Czech Technical University in Prague
Faculty of Biomedical Engineering
Department of Natural Sciences

Design and testing of algorithms for evaluation of contrast sensitivity

Návrh a testování algoritmů pro vyhodnocení kontrastní citlivosti

Master thesis

Study program: Biomedical and clinical technology
Study branch: Instruments and Methods for Biomedicine

Thesis supervisor: doc. Ing. Marie Pospíšilová, CSc.
External consultant: Ing. Václav Petrák, Ph.D.

Bc. Ondřej Řehounek

Kladno 2016/2017

Czech Technical University in Prague, Faculty of Biomedical Engineering

Academic year: 2016/2017

Diploma thesis assignment

(Master project thesis assignment)

Student:	**Bc. Ondřej Řehounek**
Study branch:	Instruments and Methods for Biomedicine
Title:	**Design and testing of algorithms for evaluation of contrast sensitivity**
Title in Czech:	Návrh a testování algoritmů pro vyhodnocení kontrastní citlivosti

Instructions for processing:

Contrast sensitivity expresses the smallest difference in brightness that is needed to recognize the object of a certain size. Reduced contrast sensitivity is a symptom of some types of the diseases and usually causes difficulties in seeing through the fog or twilight. Several principles are being used for testing of contrast sensitivity. The principles differ in the accuracy of the results, the test speed and other parameters. The aim of the project is to choose a method for testing contrast sensitivity, which allows to perform several measurements with good repeatability for a single patient without too high demands for the patient.
Within the project, student will become familiar with existing tests for evaluation of contrast sensitivity. He will use digital optotype developed in the Python programming language that he will further develop and extend.
Work can be divided into several steps:
1. Research of existing contrast sensitivity tests.
2. Implementation and optionally further development of tests for contrast sensitivity evaluation by digital optotype.
3. Measurement of completion time, accuracy, repeatability and subjective difficulty for patient of several contrast sensitivity tests
4. Statistical processing and interpretation of experimental data.

References:

[1] Richman, Jesse, George L. Spaeth, and Barbara Wirostko, Contrast sensitivity basics and a critique of currently available tests, Journal of Cataract & Refractive Surgery, ročník 39, číslo 7, 2013, 1100-1106. s.
[2] Pelli, Denis G., and Peter Bex, Measuring contrast sensitivity, Vision research , číslo 90, 2013, 10-14 s.
[3] BÜHREN, JENS, et al., Measuring contrast sensitivity under different lighting conditions: comparison of three tests, Optometry & Vision Science , ročník 83, číslo 5, 2006, 290-298 s.

Validity of assignment until date:	20.08.2018
Supervisor of diploma thesis:	doc. Ing. Marie Pospíšilová, CSc.
Consultant of diploma thesis:	Ing. Václav Petrák, Ph.D.

Head of Department — Dean

In Kladno, 27.02.2017

České vysoké učení technické v Praze, Fakulta biomedicínského inženýrství

Katedra přírodovědných oborů

Akademický rok: 2016/2017

Zadání diplomové práce

Student: **Bc. Ondřej Řehounek**

Studijní obor: Přístroje a metody pro biomedicínu

Téma: **Návrh a testování algoritmů pro vyhodnocení kontrastní citlivosti**

Téma anglicky: Design and testing of algorithms for evaluation of contrast sensitivity

Zásady pro vypracování:

Kontrastní citlivost vyjadřuje nejmenší rozdíl jasu, který je potřeba k rozeznání objektu o určité velikosti. Sníženou kontrastní citlivostí je příznakem některých typů onemocnění a obvykle způsobuje potíže při vidění v mlze nebo v přítmí. Při testování kontrastní citlivosti je v současné době používáno několik principů, které se liší v přesnosti výsledku, rychlosti provedení testu i v dalších parametrech. Cílem projektu bude vybrat metodu pro testování kontrastní citlivostí, která umožní s dobrou opakovatelností provést několik měření u jednoho pacienta bez velké náročnosti pro vyšetřovaného.

V rámci projektu se student seznámí s existujícími testy pro hodnocení kontrastní citlivost. Při své práci bude používat digitální optotyp vyvinutý v programovacím jazyce Python, který bude dále upravovat a rozšiřovat. Práci lze rozdělit do několika dílčích kroků:

1. Rešerše existujících testů kontrastní citlivosti.
2. Implementace a případně vývoj testů pro hodnocení kontrastní citlivosti na digitálním optotypu.
3. Měření rychlosti provedení, přesnosti, opakovatelnosti a subjektivního náročnosti pro pacienta u několika typů testů kontrastní citlivosti.
4. Statistické zpracování a interpretace naměřených dat.

Seznam odborné literatury:

[1] BÜHREN, JENS, et al., Measuring contrast sensitivity under different lighting conditions: comparison of three tests, Optometry & Vision Science , ročník 83, číslo 5, 2006, 290-298 s.
[2] Pelli, Denis G., and Peter Bex, Measuring contrast sensitivity, Vision research , číslo 90, 2013, 10-14 s.
[3] Richman, Jesse, George L. Spaeth, and Barbara Wirostko, Contrast sensitivity basics and a critique of currently available tests, Journal of Cataract & Refractive Surgery, ročník 39, číslo 7, 2013, 1100-1106. s.

Vedoucí: doc. Ing. Marie Pospíšilová, CSc.

Konzultant: Ing. Václav Petrák, Ph.D.

Zadání platné do: 20.08.2018

....
vedoucí katedry / pracoviště

....
děkan

V Kladně dne 05.01.2017

Declaration

I declare that I elaborated the thesis entitled "Design and testing of algorithms for evaluation of contrast sensitivity" on my own. All used literature and other materials are listed in the References.

In Kladno

……………………………………

Ondřej Řehounek

Acknowledgment

I would like to thank to my thesis supervisor doc. Ing. Marie Pospíšilová, CSc. for many helpful and encouraging advices about the thesis plus giving me the opportunity to present the thesis in OPTA 2017. Especially I am thankful to my consultant Václav Petrák who taught me so much about contrast sensitivity, programming in Python 3 and experimental approach in general and also helped me a lot in structuring the thesis and countless many other things. This work cannot be realized without MEDICEM Institute s.r.o. and their very kind support of the project and providing all the necessary instrumentation. Finally, I would like to thank to my sister for her patience in reading this thesis and finding mistakes.

Design and testing of algorithms for evaluation of contrast sensitivity

ABSTRACT:

Contrast sensitivity examination can provide important information about the visual capabilities of individuals, which may be neglected in standard visual acuity testing. It provides information on the ability of the observer to distinguish between two objects with a certain contrast. Deterioration of this ability can be caused pathologically e.g. by glaucoma or cataracts. However, the influence of each optical element of the optical system, including glasses or (intraocular) lens is significant as well. To investigate influence of these vision corrections, it is desirable to investigate the contrast sensitivity using several spatial frequencies, due to the different modulation transfer functions of the individual optical elements. It is possible to use digitalized charts for these examinations. Digitalized charts enable setting arbitrary spatial frequency or testing distance depending on the used algorithm. This study focuses on the design and evaluation of algorithms for digitalized charts designed mainly for examination of the properties of intraocular lenses.

KEY WORDS:

Contrast sensitivity, digitalized chart, automatized tests, psychophysiological methods

Návrh a testování algoritmu pro vyhodnocení kontrastní citlivost

ABSTRAKT:

Vyšetření kontrastní citlivosti může přinést významné informace o zrakových schopnostech jedince, jež se při standartním vyšetření zrakové ostrosti neprojeví. Přináší informaci o schopnosti pozorovatele rozlišit dva body s určitým kontrastem. Zhoršení této schopnosti může být způsobeno patologickým stavem – například glaukomem nebo kataraktou, nicméně vliv má každý optický prvek soustavy, přes nějž světlo prochází, tedy i brýle nebo (intraokulární) čočky. K hodnocení těchto korekcí zraku je žádoucí vyšetřovat kontrastní citlivost pro několik prostorových frekvencí, v důsledku odlišných přenosových funkcí jednotlivých elementů. Pro tato vyšetření lze využít digitálních tabulí, které v závislosti na použitém algoritmu nabízí například nastavení libovolné prostorové frekvence nebo vzdálenosti pro měření. Tato práce se věnuje návrhu a testování několika takových algoritmů pro digitální vyšetřovací tabule konstruované zejména pro ověření vlastností intraokulárních čoček.

KLÍČOVÁ SLOVA:

Kontrastní citlivost, digitální vyšetřovací tabule, automatizované testy, psychofyziologické metody

Contents

Lists of used abbreviations

CS	Contrast sensitivity
MTF	Modulation Transfer Function
cpd	cycles per degree
FACT	Functional Acuity Contrast Test
FrACT	Freiburg Vision Acuity and Contrast Test
FF-CATS	Frankfurt-Freiburg Contrast and Acuity Test System
ICS	Index of contrast sensitivity
HACSS	Holladay Automated Contrast Sensitivity System
CSF	Contrast sensitivity function

1. Introduction

A standard clinical examination of vision is based on reading letters of different sizes on a chart (e.g. Snellen chart) [1]. The black letters on the white background results in the contrast very close to 100 %. However, almost no object has such a high contrast in the everyday life. A good example of a scene with very small values of the contrast is a car moving in the foggy weather. In this case, drivers use additional fog lamps to increase the contrast between the car and the background to render the vehicle visible to oncoming drivers. An example of such a scene is displayed in the Figure 1.

Figure 1: Example of a scene with a low contrast - a road in a fog, source: smartdriving.co.uk

Nevertheless, there may be a situation when unlit objects are present on the road such as pedestrians, animals or a car without lights turned on. Quick recognition of a low contrast object by the driver is an essential requirement for a road safety. While a standard driving license vision exam tests the ability to read small, high contrast letters, it does not reveal potential inability to distinguish low contrast objects. This example demonstrates the importance of the contrast sensitivity testing. Since the first half of 18th century, when the first test of contrast sensitivity was developed by Pierre Bougner (published 1760) [2], a wide range of contrast sensitivity tests has been developed. As the evaluation of current contrast sensitivity tests conducted by Bühren (2006) proved, the results from different types of tests vary significantly thus they are not interchangeable [3].

The transfer of the contrast in the optical system is described by the Modulation Transfer Function (MTF). The (normalized) MTF always descents with the increasing spatial frequency (linearly for the ideal lens with a rectangular aperture). However, in the real situations, there are no ideal lenses, thus their properties have to be examined [4]. An example of the MTF of a lens is shown in the Figure 2 – the MTF (the red line in the graph) describes a decrement of a contrast of an object in a dependency on a spatial frequency.

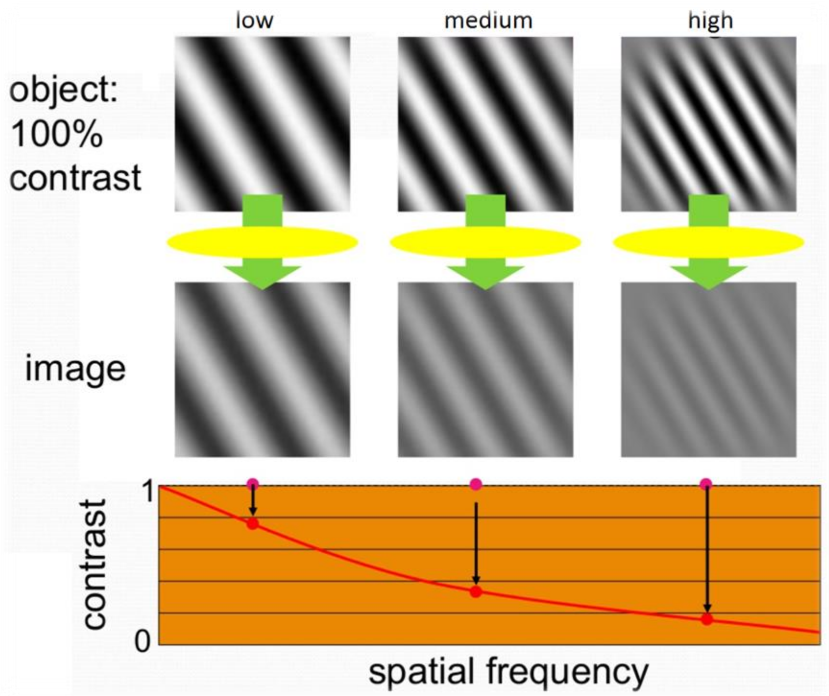

Figure 2: Example of the MTF of a real lens – the contrast decreases with increasing spatial frequency, edited, source: http://www.em-consulte.com

The differences in MTF among the types of intraocular lenses are significant as was confirmed by various studies (e.g. Santhiago 2011, Yamauchi 2013) [5, 6]. The effect of IOL on patient's contrast sensitivity should be therefore considered. These examinations should be done in the standardized fashion and take into consideration varying light conditions during daily routine to ensure that the contrast sensitivity of the subject will not be lowered too much for example in mesopic conditions or the presence of glare [6, 7].

This thesis aims to develop a robust contrast sensitivity test with acceptable demands on the tested subjects. Contrast sensitivity testing can be both physically and psychologically demanding. Therefore, it was crucial to create and optimize a contrast threshold-seeking algorithm providing reliable results, but not overly time demanding to prevent the observers from fatigue and to its associated loss of concentration.

First of all, the test measuring a reaction speed and an accuracy among groups with different age was performed. These data helped to optimize the time duration of the test to ensure that it will not be too demanding for subjects.

Afterwards, it was necessary to ensure that the test provides reliable data with a satisfactory level of repeatability – those were fundamental requirements for the test. To achieve this goal, a research of psychophysiological methods was conducted and a threshold-seeking algorithm based on the Staircase method was developed.

The next phase included testing of the algorithms in the group of volunteers and a subsequent statistical evaluation of the data. The results acquired from the data are presented in this thesis.

The created testing procedure of contrast sensitivity used in the digitalized chart was particularly developed for testing of intraocular lenses. The main goal was to develop the reliable and efficient contrast sensitivity assessment procedure applicable in different light conditions and aimed especially on the patients with implanted intraocular lenses.

The thesis is divided into the five main sections. The goal of the first part of the thesis, after the **Introduction** in the **Chapter 1**, the **Chapter 2. State of the art** reviews factors affecting contrast sensitivity and developed contrast sensitivity tests so far and possible approaches of their improvement.

The **Chapter 3. Methods** describes the procedure of the development of the tests created for this thesis and their testing and further optimization. The results of the testing are presented in the **Chapter 4. Results** and they are closer discussed in the following **Chapter 5. Discussion**.

The **Chapter 6. Conclusion** summarizes results of implemented tests and evaluates completion of the main goals of the thesis. An example of already realized application of our developed test is mentioned in Appendix.

2. State of the art (Current status of the problem)

A contrast is a physical value representing a difference of brightness between adjacent areas. There are several definitions of the contrast, but commonly used are Weber and Michelson contrast C_w and C_M. Weber' formula (1) is used for constant values of background brightness and it is defined by:

$$C_W = \frac{L_o - L_b}{L_b} \quad (1)$$

where L_o is the luminance of the object in cd·m^{-2} and L_b is the luminance of the background in cd·m^{-2} [1]. Michelson's contrast (2) is used in case when the luminance of the background varies. It is defined by a relation [1]:

$$C_M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \quad (2)$$

where L_{max} represents the maximal luminance in cd·m^{-2} whereas L_{min} in cd·m^{-2} is the minimum of the luminance in the scenery [1]. The use of Michelson's definition is recommended by American Academy of Ophthalmology [8].

Contrast sensitivity CS is defined as a reciprocal value of the contrast threshold C_{th} (minimal contrast of two objects – typically an object and its background, calculated by Michelson's deifinition) that is detected by the examined person (3) as was mentioned above.

$$CS = \frac{1}{C_{th}} \quad (3)$$

The equations (1), (2) and (3) imply dimensionless quantity of the contrast (and so the contrast sensitivity as well). It is common to use logarithmic scale of the contrast sensitivity (defined as log(CS)).

The contrast sensitivity *CS* is dependent on an angular spatial frequency[1]. The spatial frequency can be described by a number of adjacent black and white lines (creating a block) per an angle [1].

According to various studies on humans (Chung 2009, Leguire 2011, Pelli 2013), the optimal angular spatial frequency for recognizing of the contrast differences is in the range of 5-7 cycles per degree [10, 11]. The dependency of the contrast sensitivity as a function of the spatial frequency (the "contrast sensitivity curve") is shown in the Figure 4.

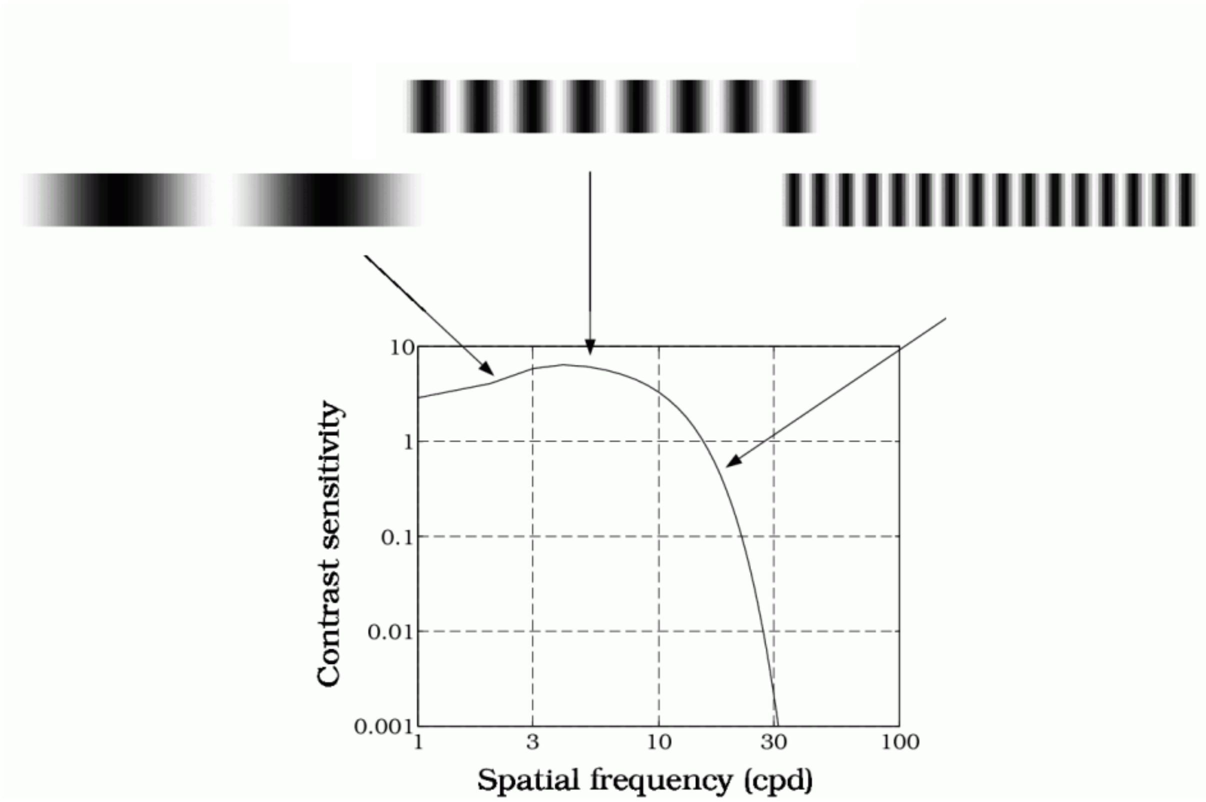

Figure 3: The contrast sensitivity dependency on angular spatial frequency –CS reaches its maxima at 5-7 cpd, then decreases significantly with the increasing spatial frequency, Wandell 1995, edited

[1] The angular spatial frequency is form of a spatial frequency commonly used for describing of image properties in distances much higher than size of the observed object (e.g. letters in charts in the distance of meters) [9].

2.1 Factors affecting contrast sensitivity and their testing

2.1.1 Environmental factors

The environment significantly affects observer's ability to distinguish a watched object and its background (for example a person in dark clothes in night). This ability is influenced basically by light conditions. The main environmental factors are described in the following paragraphs.

Glare

Glare is an optical phenomenon, which is responsible for the discomfort while watching a scene. It is caused by the high values of luminance nearby the observed object and can cause considerable difficulties – e.g. sunlight during the day or headlights at night are well known from everyday life [12]. Dr. Sanjay Dhawan defines this value as "the contrast lowering effect of stray light in a visual scene" [13]. The observer is therefore unable to differentiate edges of a lower contrast object. The effect of the glare is illustrated by the Figure 4 – the left image shows how is the scene seen by a patient with the cataract which intensifies the glare effect (described further in the following chapter) whereas the right image shows the scene seen by a healthy eye.

Figure 4: Example of the glare effect in a heavy traffic. The left image shows the magnified effect of the glare in the eye of a patient with a cataract, the image on the right displays the scene seen by a healthy observer. Edited, source: neovisioneyecenters.com

Effect of glare is furthermore magnified by the scattering of an incident high-intensity light in cornea and lens. Because of the scattering, the incident rays stimulate a larger area of the matrix of rods and cones (forming retina) and that causes further loss of the sharpness in the picture transmitted by the optical nerves [13].

Specialized contrast sensitivity tests with reflectors were developed to observe the influence of glare on subject's contrast sensitivity. The tests are based on ordinary examine procedures [14, 15]. Dependency of the contrast sensitivity on both – the glare intensity and the spatial frequency and an example of a testing device with simulation of glare are shown in the Figure 5 below.

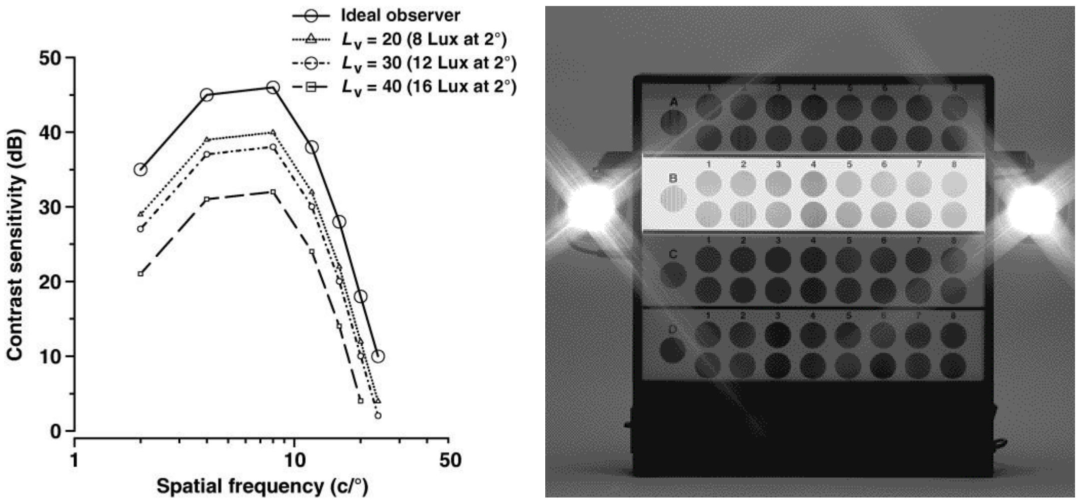

Figure 5: Glare effect on contrast sensitivity (left, *Aslem 2007) – the contrast sensitivity decreases with the increasing intensity of the glare. On the right – example of a test with a glare simulation (VectorVision)*

Luminance intensity

Our ability to recognize objects is highly dependent on the luminescence intensity in the area. Thus, the contrast sensitivity decreases significantly in mesopic[2] conditions (dusk, dawn and heavy fog) [16]. Example of the specialized commercial unit for testing mesopic vision (and glare sensitivity) is OCULUS Mesotest II. It employs Landolt C signs presented in six different positions [17]. There is also a possibility of using special glasses with mesopic (grey) filters. The glasses reduce the testing light level to the recommended luminance of 3 cd·m^{-2} [18].

2.1.2 Personal factors

Factors which are specific for each observer are called personal factors. These factors cannot be affected by experimental setup and conditions [19]. The following paragraphs describe the most significant of them.

[2] Mesopic vision is state of vision in which the human eye's spectral sensitivity is changing from the photopic state to the scotopic state [16]. There are no exact values of luminance for the mesopic range but usually the range is considered to be between 3 cd· m^{-2} and 0.01 cd·m^{-2} [20, 21].

Physiological limiting factors

The human visual system works as a band-pass filter. The low frequency cut-off is given by lateral inhibition[3] of retinal ganglion cells while the high frequency limit depends on the density of the retinal photoreceptor cells (the higher density means the better resolution) [19, 24]. The limit values of spatial frequency depend on the following factors:

Age

The contrast sensitivity is increasing with age and reaching its maxima at approximately 20 years of age and then gradually decreases with aging. This was confirmed by various studies (Allard 2013, Ross 1985) [25, 26].

However, the decrement of the contrast sensitivity seems to be specific only to some spatial frequencies. According to Ross and Clarke the contrast sensitivity for low spatial frequencies is age-independent (opposite to middle and high frequencies declining linearly with age). Taking this into the account, it is necessary to examine the contrast sensitivity in a wider range of spatial frequencies to obtain complete information about patient's contrast sensitivity [26].

Pathological factors

The contrast sensitivity is influenced by many pathological states. Refractive errors, cataract or glaucoma belong to the most significant of them. The smaller refractive errors cause a declination of the contrast sensitivity in the higher frequencies. As the degree of the refractive disorder increases, lower and middle frequencies are also affected [27].

An addition of a glare source in visual field may be especially dangerous (in terms of accident risk) for patients suffering from cataract because the cataract further increases scattering of intense light in the eye. Neurological diseases can cause the loss of the contrast sensitivity as well. The most common causes in the area are optic neuropathy and pituitary adenomas [27].

---

[3] The lateral inhibition (in neurobiology) means disabling of spreading action potentials from the original neuron to its lateral neighbors. Primarily, this process occurs at visual reception but was observed at auditory, tactile or olfactory processing as well [22]. Receiving neurons thus increase the contrast and the sharpness of the created image during processing the visual stimulus [23].

Intraocular lens

The intraocular lens (IOL) is an implantable lens utilized for treatments of cataract or presbyopia [28]. Various materials are used for manufacturing of IOLs – e.g. polymethylmethacrylate, hydrophobic acrylate, silicone etc. [29]

The modulation transfer function (MTF) defines how effectively is the contrast transferred through an optical element in the dependency on the spatial frequency. Due the fact that the MTF of lens is lower than 100 % for frequencies higher than zero, the effect of the intraocular lens on the contrast sensitivity is inevitable [30].

The variety of the lens designs (monofocal, multifocal) and the materials means that the optical properties of the different lenses vary as well. This fact brings the necessity of objective testing of IOLs. Since IOL is an optical element, it can be characterized by its MTF [30]. The comparison of the monofocal and multifocal lenses is displayed in the Figure 6.

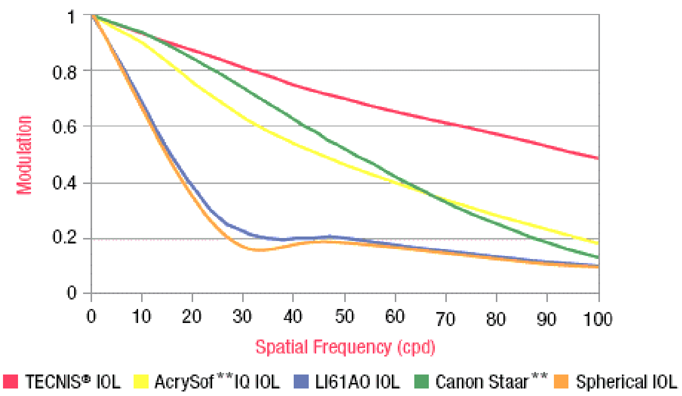

Figure 6: Comparison of MTFs of monofocal (red, green, yellow) and multifocal (orange, blue) IOLs – almost linear dependency of Tecnis® IOL closes to the ideal MTF of a lens whereas multifocal lenses tend to significantly steeper decrement of the contrast with the increasing spatial frequency. (source: Abbott Medical Optics)

The influence of MTF of the specific IOL on the subject vision can be evaluated by the contrast sensitivity tests if it is measured in the various spatial frequencies. For this reason, it is essential to examine the contrast sensitivity in different spatial frequencies especially when the test is performed to evaluate the IOLs. However, the contrast sensitivity is not affected only by IOL but by the individual visual capabilities, precision of implantation etc.

2.2 Overview of contrast sensitivity tests

The contrast sensitivity is evaluated by various types of tests significantly differing in the principle of testing. The tests can be divided into the three major groups by the principle of the testing:

1. chart tests,
2. sine wave tests
3. other (e.g. Melbourne Edge Test, picture tests) [27]

2.2.1 Letter chart tests

Pelli-Robson contrast sensitivity chart

The Pelli-Robson contrast sensitivity chart is one of the most widely used tests for the contrast sensitivity examinations. It is similar to visual acuity chart tests (e.g. Snellen chart) well-known from the medical practitioner's office. But unlike visual acuity charts with high contrast letters of decreasing size, Pelli-Robson chart uses constant size of letters with decreasing contrast between triplets of letters [31]. The contrast of letters decreases within each row from up to down and from left to right with every three letters as it is shown in the Figure 7 on the left.

The patient reads every letter in the row from left to right. The contrast sensitivity is afterwards assumed from the contrast of the last triplet of letters read with maximally one mistake.

Landolt C

The Landolt C (or The Broken Ring) optotype is based on the Sloan[4] letter "C". The name "Broken Ring" comes from the fact that the C character in the Sloan font is a ring with a gap equal to one fifth of the total sign height. The optotype is usually rotated by an angle of 90° or alternatively by 45° when eight possible rotations are used [32].

The Landolt C is standardized by EN ISO 8596 and it is widely used in the contrast sensitivity assessments [33]. Because of that it was used as one of the reference tests

[4] The Sloan letters were designed by Louis Sloan in 1959. The letters are used in charts for visual acuity examinations. The design was standardized in US for visual acuity testing by the Committee on Vision of the National Academy of Sciences' National Research Council in 1980 [34].

created within this thesis. Printed version of the test is displayed in the Figure 7 on the right.

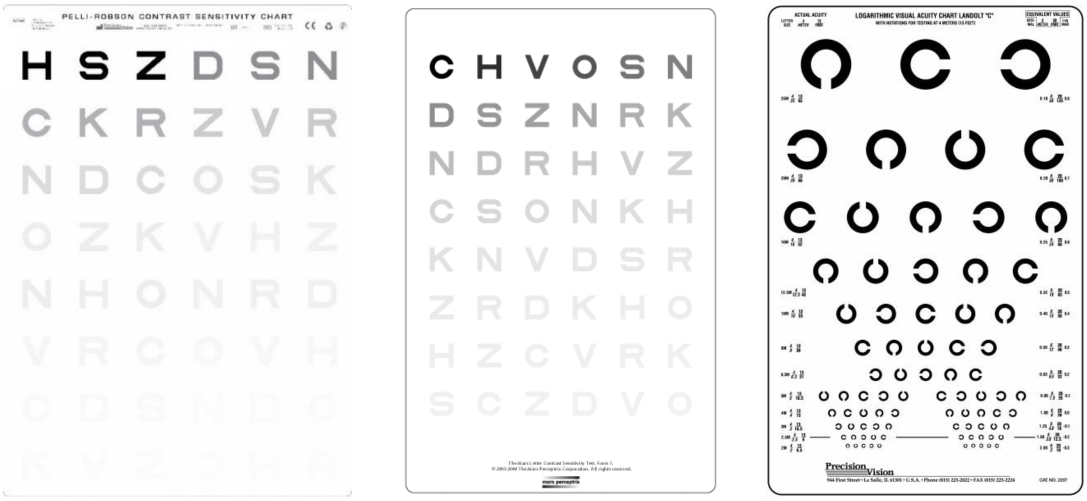

Figure 7: Examples of chart tests: Pelli-Robson chart (on the left, source: All About Vision), Mars Contrast Sensitivity Test (centre, Mars Perceptrix) and Landolt C (or broken ring) test (right, Precision Vision)

Other letter chart tests

Other chart tests among the most frequently used are the Bailey Lovie chart and the Regan (low contrast letter) chart. Both examine vision of the patient by the decreasing size of letters combined with the decrement of contrast [27].

The Mars Contrast Sensitivity Test (Figure 7, centre) is basically a portable version of the Pelli-Robson test with some differences. First, the Pelli-Robson test is in the form of an illuminated table placed on the wall opposite to Mars chart which is printed in the defined size (23 cm x 35.6 cm). The size of the chart (consisting of 48 letters in eight rows and six columns) is designed to test the contrast sensitivity in the exact distance of 1 m. The second significant difference is the decreasing contrast of every letter in the Mars chart (from 91 % to 1,2 %) [35, 36].

2.2.2 Sine wave tests

The sine wave tests utilize different approach to the contrast sensitivity measurement. The first test based on the sine wave gratings – FACT (Functional Acuity Contrast Test) was developed by Dr. Arthur Ginsburg. [27]. These tests combine the decrement of contrast in different spatial frequencies as the tests mentioned in the Chapter 2.2.1. However, instead of the characters with decreasing contrast, the dark and bright stripes are employed (creating sine wave grating pattern) [37]. Examples of the sine wave patterns used in the test developed within this thesis are displayed in the Figure 8.

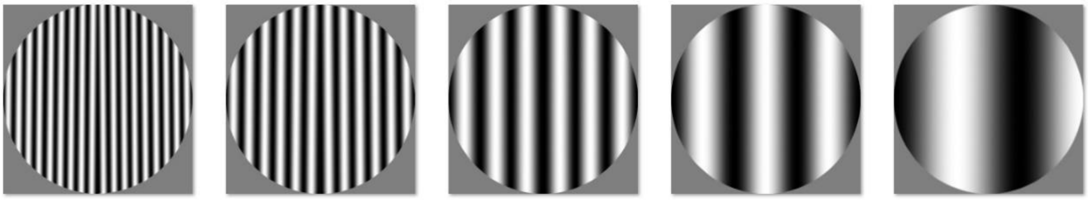

Figure 8: Sine wave patterns used in the digitalized chart for the spatial frequencies of 18, 12, 6, 3 and 1.5 cpd (size of the stimuli is adjusted according to set distance)

CSV-1000

The CSV-1000 is widespread standardized system for testing of the contrast sensitivity. The standard version (CSV-1000E) is the most used sine wave pattern contrast sensitivity test in the world [37]. This standard type (displayed in the Figure 9 on the left) uses sine wave gratings with the spatial frequencies of 3, 6, 12 and 18 cpd (lines A, B, C, D in the Figure 9) [14].

Available are some modifications combining character-based tests (CSV-1000RS), images (CSV-1000S) or rotated "C" symbols (CSV-1000SLanC) [14].

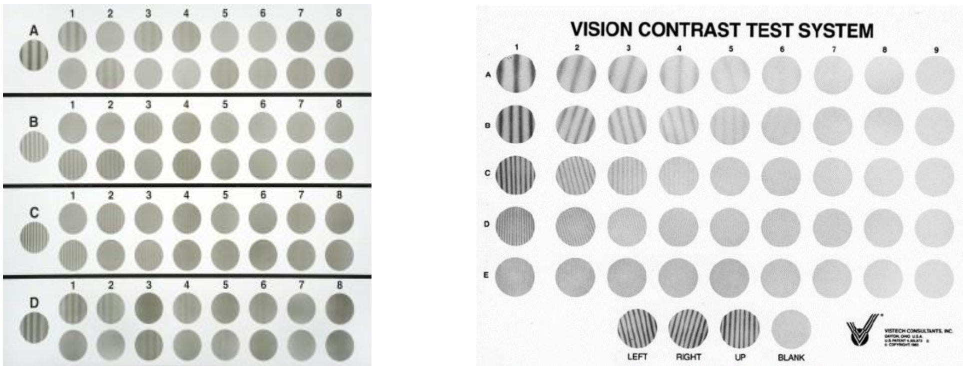

Figure 9: CSV-1000E test (left, VectorVision) – testing the spatial frequencies of 3, 6, 12 and 18 cpd by distinguishing between a circle with sine wave grating and a blank circle and its alternative – VCTS 6500 test (right, source: University of Calgary) using frequencies of 1.5, 3, 6, 9, 12 and 18 cpd.

VCTS6000 and VCT6500

The VCTS charts are another standardized tests for the contrast sensitivity (see in the Figure 9 on the right for example). The types 6000 and 6500 differ in the testing distance. VCTS6000 is designed for measuring the contrast sensitivity in reading distance (40 cm) opposite to VCTS6500 optimized for distance testing (3 m) [38]. The test is composed of 5 lines with decreasing contrast (9 columns). Each line differs from others in the spatial frequency (1.5 to 18 cpd). There are three possible orientations of gratings: vertical and turned 15 degrees clockwise or anticlockwise. The fourth option is an empty circle [27, 39, 40, 41].

Other sine wave tests

To commonly used tests based on sine wave pattern belongs e.g. CST 1800 Digital described further in the following chapter or SWCT (Sine Wave Contrast Test) using inconstant differences of the contrast between columns [42, 43].

2.2.3 Automatized PC-controlled tests

Various automatized systems were developed for an unbiased contrast sensitivity measurement. A big advantage of these systems over printed or board tests, is that the contrast threshold can be determined by more sophisticated methods thus be more accurate in shorter completion times of the test. These methods are called psychophysical and they are described in the following chapters.

Automatized tests can be divided by intended purpose into commercial and research (laboratory) tests. The first group consists of tests available for purchase as medical devices for eye care clinics and practitioners. The research tests focus on improvement of existing contrast sensitivity measurement procedures especially in the repeatability and the accuracy of the results [44].

The goal of this thesis was to further develop a digitalized chart for testing of contrast sensitivity – a device for vision examinations usually employing (calibrated) LCD screen. The main goal of the project associated with the thesis is to create a digitalized chart certified with CE marking suited especially for evaluations of intraocular lenses.

Commercial devices for clinics

The automatized systems use primarily sine wave grating tests or alternatively other standardized optotypes (e.g. Landolt C). Although there are many commercial solutions, the principle of the devices is very similar [27, 45].

The **CST 1800 Digital** contrast sensitivity tester (by Vision Sciences Research Corporation) is an example of such a device. The process of the test is following: Each eye is tested separately and afterwards both eyes are tested simultaneously. Both photoptic and mesoptic conditions are available with possibility of addition of glare. The spatial frequency of the sine wave gratings is increasing while the contrast is decreasing [46].

The **OPTEC Plus Smart Vision Screener** or the **OPTEC 6500** (by Stereo Optical, USA) has the principle similar to the one mentioned above. Recent models are sold with tablets (or PC) enabling a wireless operating and results displaying via Wi-Fi or Bluetooth [47].

Research and laboratory tests

The **Freiburg Vision Acuity and Contrast Test (FrACT)** developed by prof. Michael Bach (the first version programmed 1985) is frequently compared with above mentioned tests [3]. During the development of the test though decades the programming language changed from Pascal to C++ and the versions since year of 2002 are developed on Flash platform [48].

The latest Windows release (version 3.9.3, October 2016) contains various visual acuity and contrast sensitivity tests and its print screen is shown in the Figure 10. Program employs an anti-aliasing filter and gamma correction for the higher reliability [48]. For the contrast sensitivity testing, FrACT offers the Landolt C 8-way test or the sine wave grating test with four possible directions. The program control is very intuitive and can be used without a need of specialized training.

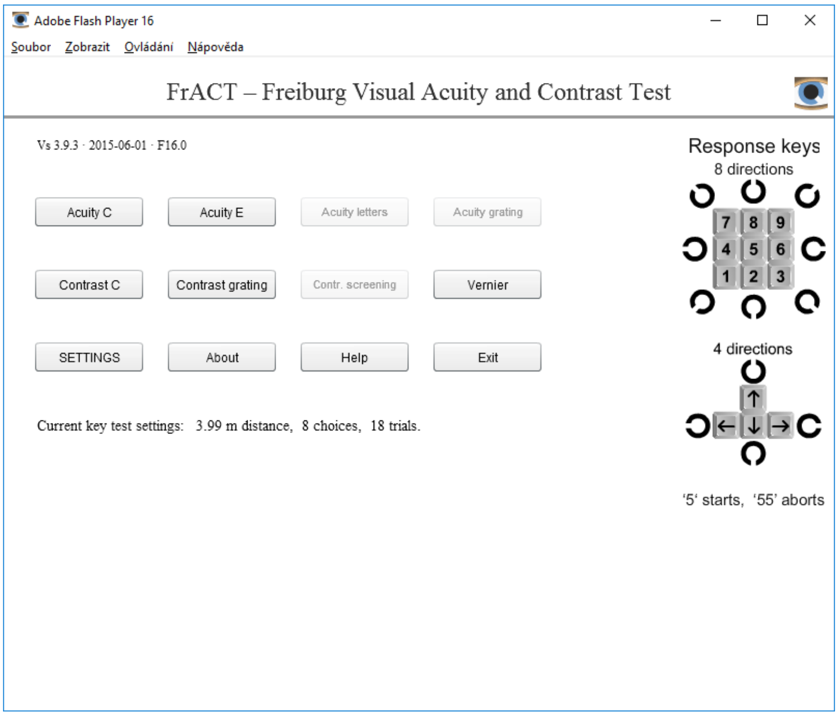

Figure 10: Print screen of the graphical user interface of the FrACT offering different types of tests of vision implemented on FLASH platform

The **Frankfurt-Freiburg Contrast and Acuity Test System (FF-CATS)** developed in 2005 is based on the FrACT. FF-CATS employs "Best PEST" algorithms (Chapter 2.3.2). The test uses the Landolt C signs and eight LEDs in a circle in front of the display for simulation of the glare (Figure 10) [44]. Frankfurt-Freiburg Contrast and Acuity Test System was recognized as a valuable psychophysical test for determining the contrast sensitivity based on studies by Bühren et. al. (2006) [3].

Another example of the automated contrast sensitivity test is the **Holladay Automated Contrast Sensitivity System (HACSS)**. HACSS primarily differs from the tests described above by using a "sinusoidal bullseye". Thanks to its radial symmetry, this pattern (Figure 11) should ensure same conditions even for patients with astigmatism. The subject has to distinguish between the bullseye pattern and flat grey disk within 10 seconds [49].

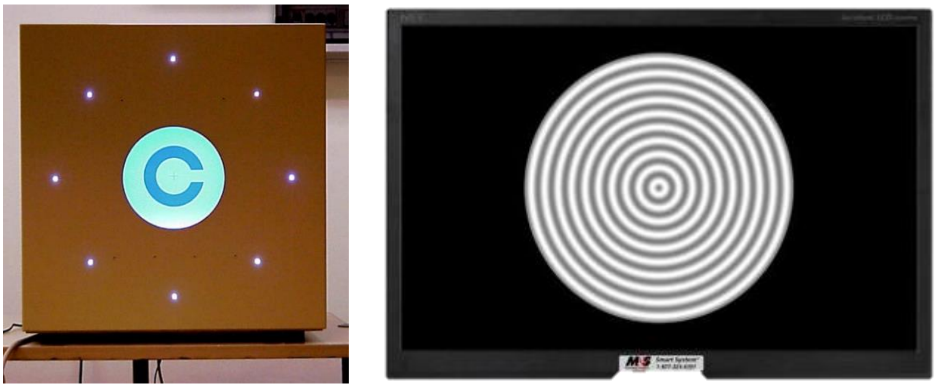

Figure 11: FF-CATS test (left, Terzi 2005) based on the FrACT test employing the Landolt C together with the Best PEST algorithm and glare diodes placed in a circle. The radial test (right, Holladay 2009) using a "sinusoidal bullseye" to prevent errors caused by astigmatism

Mobile applications

Mobile applications (and games) are available for the most used mobile platforms as Android or iOS. These applications usually test the contrast sensitivity by rather amusing form to not only test the contrast sensitivity, but also entertain or educate the user. The results of these applications are indicative only. The most active app-developing company in this area is *healthcare4mobile* offering eight different applications for testing of vision at the Google Play store.

Currently, there is a significant effort devoted to development of reliable assessment of the contrast sensitivity on portable devices (Dorr et al., 2013). The test created by Doll was realized on iPad with promising results agreeing with CRT-based laboratory equipment [50].

2.2.4 Example of other types of tests

Hiding Heidi test

Dr. Lea Hyvarinen developed picture based test called the Hiding Heidi to investigate contrast sensitivity in very young children. The test (displayed in the Figure 12) should be applicable for infants in age of 12 weeks and older. In this age (or even earlier) infants already react to a friendly smile with a happy "social smile" so it is possible to detect their response [51, 52].

Figure 12: Pictures used for the Hiding Heidi test – the contrast sensitivity test developed for examinations of CS of the infants, source: Lea-Test Ltd.

2.3 Algorithms in automatized tests

Assessment process of the contrast sensitivity usually involves both physically and psychologically demanding procedures. Moreover, the test must be repeated several times if the effect of different glasses or contact lenses is examined. To avoid the loss of subject's concentration, it is beneficial to shorten the test duration. However, the decrement of the test duration time should not adversely affect an accuracy of the examination.

The algorithms created for finding the threshold are called threshold-seeking algorithms. These algorithms can be optimized by using of psychophysical[5] methods to ensure their efficiency [53].

Psychophysics defines two basic types of threshold (minimal detectable value) which are commonly used in the field of the sensorial examinations. The *absolute threshold* represents barely detectable stimulus – every weaker stimulus will not be detected by the subject. Opposite to that, the *differential threshold* is equivalent to minimal deviation between two stimuli noticeable by the observer. Since the contrast is defined as difference in luminance, the differential threshold is the one which is determined in contrast sensitivity examinations [54].

Psychophysics traditionally used three methods which are considered as "Classical". However, these methods are being argued to be inefficient and therefore the Adaptive methods have been developed.

[5] Psychophysics is field of Psychology. It studies the relation between the stimulus and the following sensation. In the examinations of perceptual system, it also refers to the class of methods used for optimization of the testing process [54].

2.3.1 Classical psychophysiological methods

Method of Adjustment

The simplest approach of assessing the threshold is letting the subject adjust the intensity of the stimulus (visual, auditory etc.) to its noticeable minima or recognizable difference. The method is very fast; however, it relies only on the observer control (and experience). Therefore, methods with higher level of standardization are usually preferred [54, 55].

Method of Limits

An example of a method with higher level of standardization is the Method of Limits. The principle of the method is also relatively simple – intensity (or difference) of the stimuli is increasing to its recognizable level or vice versa decreasing in the descending trials. The duration of the examination process strongly depends on the chosen range of values [54, 55].

Method of Constant stimuli

Method of Constant stimuli requires data from previous measurements (usually Method of Adjustment or Limits). According to the data, set of values (five to nine typically) closest to the threshold is chosen by the experimenter [54, 55].

Afterwards, series of random sequences of these stimuli are presented. The observer decides for each stimulus whether the stimulus is detectable/differentiable. The threshold is then established as the value of the stimulus intensity (or contrast in our case) which is detected in the 50 % of the cases.

The method is considered to be the most precise of the classical psychophysiological methods. However, due its high time demands it requires an attentive and "resistant" observer [54, 55].

2.3.2 Adaptive psychophysiological methods

Staircase method

The Staircase method is based on the Method of Limits. However, the decrease of the intensity or the contrast is relatively steep with aim to achieve the first negative response earlier. When the negative response is given, the value of the stimulus is increased to the level with the last positive response. The process is repeated with still smaller differences to establish the threshold [54, 55].

Commonly used type of the staircase method uses the “1 Up / 3 Down rule”. This approach requires three correct responses of the observer to increase the difficulty (e.g. to lower the contrast) after the first wrong response is obtained. The threshold is calculated from the values of the last six reversal points (the correct response after false one or vice versa) after the seventh reversal point is obtained [56].

Best PEST Procedure

The best PEST Procedure is very similar to the staircase method. The method should be faster and more accurate by adapting the magnitude of change in the stimulus based on the previous responses. The method usually predicts the sigmoidal shape of the psychometric function. This procedure is used by FF-CATS described in the Chapter 2.2.3 [44, 55].

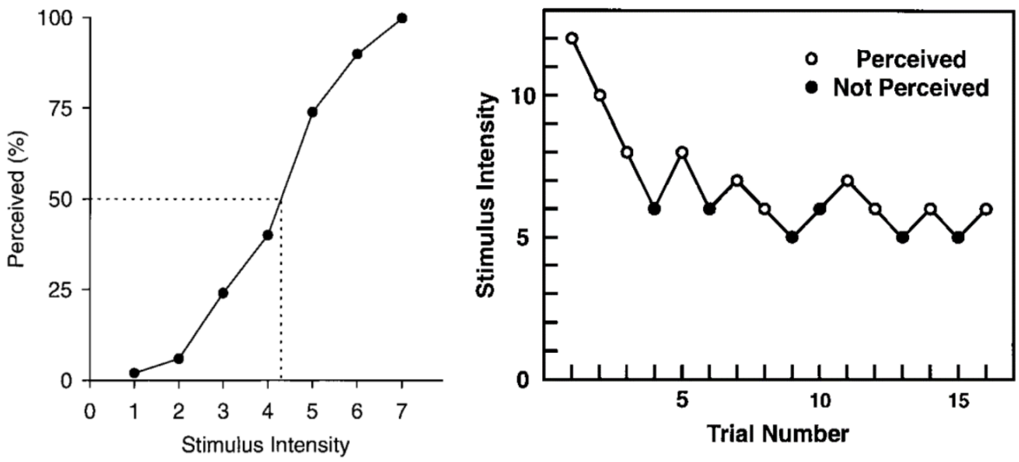

Figure 13: On the left – example of a psychometric function – dependency of the number of perceived stimuli on the stimulus intensity *(Ehrenstein 1999)*. On the right – *example of a* simple Staircase method *adapting the stimulus intensity in the dependency on perception of the stimulus (Ehrenstein 1999)*

Adaptive Variants of the Method of Constant Stimuli

By considering the fact that only the stimuli closest to the threshold provide relevant information, it is advantageous to determine the threshold in a limited range as it is done by the Method of Constant Stimuli. The range can be determined adaptively during process. For example, in the Bayesian adaptive method, the threshold is treated as variable with normal distribution and the Gaussian probability function is updated with each response. Contrast threshold is then established as the value with the highest probability.

Forced-Choice option

All the methods described so far have one significant disadvantage – if the answer is not required from the observer the experimenter must rely on the observer's impression whether he saw the difference or not. The Forced-Choice option eliminates this problem of subjectivity by requiring the observer to give a positive answer – e.g. by choosing right or left orientation of a sine wave grating [55].

According studies employing the Force-Choice, the subjects were able to select the correct answer from two possibilities in 70 to 75 % of the cases although the subjects claimed that they cannot see the difference so their success rate should be close to 50 % [56].

2.4 Overview of contrast sensitivity values from the literature

There is a question whether the results of the different types of the tests are interchangeable, even though the principles of the tests are not the same. The following paragraphs contain results comparing various approaches of the contrast sensitivity examinations obtained in the different studies. Because of contrast sensitivity being highly age-dependent, the comparison values were taken from results of young subjects (20 to 30 years, healthy eyes). In this age, the values of the contrast sensitivity are highest as mentioned before. The results are summarized in the Table 1 and 2.

Table 1: Comparison of test results in photopic conditions obtained from different studies – the values differ significantely among the studies

Study	Bühren et al. (2006)	Hohberger et.al (2007) *	Hashemi et al. (2012)* *
Type of test	Logarithmic contrast sensitivity		
FACT (1.5 cpd)	2.00 (1.63–2.00)	1.58 (1.50–1.65)	1.62 (1.58–1.66)
with glare	*2.00 (1.70–2.00)*	*1.65 (1.58–1.73)*	-
Landolt C	2.23 (1.98–2.42)	-	-
with glare	*2.19 (1.73–2.42)*	-	-
Pelli-Robson	1.85 (1.65–1.95)	-	-
with glare	*1.73 (1.40–1.90)*	-	-

* *Values obtained from graphs*

** *In this study youngest group was in the age of 40-49, so around 15 % lower results are expected [3, 58]*

Table 2: Comparison of test results in mesopic conditions obtained from different studies – the results of Bühren and Hohberger agree in mesopic conditions without the glare, however differ in a presence of the glare and strongly differ from the results of Puell.

Study	Bühren et al. (2006)	Hohberger et.al (2007) *	Puell et al. (2004) ***
Type of test	Logarithmic contrast sensitivity		
FACT (1.5 cpd)	1.78 (1.48–2.00)	1.70 (1.65–1.75)	-
with glare	*1.78 (1.56–2.00)*	*1.48 (1.40–1.55)*	-
Landolt C	1.23 (0.85–1.58)	-	0.30 (0.20–0.30)
with glare	*0.90 (0.68–1.18)*	-	*0.30 (0.10–0.30)*

*** *Measured by Mesotest II with maximal value of 0.3 (claimed as the limit during the test even for youngest participants) [RC3]*

There are several issues, which should be mentioned before making further conclusions. First of all, although the types of the tests in the rows of the tables were same, the used devices were not. To be specific, Bühren et al. used for sine wave grating test (FACT) CST 1800 whereas Hohberger et al. chose OPTEC 6500 and Hashemi et al. chose CSV-1000. Similarly, at Landolt C tests Bühren et al. chose FF-CATS opposite to Puell using Mesotest II [3, 58, 59, 60].

Second, the contrast sensitivity of the observed group reached the highest attainable level in the experiments (FACT tests of Bühren and mesopic Landolt C test conducted by Puell) [3, 60].

Third, in the study led by Hashemi, there were no data from the spatial frequency of 1.5 cpd so the values from measurement for 12 cpd were taken [58] (These frequencies agree the best according the dependency curves of the contrast sensitivity on the spatial frequency [8]).

Fourth, the background luminance levels and the illuminance of the glare vary throughout the tests as well. More specifically, Bühren et al. measured at 167 cd·m^{-2} (photopic) and 0,167 cd·m^{-2} (mesopic) with the glare illuminance 50 lux (photopic) and 0.32 lx (mesopic) while Hohberger used 85 cd·m^{-2} for daylight measurements and 3 cd·m^{-2} for mesopic (the glare of 10 and 1 lx respectively). Puell chose for his mesopic measurements luminance of 0.032 cd·m^{-2} without the glare and 0.10 cd·m^{-2} with the glare corresponding to the brightness of traffic at twilight [3, 59, 60].

The following graphs visualize the data from the Table 1 and 2. The graph in the Figure 14 compares results of the mentioned studies in photopic conditions. These results do not differentiate as significantely as the results in the comparison for mesopic conditions in the Figure 15. However, it should be taken into consideration that the scale is logarithmic so the results differentiate more than it might be assumed on the first sight. The comparisons show the importance of a standardization of the contrast sensitivity testing especially in mesopic conditions and in simulations of the glare.

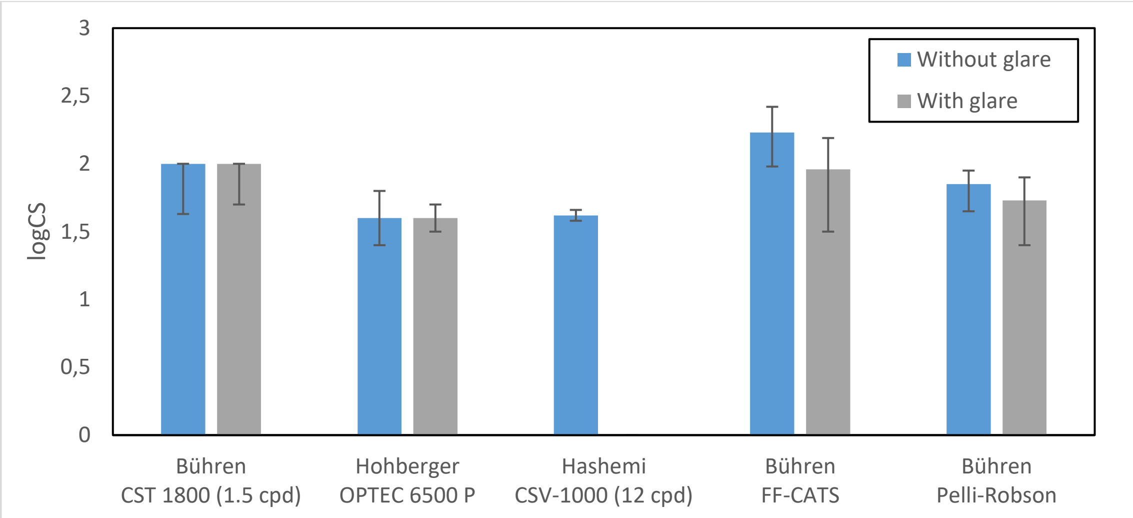

Figure 14: Graphical comparison of the results for photopic conditions obtained from the different studies and employing different types of tests (for details see Table the 1), the error bars show the range of the measured logCS values

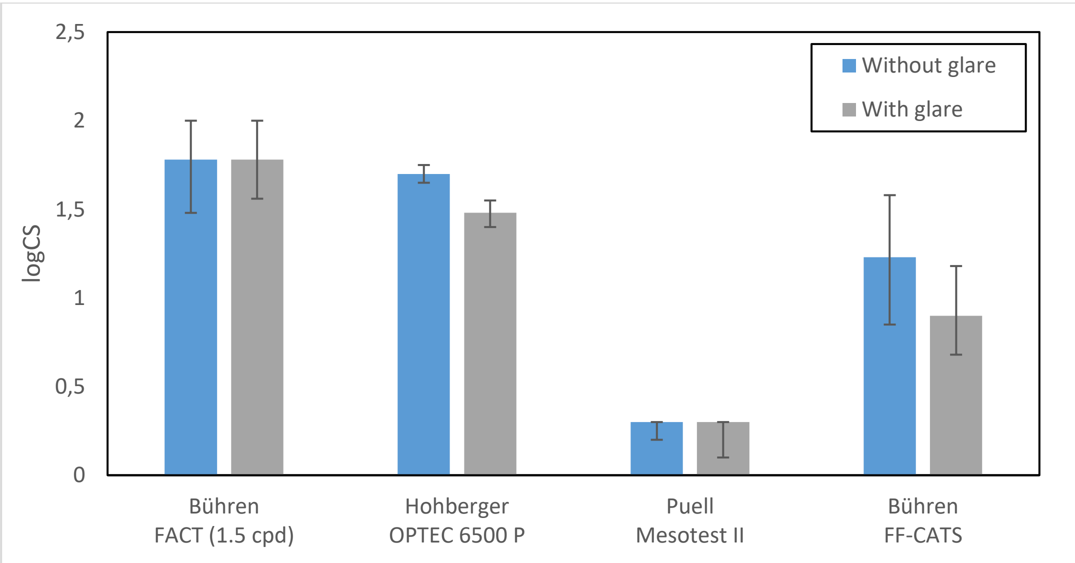

Figure 15: Graphical comparison of the results for mesopic conditions obtained from the different studies and employing different types of tests (for details see the Table 2), the error bars show the range of the measured logCS values

2.5 Index of contrast sensitivity (ICS)

The contrast sensitivity is usually tested in several spatial frequencies. Therefore, the contrast sensitivity is usually represented by five values at different spatial frequencies. To facilitate a single-index criterion, Haughom & Strand (2013) defined index of contrast sensitivity (ICS).

The ICS is calculated as a simple weighting function reflecting the eye's contrast sensitivity peak at 6 cpd [61, 62]. It is defined by a relation,

$$ICS = dCSF(1.5) + 2 \cdot dCSF(3) + 3 \cdot dCSF(6) + 2 \cdot dCSF(12) + dCSF(18) \quad (4)$$

where *dCSF(f)* is the deviation of the value of the measured contrast sensitivity function (CSF) and the median value at the spatial frequency *f*:

$$dCSF_i(f) = CSF_i(f) - median(CSF(f)) \quad (5)$$

3. Methods

3.1 Reaction speed and accuracy test

Prior to the creating the contrast sensitivity test, an initial study of the reaction speed and the accuracy was conducted. Purpose of the test was to investigate the dependency of the reaction speed and the accuracy of observers on number of options and to acquire data about time demands for such a type of test and to get some insight into psychology of observes performing the test. The data helped to find the ideal duration and the possible number of choices of the automatic contrast sensitivity test.

The test was developed in Python 3.4 using PyGame 1.9.2 library. The test had six levels, each with 50 consecutive images of arrows. Observers matched the direction of the arrow by pressing the appropriate key on the keyboard. The test was performed on six elder subjects (50-75 years) and seven young subjects (20-25 years).

The first difficulty level contained only left and right arrow. By adding a straight line (space key) to the options, the second difficulty was created. The third difficulty consisted of arrows of three directions (left, right, up). The fourth one added again straight line. Last two difficulties included four directions plus straight line for the sixth level. The differences among the levels are displayed in the Table 3.

Table 3: Used symbols (arrows and a line) for each level of difficulty in the Reaction speed and accuracy test

Difficulty	Left arrow	Right arrow	Up arrow	Down arrow	Straight line
1	✓	✓	✗	✗	✗
2	✓	✓	✗	✗	✓
3	✓	✓	✓	✗	✗
4	✓	✓	✓	✗	✓
5	✓	✓	✓	✓	✗
6	✓	✓	✓	✓	✓

Difficulties were increased gradually from the first to the sixth. For each one the total time and the accuracy of the answers were recorded giving results displayed in the Chapter 4. To objectively compare performance among the participants, the parameter called "The Accuracy to time ratio" was calculated simply by dividing the accuracy in %

by completion time in seconds. The main motivation for introduction of this parameter was to take into the account different approaches to the test – some individuals preferred complete the test in longer period of time with a greater accuracy whereas others (more competitive subjects) tried to complete the test in the shortest time possible but with a higher probability of making mistake.

3.2 Contrast sensitivity testing

The contrast sensitivity tests for the digitalized chart were also programmed in Python 3.4 using PyGame 1.9.2 and Numpy 1.11.0 libraries. The PyGame library was used to create graphical user interface whereas Numpy provided advanced mathematical operations.

The digitalized chart allows to set necessary parameters of the tests – distance, gender, tested eye, vision correction and light conditions. The size of the stimuli (sine wave gratings, Landolt C) is adjusted according to the distance to keep the correct angular spatial frequency.

A test was conducted on the group of thirteen young healthy subjects (age between 20 and 30 years) with corrected vision. The test consisted of the three subtests described in the following paragraphs and displayed in the Table 4 the end of the chapter.

Graphical results were presented after completion of each subtest for several seconds and the subject continued in the test (order of the subtests was constant for all examinations as displayed in the Table 4).

Used stimuli are shown in the Figure 16. Edges of the stimuli for both types were defocused to ensure that the observer cannot detect orientation from the edges (with a higher spatial frequency).

Figure 16: Used stimuli for the Landolt C test (left) and the Customized sine wave grating test (right)

The observers responded to stimuli by pressing the key to match the presented orientation of the grating or Landolt C respectively. Prior to testing, it was reminded to every subject that the completion time is not determinative in the test. However, duration times of each test were measured automatically on the background to evaluate time demands of the tests.

Luminance of the display was adjusted to 85 cd·m^{-2} as recommended by The Committee on Vision (National Research Council, 1980) [32]. The values were checked by the Datacolor Spyder5ELITE Display Calibration System. This system was used for calibrating of the display as well. Data from the calibration and the luminance adjustment are shown in the following Figure 17.

Generic PnP Monitor-2

Brightness (Candelas):		
	Black	White
Uncalibrated	0,25	194,2
Target	na	na
Calibrated	0,27	191,7
White Point (CIE xy):		
Uncalibrated	0,307	0,319
Target	0,313	0,329
Calibrated	0,314	0,332
Primaries (CIE xy):		
Red	0,657	0,334
Green	0,307	0,614
Blue	0,145	0,057
DeltaE (Lab):		
White Point	1,7	
50% Gray	0,8	
Gamma:		
Uncalibrated	2,30 (0,37)	
Target	2,20 (0,00)	
Calibrated	2,24 (0,07)	

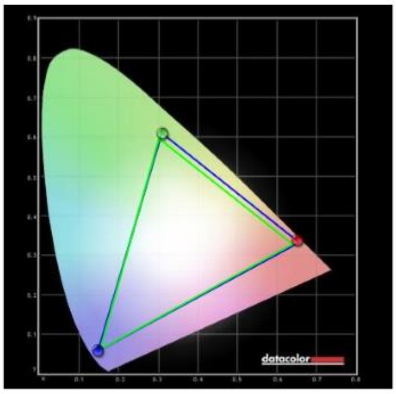

Figure 17: Table of adjustments made by Spyder5ELITE system with graph of RGB balance. The most important value is Brightness which should be calibrated for black and white colour on the same value for all used displays to receive same luminance of all the displays

The Figure 17 shows the calibration data for one of the used displays – LG FLATRON W2253TQ-PF. The calibration of the displays provides the possibility of using different displays for the measurements without influencing the outcome of the tests.

The brightness adjustment ensures that the luminance of the shades of grey used in the tests is close to the value of 85 $cd \cdot m^{-2}$ (this value represents the luminance of the test background with RGB: 127-127-127).

The settings of the balance of the primary colours (RGB – Red, Green, Blue) influence how is the colour presented on the display. Since the grey colour is created by an equal combination of the three colours (e.g. 128-128-128), this setting should be calibrated for each used display as well.

These settings (White Point, Primaries, DeltaE and Gamma)[6] were adjusted automatically by the system according to recommendations of the International

[6] The parameters describing balance of the "Primaries" – three basic colours. The White Point represents position of the white colour in the colour space, DeltaE stands for difference between two colours and Gamma defines the ratio among the three colours [64].

Commission on Illumination (CIE for its French name, Commission internationale de l'éclairage) [63].

To ensure that the grey colour will be presented really the same on the different displays, the program automatically sets the Gamma when started. The correct luminance of the grey colour with RGB 127-127-127 was always evaluated before the measurement by the Colorimeter tool of the Spyder5ELITE system.

The mesoptic conditions were simulated by the Precision Vision Mesopic Glasses 3 $cd \cdot m^{-2}$. Glare was realized by two white LED panels (both consisted of 5 diodes) fasten to the display.

3.2.1 Customized sine wave grating test with staircase algorithm

The test was programmed to assess the contrast sensitivity of the observer in the predefined spatial frequencies which are commonly used in contrast sensitivity testing – 1.5, 3, 6, 12 and 18 cpd [1]. The spatial frequency increased to the next level after completing the assessment of the contrast sensitivity for the current spatial frequency.

The staircase method was used to determine the contrast threshold for each frequency. Specifically, the "1 Up / 3 Down rule" was implemented as described in the Chapter 2.3.2. As in other tests, the results were saved to the text file (with info about the subject) and displayed graphically on the screen.

Three different orientations were presented randomly (based on the Python random number generator) – vertically oriented lines alternatively rotated by an angle of 15° clockwise or anticlockwise. The option not to answer was available if the observer was not able to distinguish the orientation.

The simplified flowchart of a test with the Staircase algorithm implemented according to the description above is presented in the Figure 18.

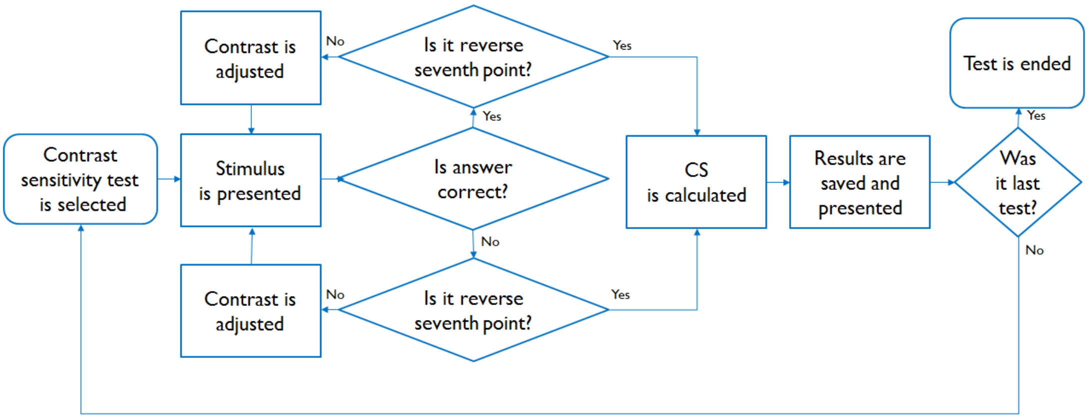

Figure 18: Flowchart of the test – after the answer on stimulus is received, it is evaluated (correct or false) and it is tested if it is a reverse point (black dots in the Figure 19). If it is the seventh reverse point, the CS is calculated from the last six reverse points, results are presented and the next subtest is started or test is ended.

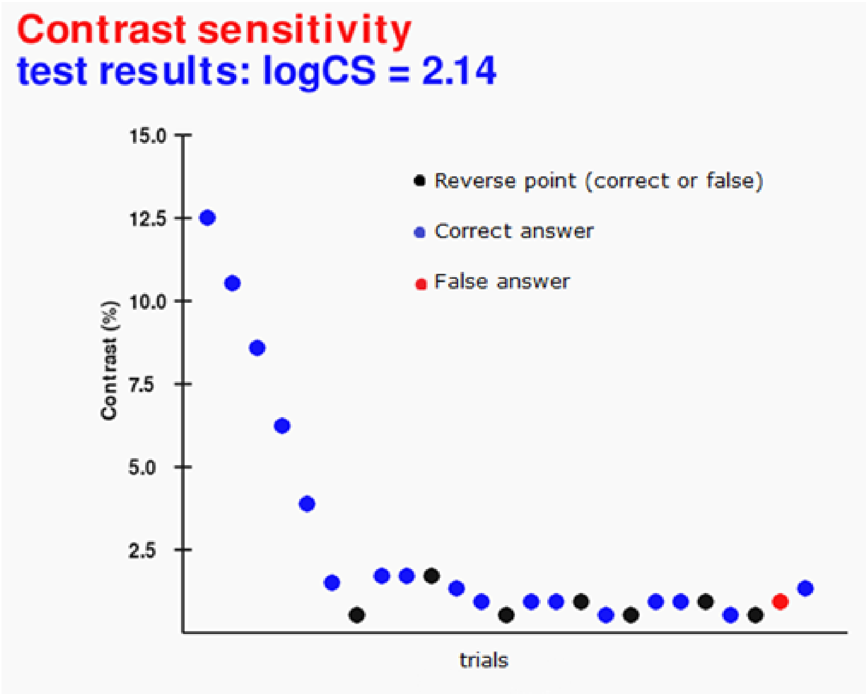

Figure 19: The typical progress of a test with staircase algorithm displayed after completion of the test – the black dots represent reverse points (the third consequential correct answer after a false one or a false answer after a correct one)

3.2.2 Landolt C test with staircase algorithm

The Landolt C tests use letter "C" printed in Sloan font. The sign was presented in four different rotations. The goal of the observer was to determine on which side (left, right, up, down) is the gap of the C sign located. (The gap width, same as the stroke width, equals one fifth of the sign diameter as standardized by EN ISO 8596 [33].) The option not to answer was allowed. The Landolt C test was chosen because it is accepted as a standard of the contrast sensitivity testing [34].

According to the chosen distance, the size of the letter was set to 1.3 LogMAR[7]. The same value was used for example in the Frankfurt-Freiburg Contrast and the Acuity Test System [3]. The contrast values changed by the staircase algorithm and the angle of rotation was generated by Python random generator as used in the Customized sine wave grating test.

3.2.3 CSV-1000E test

The digital form of the standardized CSV-1000E test was implemented, as a reference. The implementation of the test used the spatial frequencies and contrast values identical with CSV-1000E test values available on manufacturer's website [65]. However, the stimuli were presented in three different directions to keep the test comparable to the developed contrast sensitivity test referred as "Customized".

The contrast values were lowering until the false response was given. Afterwards, the spatial frequency was increased to the higher level. The contrast threshold was determined as the last value of the contrast correctly recognized by the observer (Method of Limits) [65].

Comparison of the subtests is displayed in the Table 4. Column "PP method" represents psychophysiological method used for determination of the contrast threshold. Column "Rotations" shows how many possible answers were available – as mentioned above, Landolt C was rotated randomly in four different orientations (rotated by multiples of

[7] The LogMAR (Logarithm of the Minimum Angle of Resolution) chart is used for visual acuity testing. The logarithmic angle value of 1.3 is the threshold value of legal blindness established by WHO.

90°), whereas the sine wave gratings were presented randomly oriented vertically or rotated by ± 15°.

Table 4: Comparison of the subtests in the study – the subtests differed in the type of stimulus (Landolt C or sine wave grating), psychophysiological method (Staircase or Method of Limits), number of possible rotations of the stimulus and examined spatial frequencies)

Test name	Stimulus	PP method	Rotations	Frequencies
Landolt C	Letter "C"	Staircase	4	-
CSV-1000E	Sine wave	Limits	3	3; 6; 12; 18
Customized	Sine wave	Staircase	3	1.5; 3; 6; 12; 18

3.3 Repeatability testing

To evaluate the consistency of the results given by the staircase algorithms, the Landolt C and sine wave tests were repeated by three volunteers five times each. The subjects were given short period of time to recover after the completion of each test.

The Forced-Choice method was used for these examinations (subjects were required to always provide an answer). Afterwards, the whole series of the test was repeated with the option not to answer (subject could pass the answer by hitting Space key).

The tests were performed in the same conditions as previously described for examinations of the contrast sensitivity. The experimental setup was also the same only used display was 14" Full HD IPS LCD of Lenovo Yoga 510 calibrated by procedures described above. Data were processed statistically and presented in the following chapter.

4. Results

4.1 Reaction speed and accuracy test

The following pair of graphs depicts completion times and the accuracy among the groups. The value in the brackets indicates age of the subject.

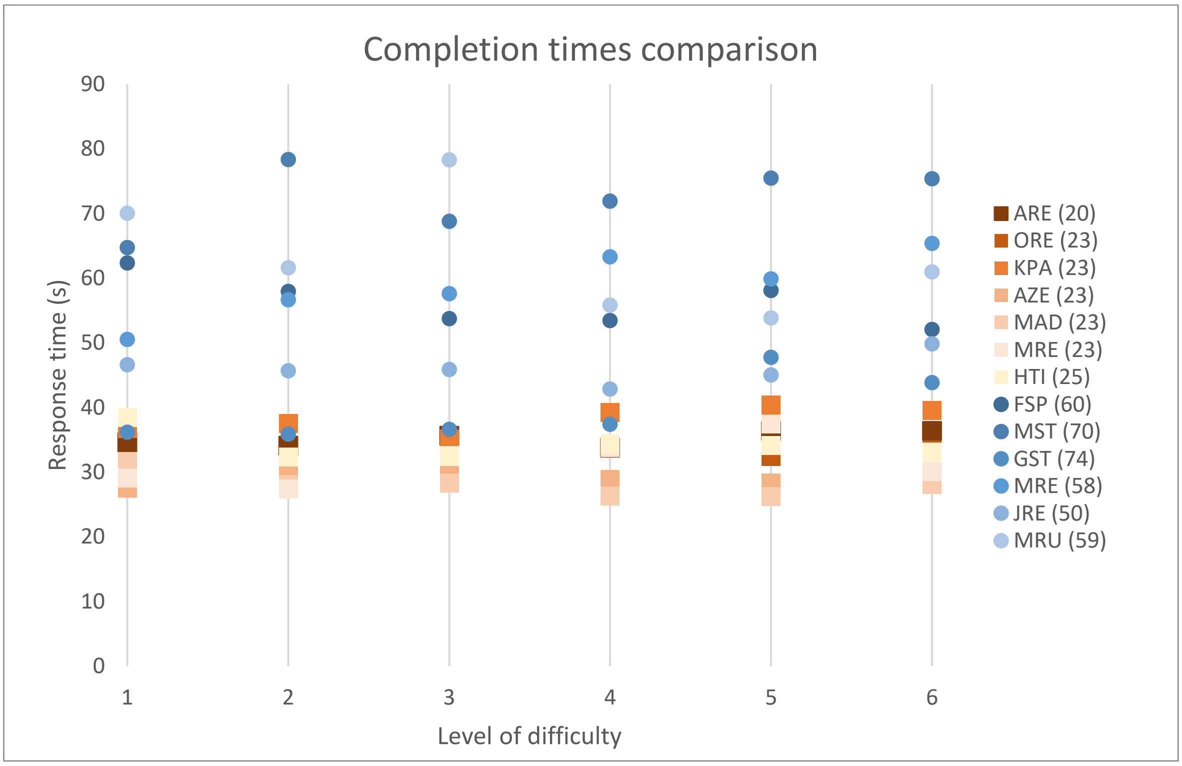

Figure 20: Graph of the completion times among tested subjects (age of a subject is given in a bracket, the completion times of elder subjects are displayed as blue circles and the times of young subjects as orange squares) – according to our expectations, the completion times of the elder subjects were significantly higher plus they have higher standard deviation

As seen in the Figure 20, the completion times varied much more among the older group of participants. This can be caused by various factors discussed in the next chapter. As expected, the completion times of the younger subjects were significantly lower (mean completion time of 32.5 ± 0.7 s) than among the older group (56.1 ± 1.2 s).

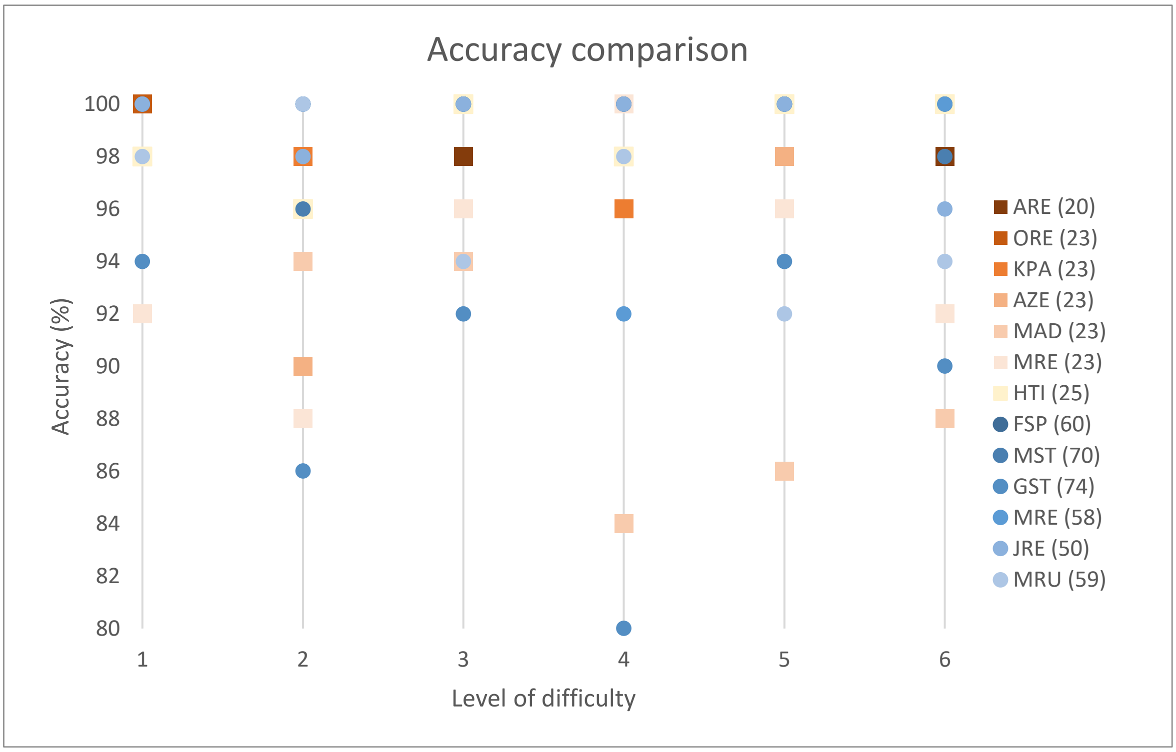

Figure 21: Graph of accuracy results among tested subjects – opposite to the expectations, the accuracy of the subjects did not differ dependently of their age

The accuracy (percentage of the right answers to the total number of stimuli) brought on the other hand very similar results among the two tested groups as seen in the Figure 21. The mean accuracy of the younger group was 96.0 ± 1.0 % whereas accuracy of the older group was even slightly higher, exactly 97.0 ± 1.2 %.

Table 5: Comparison of the results of the groups

	Difficulty	1	2	3	4	5	6
Completion time (s)	Young	32	31	32	33	34	33
	Old	55	56	57	54	57	58
Accuracy (%)	Young	96	94	97	96	97	95
	Old	99	97	98	95	98	96
Accuracy to time ratio ($\%\cdot s^{-1}$)	Young	3.0	3.0	3.1	2.9	2.9	2.9
	Old	1.8	1.7	1.7	1.8	1.7	1.7

The Table 5 displays the values visualized in the graphs in the Figure 20 and 21. The results of the test were used to optimize the duration of the contrast sensitivity tests whose results are presented in the following chapter.

4.2 Repeatability testing

The graphs in the Figure 23 a 24 depict the obtained results which are summarized in the Table 6. Figure 23 displays the average (logarithmic value of) contrast sensitivity obtained from each method. The scores of tests with the Forced-choice option (FC) and tests without it did not differ statistically.

The independent two-sample t-test (with unequal variances according to the F-test of equality of variances) was performed on the significance level 0.05 for both types of tests – the Landolt C (p-value 0.27) and the Customized (p-value 0.12). The normality of the values was evaluated by the histograms presented in the Figure 22. These results indicate that the Forced Choice option does not influence results of the tests significantly.

Table 6: Comparison of the results from the tests

Test	*logCS*	*std. deviation*	*ΔlogCS*
Customized (with FC)	1.95 (1.82–2.09)	0.09	0.26
Customized (without FC)	1.99 (1.88–2.16)	0.10	0.28
Landolt C (with FC)	1.87(1.81–1.93)	0.04	0.12
Landolt C (without FC)	1.90 (1.86–1.94)	0.03	0.08

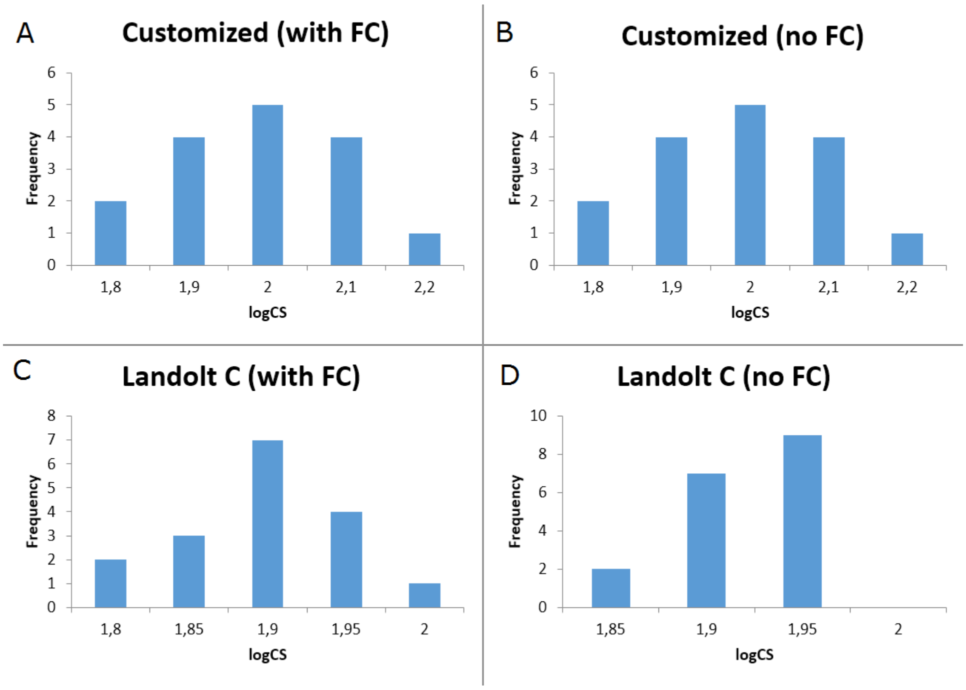

Figure 22: Histograms of the results acquired from the different modifications of the tests – the normality of the data was evaluated by the histograms with a good agreement especially for the Customized test. Higher number of trials would probably increase the normality

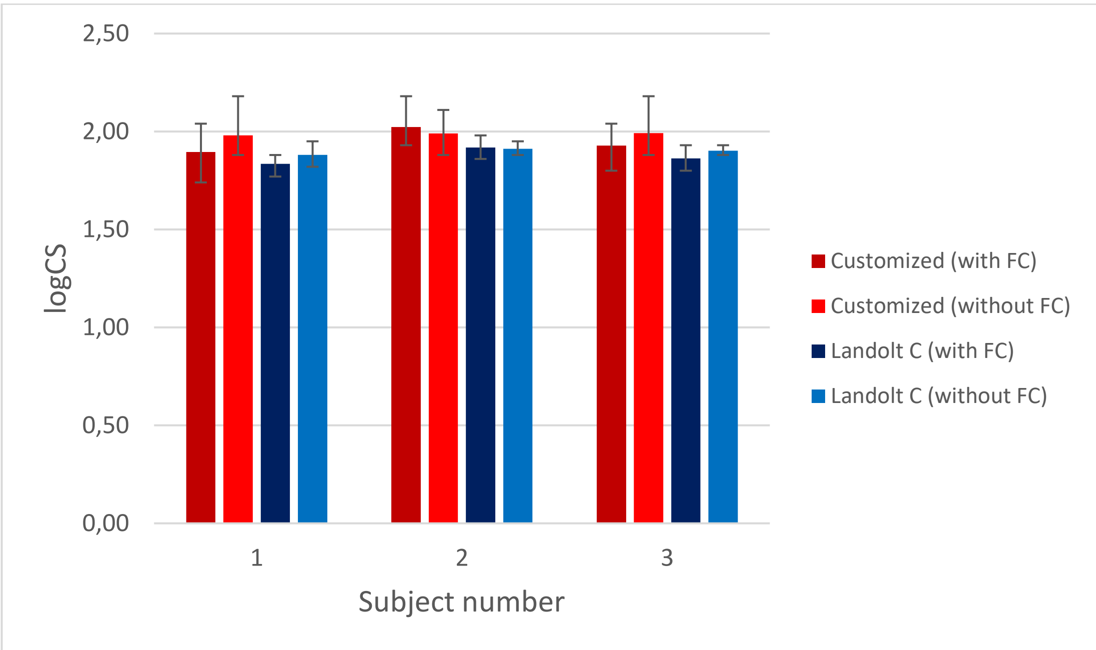

Figure 23: Comparison of results given by each method – results from the tests employing and not employing Forced-choice did not differ statistically (for Landolt C p = 0.27 and Customized test p = 0.12)

The slightly lower values of the *logCS* obtained from the Landolt C test were expected because this type of the test examine slightly lower spatial frequencies than 3 cpd and thus the contrast sensitivity is physiologically decreased.

However, the Landolt C test proved to give more consistent results as it appeared from the results acquired from testing before. It is displayed in the Figure 24 – the graph shows average interval width of the gained values of contrast sensitivity *ΔlogCS* (in other words the difference between the best and the worst achieved score) obtained from each tested subject.

The bars corresponding to the CSV-1000E were added for the comparison with the results of the CSV-1000E test acquired from the testing of algorithms described in the following chapter. The bar marked with an asterisk symbol contains unprocessed data – it means that the significantly lower results of CS caused probably by an accidental error of the subject were not eliminated (this post-processing is not needed when the Staircase method is used because the accidental errors are eliminated by the algorithm itself).

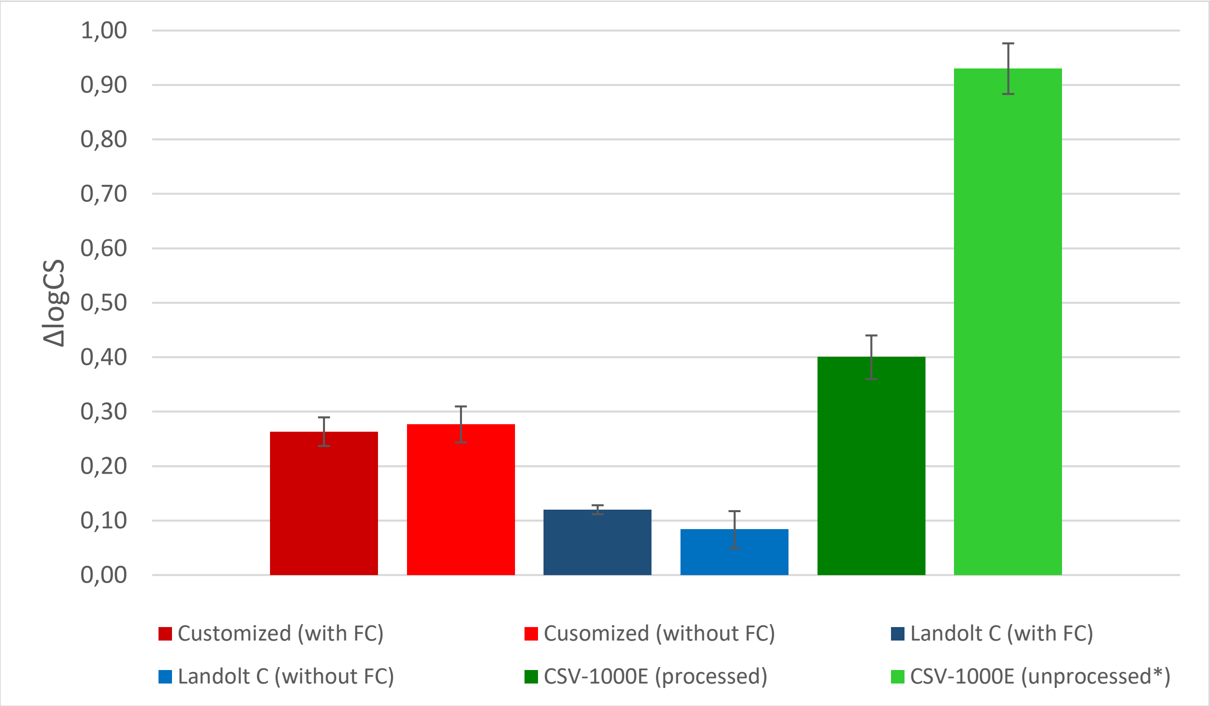

Figure 24: Comparison of the average interval width of results obtained from each method – the graph demonstrates the significant difference between consistency of the results of the Staircase method (Customized, Landolt C tests) and Method of Limits (CSV-1000E) which requires further post-processing of the data

4.3 Testing of algorithms for CS evaluation

Results from the examinations were saved into the text files together with the information about subject, date, time, version of the program etc. These data were processed statistically and visualized by the following graphs. The raw data were exported into the tables and they are included as attachments to this thesis. Graphs in the following Figures 25 and 26 display the contrast sensitivity curves created from average results obtained from the sine wave grating tests (CSV-1000E and Customized).

As can been seen in the graph in the figures, the results between the two tests differed the most in the spatial frequency of 6 cpd. This might be connected to the fact that CSV-1000E test uses stimuli with the lowest contrast (highest CS) for this particular frequency because the highest CS is expected [14].

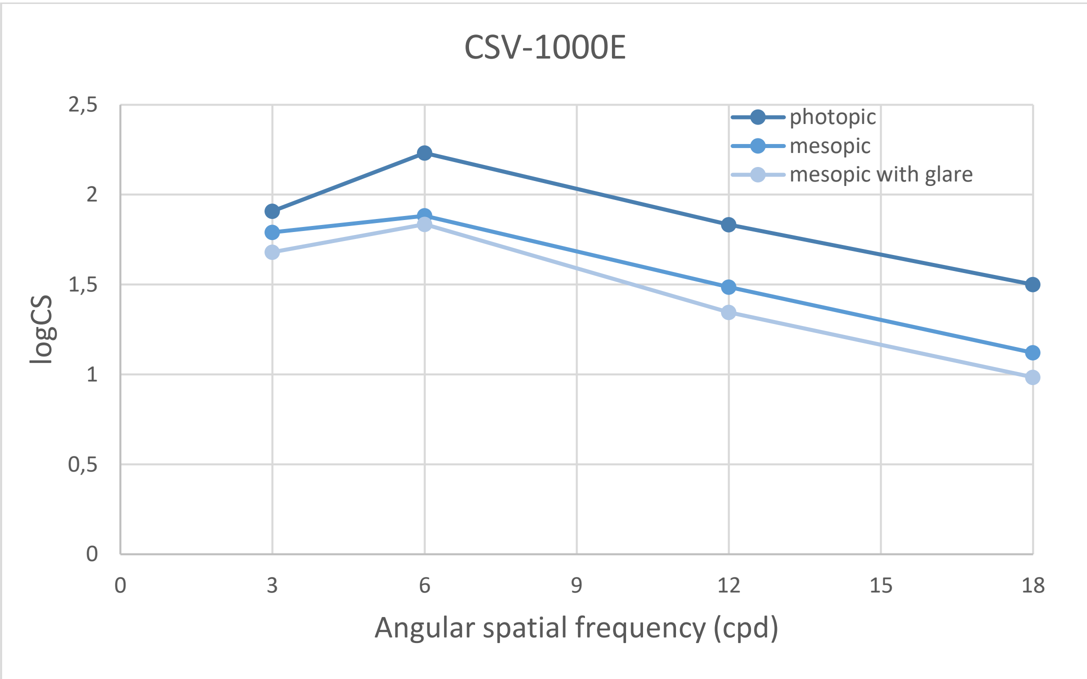

Figure 25: Contrast sensitivity curve obtained from the mean CS values of CSV-1000E test for different light conditions – the curve has its expected shape reaching maxima at 6 cpd

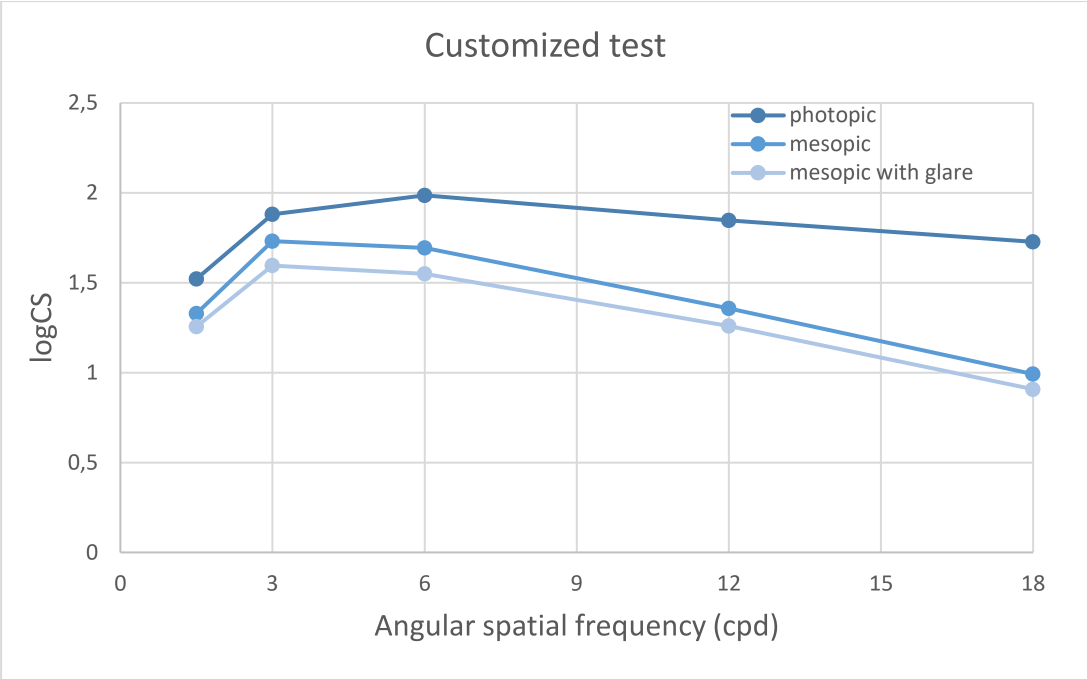

Figure 26: Contrast sensitivity curve obtained from the mean CS scores of the Customized test acquired in different light conditions – the curves reach their maxima at 6 cpd (in agreement with Leguire (2011) and Wandell (1995)) and then decrease to logCS = 1 in mesopic conditions

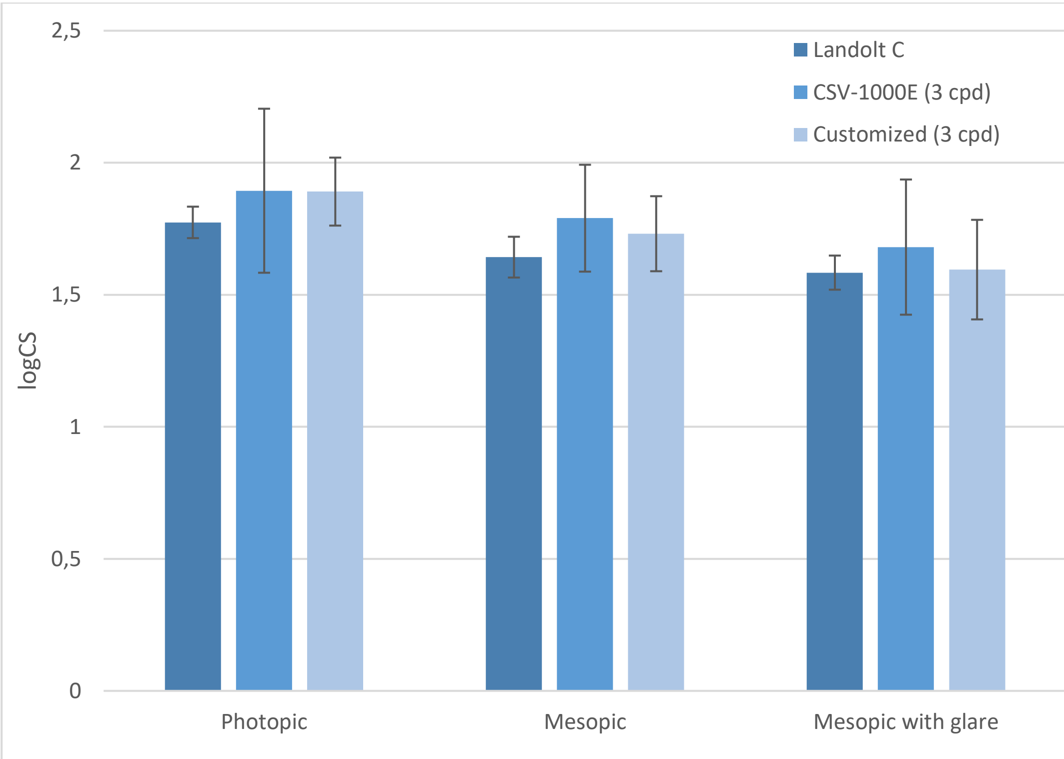

Figure 27: Graphical comparison of the averages of the assessed contrast sensitivity values – the values among the tests did not differ statistically (see Table 8) and differed among light conditions (Table 9)

The Figure 27 displays comparison of the results obtained from the tests for all tested light conditions. As seen in the figure, the (logarithmic) contrast sensitivity values did not differ significantly among the tests for the particular light conditions (level of significance α = 0.05). The exact values are listed in the Table 7.

Table 7: Contrast sensitivity results in logarithmic values - comparison of the subtests for different light conditions – as shown in the Tables 8 and 9, the values did not differ statistically among the tests but did differ among the light conditions

logCS (-)	Photopic	Mesopic	Mesopic with glare
Landolt C	1.77 ± 0.06	1.64 ± 0.08	1.58 ± 0.06
CSV-1000E	1.89 ± 0.31	1.79 ± 0.20	1.68 ± 0.26
Customized	1.89 ± 0.13	1.73 ± 0.14	1.60 ± 0.19

The contrast sensitivity values of the sine wave tests displayed in the table were assessed for the spatial frequency of 3 cpd. The spatial frequency of the Landolt C cannot be determined as a single value but according the Fourier analysis of the sign, the dominant angular spatial frequency for used LogMAR equivalent of 1.3 is approximately 1.5 cpd [3, 66]. Since the CSV-1000E does not test this spatial frequency, the closest value was chosen for the comparison. It should be noted that the CSV-1000E test based on the Method of Limits had considerably higher values of the standard deviation than the tests employing Staircase method (especially in comparison to the Landolt C test).

The summarization of the statistical comparison of the results of CSV-1000E and Customized test (spatial frequency of 3 cpd) is presented in the Table 8. The highest differences were expected in the photopic conditions due to the fact that the observers achieved the highest possible score several times, but the last value of the test (the lowest contrast) was usually guessed. This factor of "lucky guesses" is eliminated by Staircase algorithm by requiring multiple correct answers to lower the contrast of the stimulus.

Table 8: Statistical comparison of the results of CSV-1000E and Customized subtests for the different light conditions – the values did not differ on level of significance α = 0.05 for all light conditions

Conditions	Variances equality*	Values equality**	p-value***
Photopic	No	Yes	0.30
Mesopic	Yes	Yes	0.13
Mesopic with glare	Yes	Yes	0.18

* *F-test of equality of variances (level of significance α = 0.05)*

** *Two-sample t-test (with equal or unequal variances depending of F-test results)*

*** *p-value of the Two-sample t-test for equality of two mean values*

A similar analysis was performed to decide whether the results from different light conditions differed or not. The statistical tests were conducted on the results obtained from Customized test and they are summarized in the Table 9.

Table 9: Statistical comparison of the results obtained from Customized test results in different light conditions – the values differed statistically (level of significance α = 0.05) according to the Two-sample t-test with equality of variances (according to F-test)

Compared conditions	Variances equality	Values equality	p-value
Photopic, mesopic	Yes	No	0.003
Mesopic with and without glare	Yes	No	0.031
Photopic, mesopic without glare	Yes	No	<0.001

The values of the completion times for each subtest in different light conditions are displayed in the Table 10. The comparison graph of these values is presented in the Figure 28.

Table 10: Comparison of completion times of the subtests for different light conditions – the significantly lower completion times of the CSV-1000E corresponds with used the Method of Limits. However, is has to be taken into consideration that tests employing the Method of Limits should be repeated at least five times

Completion time (s)	Photopic	Mesopic	Mesopic with glare
Landolt C	85.3 ± 27.2	62.3 ± 17.4	66.5 ± 17.0
CSV-1000E	13.3 ± 1.9	11.6 ± 6.2	9.4 ± 2.0
Customized	56.5 ± 18.1	57.6 ± 15.6	52.5 ± 13.5

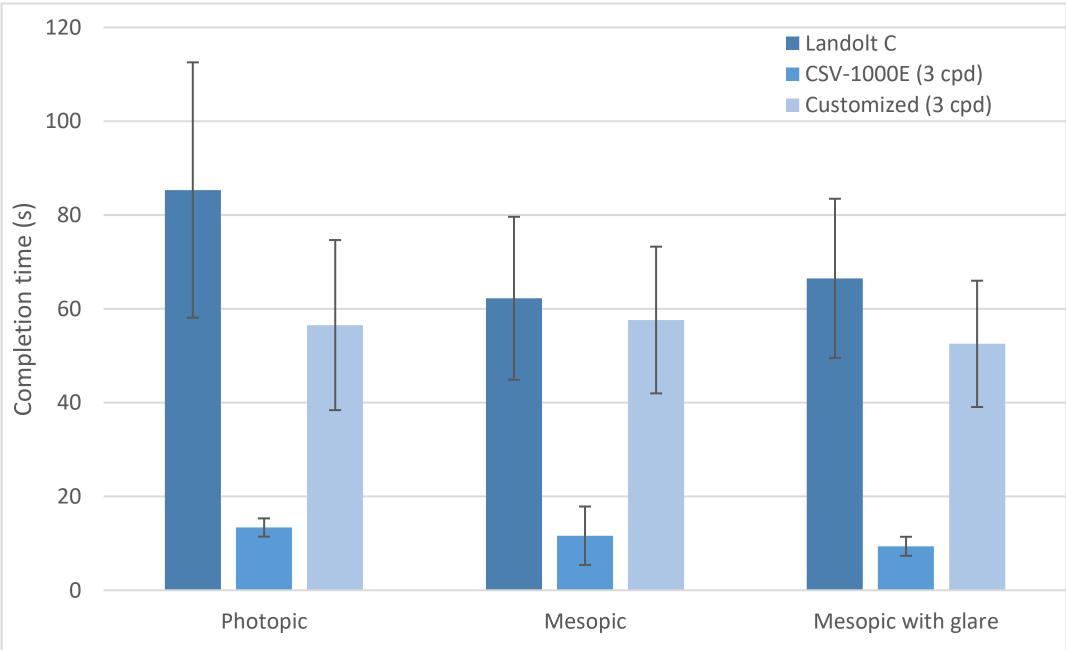

Figure 28: Graphical comparison of the completion times for the subtests in the different light conditions – the CSV-1000E test based on the Method of Limits was competed in the shortest times. The Customized test employing sine wave grating was completed faster than the Landolt C test although they both used the Staircase algorithm.

To briefly summarize the results, the Staircase algorithm tests have results with lower standard deviations in the comparison to the Method of Limits but at the cost of several fold longer examination times.

5. Discussion

5.1 Reaction speed and accuracy test

The accuracy to time ratio was significantly higher for the younger group (p-value < 0.001). The difference was given only by the faster completion times which differed significantly (p-value < 0.001). These results agree well with various studies (Woods (2015) [66], Stelmach (1988) [67], Wilkinson (1989) [68]). On the other hand, the accuracy of the subjects did not differ statistically in the dependence on age (p-value 0.16).

The values of the accuracy tended to be more dependent on subject's temper. Furthermore, less experienced PC users made less mistakes by pressing of keys more carefully (significantly increasing the total time of the test on the other hand). Those factors should be taken into account when automatized tests on PC are employed. For example, in the contrast sensitivity tests for which time is not relevant, the keyboard can be operated by the examiner.

From the average times for each difficulty, it is possible to assume that the number of choices influenced total time rather insignificantly (especially in the junior group). However, the addition of the straight line (choice slightly differing from others) has always caused decrement of the accuracy.

Similarly to accuracy, the response times were influenced by the subject's temper and how is the subject experienced with using PC. It can be seen in the Figure 20 – the oldest subject of the study had the fastest response times among the elderly group. This result might be caused by the fact that the subject uses PC the most of all elderly participants plus it probably corresponds with subject's lively temperament.

These results are in the agreement with the conclusions of Clarkson (1978) stating that the response time is significantly influenced not only by age but by everyday activities as well [69]. Actual psychological state is also a considerable factor.

The number of the pictures in the test (50) seems to be appropriate considering six repetitions of the sequence. The subjects did not seem to be exhausted after completing the test. However, for the development of the contrast sensitivity tests, it has to be considered that the contrast sensitivity tests require more of the subject's attention and they are more psychologically and physically demanding.

5.2 Contrast sensitivity testing algorithms

The staircase algorithm used in the created contrast sensitivity tests was designed and optimized according the results discussed in previous paragraphs. The obtained results corresponded well with theoretical expectations. The contrast sensitivity decreased as the light conditions were becoming more demanding for the observer. This decrement of the contrast sensitivity indicates that the simulation of the mesopic conditions by a grey filter glasses was effective as well as the glare realized by white LEDs.

The results of the individual tests agreed well among each other and with the results from different studies (Puell 2004, Bühren 2006, Hohberger 2007, Hashemi 2012) as well. This fact indicates that the test should provide reliable data about the contrast sensitivity of the observer.

The standard deviation of the results is an important parameter for the comparison of different approaches of the threshold determination. A smaller standard deviation of results means better consistency of the results thus better repeatability of a test. Since every tested person completed all the subtests, the standard deviations of the results obtained from the tests can be compared.

As seen in the Table 7 and the Figure 27 the CSV-1000E test based on the Method of Limits has the highest standard deviation. The standard deviations (photopic: 0.31, mesopic: 0.20, mesopic with glare: 0.26, in logarithmic units) are substantially higher than the standard deviations of the Landolt C test (photopic: 0.06, mesopic: 0.08, mesopic with glare: 0.06). The standard deviations of the results of the Customized test with the Staircase algorithm were in the photopic conditions: 0.13, mesopic: 0,14 and mesopic with glare: 0.19. This result indicates that not only the chosen psychophysiological method but the type of the stimulus can also influence the variance of the results.

This result was expected because of the principle of the Method of Limits (the threshold is determined as the last value with a correct response). The variance would be probably even higher if the CSV-1000E tested higher contrast sensitivity values (lower contrast) because many observers achieved the best possible result so there was zero variance among these results.

On the other hand, the Method of Limits proved to be very time-efficient and thus considerably less physically (and psychologically) demanding for the tested subjects. It should be noted that the completion times of the tests are strongly dependent on the subject's nature as well as the other factors e.g. the physical and psychological condition.

The average completion times (Figure 28 and Table 10) of the CSV-1000E test were approximately four times lower than completion times of the Customized test with the Staircase algorithm. To be precise, the comparison times of the CSV-1000E were in the range 9.4 to 13.3 s compared with 52.5 to 57.6 s (Customized test) or even 62.3 to 85.3 s of the Landolt C test.

However, it should be noted that tests using the Method of Limits should be repeated several times and then averaged to provide a more consistent data. This repetition would increase the completion time of the CSV-1000E to the values of the Staircase algorithms tests or even higher when the reasonable number of repetitions is considered as five or more [55].

The Landolt C test was subjectively rated by observers as less demanding (both psychologically and physiologically) than the sine wave tests. This outcome is most likely connected to the fact that the "C" characters of the Landolt C test are rotated by an angle of 90° in comparison to only 15° used in sine wave tests.

These attributes might make the Landolt C test less prone to errors. The orientation of the Landolt C can be distinguished by more spatial frequencies at the same time as the different parts of the "C" are represented by lines with different spatial frequencies [70]. This property helps the observer as well.

Taking these results in mind, the adjustment of the used Staircase algorithm should be considered. For example, there is an opportunity to use "1 Up / 2 Down" or even

“1 Up / 1 Down” rule instead of slower “1 Up / 3 Down” as described in the Chapter 2.3.2. It is also possible to count the threshold value from less than six reverse points – the decrement of this value to four for instance should shorten the completion times by approximately one third. However, these adjustments might bring the less consistent results.

A further improvement of the created test could be achieved by hardware modifications. Especially using LCD with higher colour depth than used 8-bit would ensure the proper rendering of sine wave gratings. As the difference between the lightest and darkest stripes is close to one shade of grey of 8-bit display for *logCS* around 2 log units, it is desirable to use LCD with at least 10-bit colour depth to reach a requisite rendering of sine waves in the low contrast stimuli.

Various (medical) LCDs with such a colour depth are commercially available. Mostly offered colour depths of the monitors are 10-bit (1024 shades of grey) and 14-bit (16 384 shades of grey). Since the healthy human eye is able to recognize around 450 shades of grey in luminance recommended for the contrast sensitivity testing [71], the 10-bit might be sufficient for the examinations employing sine wave grating.

5.3 Repeatability testing

The repeatability testing actually observed two factors: influence of the stimulus type (sine wave grating of the Customized test and the Landolt C) and used psychophysiological method – specifically employment of the Forced-choice method.

According to the results of the previous tests, it was expected that the Landolt C will provide more consistent results. The possibility to give up the answer if the observer cannot see the difference was supposed to increase the consistency of the results as well by eliminating the false positive answer generated by lucky guesses.

However, according to the obtained results, this factor is rather insignificant because the addition of the possibility not to give an answer did not bring any difference to the results.

To objectively evaluate repeatability, a standard deviation of the results given by each test was calculated. As stated in the Table 6 the results Landolt C based tests had standard deviation $s = 0.03$ of logarithmic units (0.04 with forced choice) which is significantly smaller in comparison to $s = 0.10$ (0.09 respectively) of the sine wave tests.

The repeatability of the CSV-1000E test was evaluated by the Pomerance et al. (1994). The standard deviation was the smallest for the spatial frequency of 3 cpd. Nevertheless, the value of $s = 0.16$ (logarithmic units) obtained for this frequency is still significantly higher in a comparison to the standard deviations of the results of the Staircase algorithms based tests listed above [72].

The range of the contrast sensitivity scores (difference between the best and the worst achieved score) from the tests depicts the repeatability of the test as well. The average intervals of the Landolt C (0.08 and 0.10) were approximately three times smaller than the ones of the Customized test (0.28 and 0.26).

5.4 Comparison with recommendations

The digitalized chart was optimized to meet recommendations of American Academy of Ophthalmology Task Force Consensus Statement for Extended Depth of Focus Intraocular Lenses. The recommendations are defined for mesopic conditions [8]. The following list summarizes the recommendations (in italics) and our approach to meet them.

- *Used spatial frequencies should be 1.5, 3.0, 6.0 and 12.0 cpd (3.0, 6.0, 12.0 and 18.0 cpd for photopic conditions).* – We used 1.5, 3.0, 6.0, 12.0 and 18.0 for all measurements.
- *Ends of linear gratings must be blurred to avoid edge detection.* – Edges of all stimuli were blurred in GIMP 2.8.
- *The contrast of the gratings should use the Michelson definition and maintain an average spatial luminance of 2.7 cd·m^{-2} for mesopic conditions. Mesopic light levels can be achieved by neutral density filters, which results in a recommended luminance in the range of 2.5-3.2 cd·m^{-2}.* – The luminance of 3 cd·m^{-2} was achieved by using Precision Vision Mesopic Glasses 3 cd·m^{-2}. Average luminance of 85 cd·m^{-2} for photopic conditions was set as recommended by The Committee

on Vision (National Research Council, 1980) [32]. The values were confirmed by the Datacolor Spyder5ELITE Display Calibration System.

- *Testing must be performed with and without glare.* – All measurements in mesopic conditions were performed with and without glare simulated by two strips of four white LEDs.
- *An application of the glare should decrease contrast sensitivity significantly (e.g. by 0.1 log units) at least at one tested frequency (for young adult subjects with no pathology).* – The application of the glare in the Customized test resulted in average decrement of the logCS in the tested group by 0.11 of log units.

To briefly summarize the list, our digitalized chart should meet all the recommendations together with the recommendations of The Committee on Vision [8, 32]. Space for improvement might be in the simulation of the glare in mesopic conditions. Used glasses for the simulation of mesopic conditions significantly decreases the intensity of diodes and therefore the effect of the glare.

6. Conclusion

The main goal of this thesis was to create a robust contrast sensitivity test with acceptable demands on the tested subjects. After research of the actual contrast sensitivity tests and the psychophysiological methods used for threshold determination, the contrast sensitivity test employing the sine wave grating and the Staircase method was created.

Objective evaluation of the intraocular lens was the main motivation of this work. The created contrast sensitivity test was implemented into a digitalized chart used for the testing of patients with visual disorders especially cataract and presbyopia.

The sine wave test was chosen because of a possibility to set angular spatial frequency which is necessary for example for the evaluation of intraocular lenses. More importantly, the sine wave pattern is a standard in the contrast sensitivity evaluations thus it has been possible to compare results with commonly used tests.

Two other tests of the contrast sensitivity were implemented for a comparison with the created Customized test. The first one employs the Method of Limits. As expected, the completion times (of single test) were significantly lower than for other tests, but it has to be considered that the tests using the Method of Limits should be repeated at least five times [55] what would bring higher time demands than Staircase algorithms tests. These repetitions would be necessary to bring the level of results consistency to the one of the Staircase algorithm tests.

The second test created for comparison with the implemented sine wave test was the Landolt C test. Before further conclusions, it is must be pointed that the Landolt C does not offer the possibility of testing single (angular) spatial frequency and therefore it is not suitable for appropriate evaluation of intraocular lenses.

However, the Landolt C is widespread optotype used for the contrast sensitivity assessments and that is the reason why it was used as the second reference. The Landolt C test provided even more consistent results than the sine wave test. This might be connected with the fact that the Landolt C was rated subjectively less demanding by observers plus that the differences among the choices in the test (four rotations of "C" characters by an angle of 90°) differ more than the three orientations of sine wave test differing only by 15°.

These results suggest the idea that the Landolt C test could be used for patients who would regard the sine wave test too physically or psychologically demanding, alternatively for patients who are not evaluated because of intraocular lens implantation.

Grating more rotated (for example by an angle of 45°) could bring more consistent results, but at the cost of a loss of a direct comparison with commercial contrast sensitivity tests.

Further improvement of the created test could be performed by reducing number of reverse points used for the calculation of the contrast threshold. For instance, instead of a reduction from six to four reverse points should bring the decrement of average completion time by approximately one third. Implementation of less strict form (e.g. "1 Up / 2 Down" or even "1 Up / 1 Down" rule instead of used "1 Up / 3 Down") of the Staircase algorithm might be beneficial as well. However, these adaptations might bring a slight decrement of results consistency.

According to the statistical analysis of the results, the developed contrast sensitivity test should be suitable for the contrast sensitivity tests. The test provides results with solid repeatability and it can be simply modified for needs of a specific evaluation as it is mentioned in the Appendix.

Appendix

After the completion of trials of the algorithm described in this thesis, the developed contrast sensitivity test was used for comparison of six intraocular lenses conducted within bachelor thesis of Markéta Zawadová. The study was performed on three subjects in mesopic conditions and mesopic conditions with glare simulated same way as described in this thesis.

Because the high number of the tested lenses the algorithm was updated to decrease completion times by more than one third by reducing the required reverse points from seven to five plus implementing the Staircase algorithm rule "1 Up / 2 Down" instead of "1 Up / 3 Down".

The source code of the test is written to make these modifications as simple as possible. There is also a possibility to show these settings in GUI of the chart and thus increase the flexibility of the test.

The examiner would then have the opportunity to modify the test according the needs of specific examination – for example a less strict options would be used for tests which have to repeated (e.g. different IOLs) and the settings increasing the completion time would be used for more thorough examinations.

Example of results for the IOLs[8] is presented in the following Figures 29 and 30. It is possible to assume from the graphs that the modulation transfer function differs among the tested models – for example the model 2 provides the best results in lower spatial frequencies but has the worst results for higher frequencies. On the contrary, the model 3 has the smallest decrement of the contrast sensitivity with an increasing spatial frequency as seen in the figures.

However, further conclusions should be made after trials with more subjects which might be performed later by Markéta Zawadová.

[8] The IOLs are referred as "model" to avoid mentioning manufacturer names because the study has not been completed yet and its results are not a subject of this thesis.

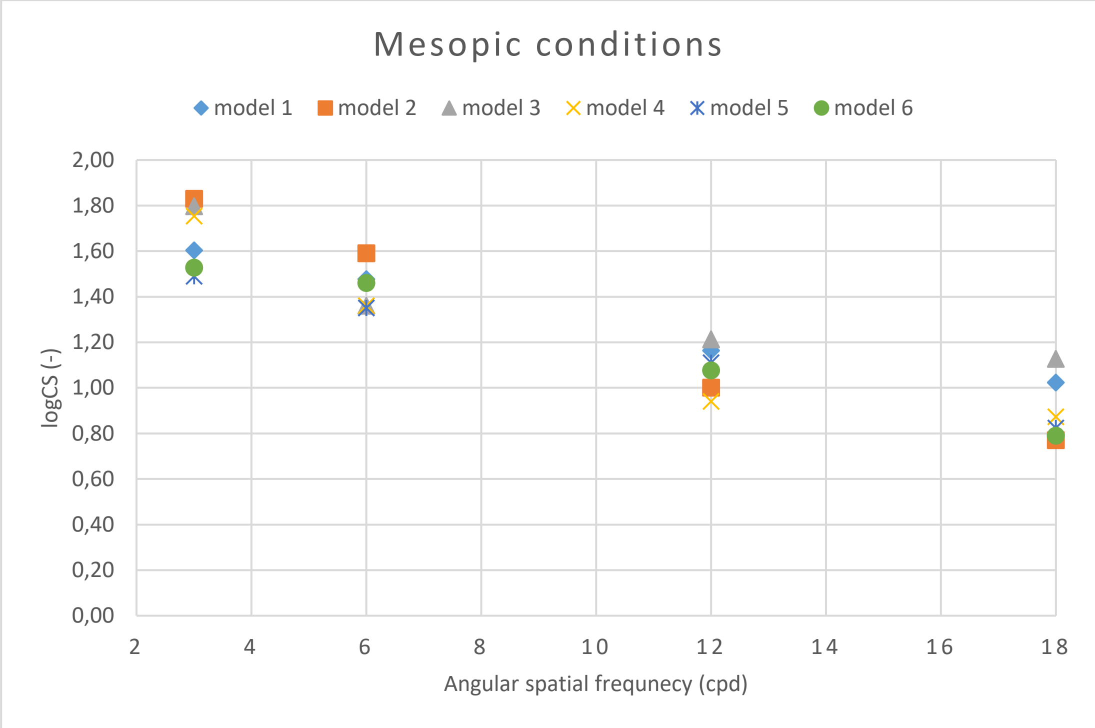

Figure 29: The average contrast sensitivity results of subjects for each intraocular lens in mesopic conditions – the graph shows different dependencies of contrast transfer on the spatial frequency among tested models

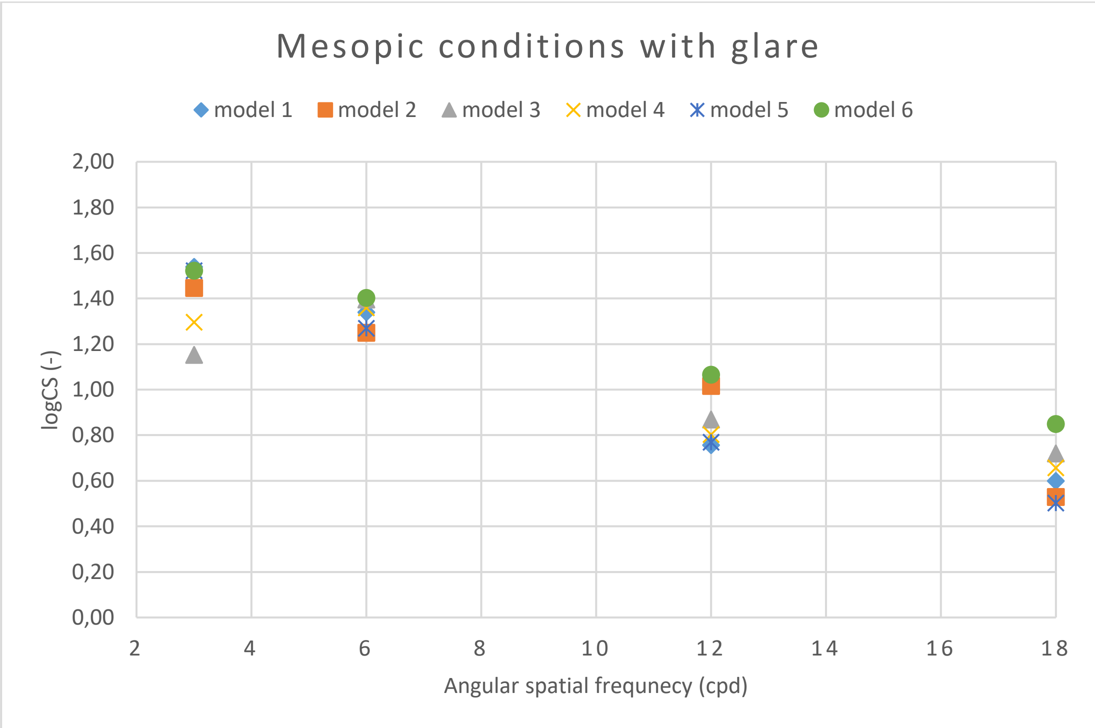

Figure 30: The average contrast sensitivity results of patients for each intraocular lens in mesopic conditions with glare – the differences in the measured CS among the models are most significant at the lowest and highest spatial frequencies

References

[1] RICHMAN. Jesse; SPAETH. George L.; WIROSTKO. Barbara. Contrast sensitivity basics and a critique of currently available tests. Journal of Cataract & Refractive Surgery. 2013. 39.7: 1100-1106.

[2] BOUGUER, Pierre. Traité d'optique sur la gradation de la lumière. De l'imprimerie de HL Guerin & LF Delatour, 1760.

[3] BÜHREN. JENS. et al. Measuring contrast sensitivity under different lighting conditions: comparison of three tests. Optometry & Vision Science. 2006. 83.5: 290-298.

[4] Introduction to Modulation Transfer Function. Edmund Optics [online]. Barrington, NJ USA, 2011 [cit. 2017-03-17]. Accessed at: https://www.edmundoptics.com/resources/application-notes/optics/introduction-to-modulation-transfer-function/

[5] SANTHIAGO, Marcony R., et al. Wavefront analysis and modulation transfer function of three multifocal intraocular lenses. Indian journal of ophthalmology, 2010, 58.2: 109.

[6] YAMAUCHI, Tomofusa, et al. Comparison of visual performance of multifocal intraocular lenses with same material monofocal intraocular lenses. PloS one, 2013, 8.6: e68236.

[7] UOZATO, Hiroshi, et al. Modulation transfer function of intraocular collamer lens with a central artificial hole. Graefe's Archive for Clinical and Experimental Ophthalmology, 2011, 249.7: 1081-1085.

[8] MACRAE, Scott, et al. Special Report: American Academy of Ophthalmology Task Force Consensus Statement for Extended Depth of Focus Intraocular Lenses. Ophthalmology, 2017, 124.1: 139-141.

[9] BOREMAN, Glenn D. Modulation transfer function in optical and electro-optical systems. Bellingham, WA: SPIE press, 2001.

[10] LEGUIRE. L.E. A. ALGAZE. N.H. KASHOU. J. LEWIS. G.L. ROGERS a C. ROBERTS. Relationship among fMRI. contrast sensitivity and visual acuity. Brain Research [online]. 2011. 1367. 162-169 [cit. 2016-10-07]. DOI: 10.1016/j.brainres.2010.10.082. ISSN 00068993. Accessed at: http://linkinghub.elsevier.com/retrieve/pii/S0006899310023875

[11] WANDELL. B.A. Foundations of Vision. Chapter 5: The Retinal Representation. 1995. Sinauer Associates. Inc. Accessed at https://www.stanford.edu/group/vista/cgi-bin/FOV/chapter-5-the-retinal-representation/#centersurround

[12] MORGAN. Erinn. Glare Defined. Eyecare Business. 2007. 8(7).

[13] DHAWAN. Sanjay. Glare. Eye Care Delhi [online]. Delhi. India. 2007 [cit. 2016-10-20]. Accessed at: http://sdhawan.com/ophthalmology/glare.html

[14] Standardized Contrast Sensitivity Tests. VectorVision [online]. 2014 [cit. 2016-10-08]. Accessed at: http://www.vectorvision.com/csv1000-contrast-sensitivity/

[15] ASLAM. Tariq M.; HAIDER. David; MURRAY. Ian J. Principles of disability glare measurement: an ophthalmological perspective. Acta Ophthalmologica Scandinavica. 2007. 85.4: 354-360.

[16] Mesoptic vision. McGraw-Hill Dictionary of Scientific & Technical Terms. 6E. (2003). [cit. 2016-10-09]. Accessed at: http://encyclopedia2.thefreedictionary.com/mesoptic+vision

[17] Mesotest II. OCULUS Optikgeräte GmbH [online]. Wetzlar. 2014 [cit. 2016-10-09]. Accessed at: http://www.oculus.de/en/products/visual-test-equipment/mesotest-ii/highlights/

[18] CSV-1000 Trials. VectorVision [online]. [cit. 2016-11-22]. Accessed at: http://www.vectorvision.com/clinical-trials-csv1000/

[19] Human eye. The New Encyclopaedia Britannica. 15th ed. Chicago: Encyclopaedia Britannica. c2007. Micropaedia. ISBN 1593392923.

[20] Spectral effects of lighting on visual performance at mesopic light levels. New York. NY: Illuminating Engineering Society of North America. 2012. ISBN 9780879952693.

[21] DILAURA L. DAVID. Kevin W. HOUSER. Richard G. MISTRICK a Gary R. STEFFY. The Lighting Handbook: Reference and Application. 10th edition. New York: Illuminating Engineering Society of North America. 2011. ISBN 978-0-87995-241-9.

[22] Lateral inhibition. Sensation and perception. New York. NY: Worth Publishers. 2014. s. 77. ISBN 0716757540.

[23] BECK. J. Sensory Inhibition. Georg von Bekesy. Princeton University Press. Princeton. N.J.. 1967. 277 pp.. illus. $8.50. Science. 1967. 158(3806). 1296-1298. DOI: 10.1126/science.158.3806.1296. ISSN 0036-8075. Accessed at: http://www.sciencemag.org/cgi/doi/10.1126/science.158.3806.1296

[24] Biological contrast sensitivity. In: Wikipedia: the free encyclopedia [online]. San Francisco (CA): Wikimedia Foundation. 2016 [cit. 2016-10-09]. Accessed at: https://en.wikipedia.org/wiki/Contrast_(vision)#Biological_contrast_sensitivity

[25] ALLARD. Rémy. et al. Contrast sensitivity. healthy aging and noise. Vision research. 2013. 92: 47-52.

[26] ROSS. J. E.; CLARKE. D. D.; BRON. A. J. Effect of age on contrast sensitivity function: uniocular and binocular findings. British Journal of Ophthalmology. 1985. 69.1: 51-56.

[27] Laxmi Eye Institute - Contrast sensitivity. LinkedIn [online]. 2016 [cit. 2016-10-08]. Accessed at: http://www.slideshare.net/laxmieyeinstitute/contrast-sensitivity

[28] GÜELL. Jose Luis. et al. Phakic intraocular lenses: part 1: historical overview. current models. selection criteria. and surgical techniques. Journal of Cataract & Refractive Surgery. 2010. 36.11: 1976-1993.

[29] BELLUCCI, Roberto. An introduction to intraocular lenses: material, optics, haptics, design and aberration. In: Cataract. Karger Publishers, 2013. p. 38-55.

[30] MONTÉS-MICÓ. Robert; ALIÓ. Jorge L. Distance and near contrast sensitivity function after multifocal intraocular lens implantation. Journal of Cataract & Refractive Surgery. 2003. 29.4: 703-711.

[31] HEITING. Gary a Michelle STEPHENSON. Contrast Sensitivity Testing. In: All About Vision [online]. AAV Media. LLC. 2016 [cit. 2016-10-07]. Accessed at: http://www.allaboutvision.com/

[32] DANILOVA, Marina V.; BONDARKO, Valeria M. Foveal contour interactions and crowding effects at the resolution limit of the visual system. Journal of Vision, 2007, 7.2: 25-25.

[33] SCHRAUF, Michael; STERN, Claudia. The visual resolution of Landolt-C optotypes in human subjects depends on their orientation: the'gap-down 'effect. Neuroscience letters, 2001, 299.3: 185-188.

[34] Selecting an Eye Chart - Sloan Letters or Snellen? School Health [online]. 2011 [cit. 2016-11-18]. Accessed at: https://www.schoolhealth.com/blog/selecting-an-eye-chart-sloan-letters-or-snellen/

[35] Mars letter test. In: Marsperceptrix [online]. [cit. 2016-10-08]. Accessed at: http://www.marsperceptrix.com/

[36] User manual Mars letter CS test. In: Marsperceptrix [online]. [cit. 2016-10-08]. Accessed at: http://www.marsperceptrix.com/sites/marsperceptrix.com/files/downloads/MarsLetterCSTestUserManualEnglish.pdf Mars chart manual

[37] Contrast Sensitivity Background. VectorVision [online]. 2014 [cit. 2016-10-08]. Accessed at: http://www.vectorvision.com/contrast-sensitivity-background/

[38] Testing for Contrast Sensitivity. University of Calgary [online]. Calgary. 2015 [cit. 2016-10-08]. Accessed at: http://www.ucalgary.ca/pip369/mod4/spatial/testingsensitivity

[39] FRANCO. Sandra. et al. Comparison of the VCTS-6500 and the CSV-1000 tests for visual contrast sensitivity testing. Neurotoxicology. 2010. 31.6: 758-761.

[40] REEVES. Barnaby C.; HILL. A. R. Vistech VCTS 6500 Charts-Within-and Between-Session Reliability. Optometry & Vision Science. 1991. 68.9: 728-737.

[41] KUMAGAI. Jason K.; WILLIAMS. Sheri; KLINE. Donald. vision standards for aircrew: Visual acuity for pilots. DRDC Toronto CR. 2005. 142.

[42] WILLIAM R. HENDEE. PETER N.T. WELLS. edited by William R. Hendee. Peter N.T. Wells. The Perception of Visual Information. Second edition. New York. NY: Springer New York. 1997. ISBN 9781461218364.

[43] ZALEVSKY. Zeev. et al. Thin spectacles for myopia. presbyopia and astigmatism insensitive vision. Optics express. 2007. 15.17: 10790-10803.

[44] TERZI. E. et al. Das „Frankfurt-Freiburg Contrast and Acuity Test System "(FF-CATS). Der Ophthalmologe. 2005. 102.5: 507-513.

[45] IFFT Desiree. Does Contrast Testing have a Place in YOUR CLINIC? Ophthalmology Management [online]. 2003. 4(11) [cit. 2016-10-08]. Accessed at: http://www.ophthalmologymanagement.com/articleviewer.aspx?articleid=85936

[46] Vision Sciences Research Corporation. Instruction Manual. Contrast Sensitivity Tester: Model 1800 Digital. San Ramon. California: Vision Sciences Research Corporation. 2002. Accessed at: https://www.hitpages.com/doc/5232859438645248/

[47] Optec® Plus Smart Vision Screener. Stereo Optical [online]. Chicago. IL USA. 2016 [cit. 2016-10-14]. Accessed at: http://www.stereooptical.com/shop/vision-screeners/optec-plus-smart-vision-screener/

[48] Freiburg Vision Test ('FrACT'). Michael Bach [online]. Freiburg. 2016 [cit. 2016-10-14]. Accessed at: http://www.michaelbach.de/fract/index.html

[49] HOLLADAY. Jack T. Advancing Contrast Testing. Ophthalmology Management. 2009. 13.4: 49-51.

[50] DORR. Michael. et al. Rapid and Reliable Assessment of the Contrast Sensitivity Function on an iPad. Contrast Sensitivity Function Assessment. Investigative ophthalmology & visual science. 2013. 54.12: 7266-7273.

[51] CHEN. Ai Hong; MOHAMED. Diana. New paediatric contrast test: Hiding Heidi low-contrast 'face' test. Clinical & experimental ophthalmology. 2003. 31.5: 430-434.

[52] Hiding Heidi - Low Contrast Face Test for Communication Distances. Lea Vision Test System [online]. Helsinki. 2015 [cit. 2016-10-08]. Accessed at: www.lea-test.fi/en/vistests/instruct/hidinghe/hidinghe.html

[53] PELLI. Denis G.; FARELL. Bart. Psychophysical methods. Handbook of Optics. Second ed. New York: McGraw-Hill. 1995.

[54] GESCHEIDER. George A. Psychophysics: the fundamentals. 3rd ed. Mahwah. N.J.: L. Erlbaum Associates. 1997. ISBN 080582281X.

[55] EHRENSTEIN. Walter H.; EHRENSTEIN. Addie. Psychophysical methods. In: Modern techniques in neuroscience research. Springer Berlin Heidelberg. 1999. p. 1211-1241.

[56] Adaptive Verfahren in der Psychophysik: Effiziente Bestimmung von Absolut- und Unterschiedsschwellen. Ergonomie aktuell [online]. 2012, 13(1), 78-84 [cit. 2016-11-18]. ISSN 0340-0131. Dostupné z: http://www.lfe.mw.tum.de/wp-content/uploads/2012/11/zeitung13.pdf

[57] ROBERT SEKULER. Randolph Blake. Perception. 5th ed. New York: McGraw-Hill. 2006. ISBN 9780071112727.

[58] HASHEMI. Hassan. Mehdi KHABAZKHOOB. Ebrahim JAFARZADEHPUR. Mohammad Hassan EMAMIAN. Mohammad SHARIATI a Akbar FOTOUHI. Contrast Sensitivity Evaluation in a Population-Based Study in Shahroud. Iran. Ophthalmology [online]. 2012. 119(3). 541-546 [cit. 2016-10-21]. DOI: 10.1016/j.ophtha.2011.08.030. ISSN 01616420. Accessed at: http://linkinghub.elsevier.com/retrieve/pii/S0161642011007950

[59] HOHBERGER. Bettina. Robert LAEMMER. Werner ADLER. Anselm G. M. JUENEMANN a Folkert K. HORN. Measuring contrast sensitivity in normal subjects with OPTEC® 6500: influence of age and glare. Graefe's Archive for Clinical and Experimental Ophthalmology [online]. 2007. 245(12). 1805-1814 [cit. 2016-10-21]. DOI: 10.1007/s00417-007-0662-x. ISSN 0721-832x. Accessed at: http://link.springer.com/10.1007/s00417-007-0662-x

[60] PUELL. María C.. Catalina PALOMO. Celia SÁNCHEZ-RAMOS a Consuelo VILLENA. Mesopic contrast sensitivity in the presence or absence of glare in a large driver population. Graefe's Archive for Clinical and Experimental Ophthalmology [online]. 2004. 242(9). 755-761 [cit. 2016-10-21]. DOI: 10.1007/s00417-004-0951-6. ISSN 0721-832x. Accessed at: http://link.springer.com/10.1007/s00417-004-0951-6

[61] EPPIG, Timo, et al. Index of contrast sensitivity (ICS) in pseudophakic eyes with different intraocular lens designs. Acta ophthalmologica, 2015, 93.3: e181-e187.

[62] HAUGHOM, Bente; STRAND, Trond-Eirik. Sine wave mesopic contrast sensitivity–defining the normal range in a young population. Acta ophthalmologica, 2013, 91.2: 176-182.

[63] CIE - INTERNATIONAL COMMISSION ON ILLUMINATION [online]. Vienna, Austria [cit. 2017-01-05]. Accessed at: http://www.cie.co.at/index.php/LEFTMENUE/index.php?i_ca_id=257

[64] BACKHAUS, Werner., Reinhold KLIEGL a John Simon. WERNER. Colour vision: perspectives from different disciplines. New York: Walter de Gruyter, 1998. ISBN 3110154315.

[65] Norms: Contrast Sensitivity Values and Norms for the CSV-1000E. VectorVision [online]. [cit. 2016-11-18]. Accessed at: http://www.vectorvision.com/csv1000-norms/

[66] WOODS, David L., et al. Factors influencing the latency of simple reaction time. Frontiers in human neuroscience, 2015, 9: 131.

[67] STELMACH, George E.; GOGGIN, Noreen L. Psychomotor decline with age. choice, 1988, 247.307: 24.

[68] WILKINSON, Robert T.; ALLISON, Sue. Age and simple reaction time: Decade differences for 5,325 subjects. Journal of gerontology, 1989, 44.2: P29-P35.

[69] CLARKSON, Priscilla M. The effect of age and activity level on simple and choice fractionated response time. European journal of applied physiology and occupational physiology, 1978, 40.1: 17-25.

[70] BONDARKO, Valeria M.; DANILOVA, Marina V. What spatial frequency do we use to detect the orientation of a Landolt C?. Vision Research, 1997, 37.15: 2153-2156.

[71] KIMPE, Tom; TUYTSCHAEVER, Tom. Increasing the number of grey shades in medical display systems—how much is enough?. Journal of digital imaging, 2007, 20.4: 422-432.

[72] POMERANCE, Glenn N.; EVANS, David W. Test-retest reliability of the CSV-1000 contrast test and its relationship to glaucoma therapy. *Investigative ophthalmology & visual science*, 1994, 35.9: 3357-3361.