättyi.\nNäit"+threshold+" pikselin
                dispariteetin.\n \n\n Antamasi vastaukset (1 = oikein, 0 = väärin) ja
                niiden alla vastaavat kuvapoikkeutusarvot pikseleinä:\n"+answers+
                "\n"+disparities);
            return;
            }
        else {
            nextDisparity();  //defines the next disparity value
            index += 1;
            showPlus();  // shows a plus sign on the stage for a moment
            generateStimulus(); // generates the next stimulus on the stage
            }
        }
    else{// instructions to press a valid key
        txt.text = controlkey;
        }
    }
}

stop(); // Stops the play head
createPlus(); // Creates the plus sign on the stage
txt.text = "";
removePlus(); // Removes the plus sign from the stage
```

Appendix C: Pre-questionnaire

Ikä ☐ **vuotta**

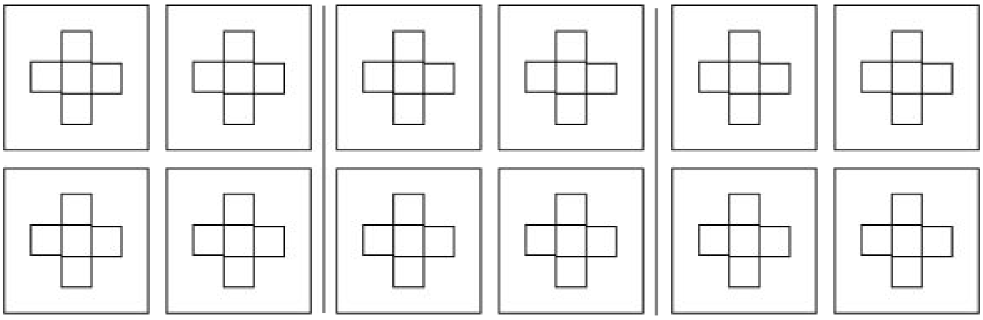
Näön korjaus linsseillä testin tekemisen aikana ☐ **?**

Mikä vika korjattu linsseillä? ______________________________

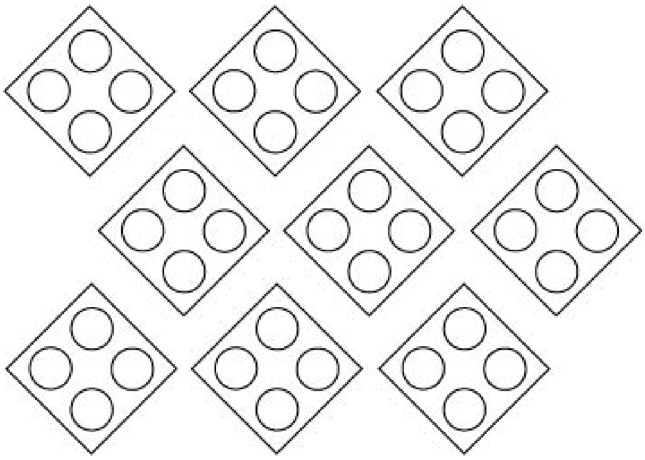
Millaiset linssit? ______________________________

Nainen ☐ **Mies** ☐

TNO vastaukset:



Titmus vastaukset:



Appendix D: Post-questionnaire

	Ei ollenkaan	Vähän	Kohtalaisesti	Paljon
1. Huimaako sinua nyt, jos suljet silmäsi?	☐	☐	☐	☐
2. Huimaako silmät auki?	☐	☐	☐	☐
3. Oliko sinulla epämukava olo testin tekemisen aikana?	☐	☐	☐	☐
4. Uuvuttiko testin tekeminen?	☐	☐	☐	☐
5. Aiheuttiko testi päänsärkyä?	☐	☐	☐	☐
6. Rasittiko testi silmiäsi?	☐	☐	☐	☐
7. Oliko sinulla vaikeuksia tarkentaa kuvaan?	☐	☐	☐	☐
8. Koitko matkapahoinvointioireita testin tekemisen aikana?	☐	☐	☐	☐
9. Oliko sinulla vaikeuksia kohdistaa katsettasi testikuvaan?	☐	☐	☐	☐
10. Oliko sinulla vaikeuksia keskittyä testin tekemiseen?	☐	☐	☐	☐
11. Näitkö kuvan epäselvänä tai sumeana?	☐	☐	☐	☐
12. Näitkö kuvissa häiritsevää valovälkyntää?	☐	☐	☐	☐
13. Näitkö kuvissa häiritsevää värivälkyntää?	☐	☐	☐	☐

14. Häiritsikö testin tekemisessä jokin muu asia? Mikä?

15. Lisäkommentteja yllä antamistasi vastauksista?

16. Oliko jompikumpi kuvioista helpompi/vaikeampi havaita? Miksi?

17. Oliko jompikumpi kuvio miellyttävämpi katsoa kuin toinen? Miksi?