UNIVERSITY OF LATVIA

Summary of Doctoral Thesis

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DEVELOPMENT OF A METHODOLOGY FOR EVALUATING VISION CHANGES CAUSED BY CATARACTS

Riga 2023

UNIVERSITY OF LATVIA

FACULTY OF PHYSICS, MATHEMATICS AND OPTOMETRY

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SUMMARY OF THE DOCTORAL THESIS

Submitted for the degree of Doctor of physics and astronomy

Subfield of medical physics

Riga 2023

The doctoral thesis was carried out at Faculty of Physics, Mathematics and Optometry University of Latvia and Institute of Physics University of Latvia from 2018 to 2023.

The thesis contains the introduction, four chapters, summary, and reference list.

Form of the thesis: collection of research papers in field of physics and astronomy, subfield of medical physics.

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3) Prof. Dr. **Jan Kremers**, Friedrich-Alexander University of Erlangen-Nuremberg, Germany

The thesis will be defended at the public session of the Doctoral Committee of field of physics and astronomy, University of Latvia, on 15th of December, 2023.

The thesis is available at the Library of the University of Latvia, Raiņa bulvaris 19.

Chairman of the Doctoral Committee: Dr. phys. **Gunta Krūmiņa**

Secretary of the Doctoral Committee: **Sintija Siliņa**

ISBN 978-9934-36-112-8
ISBN 978-9934-36-113-5 (PDF)

ABSTRACT

This work is dedicated to researching the possibilities to develop new methodology for monitoring the progression of cataracts. Nowadays, when any symptomatic cataract is a surgically disorder, it is warranted to identify novel techniques. It has been experimentally proven that daily activity and color vision questionnaires can be an additional tool to evaluate patients with cataract, and the results show strong positive correlation with clinical tests like visual acuity, contrast sensitivity and color vision tests. Based on the results of color vision sensitivity measurements, cap arrangement tests are sensitive to detect color vision shift before and after cataract surgery. It is proven that color vision sensitivity stabilized 2 till 6 months after cataract removal, but patients experienced subjective color vision change 2 weeks after cataract surgery.

It has been experimentally proven that objective scattering index can be an additional method to differentiate cataract types. The results provide healthcare professionals with a better perspective regarding patient experiences depending on cataract type, both before and after cataract surgery, related to color vision.

The obtained results were published in 5 SCOPUS-indexed scientific articles and they were presented in 16 international conferences and seminars.

Keywords: Cataract, questionnaire, color vision, contrast vision, light scattering

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GENERAL DESCRIPTION

Introduction

A cataract is a clouding or opaque of the crystalline lens in the eye. It is a common condition after age of 40 and still the leading cause of low vision and blindness worldwide. [1, 2] It is prognosed that cataract prevalence is going to increase 2 times per 2050 year due to unhealthy lifestyle. Cataract develops when the proteins in the lens of the eye begin to break down and clump together, leading to clouding of the lens. [3] The main risk factors are aging, genetics, smoking and alcohol consumption etc. [4] In Europe 4.7 million surgeries per year are performed, but in Latvia, around 30,000 cataract surgeries are performed each year. [4]

Cataracts can be classified based on their location within the crystallin lens. The three most common types being: nuclear (opacity in nucleus), cortical (wedge-shaped opacities or streaks on the outer edge of the lens cortex), and posterior subcapsular (opacification in the posterior or back portion of the crystalline lens). [1] These types can occur individually or in combination. Cataract progression varies depending on the type of cataract and other factors such as general health and environmental factors. [3, 5] Nuclear cataracts tend to progress more slowly, while posterior subcapsular (PSC) cataracts progress more rapidly than cortical and nuclear cataracts. [5] By removing the cataract as soon as possible, the patient reduces the risk of developing a significant reduction in quality of life, secondary glaucoma (increased intraocular fluid), low vision and inability to work (reduced payments to the state). General health conditions such as hypertension and diabetes have also been linked to the development of cataracts. Hypertension can lead to changes in the lens capsule and disruptions in ion transport in lens epithelial cells, as well as an increase in oxidative free radicals. [6] Other studies have shown an association between obesity, hyperlipidaemia, and cataracts, particularly PSC cataracts. [7] Nowadays, when people become sedentary, get sick more, eat unhealthy food – an increase in cataracts is expected and this can significantly affect the workload of the health system.

Cataract treatment is surgical removal of cloudy lens and its replacing with intraocular lens (IOL). But there is no consensus in the industry on when to recommend cataract surgery. In the literature, the threshold why the surgery was recommended was visual acuity for the cataract eye 0.5 decimal units or worst. Reduced visual acuity combined with cataract symptoms, refractive difference between the eyes or 79 years of age, is also a common reason when cataract surgery was recommended. [8–10] But in 2021 the American Academy of Ophthalmology relisted new guidelines stated that "any kind of symptomatic cataracts are considered a surgical disorder". [1] Previously clinical tests like visual acuity and objective refractive correction was the briefly used methods to asses cataract progression and was a gold standard for monitoring. [8–11] Visual function can be assessed using standard visual acuity tests and contrast sensitivity charts, but these tests may not cover all daily activities and patients complaints. [12] A patient may have very good visual acuity in the dark room where the eye test is performed, but in the light room the visual acuity is significantly lower. In bright light, cataracts can cause glare, which can interfere with the patient's ability to drive a car. If a patient is complaining of worsening vision and lens change is absorbed, contrast sensitivity testing may show a significant loss of visual function that is not assessed by visual acuity testing alone. A set of clinical tests is essential for assessing cataract progression, but a single test cannot individually cover all possible cataract symptoms. That is why it is important to find new methods how we can assess cataract progression covering all daily life activities and compare these subjective findings with clinical tests. An early diagnosis of cataracts or the prompt detection of adverse changes in their progression facilitates timely surgical intervention. Cataract surgery can effectively alleviate patient discomfort and enhance their overall quality of life. Primary vision care providers, such as optometrists, family doctors, and nurses, can undertake cataract monitoring. However, it is imperative to assess the efficacy of clinical tests in diagnosing these changes.

Nowadays cataract is diagnosed subjectively by ophthalmologist with slit lamp examination, but there are no objective methods available. [1] Examining the lens of the eye with a slit lamp is a subjective method based on the experience and knowledge of a specialist. Research has shown promising results in the diagnosis of cataracts using aberrometry (a method for assessing image distortion in the optical system). By analyzing the deformation of the light wavefront caused by the optical elements of the eye, it is possible to observe relatively small opacities in the lens of the eye. [13, 14] The lens of a healthy eye produces negative spherical aberrations, compensating the positive aberrations of the cornea. As the cataract develops, the value of spherical aberrations becomes more positive, which can indicate the changes in the lens. The application of aberrometry would be particularly useful if the patient has good visual acuity but severe complaints that may be due to cataract. [15, 16] There are only a few studies in the literature, with a small number of patients, so further data analysis is needed to better understand whether the technique could be implemented as a standard method for cataract diagnosis in routine practice. Currently, aberrometry is used for intraocular lens selection but not for cataract diagnosis. [16] Aberrometry devices are not available in most eye clinics and optometry practices due to their high cost. Therefore it is essential to find new, affordable methods for primary care professionals to diagnose and monitor cataract progression.

The treatment outcomes are important and relevant to each patient, and the criteria for a successful outcome can vary depending on patient needs, lifestyle, and medical condition. The outcomes may include reduced visual symptoms, improved visual function, achievement of the desired refractive condition, and improved mental health. [2, 17] After cataract removal, people may be able to perform everyday tasks more easily and with greater independence, including activities such as driving, reading, and watching TV. Studies have shown that mental health, physical function, and quality of life can be enhanced when visual function is restored through cataract surgery. [18–25] However, there is a lack of information in the literature about pre and post-surgery satisfaction for different types of cataracts, which has a significant role in recommending the surgery or explaining the expected post-surgery condition. For example, in some cases people with nuclear cataract are able to read in near without glasses due to myopic refraction. After the surgery they will have increased complains about near work, which should be addressed before surgery). It is therefore necessary to develop methodologies and new techniques to assess patients' symptoms, visual function and optical parameters more accurately. The results would explain patients' complaints and serve as a tool for cataract diagnosis, monitoring and surgery recommendations.

Light scattering in the eye

Cataract usually develop slowly and may not cause symptoms at first. Common symptoms are reduced visual acuity, optical correction change, glare, monocular diplopia, color vision shift, contrast vision decreased in medium and high spatial frequencies. Depending on the location of the opacity, cataract can affect vision differently, causing different symptoms in each type. If the opacity is located in the center of the lens (nuclear cataract), it may affect visual acuity more at a distance than up close. If the opacity is in the form of spokes (cortical cataract), patients may complain about glare and monocular diplopia (see Fig. 1). [1, 5] If the opacity is located just inside the posterior lens capsule (PSC), can cause significant visual impairment if it affects the optical axial region of the lens (see Fig. 2) The severity of symptoms such as reduced visual acuity, reduced contrast vision, glare, and impaired color vision may vary at different stages of cataract. [26]

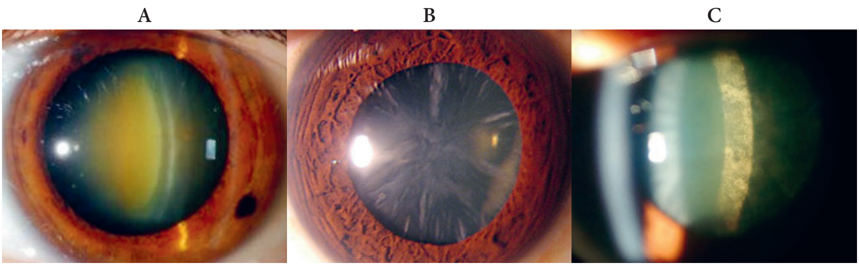


Figure 1. Cataract types: nuclear (A), cortical (B) and posterior subcapsular cataract (C) [27-29]

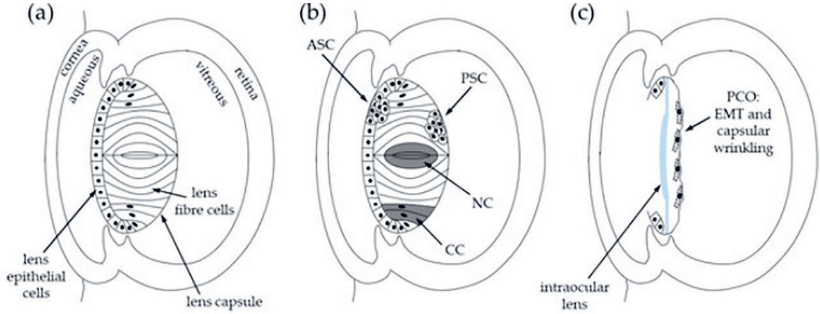


Figure 2. Schematic drawing of the human crystalline lens. Figure (a) shows a healthy eye: black dots represent epithelial cells, lines – lens fibers. Image (b) describes anterior subcapsular cataract (ASC), nuclear (NC), cortical (CC) and posterior subcapsular cataract (PSC). Image (c) shows an intraocular lens (IOL) in the capsule after cataract surgery. [34]

Human eye isn't a perfect optical system; it's influenced by diffraction, aberration, and scatter. [30] Any eye condition that impacts the clarity of its optical components results in increased ocular scattering. In fact, elevated levels of ocular scattering have been noted in older patients. Thus, scattering acts as an extra constraint on the resolution of the ocular optical system, and its assessment should also be integrated into clinical practice. Light scattering occurs because of tiny irregularities within the eye's structures. These irregularities alter the light's initial path inside the eye due to differences in their refractive indices compared to the surrounding media. [30–33] These irregularities can influence how light travels within the eye and reduce the clarity of the image on the retina. Small elements like particles, foreign substances, variations in density, and uneven surfaces of the eye's optical components can serve as microscopic scatterers due to their non-uniformities. It's worth noting that the cornea and lens are made up of cells and connective tissue, which might exhibit irregularities roughly the size of the light's wavelength. These minute discrepancies can diminish the quality of the image on the retina, casting a haze of stray light over it. Studies have identified particles around 1.4 μm in diameter within the lens, believed to be multilamellar bodies, as significant contributors to the prevalent forward scattering observed in the eye. The accumulation of fibrous membranes and proteins in the cytoplasm of the cells in the lens of the eye causes a significant difference in the refractive index of the light, resulting in significant intraocular scattering. [33–35]

Intraocular scatter is intricate because it's influenced by the shape, size, and refractive index of the scattering structures relative to their surrounding media. Generally, these elements are assumed to be round, allowing for the application of Mie scatter modelling solutions and the relevant approximations (Fig. 3). [34, 35] When the particle's size is similar to the wavelength,

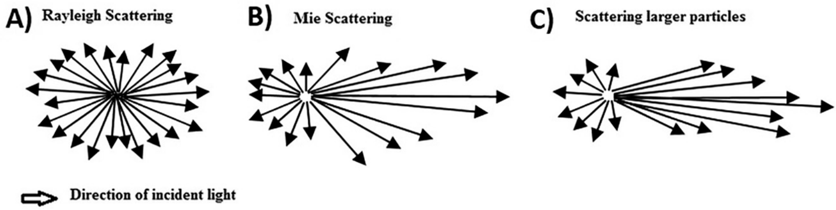


Figure 3. Scattering types based on particle sizes: Scattering pattern for Rayleigh (A) scatter, when a particle's size is under 1/10 of the incident wavelength, is mainly. Rayleigh yielding a uniform scattering pattern around the particle. For particles larger than the incident wavelength, Mie scattering occurs (B and C). The scattering pattern of Mie due to larger particles is more focused in the forward direction as the particle size increases (C).

the Mie scatter approximation applies, and the majority of the scattered light is directed forward. With an aging, the proteins in the central part of the eye lens stick together, forming multilamellar bodies. They are spherical in shape and are located on the equatorial axis of the lens. Multilamellar bodies have been observed to produce Mie light scattering. When the scattering elements are significantly smaller than the light's wavelength, the Rayleigh approximation becomes applicable. [36–38] Rayleigh scattering happens in both the forward and backward directions. When the particle size greatly exceeds the wavelength, light is mainly scattered in the backward direction (ranging from 30° to 180°), and a geometrical approximation can be applied. [35, 39–41] Mie scattering is accurate for spherical particles of any dimension, whereas Rayleigh scattering is only accurate for very tiny particles, whether spherical or not, that are less than a tenth of the wavelength of the incident light. Rayleigh scattering has been detected in the human lenses. Nonetheless, in the eye, scattering is primarily driven by larger particles, which exhibit a reduced dependency on wavelength.

Intraocular scatter can be classified into two categories based on how it alters the direction of incoming light. If the deviation angle is less than 90°, it's referred to as forward light scatter (FLS). FLS reaches the retina, resulting in a masking brightness, often termed as straylight. This diminishes the contrast of the image on the retina and could potentially affect visual clarity. When the angle of deviation exceeds 90°, the light doesn't hit the retina. This occurrence is termed backward light scatter (BLS). [38, 39] As cataract develops, FLS increases, BLS decreases. It is possible that after cataract removal FLS increase. Increased scatter happen due to opacification of posterior lens capsule (secondary cataract) and can be easily treated. The way intraocular scatter varies with angle and its effect on our vision is commonly characterized by the Stiles-Holladay equation:

$$L_{eq} = k \times E_{glare} \times \theta^{-n} \quad (1)$$

L_{eq} represents the equivalent veiling background (cd/m^2), while E_{glare} denotes the illuminance on the pupil's plane caused by the glare source (lux). θ given in degrees, indicates the angle between the direction of viewing and the scatter source. The constants k is a multiplier and age dependent (for a person at the age of 70 $k = 20.21$; at age 25 $k = 10$) and n is a parameter witch vary with an angle of the glare source ($n = 2.3 - 0.07 \times (\log(\theta))$.

If a point of light is imaged on the retina, the light distribution on the retina is called the point spread function (PSF) of the eye. The PSF can be categorized into two areas: (1) the central peak, influencing the 'clarity' of images projected onto the retina, and (2) the outskirts, which determine the image's glare sensitivity and contrast. The central peak is primarily influenced by optical aberrations, including defocus, astigmatism, and other advanced aberrations. Light that hits the outskirts, at angles exceeding 1 degree for instance, is commonly referred to as straylight or scattered light and is calculated:

$$PSF_{ac\bar{i}} (\theta, A, p) = \frac{10}{\theta^3} + (\frac{5}{\theta^5} + 0.1 \times \frac{p}{\theta}) (1 + (\frac{A}{62.5})^4 + 0.0025 \times p, \quad (2)$$

where A is the patient's age, p is a parameter that depends on the patient's eye color (blue eye color $p = 1.2$; blue-green $p = 1$; brown eye color $p = 0.5$), viewing angle θ (degrees). Patients with posterior surface subcapsular cataracts have the highest PSF value. [38, 39]

The fibrous membrane in the lens of the eye and the accumulation of proteins in the cytoplasm of the cells cause a difference in the refractive index of the light, resulting in a significant scattering of light (Fig. 4). Studies confirm that increased light scattering occurs due to the difference in light refraction index, which is most clearly observed in case of the posterior and polar surface cataract. [40–43] The change in density in the clouding is pronounced, causing

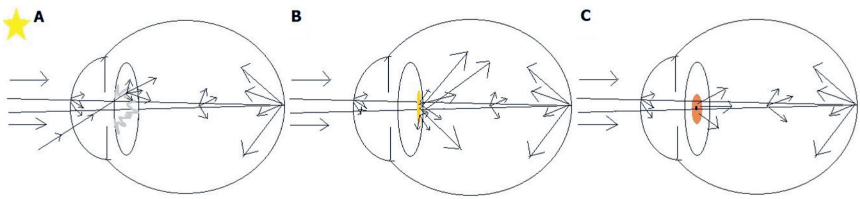


Figure 4. Schematic drawing of ocular scattering depending on cataract type: cortical (A), posterior subcapsular (B) and nuclear cataract (C). Scheme demonstrates the scattering of incident light into the eye. Intraocular scatting happen due to the small, optical inhomogeneities of the cornea, tear film, lens, vitreous body and retina. In the case of cortical cataract (A) light scatter is significant if the incident light passes through the clouding in the periphery of the lens of the eye (grey zone). Opacity in the posterior subcapsular cataract (B) is located in the posterior pole (yellow zone). Opacity is dense and there are significant differences in the refractive index in the intercellular space, which causes significant light scattering. In a nuclear cataract (C), the clouding is in the center of the lens (brown zone). The refractive index of the clouding is insignificantly different from the refractive index of the rest of the lens without causing significant light scattering.

a significant difference in the refractive index. Studies have shown that patients with PSC may have good visual acuity, but have severe light scattering, which reduces contrast vision significantly. In the case of nuclear cataract, changes in the refractive index are insignificant. Although protein accumulation in the central part is observed during the formation of nuclear cataract, histological changes do not cause a significant increase in the refractive index. [45] Light scattering in the eye is negligible, unless the nucleus of the lens has prolapsed (in the late stage of cataract), causing severe damage to the lens fibers. In the initial case of cortical cataract, no pronounced light scattering is observed. Although cortical cataract opacities are spike shaped, they are not deep and similar in density.

Light absorption increases with an aging. If the cataract is dense, brown or yellow in the color it can absorb more light than a healthy lens. As a result, the amount of light reaching the retina decreases and vision becomes dimmer, and more light in the short-wavelength spectrum is absorbed. It can also lead to a more yellow or brown color perception. [44–46] A healthy lens will have a higher absorption coefficient in the UV range and a lower absorption coefficient in the visible range. It is difficult to describe mathematically lens absorption of cataract because the lens of the eye is not a homogeneous mass but a complex, multi-layered structure with different properties at different depths. Similarly, the exact composition of the lens, including the distribution and concentration of proteins, changes with age and depends on a person's overall health. [47]

To gain insight into the absorption of the eye lens, Monte Carlo simulations can be used. [48] The Monte Carlo simulation is a statistical method based on the generation of random numbers to obtain specific results. Simulations can be used to model light absorption in the eye lens, tracking the path of photons as they enter the eye from various directions and angles. The Monte Carlo simulation is powerful because it allows us to understand complex systems like cataracts, which might be difficult or even impossible to analyze using traditional mathematical methods. However, since the method is based on randomness, it requires significant computational power to produce accurate results. Monte Carlo simulation plays a crucial role in medical research, for example, in understanding how to protect the eye from harmful radiation or understanding how different radiations can affect eye health. [48, 49] The simulation can be defined by describing:

1. The geometry and composition of the eye lens (absorption, scattering coefficients).
2. Properties of the photon source, such as its energy, wavelength, and scattering angles.
3. The interaction rules between photons and the eye lens (for instance, the probability that a photon is absorbed, scattered, or induces another reaction).

Subsequently, many photons are simulated in the method, tracking each individually as they penetrate the lens. In the end, data is compiles – how many photons were absorbed, how many were scattered. To obtain statistically significant results, this simulation needs to be repeated hundreds of thousands or even millions of times. Unfortunately, there is no literature available on the results of Monte Carlo simulations for cataract patients. [48, 49]

Aim and tasks of the thesis

The aim of the thesis is to develop a methodology that would enable vision care specialists to more fully evaluate the progression of cataracts, taking into account clinical tests and patient subjective evaluations.

The main objectives of the thesis are:

1. To develop and evaluate the applicability of a questionnaires for cataract patient care;
2. To evaluate the correlation between patients' subjective sensations and clinical vision care tests (color vision, visual acuity, contrast sensitivity);
3. To evaluate which color vision test is most sensitive in optometric practice for assessing changes in color vision sensitivity before and after cataract surgery;
4. To evaluate the applicability of eye light scattering coefficients in the diagnosis of cataracts.

List of publications and conferences

Approbation of the results

[dis1] **Jansone-Langina, Z.**, Solomatin, A., Ozolinsh, M., Solomatins, M., Krumina, G. (2023) Quality of life assessment for nuclear cortical posterior subcapsular patients before and after cataract surgery, *Journal of Optometry* – accepted on the 12th of September, 2023

[dis2] **Jansone-Langina, Z.**, Ozolinsh, M. (2023) Color vision sensitivity screening before and one week after cataract removal surgery, Proc. SPIE 12627, *Translational Biophotonics: Diagnostics and Therapeutics III,* 126271K. https://doi.org/10.1117/12.2672952

[dis3] **Jansone-Langina, Z.**, Ozolinsh, M. (2023) Evaluation of Color Vision Related Quality of Life Changes Due to Cataract Surgery, *J. Opt. Soc. Am. A*, 40, A139-A148. https://doi.org/10.1364/JOSAA.477090

[dis4] **Jansone-Langina, Z.**, Truksa, R., Ozolins, M., Solomatin, A., Solomatins, I. (2022) Contrast sensitivity at different background brightness levels and objective scattering index changes in patients before and after cataract removal surgery, Proc SPIE, *Tissue Optics and Photonics* II, 121470B. https://doi.org/10.1117/12.2624513

[dis5] **Jansone, Z.**, Truksa, R., Ozolinsh, M. (2020) Visual acuity and color discrimination in patients with cataracts, *J. Opt. Soc. Am. A,* 37, A212-A216. https://doi.org/10.1364/JOSAA.382397

Participation in conferences

[conf 1] **Jansone-Langina, Z**. & Ozolinsh, M. (2023) Colour vision screening test sensitivity before and one week after cataract, Scottish Vision Group 2023, Dundee, UK

[conf 2] **Jansone Langina, Z**. & Ozolinsh, M. (2022) Cataract type dependence on lens thickness parameter, AVA Virtual Christmas, Nottingham, UK

[conf 3] **Jansone-Langina, Z.,** Truksa, R., Ozolins, M., Solomatin, A., & Solomatins, I. (2022). Contrast sensitivity at different background brightness levels and objective scattering index changes in patients before and after cataract removal surgery, SPIE Photonics Europe 2022, Strasbourg, France

[conf 4] **Jansone Langina, Z.,** Mikelsone, R. & Gertnere, J. (2022). Differences of corneal biomechanical parameters for keratoconus patients, SPIE Photonics Europe 2022, Strasbourg, France

[conf 5] **Jansone-Langina, Z.,** Solomatin, A., Jurjane, M., Solomatins, M., Solomatins, I. (2022) Quality of life assessment before and after cataract surgery, EAOO 2022, EAOO & ECOO General Assembly, Dublin, Ireland

[conf 6] **Jansone-Langina, Z.,** Ozolinsh, M., Truksa, R., Fomins, S. (2022) Contrast sensitivity changes at different background brightness levels in patients before and after cataract removal surgery, AVA Virtual Christmas meeting, London, UK

[conf 7] **Jansone-Langina, Z.,** Ozolinsh, M., Truksa, R., Fomins, S. (2022) Evaluation of color vision related quality of life changes due to cataract surgery, ICVS 2022, Heraklion, Greece

[conf 8] **Jansone-Langina, Z.** (2022) Dzīves kvalitātes izvērtēšana pirms un pēc kataraktas operācijas, LOOA un Optometrijas un redzes zinātnes nodaļas, Latvijas Universitātes 80. starptautiskā zinātniskā konference, Riga, Latvia

[conf 9] **Jansone-Langina, Z**. (2021) Diagnostics of near vision functions for children, See the future 2021, Riga, Latvia

[conf 10] **Jansone-Langina, Z.,** Truksa, R., Jurjane, M. (2021) Colour vision sensitivity changes one week after cataract removal surgery, European Academy of Optometry and Optics HELSINKI 2021, Helsinki, Finland

[conf 11] **Jansone-Langina, Z**. (2021) Kontrast redzes izmaiņas pacientiem pirms un pēc kataraktas operācijas, Cilvēka fizioloģijas un uztveres sekcijas un LU un LOOA klīniski praktiskās konferences tēžu krājums, Latvijas Universitātes 79. starptautiskā zinātniskā konference, Riga, Latvia

[conf 12] **Jansone, Z.** (2019) Development of a comparative eye structure table, Developments in Optics and Communications 2019, Riga, Latvia

[conf 13] **Jansone, Z.** & Ozonish, Maris (2019) Visual acuity, colour discrimination in patient with cataract, 25th Symposium of the International Colour Vision Society, Riga, Latvia

[conf 14] **Jansone, Z**. & Ozolinsh, M. (2018) Effects of cataract surgery on patient color vision sensitivity, 10th Conference of the Lithuanian Neuroscience Association (LNA) and 2nd International Symposium on Visual Physiology, Environment and Perception (VisPEP), Vilnius, Lithuania

[conf 15] **Jansone, Z**. & Ozoliņš, M. (2018) Patient color vision sensitivity changes before and after cataract surgery, Developments in Optics and Communications 2018, Riga, Latvia

[conf 16] **Jansone, Z.,** Ozoliņš, M., Laganovska, G. (2017) Colour sensitivity changes before and after cataract surgery, AVA Applied scientist association Xmas 2017 meeting, London, UK

Participation in scientific projects

Participation in the renewal and competence improvement of academic staff at the University of Latvia under the contract No. 8.2.2.0/18/A/010, registration No. ESS2018/289. The project is funded under the specific support objective 8.2.2. "Stiprināt augstākās izglītības institūciju akadēmisko personālu stratēģiskās specializācijas jomās".

Author's contribution

As part of the doctoral thesis, the author was involved in all research activities including design processes and realization of the experiments, processing of results and other work stages of the described methodology.

The author independently developed methodology, experiments [dis1, dis2, dis3, dis 4, dis 5] and performed analytical evaluations of the cataract patient results. The author was the main person in the implementation of all experiments, processing the results and drawing conclusions. The author is the corresponding author of all five mentioned publications. Author independently wrote publications, research proposals and formed a collaboration with Latvian eye clinics. (Dr. Solomatin eye center, Dr. Lukin eye center, Pauls Stradiņš Clinical University Hospital).

Structure of the thesis

The thesis consists of research described in five publications. The research is presented by dividing the work into four subfields. Accordingly, this summary is divided into four main chapters – development and evaluation the applicability of a questionnaires for cataract patients (chapter 1), contrast sensitivity changes due to cataracts (chapter 2), color vision test sensitivity to detect color vision change after cataract surgery (chapter 3) and evaluate patients subjective feeling correlation to color vision test results (chapter 4).

At the beginning of **Chapter 1**, the motivation of the study and the research so far for cataract diagnostics and new guidelines are described indicating the need to find new ways to monitor cataract progression over time. The chapter continues with methodology of quality of life and color vision assessment using Visual Function-14 and newly developed color vision questionnaire. Further, the results are presented describing each cataract type differences in daily life activities.

Chapter 2 shows the study were we look on factors which could influence the questionnaire scores like contrast sensitivity and light scattering in the eye. The method has never been published before and demonstrate patients contrast sensitivity on different backgrounds brightness levels (e.g. phones, computers). The chapter continues with description of how light scattering index correlates with cataract type and can serve as an objective method how to differentiate cataract types.

The **Chapter 3** begins with a literature review to show color vision sensitivity change due to aging and cataracts, and color vision test usage in optometrists practise. The results demonstrate that cap arrangements tests are sensitive to detect color vision shift before and after cataract surgery, and can serve as additional method to monitor cataract progression.

But to gain better understanding of patients subjective complaints and their relationship with clinical test findings, the correlation between color vision questionnaire scores and color vision tests were demonstrated in **Chapter 4**.

At the end of this summary, the main conclusions are presented. After the conclusions, acknowledgement and list of references is provided.

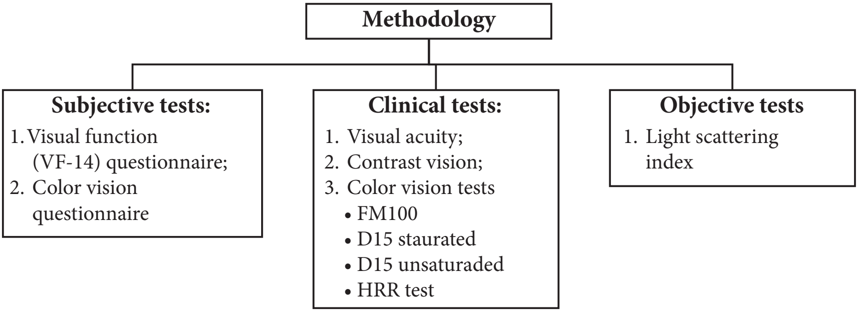
Novelty of the study

The scientific novelty of the results obtained in this study is supported by five articles published in international journals indexed in the SCOPUS database, as well as five conference proceedings that can also be found in the SCOPUS database.

The author has published an original research paper describing the use of a subjective questionnaire for evaluating cataracts in the Latvian population. This questionnaire has been implemented in two Latvian clinics and has been recommended to general health specialists for evaluating cataract progression. The thesis results demonstrate a methodology that could serve as a more objective method and be used as a criteria for recommending cataract surgery for optometrists worldwide. The findings describe the relationship between a patient's subjective feelings and clinical test results and provide additional tools, such as color vision tests and light scattering in the eye, for evaluating the progress of cataracts.

Methodology

To develop methodology I evaluate subjective, objective and clinical tests and their application in the diagnosis and monitoring of cataracts:



Overall, doctoral theses describes the results of 571 cataract patients (924 eyes). Patients with additional eye diseases like age-related macular degeneration, diabetic retinopathy, glaucoma and optical nerve edema were excluded from the research and their results are not demonstrated. Patient eye structures before and after cataract removal surgery were examined by an ophthalmologist using a slit lamp, lens photography, anterior and posterior ocular coherent tomography (Zeiss Cirrus 6000). Written consent was obtained following the tenets of the Declaration of Helsinki and approved by the Ethical Committee of University of Latvia.

1. LIFE QUALITY AND COLOR VISION ASSESSMENT BEFORE AND AFTER CATARACT SURGERY

1.1. Introduction

Nowadays, when any symptomatic cataract is a surgically disorder, subjective complaints can serve as a reason to consider the cataract surgery. Patients can assess the impact of cataracts on their visual function subjectively by reporting their functional status or difficulty with vision. Questionnaires can be a useful method for comparing objective and subjective findings. They help to monitor cataract progression and patient complaints relationship to the condition. [1, 42] When examining cataract patients questionnaires are currently not a standard method of eye examination, focusing more on clinical vision tests. But as the guidelines change [1], it is necessary to improve the eye examination, providing a comprehensive test (objective, clinical, subjective tests). Over time, patients may adapt to their visual impairment and fail to notice the functional decline that comes with the gradual progression of cataracts (e.g. first stages of cataract). [18, 24] Color vision sensitivity change is gradual prior to cataract surgery and patients do not notice it. [50, 51] However, different types of cataracts can cause different complaints. Questionnaires can serve as a tool to convince the patient that cataract surgery is necessary because of noticeable changes in the quality of life.

The aim of our study was to evaluate patient's quality of life before and after cataract surgery. The experiment was carried out in two parts; First, we looked on overall subjective questionnaire scores and evaluated the differences between the responses of patients with nuclear, cortical, and posterior subcapsular cataracts, which have not been mentioned in the literature before. [dis1] Secondly, I developed a new questionnaire concentrating on color vision related daily activities, to better examine if patient with cataract detect color vision change subjectively. [dis3] The results of our study can serve as informative material for eye health specialists to help prepare patients for what to expect after cataract surgery depending on their cataract type, and be a research tool to monitor cataract progression in dynamic. So far, daily life activity questionnaires has not been used in Latvia, as a tool to monitor cataract progression, but due to our findings, were implemented as a standard toon in two Latvian clinics.

1.2. Method "Quality of life assessment"

The study analyzed 210 cataract patients (420 eyes, mean age 64 ± 6 years). All the patients were divided in 3 groups depending on their cataract type: nuclear (*n* = 80 patients; 160 eyes), cortical (*n* = 70), posterior subcapsular

(n = 60). An ophthalmologist identified the type of cataract, but there is no mention of the cataract grade in the patient's medical history, and therefore this study cannot provide any information on it. Both eyes of the patient underwent cataract surgery, with a gap of two days between the surgeries. For all patients surgeons implanted monofocal intraocular lens, with a target refraction 0 Dioptres. Before and after cataract surgery patient visual acuity was measured monocularly using the Snellen chart (decimal units). An optometrist collected data on visual acuity in both far and near distance, as well as information on refractive optical correction, prior to the cataract surgery, as well as at 2 weeks and 1 month follow up. Binocular vision and stereopsis were evaluated in all patients both before and after the cataract surgery.

In order to gain a better understanding of the subjective experiences of patients before and after cataract surgery, we utilized the Visual Function Questionnaire (VF-14) to collect data. [18, 52] The VF-14 is a concise questionnaire that is specifically designed to evaluate the functional impairment of patients resulting from cataract. It comprises 14 questions (qn.) that cover various daily activities such as reading different sizes of print, recognizing people, driving, etc. Patients has to grade their answer form: no = 4 ; yes, with a little difficulty = 3; yes, with a moderate amount of difficulty = 2; yes, with a great deal of difficulty = 1; yes, and am unable to do the activity = 0; blank if the question is not applicable. Questionnaire scores are calculated as the summated responses divided by the number of valid responses multiplied by 25. The final score range is between 0 and 100. A score of 100 indicates able ability to do all applicable activities, 0 indicates unable inability to do them. Results from 0–29 indicated severe; 30–74 moderated; 75–98 mild; 99–100 no visual impairment.

1.3. Results

The study investigated the impact of cataracts on patients' subjective quality of life. [dis1] Before cataract surgery, patients reported significant problems with reading small print. The questionnaire score for the first question showed the lowest result compared to the other questions. After cataract surgery, patients experienced significant improvement at the 2-week and 1-month follow-up (see Table 1).

Before and 2 weeks after cataract surgery, cortical and nuclear cataract patients had the lowest subjective satisfaction with reading small print (qn. 1). However, there was no statistically significant difference between questionnaire results before and 2 weeks after the surgery. The cortical cataract group experienced the greatest improvement after cataracts removal in the first question (see Fig. 5).

Table 1. VF-14 questionnaire mean score along with their standard deviations before and after cataract surgery. Table describes patient answers ($n = 210$) before, 2 weeks and 1 month after the cataract surgery. The questionnaire score is analysed by comparing different follow-up period answers. *P* values in bold demonstrate statistically significant difference between questionnaire score in different time periods.

Question No.	Questionnaire score, units			*p* value		
	Before	2 weeks	1 month	Before vs 2 weeks	2 weeks vs 1 month	Before vs 1 month
1.	41 ± 29	67 ± 26	87 ± 26	**<0.01**	**<0.01**	**<0.01**
2.	64 ± 34	79 ± 24	91 ± 31	**<0.01**	**<0.01**	**<0.01**
3.	85 ± 28	93 ± 16	92 ± 18	**<0.01**	**<0.01**	0.23
4.	88 ± 22	95 ± 14	81 ± 18	**<0.01**	0.38	**<0.01**
5.	91 ± 18	96 ± 12	85 ± 22	0.34	**<0.01**	0.33
6.	88 ± 18	92 ± 16	86 ± 20	**<0.01**	0.21	**<0.01**
7.	61 ± 30	79 ± 24	92 ± 16	**<0.01**	**<0.01**	**<0.01**
8.	70 ± 29	81 ± 24	94 ± 15	**<0.01**	**<0.01**	**<0.01**
9.	71 ± 25	88 ± 26	87 ± 21	**<0.01**	**<0.01**	**<0.01**
10.	83 ± 25	94 ± 14	88 ± 20	**0.02**	0.08	0.41
11.	90 ± 18	89 ± 20	85 ± 22	**<0.01**	0.24	**<0.01**
12.	77 ± 24	87 ± 24	77 ± 36	**<0.01**	**<0.01**	0.07
13.	80 ±2 7	76 ± 29	76 ± 33	0.06	0.32	**0.04**
14.	78 ± 25	82 ± 31	77 ± 33	0.34	0.32	0.44

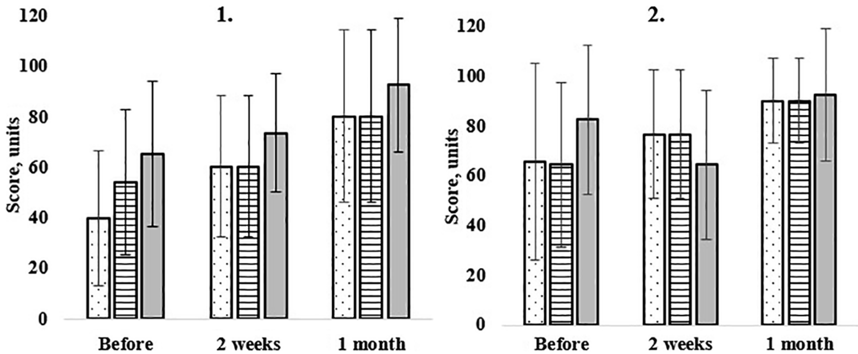


Figure 5. Patient questionnaire scores to the first (left) and second (right) question. Figure demonstrates patient ($n = 210$) answers before, 2 weeks and 1 month after the cataract surgery. Dotted bars corresponds to cortical ($n = 80$), lined bars to nuclear ($n = 70$) and grey color bars to posterior subcapsular patient answers ($n = 60$) at the different time periods. In the first question before the surgery cortical cataract patients showed the worst subjective feelings about reading small print. In the second question, there were no statistically significant difference between cataract groups ($p > 0.05$).

Patients experienced significant improvement in reading medium-sized letters (qn. 2) after cataract surgery. There was no statistically significant difference between the questionnaire scores of the three cataract groups before, 2 weeks, and 1 month after cataract surgery. Two weeks after the surgery, posterior subcapsular patients reported a subjective reduction in reading activity, which improved at the 1-month period.

Before and after cataract surgery, all patients had binocular vision and stereopsis, which was measured with Worth test, polarization test in far distance. Before the surgery, nuclear cataract patients had a statistically significant different questionnaire score compared to PSC. Two weeks after cataract surgery, the nuclear cataract group had the biggest questionnaire score improvement for the fifth question but did not show a statistically significant difference compared to the PSC and cortical cataract groups (see Fig. 6). At the 1-month follow-up, there was no difference between cataract groups, but the questionnaire score decreased dramatically and showed a big standard deviation.

Based on the results of the study, patients experienced statistically significant improvements in their ability to read traffic, street or store signs, perform handwork activities such as sewing and knitting, and complete daily activities like writing checks or filling out forms after cataract surgery. These improvements were observed at both the 2-week and 1-month follow-up periods. Before the surgery all cataract types groups had demonstrated a statistically significant difference between questionnaire score ($p < 0.05$) to the seventh question (handwork). In terms of handwork activities, cortical cataract patients experienced the most difficulty before surgery, but had the biggest improvement

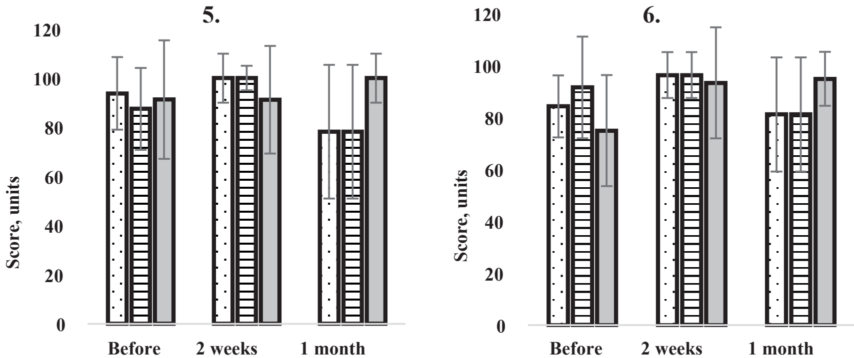


Figure 6. Patient questionnaire scores to the fifth (left), and sixth (right) question. Figure demonstrates patients (n = 210) answers before, 2 weeks and 1 month after cataract surgery. Dotted bars correspond to cortical (n = 80), lined bars to nuclear (n = 70) and grey color bars to posterior subcapsular patient answers (n = 60) at the different time periods. Before the cataract surgery there was a statistically significant difference in the fifth and sixth question between posterior subcapsular and nuclear patient scores.

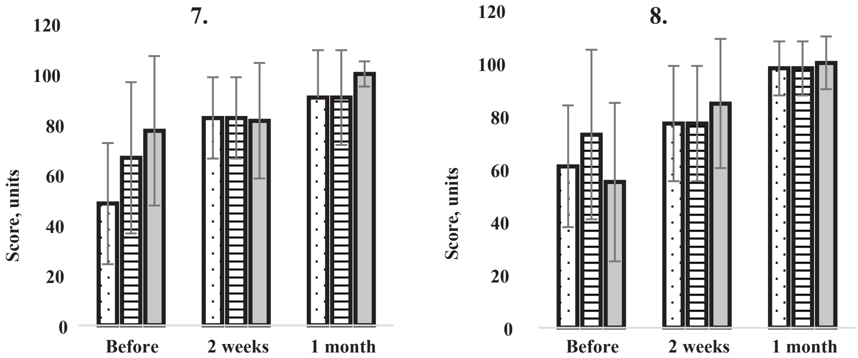


Figure 7. Patient questionnaire scores to the seventh (left), and eight (right) question. Figure demonstrates patients (n = 210) answers before, 2 weeks and 1 month after cataract surgery. Dotted bars correspond to cortical (n = 80), lined bars to nuclear (n = 70) and grey color bars to posterior subcapsular patient answers (n = 60) at the different time periods. Before the cataract surgery there was a statistically significant difference between all the groups (seventh question). Nuclear and posterior subcapsular patient scores were statistically significantly different only before the surgery (eight question).

after surgery. Two weeks after surgery cortical and nuclear group results were not statistically significant ($p = 0.50$), but there were was a difference with PSC group results. At the 1 moth follow-up PCS patients showed almost perfect questionnaire score which shows no problems performing handwork activities (see Fig. 7). To the eight question, before the surgery the questionnaire score was not statistically significant between all cataract groups ($p < 0.10$). PSC patients had the most difficulty filling out forms before surgery, but had significant improvements after surgery.

The results indicate that cataract surgery can improve the ability to play board games, as demonstrated by improved questionnaire scores at 2 weeks and 1 month after surgery. While the cortical group patients experienced the most trouble performing this task, due to the high standard deviation, this cannot be completely confirmed (see Fig. 8). Cataract patients often experience fear of falling, which makes them more careful when doing sport. However, the questionnaire score to the tenth question statistically significantly changed two weeks after cataract surgery, indicating an improvement in this area. The subjective score did not change at the 1 month follow-up. All the cataract group results were not statistically significant before, 2 weeks, and 1 month after cataract surgery ($p > 0.05$).

Cataract surgery also improved the ability to watch television (qn.11), as demonstrated by statistically significant improvement immediately after surgery. Before and 2 weeks after the surgery, PSC patients subjectively felt more affected while watching television than Nuclear and Cortical patients ($p < 0.05$). But at the 1 month follow up questionnaire scores to the eleventh question were not statistically significant ($p > 0.08$).

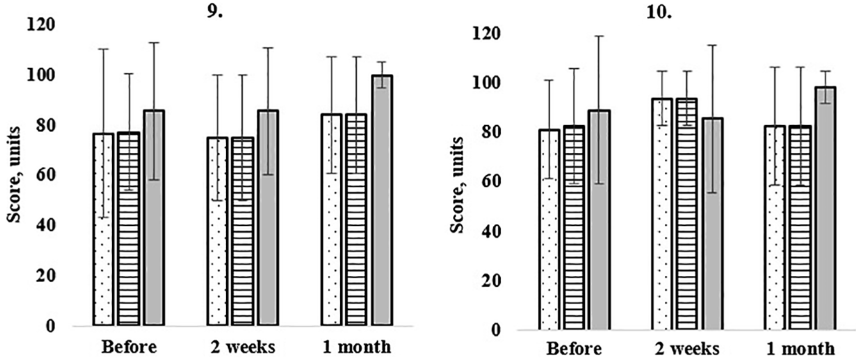


Figure 8. Patient questionnaire scores to the seventh ninth (left) and tenth (right) question. Figure demonstrates patients (n = 210) answers before, 2 weeks and 1 month after cataract surgery. Dotted bars correspond to cortical (n = 80), lined bars to nuclear (n = 70) and grey color bars to posterior subcapsular patient answers (n = 60) at the different time periods. Before the surgery cortical cataract group results were statistically significantly different as compared to nuclear and PSC group results ($p = 0.05$) (ninth question). At the one month follow-up the mean results were not statistically different. To the tenth question all the cataract group results were not statistically significant before, 2 weeks, and 1 month after cataract surgery ($p > 0.05$).

Before the surgery driving during daylight was most uncomfortable for patients with nuclear ($p < 0.05$). However, two weeks after surgery, the greatest subjective improvement was noted in the nuclear group. At the 1 month follow-up, there was statistically significant improvement in driving during daylight. There were no statistically significant differences between the cataract groups at the 2 week and 1 month follow-up. Driving during night time did not show subjective changes after cataract surgery. The greatest improvement after cataract surgery was experienced by the cortical cataract group, which had a statistically significant difference in questionnaire scores compared with nuclear and posterior subcapsular patients. [dis1] There was no statistically significant difference in results between the cataract groups at the 2 week and 1 month follow-up.

1.4. Method "Subjective color vision assessment"

Subjective color sensitivity study analyzed 80 nuclear cataract patients (mean age 61 ± 21 years). [dis3] The surgery was performed for both eyes with a two day delay between surgery of each eye. The nuclear cataract type was diagnosed by an ophthalmologist but the information about cataract grade was not indicated in the patient history and cannot be addressed in this study. At the first eye examination, patients filled out a form where they noted complaints, optical refraction, eye health history, and marked if they have a color vision deficiency. All observers were normal trichromats based upon the Hardy Rand and Rittler (HRR) color vision testing. [53]

Table 2. Modified questionnaire questions. The first 3 questions are from the original Visual Activities Questionnaire, while the remaining 5 have been gathered from various sources. [51, 55, 56]

No.	Color vision related questions
1.	I tend to confuse colors
2.	The color names that I use disagree with those that other people use
3.	I have difficulty distinguishing between colors
4.	I feel that colors appear different than before
5.	The colors appear bluer than before
6.	It is hard for me to distinguish whether the food is ready depending on its color
7.	I feel that the colors appear yellower
8.	I feel that the colors have changed their brightness

To better understand the subjective feelings of patients before and after cataract surgery we collected information with the modified Visual Activities Questionnaire (VAQ). [55] The questionnaire is used to assess an individual's problems in performing visual activities typical in everyday life. The VAQ contains 33 questions which can be divided in 8 categories. In the VAQ there are 3 questions about color discrimination (1st–3rd question), but we added 5 additional questions (4th-8th question) to better understand the color vision subjective change (see Table 2). The five additional questions were chosen from the findings from other studies and were not validated. [51, 55, 56] To score an individual item on the VAQ, the following point scale is used: never = 1; rarely = 2; sometimes = 3; ofte*n* = 4; always = 5. The composite score for a visual function is defined as the mean response for the items listed for that visual function. The results of color vision questionnaire was compared with Farnsworth Munsell 100 hue test results. [57] Questionnaires and color vision test were filled out before, 2 weeks and 6 months after cataract surgery.

1.5. Results

The summary of the questionnaire scores are collected in Table 3. [dis3] To the first question "I tend to confuse colors", patient answers did not show a statistically significant change 2 weeks after the cataract surgery ($p = 0.26$), but there was a statistically significant difference at the 6 month follow up as compared to before and 2 weeks answers ($p < 0.01$). Before and 2 weeks after the surgery patients noted color confusion, but at the 6 month follow up complaints were mentioned less. Color confusion was the most prevalent issue before the surgery and had the highest score on the questionnaire compared to other questions ($p < 0.05$). To the second question observers reported

Table 3. Modified Average Questionnaire Scores with their standard deviations at various time periods with respect to the cataract removal surgery in normal, *tritan*, *protan* and *deutan*, and unspecific group [a,b]. Red lines represent questionnaire score which are rated as 2 – sometimes to 4 – often.

Before	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Normal	1.4 ± 0.6	1.1 ± 0.3	1.8 ± 0.7	1.2 ± 0.6	1.0 ± 0.2	1.3 ± 0.5	1.3 ± 0.6	1.2 ± 0.5
Unspecific	2.6 ± 0.5	1.6 ± 0.5	1.8 ± 0.8	1.2 ± 0.4	1.2 ± 0.4	1.6 ± 0.5	1.8 ± 0.8	2.2 ± 1.6
Tritan	2.7 ± 0.7	1.4 ± 0.5	2.6 ± 0.3	1.2 ± 0.4	1.2 ± 0.4	1.4 ± 0.7	1.3 ± 0.5	1.2 ± 0.4
Protan/Deutan	1.6 ± 0.7	1.7 ± 0.6	2.0 ± 0.8	1.4 ± 0.5	1.3 ± 0.7	2.1 ± 0.9	1.3 ± 0.5	1.3 ± 0.4
All (*n* = 80)	2.8 ± 0.8	1.4 ± 0.3	2.2 ± 0.5	1.2 ± 0.3	1.1 ± 0.1	1.5 ± 0.5	1.5 ± 0.5	1.5 ± 0.5
2 weeks	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Normal	1.4 ± 0.6	1.2 ± 0.6	1.3 ± 0.7	2.7 ± 0.9	2.9 ± 0.9	1.4 ± 0.6	1.1 ± 0.3	2.9 ± 0.9
Unspecific	2.0 ± 1.0	1.8 ± 0.8	1.8 ± 0.8	3.2 ± 0.8	3.2 ± 0.4	1.4 ± 0.5	1.2 ± 0.4	3.2 ± 1.5
Tritan	1.8 ± 0.9	1.2 ± 0.5	1.5 ± 0.6	2.8 ± 0.8	2.6 ± 1.2	1.5 ± 0.7	1.1 ± 0.3	1.4 ± 0.9
Protan/Deutan	1.4 ± 0.8	1.5 ± 0.7	2.1 ± 0.9	2.0 ± 1.4	1.8 ± 0.8	1.3 ± 0.5	3.1 ± 0.9	1.6 ± 0.7
All (*n* = 80)	1.6 ± 0.6	1.3 ± 0.4	1.4 ± 0.4	2.7 ± 1.4	2.4 ± 1.1	1.4 ± 0.4	1.6 ± 0.6	1.5 ± 0.6
6 months	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Normal	1.2 ± 0.5	1.1 ± 0.4	1.3 ± 0.7	2.4 ± 0.5	1.3 ± 0.5	1.3 ± 0.4	1.1 ± 0.2	2.5 ± 1.0
Unspecific	1.2 ± 0.4	1.4 ± 0.5	1.8 ± 0.8	2.2 ± 0.4	1.4 ± 0.5	1.4 ± 0.5	1.0 ± 0.1	3.0 ± 1.2
Tritan	1.2 ± 0.4	1.2 ± 0.5	1.4 ± 0.5	2.6 ± 0.8	1.4 ± 0.6	1.4 ± 0.6	1.0 ± 0.2	2.2 ± 0.9
Protan/Deutan	1.6 ± 0.6	1.3 ± 0.6	1.5 ± 0.7	2.9 ± 0.8	1.1 ± 0.3	1.8 ± 0.7	1.1 ± 0.3	3.1 ± 1.2
All (*n* = 80)	1.2 ± 0.2	1.2 ± 0.2	1.4 ± 0.2	2.1 ± 0.7	1.3 ± 0.3	1.3 ± 0.3	1.2 ± 0.2	1.2 ± 0.2

[a] Table describes eight question answers scored from 1 (never) to 5 (always).

[b] Normal; tritan; protan and deutan; unspecific.

a statistically significant color naming improvement at the 6 month follow up as compared to the results before the surgery ($p = 0.05$). Before the cataract surgery observers experienced color distinguishing problems (qn. 3) and showed the second highest questionnaire score in this question ($p < 0.05$ compared to all questions). The higher the questionnaire score, the more often the patient experiences the complaint. After cataract surgery patients did not experience changes in color distinguishing ($p > 0.12$ in all time follow-ups), but there was a statistically significant improvement at the 6 month follow up as compared to the answers before the surgery ($p < 0.01$).

Regarding the fourth question about color appearance, after the cataract surgery there was a statistically significant change at the 2 week period ($p = 0.02$) and the 6 month follow up ($p < 0.01$). Patients reported changes in color appearance and had higher scores on the questionnaire ($p < 0.05$). Before the surgery patients did not experience objects in daily life becoming bluer (qn. 5), but 2 weeks after the surgery, more patients reported this feeling. At the 6 month follow up the questionnaire score decreased and was statistically significantly different as compared to the 2 weeks results ($p < 0.01$). Patients with color vision deficiency often have difficulty distinguishing between different types of cooked food.

In this study, we asked patients if they found it hard to tell if food was cooked by its color. [56] To the sixth question "It is hard for me to distinguish if the food is ready depending on its colors" patients did not report any improvement in this aspect ($p > 0.18$). Regarding the seventh question, it is seen in the literature that nuclear sclerotic cataract can make everything appear more yellow. [57] Usually patients do not notice yellowing of the objects because of the gradual changes, which matches with our results before the surgery. At the 2 week follow up patients experienced complaint more often and showed a statistically significant shift as compared to the result before the surgery ($p = 0.03$), however this effect had disappeared by the 6 month follow up ($p = 0.10$). Patients who underwent cataract removal reported a significant change in brightness change immediately after the surgery ($p < 0.01$) but this perception did not change after 2 weeks compared to 6 month results ($p = 0.09$).

This study examined the impact of cataract surgery on color vision in patients. The results showed that before surgery, color confusion was the most prevalent issue and had the highest score on the questionnaire. However, at the 6 month follow-up, complaints about color confusion were mentioned less often. Additionally, observers reported a statistically significant improvement in color naming at the 6 month follow-up compared to before surgery. Before surgery, observers experienced color distinguishing problems and showed the second highest questionnaire score in this question. After cataract surgery, patients reported changes in color appearance and had higher scores on the questionnaire. Patients did not experience changes in color distinguishing immediately after surgery, but there was a statistically significant improvement at the 6 month follow-up. Patients also reported that objects in daily life appeared bluer 2 weeks after surgery, but this feeling decreased by the 6 month follow-up. Finally, patients reported a significant change in brightness immediately after surgery, but this perception did not change after 2 weeks compared to 6 month results.

2. CONTRAST SENSITIVITY CHANGE DUE TO CATARACT

2.1. Introduction

Nowadays cataract is diagnosed subjectively, and this has led to the development of different approaches to cataract categorization, which could potentially allow standardization of the procedure, making the diagnosis more objective. [58] Tests that assess neurosensory vision, such as contrast vision, color vision, and glare testing, can be used to better understand a patient's complaints and determine the progression of cataracts. Contrast vision, in the context of visual perception and neuroscience, refers to the ability of the visual system to distinguish differences in luminance (brightness) or color between adjacent or spatially separated regions in a visual scene. [59] Contrast is a fundamental aspect of vision and plays a crucial role in perceiving and distinguishing objects, edges, textures, and patterns in the environment. Mathematically, contrast (C) can be described as:

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}},$$

where L_{max} is the maximum luminance value of the two areas being compared and L_{min} (cd/m^2) is the minimum luminance value of the two areas being compared. [60] The contrast threshold stands as the minimal contrast necessary for perceiving an object with clarity. Contrast vision entails the discernment of variances in luminance or chromaticity, facilitating the differentiation of patterns and textures. On the other hand, visual acuity pertains to the precision of vision, delineating the capacity to resolve minute and intricate objects at specified distances. Person can have good visual acuity, but contrast vision could be decreased.

Color and contrast vision tests can provide additional information that may not be detected through other visual function tests like visual acuity. [60] Repeatedly testing contrast sensitivity can be particularly effective in assessing the effectiveness of treatment, as it is more sensitive to changes than other visual functions. The measurement of contrast sensitivity is valuable in evaluating a patient's vision quality in different light environments. [61, 62] For instance, if the opacity of the eye lens is small, the visual acuity may appear normal, but patient may still experience visual difficulties under different conditions, such as when exposed to bright light objects. When cataracts begin to develop, the ability to perceive contrast vision may decrease. [63, 64] This can cause problems with spatial awareness, mobility, and increase the risk of accidents. For example, it may become difficult to walk up or down steps, recognize faces, or drive safely.

Lighting is an important environmental factor that affects contrast sensitivity Weber’s law states that differential sensitivity decreases as the size of the elements in the difference increases; conversely, relative differential sensitivity remains consistent irrespective of size. According to Weber's law, it is generally assumed that the characteristics of the stimuli being viewed do not influence the results of contrast sensitivity testing. The value of the Weber fraction can vary depending on the sensory modality being considered. [64, 65] Therefore, changing the background level, would not be expected to affect the results of these tests. Researches suggests that individuals with cataracts, may require better lighting to perform tasks such as reading or working at close distances. However, there is currently no research that has evaluated changes in contrast sensitivity in cataract patients under different backgrounds before and after surgery. [63, 64] Different background brightness levels can be found in cell phones, computers and tablets. The objective of our study was to assess contrast vision sensitivity at various background levels and compare the level of light scattering in patients before and after undergoing cataract surgery. Nowadays, cataract is diagnosed subjectively and this has encouraged the development of different approaches for categorizing cataracts, which could potentially enable a more standardized procedure, become more objective. [65] That is why we conducted a comparison of the changes in contrast sensitivity at different background levels, spatial frequencies, and Weber's constant values in patients before and after their cataract surgery. [dis4]

2.2. Method

This study included the analysis of 56 control group patients (112 eyes; age 56 ± 17 years) and 82 cataract patients (73 eyes; age 66 ± 12) from the previous study. [dis1] The cataract patients were divided in 3 groups depending on their cataract type: cortical (n = 23 eyes), nuclear (n = 18) and posterior subcapsular (PSC) (n = 18). All patients were measurements 2 hours before and 2 weeks after undergoing cataract removal surgery. Two weeks after the surgery measurements were taken after an ophthalmologist had confirmed that the eye was completely healed and there were no signs of any complications. [dis4]

Contrast sensitivity

Contrast sensitivity was assessed using the alternative forced (AFC) choice test design (see Fig. 9). [66, 67] This test was conducted monocularly, using the best optical correction available for each patient. During each trial of the test, a single stimulus was displayed for a brief period, either horizontally or vertically. Once the stimulus disappeared, two options were presented on the screen, and the patient had to select the one that corresponded to the position of the previously displayed stimulus (*h* or *v*). If the answer was correct, the contrast level of the stimulus was automatically increased. This process was repeated until the test was completed, and the contrast sensitivity threshold for

Figure 9. Alternative forced choice test (AFC) stimuli.

the patient was determined and displayed as a percentage value on the monitor. The results of the contrast sensitivity were expressed in percentages, with a higher percentage indicating a lower level of contrast sensitivity. The contrast sensitivity was calculated using Michelson's Formula:

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \times 100,$$

where C is contrast sensitivity (percent) L_{max} is the maximum luminance value of the two areas being compared and L_{min} is the minimum luminance value of the two areas being compared (cd/$m^{2)}$. [68] Spatial frequencies at which measured contrast sensitivity were demonstrated in ascending order – 4; 6; 12; 18 cycles/degrees (cpd) at monitor brightness 60; 85; 100 cd/m^2, in the same order for all patients.

The present study aimed to compare the mean values of Weber's law constants and contrast sensitivity between the pre-operative and post-operative groups at different illumination levels. [69] The Weber fraction, often denoted as k, is a constant that represents the proportion of a just-noticeable difference (JND) relative to the magnitude of the stimulus. According to Weber's law, the background brightness levels should not have an impact on the value of the constant, and the result should be situated on the linear regression line. Weber's fraction is calculated:

$$k = \frac{\Delta I}{I},$$

where ΔI is the just-noticeable difference (JND) or the smallest change in intensity and I is the initial intensity or magnitude of the stimulus. The Weber coefficient is on a scale from 0 to 10, predicting – higher the value, greater the difference in stimulus intensity must be to distinguish it. [68–70] For example, if the cataract did not affect the contrast sensitivity values, the results at different background brightness levels would be on the same line. Thus, the study evaluated whether a statistically significant correlation existed between the mean values of Weber's law constants at each illumination level and between the mean values of contrast sensitivity in the preoperative and postoperative groups. If a statistically significant correlation was observed, it would suggest that Weber's law was not fulfilled.

Objective scattering index

The objective scattering index (OSI) is a parameter used to evaluate objective intraocular scattering. It is calculated by assessing the amount of light in the periphery of a patient's double-pass image relative to the light in its central part (see Fig. 10). [71, 72]. Double-pass imaging facilitates the separation and quantification of aberrations originating from different optical components. Analyzing the retinal image after two passes through the eye's optics simplifies the identification of specific aberrations. This approach increases sensitivity to lower-order aberrations and subtle imperfections, enhancing the accuracy of optical performance assessment. Additionally, double-pass techniques are less influenced by the eye's accommodation response, minimizing potential underestimations present in single-pass methods. This analysis evaluates image contrast and quality by assessing light spread across spatial frequencies, unveiling the optical system's preservation of fine details while minimizing scatter. To evaluate image they use the Modulation Transfer Function (MTF). [73] The MTF is a fundamental concept in optics and image analysis that describes the ability of an optical system to faithfully transmit variations in contrast and spatial frequency from an object to its image. Furthermore, double-pass methods enable the measurement of light scatter within the optical system, vital for understanding visual performance, particularly in the presence of conditions like cataracts that can elevate scatter effects.

The HD Analyzer measures the PSF for both the smaller and larger apertures, simulating smaller and dilatated pupil. The PSF represents the intensity distribution of light on the retina after passing through the optical system. Differences in the PSF between the two apertures indicate the extent of light scatter. Typically, a smaller aperture simulates the eye's natural pupil size, and a larger aperture simulates a dilated pupil. OSI is calculated:

$$\text{OSI} = \frac{1}{4} \times \frac{V_{dilatated} - V_{miosis}}{V_{miosis}},$$

where $V_{dilatated}$ is the point spread function (PSF) value at a larger aperture (e.g., 8mm) that simulates a dilated pupil and V_{miosis} is the PSF value at a smaller aperture (e.g., 3 mm) that simulates a more natural, daytime pupil size. Wider aperture is helps to capture wider amount of scattered light and evaluate the impact of scattering across a broader range of conditions Eyes with normal scattering levels (i.e., young eyes) typically have an OSI value of less than 1.0 units. Values lower than 2 are often associated with low-scattering eyes and may indicate the onset of cataract. OSI values ranging from 2 to 4 units correspond to eyes with moderate light scatter. The validity of OSI has been demonstrated for a new objective classification of cataract development, which is more robust and accurate than the subjective classifications that were previously used. [74]

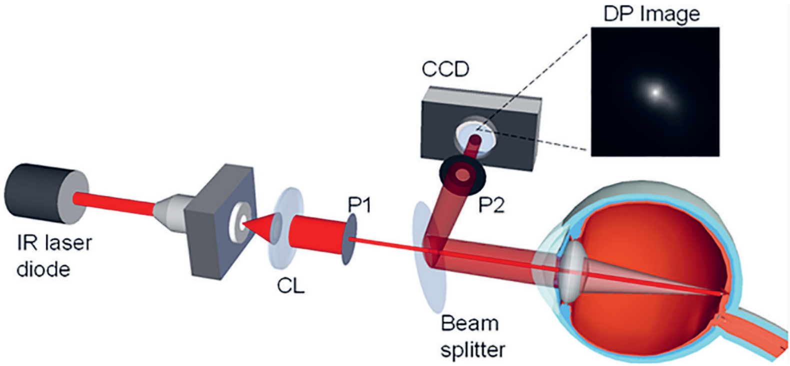


Figure 10. Schematic representation of the double-pass method. A collimated infrared diode laser (CL) is directed into the eye after traversing the entrance aperture (P1). Following reflection in the retina and double passage through the ocular media, the light is reflected by a beam splitter and proceeds through the exit aperture (P2) before being captured by a digital camera. [72]

2.3. Results

2.3.1. Contrast sensitivity before and after cataract surgery in different background brightness levels

The study conducted measurements at different background brightness levels and spatial frequencies. [dis4] Figure 11 illustrates the outcomes at a background brightness level of 60 cd/m^2, revealing a statistically significant difference in contrast sensitivity results among the control group, pre-operative and post-operative group for all spatial frequencies ($p < 0.01$). A higher contrast sensitivity percentage corresponds to a lower contrast sensitivity threshold, with a patient having a contrast sensitivity of 25.16 ± 2.16 % exhibiting a worse contrast sensitivity threshold compared to a patient with a contrast sensitivity of 7.39 ± 1.10 %. The most significant improvement in contrast sensitivity was observed at 12 and 18 cycles per degree after cataract removal surgery.

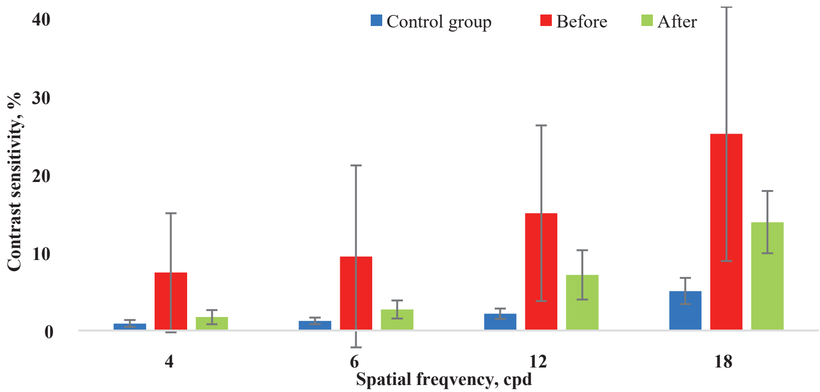


Figure 11. Results of contrast sensitivity at 60 cd/m^2 background level. Control group results – blue; before the cataract removal surgery – red; after – green.

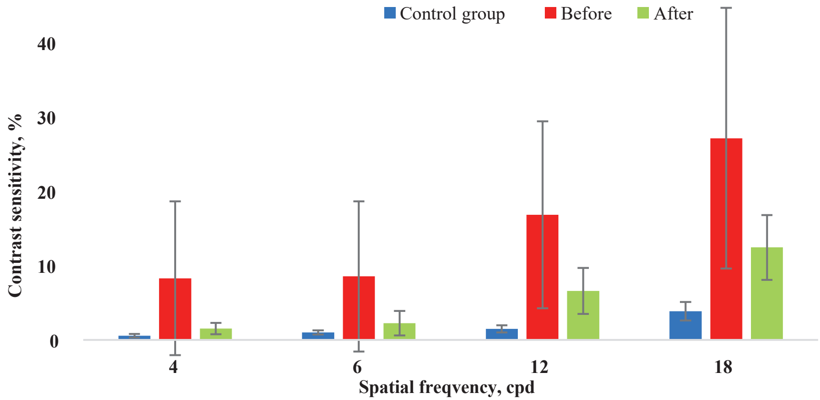


Figure 12. The graph demonstrates the results of contrast sensitivity at 85 cd/m^2 background level. Control group results – blue; before the cataract removal surgery – red; after – green.

The trend remained consistent with the previous findings, where the contrast sensitivity threshold decreased as spatial frequency increased (see Fig. 12). The individuals with cataracts had the lowest contrast sensitivity at both brightness levels. The results for spatial frequencies 4 cpd and 8 cpd did not show any statistically significant differences in contrast sensitivity before and after the surgery ($p = 0.07$ and $p = 0.09$, respectively). However, after cataract removal surgery, the patients' contrast vision sensitivity results were different from those of the control groups ($p < 0.001$).

At background lightness levels of 60 and 85 cd/m^2, cataract surgery resulted in a significant improvement in contrast sensitivity at 4 cpd and 18 cpd spatial frequencies. At 100 cd/m^2 background lightness level, significant improvements were observed at all spatial frequencies after cataract surgery. The results showed that after surgery, at a lower background illumination level of 60 cd/m^2, the contrast sensitivity results at medium spatial frequencies (4 cpd and 6 cpd) were comparable to those of the control group, but at higher spatial frequencies, the results showed significant differences. These findings partially agree with Packer et al.'s (2006) study, which reported that post-operative contrast sensitivity results did not differ significantly from those of the control group. [75] After cataract removal and IOL implantation, the optical quality of the image is also influenced by the aberrations and light scattering caused by the IOL.

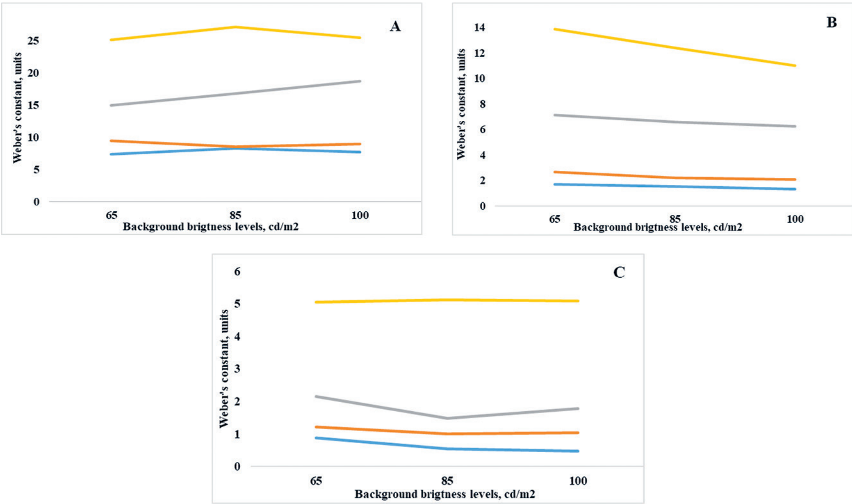


Figure 13. The mean values of the Weber constant at different background brightness levels across all spatial frequencies. Subfigure A demonstrates the results before cataract surgery, B after the surgery, C control group. Colored lines represent spatial frequency change to background brightness level changes (blue 4 cpd ; orange 6 cpd ; gray 12 cpd yellow 18 cpd.

The study compared the mean values of Weber's coefficients across different background brightness levels, spatial frequencies, and groups (before cataract surgery, after surgery, and control group). Results (shown in Figure 13) indicated that there were no significant differences in Weber's constant changes due to background changes in any of the three groups (before, after, and control) ($p > 0.05$). However, at high spatial frequencies of 12 and 18 cpd, Weber's law did not fulfil before the cataract surgery, indicating that lens opacities reduced contrast vision. After surgery, other factors may have affected the results. The only statistically significant differences in Weber's constant were observed between 4 and 6 cpd results in all three groups (before $p = 0.03$, after $p = 0.03$, control group $p = 0.05$), while other spatial frequency results showed no similarities ($p > 0.42$).

2.2.2. Objective scattering index

The study found that the mean objective scattering index (OSI) of the cataract groups was 3.75 ± 1.62 units, indicating moderate changes in light scatter. [dis4] This value was statistically significantly different from the control group results (OSI 0.96 ± 0.27 units; $p = 0.002$). The mean OSI index for different types of cataracts was as follows: cortical cataract (2.93 ± 2.0 units), nuclear cataract (4.63 ± 3.00 units), and posterior subcapsular cataract (3.93 ± 1.67 units). The posterior subcapsular cataract group showed the highest levels of light scattering. There was a statistically significant difference between the cortical and nuclear cataract groups ($p = 0.001$) and between the cortical and posterior subcapsular cataract groups ($p = 0.02$), but no significant difference was found between the posterior subcapsular and nuclear cataract groups ($p = 0.12$). The results demonstrated a strong negative correlation between the best corrective distance visual acuity (DCVA) and the OSI parameters ($r = -0.80$), indicating that as the objective scattering index increased, visual acuity decreased, which is demonstrated in figure no. 14.

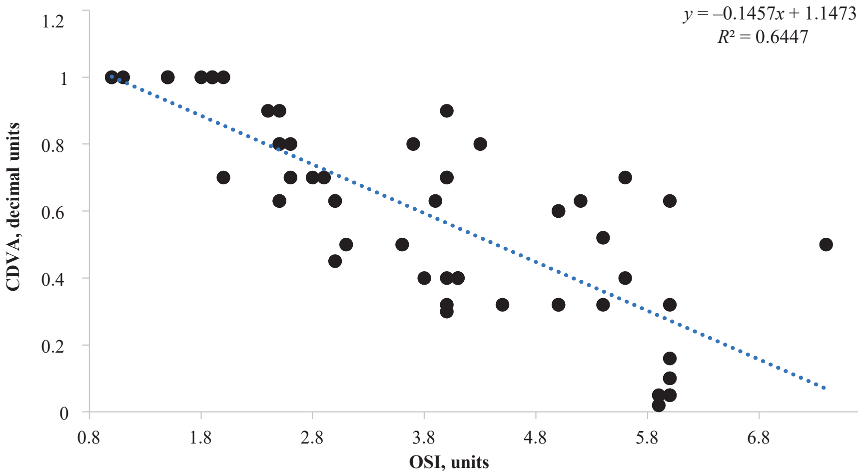


Figure 14. Results demonstrate a negative correlation between the objective scattering index (OSI) and the best correction distance visual acuity corrected distance visual acuity (CDVA) ($r = -0.80$).

3. APPLICABILITY OF COLOR VISION TESTS FOR EVALUATING COLOR VISION SENSITIVITY BEFORE AND AFTER CATARACT SURGERY

3.1. Introduction

As humans age, the density of their crystalline lens increases, causing changes in the way how light is filtered through the lens and reaches retina. [76] This leads to physiological changes in color vision due to factors such as decreased pupil size, reduced photon absorption efficiency of cones, and loss of retinal ganglion cells. The human eye's ability to transmit different wavelengths of light changes with age, with shorter wavelengths being less effectively transmitted due to yellowing of the lens. [76–80] While color appearance remains stable throughout life due to mechanisms such as color constancy and long-term chromatic adaptation, there is a decline in the ability to distinguish different colors. [79, 80]

In most cases, patients do not typically perceive changes in color vision before undergoing cataract surgery, unless they have an advanced nuclear cataract. However, multiple studies have shown that patients may experience changes in color vision sensitivity after cataract removal. [81–83] After cataract removal, patient color vision sensitivity shifts to the direction of yellow to adjust for increased short-wavelength light that reaches the retina. One day after the surgery, achromatic settings still are relatively close to the condition before the surgery, and it takes about 3 months to stabilize. Currently there are only few studies that explore the long term color vision sensitivity adaptation [79, 80, 84], but more data should be gathered to make conclusions.

Color vision tests are not commonly used in optometry practice to monitor the progression of cataracts. However, these tests can be useful in detecting the development of cataracts and understanding any color vision differences that patients may experience before and after cataract surgery. This can help optometrists better understand their patients' complaints and monitor changes in color vision over time, which could influence the decision when to send patient to cataract surgery. The aim was to evaluate optometrist frequently used color vision tests, to determine which one can be useful to detect color vision shift for cataract patients.

3.2. Method

To determine which test is the most sensitive to detect color vision sensitivity changes before and after cataract surgery, we used 4 color vision tests: Farnsworth D-15 (D15) saturated and unsaturated version; Farnsworth-Munsell 100 hue test (FM100); Hardy Rand and Rittles 4th edition test (HRR). The goal of research was to understand which test could be used in optometrist practise to detect color vision shift after cataract surgery. All the tests were chosen because of short duration time, they are portable and it is possible to detect color vision deficiency in *tritan*, *protan* and *deutan* confusion line directions. Descriptive information about participants and testing timeline can be found in table 4.

Farnsworth D-15 (D15) hue test affords the capability to differentiate between normal color vision and color deficiencies, as well as to distinguish between varying degrees of severity. [85] During the D15 test, 15 small caps are arranged by observers based on their chromaticity, commencing from a fixed reference cap (Fig. 15). Subsequently, the test is manually recorded and evaluated through visual inspection of the cap arrangement in color space, with the objective of determining the nature and extent of any color deficiency. During testing we used saturated and unsaturated D15 test versions. The tests were performed monocularly under lighting conditions of 500 lux.

The Farnsworth-Munsell 100 Hue Color Vision Test is a widely recognized and standardized assessment tool for color vision that evaluates an individual's capacity to discriminate and arrange colors in a specific order of hue (see Fig. 16). [87] The test comprises four trays, containing 85 color disks arranged in a random order, and the examinee is required to arrange the disks in a sequence of hues, progressing from one color to the next across each tray. The cap arrangement sequence results are utilized to diagnose and assess the extent of color vision deficiencies, specifically red-green color blindness, as well as to monitor the evolution of color vision over time.

Figure 15. Farnsworth D-15 (D15) hue test. [86]

Figure 16. The Farnsworth-Munsell 100 Hue Color Vision Test. [88]

Figure 17. Hardy Rand and Rittles 4th edition color vision test. [90]

Table 4. Descriptive information about experimental conditions.

Color vision test	Farnsworth D-15 hue test (saturated version)	Farnsworth D-15 hue test (unsaturated version)	Farnsworth Munsell 100 hue test (FM100)	Hardy Rand and Rittles pseudoisochromatic Test 4th edition (HRR)
Participants	n = 92 eyes senilis cataract	n = 108 eyes senilis cataract	n = 160 eyes (nuclear cataract)	n = 108 eyes senilis cataract
Time line	1 day pre-surgery and 1 moth post-cataract removal	2 hours pre-surgery, 1 week post-surgery	1 day pre-surgery, 2 weeks and 6 month post-surgery	2 hours pre-surgery, 1 week post-surgery

Hardy Rand and Rittles 4th edition pseudoisochromatic color vision test (HRR) is a clinical tool utilized for the diagnosis and evaluation of congenital and acquired color vision deficiencies, particularly those affecting red-green color vision (see Fig. 17). [89] The test is comprised of a set of 24 pseudoisochromatic plates, each containing a pattern of circles or ellipses made up of dots of different hues and intensities arranged in a specific configuration. The examinee must identify the hidden number or shape within the pattern. The HRR test is considered to be a reliable and valid color vision screening tool and is commonly utilized in clinical settings. These tests was performed monocularly, at 500 lux lighting for all the patients, at the 0.40 m distance. The results were analysed taking into account the existing error counting method in the manual.

3.2.1. Color vision arrangement test analyses

Various techniques have been proposed to quantitatively evaluate the D15 and FM100 color vision tests. Bowman's method can predict whether changes are present, but it is not possible present what kind of color vision deficiency patient has. [91] The method calculates a total error score (TES) by adding up the differences in color space from the CIE Lab color coordinate system. The difference (ΔE) between any two colors is calculated using the formula:

$$\Delta E = [(L)^2 + (\Delta a)^2 + (\Delta b)^2]^{½} \quad (3)$$

The norms of TES is 165 ΔE (when assembled in perfect order), the number increases with the increase of transpositional intersections.

Another method proposed by Vingrys and King-Smith (VK-S) uses color difference vectors to determine the severity, selectivity, and type of color deficiency represented by specific cap arrangements. [92, 93] A modified technique incorporates color difference vectors (CDVs) from errors made in cap arrangements, which reduced the scatter and confusion indices for normal arrangements but increased their interdependence, limiting its usefulness. Vingrys and King-Smith developed four indicators based on an averaging technique (moment of inertia) applied to the CDVs of any arrangement pattern. Predictive indices for each color vision deficiency are listed in Table 5, with the confusion angle identifying the type of defect, the confusion index (*C*-index) quantifying the severity of color loss, and the selectivity index (*S*-index) quantifying the specificity of a cap arrangement. The angle of confusion is calculated by knowing the coordinates of the two mixed color stimuli in the CIExyz chromaticity diagram. The second step is to calculate Calculate the slope *m* of the line (line of confusion) that passes through these two points using the formula: $m = \frac{y_2 - y_1}{x_2 - x_1}$. Calculate the confusion angle using the arctangent function: Angle = arctan(*m*). This angle is usually measured from the x-axis. The first step to calculate the confusion index (*C* index) is for each cap to calculate the difference between its observed position and its correct position. The square each of these differences, sum up all these squared differences and divide by the number of cap as it is demonstrated in fallowing formula: $C = \frac{1}{N} \sum_{i=1}^{N} (O_i - C_i)^2$,where *N* is the number of caps, O_i is the observed position of cap *i* and C_i is the correct position of cap *i*. A larger *C*-index indicates a greater degree of scatter and therefore a more severe color vision deficiency. Selectivity index is calculated: $S_{index} = \frac{C_{index}}{TES}$, where C_{index} is the Confusion Index (which quantifies the extent of disorder or randomness in a subject's arrangement of the color caps) and Total Error Score *(TES)* is the sum of all the individual error scores (the differences in cap positions). The *S* index provides a relative measure of the "quality" of the errors. A higher *S* index indicates that the errors are more localized and that there are specific color confusions, while a lower *S* index suggests more diffuse and less selective color discrimination problems.

C-index greater than 1.77 is expected to indicate an abnormal cap arrangement. The *S*-index is useful when it is low relative to the *C*-index, which is more likely to occur with acquired defects. The confusion angle (Angle) represents the orientation of the cap arrangement. The classification of color vision deficiency is based on the proximity of the best fit line to the known confusion axes. threshold, which is assumed to distinguish *protan* color deficiency from *deutan*, is +0.70 degrees, and the type of error is determined by the angular proximity of the best fit line to known confusion axes representing *protan*, *deutan*, *tritan*, or unspecified color defects. Confusion angle norms for unsaturated D15 test is 55.71 degrees. Severity is the sum of the color difference vector lengths of all errors made, and selectivity is determined by the adjusted variance of the least squares fit.

Table 5. Proposed predictive indices from Vingrys and KingSmith (VK-S). [93]

Defect	C index, units	S index, units	Confusion angle, degrees
Norms	1.00	1.38	+62
Deutan	< 1.77	< 1.40	–11 … –4
Protan	> 1.77	> 1.68	0… +30
Tritan	> 1.77	< 4.00	0 … –70

3.3. Results

3.3.1. Saturated D15 test

The findings of this study were analysed using Bowman's method and are presented in Figure 9. The comparison of the average units of color difference before surgery 190.87 ± 0.41ΔE units and after surgery 132.18 ± 0.42 ΔE showed a statistically significant difference ($p = 0.001$; $n = 32$) (see Fig. 18). The decrease in color difference units resulted in fewer errors in the D15 arrangement sequence. [dis5]

The study found that before the cataract surgery, seven eyes had a deviation towards the *tritan* confusion axis direction and eight eyes showed no specific

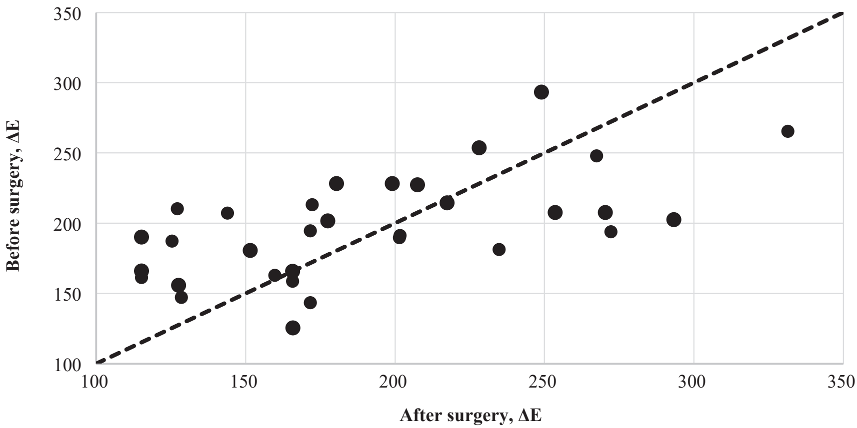


Figure 18. Color difference TCDS (ΔE) sums for patients (dot)before and after cataract surgery (n = 32) for D15 color vision test. The dashed line represents no change (ΔE = 0) in color difference sums.

color vision deficiency but had a deviation towards the *tritan* side (see Fig. 19). The results of 17 eyes showed no significant differences compared to the norm values found in the literature. After the surgery, 24 eyes did not show statistically significant color sensitivity changes. Results of three eyes showed similarities to the characteristics of a protanomalous patient, and one eye showed similarities to the *deutan* confusion axis direction. Data of two eyes had color sensitivity changes to the *tritan* confusion axis side. After the surgery, seven patients who showed color sensitivity shift to the *tritan* confusion axis side did not show any color sensitivity changes. One patient stayed in the same position, and another patient migrated to the *tritan* confusion line side.

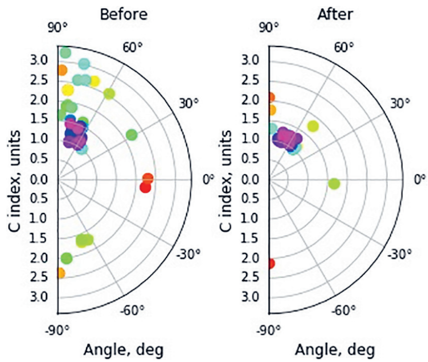


Figure 19. Patients D15 color arrangement sequence corresponding confusion index (C index) and confusion angle (degrees)before and after cataract surgery using saturated D15 test. Colored points demonstrate individual participants cap arrangement sequence

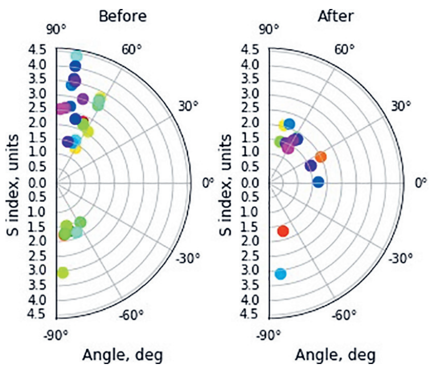


Figure 20. Patient's D15 color arrangement sequence corresponding to the selectivity index (*S* index) and confusion angle (degrees) before and after cataract surgery. Colored points demonstrate individual participants cap arrangement sequence. Before surgery 7 eyes had color sensitivity changes to the *tritan* confusion axis. After the surgery 6 eyes showed color sensitivity changes

The *S* index parameter is used to quantify the degree to which the arrangement sequence of patients is parallel to the angle of confusion. Prior to the surgical procedure, the mean *S* index was found to be 2.33 ± 0.78 units, whereas after the procedure, it was 1.71 ± 0.10 units. The observed difference in *S* index before and after surgery was statistically significant ($p < 0.01$). Following the surgical removal, changes in color vision sensitivity were not found to be as pronounced, and the arrangement sequence of caps was more precise (see Fig. 20). [dis5]

3.3.2. Unsaturated D15 test

The results, analyzed with Bowman's method shows that there is a statistically sensitivity difference ($p = 0.001$) between before and 1 week after cataract surgery results (Fig. 21). Color difference units decreased, which lead to less mistakes in the unsaturated D15 arrangement sequence. Statistically, there was a significant difference ($p = 0.02$) by Student t test analysis after cataract surgery comparing it to Bowman's method norm (ΔE = 55.71 units) which shows changes in chromatic resolution. [dis2]

To determine color sensitivity before and after cataract surgery the average patient *C* index, indicating that there was a statistically significant ($p < 0.01$) (Fig. 22). The *S* index characterizes the parallelist of the patient arrangement sequence to the confusion angle. There was no statistically significant difference before and after cataract surgery to the *S* index value ($p = 0.12$) Overall, after the surgery color vision sensitivity changes were not that severe and cap

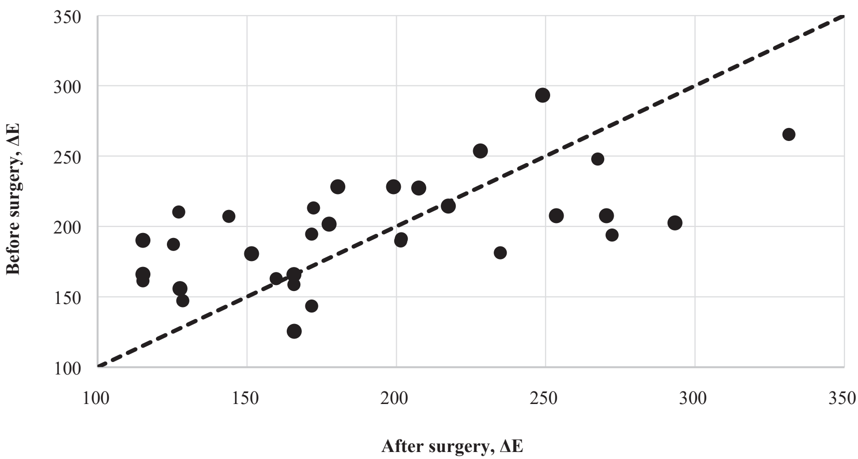


Figure 21. Color difference TCDS (ΔE) sums for patients (dot)before and after cataract surgery ($n = 104$) for unsaturated D15 color vision test. The dashed line represents no change (ΔE = 0) in color difference sums.

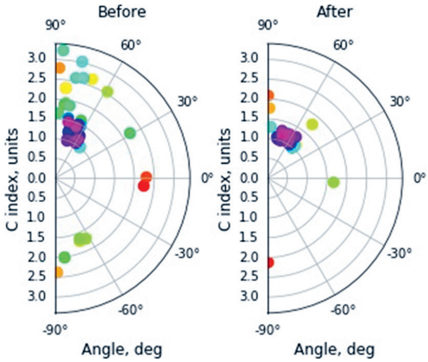


Figure 22. Patients D15 color arrangement sequence corresponding confusion index (C index) and confusion angle (degrees) before and after cataract surgery using unsaturated D15 test. Colored points demonstrate individual participants cap arrangement sequence.

arrangement sequence was more precise. Before the surgery 6 patients showed color sensitivity shift to the *tritan* confusion axis side, did not show any color sensitivity abnormalities after one week. Four eyes which showed normal cap arrangement sequence before the surgery, after showed nonspecific color sensitivity changed closer to *protan* confusion axis. It is possible that patient's the visual system is still compensating for cataract and one month is not enough for the vision system to adapt to the new IOL. [dis2; dis5]

3.3.3. FM100 hue test

The study found [dis3] that before the cataract surgery, 7 eyes results had a deviation towards the *tritan* confusion axis direction and 8 patient results showed unspecific color vision deficiency but had a small deviation towards the *tritan* side (Fig. 23). The results of 17 eyes showed no significant differences compared to the average values found in the literature. It was found that before the cataract surgery 39 patients showed no inertia moment offset outside the normal range. After the surgery, 24 eyes did not show statistically significant color sensitivity changes. However, arrangement sequence errors in three eyes indicated color sensitivity towards the *protan* confusion axis direction. Results of 3 eyes showed similarities to the characteristics of a protanomalous patient, and one eye showed similarities to the *deutan* confusion axis direction. Data of 2 eyes had color sensitivity changes to the *tritan* confusion axis side. After the surgery, 7 patients who showed color sensitivity shift to the *tritan* confusion axis side did not show any color sensitivity changes (normal). One patient stayed in the same position, and another patient migrated to the *tritan* confusion line side. There was a large increase in short-wavelength light reaching the retina after the surgery, resulting in a bluer appearance.

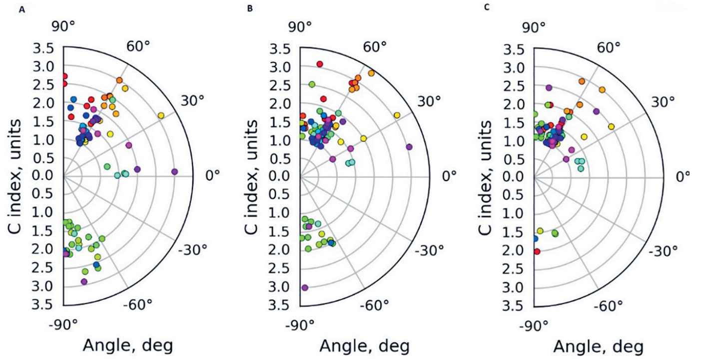


Figure 23. The figure displays cap arrangement sequences of individual patients, representing the relationship between the confusion index (C index) and confusion angle (angle) of all participants (*n* = 80). The cap arrangement sequences are shown before surgery (A), 2 weeks after surgery (B), and 6 months after surgery (C). Before the surgery, 25 patients had cap arrangement sequences similar to *tritan* color vision deficiency, 10 patients had sequences similar to *protan* or *deutan*, 6 patients had unspecific color vision deficiency, and 39 patients had normal color vision sensitivity. Each patient is denoted by a single color in all subfigures, but the color is not related to any color deficiencies.

3.3.4. HHR results

Before the surgery none of the patients 54 patients showed color vision sensitivity abnormalities with HRR test. [dis2] After the cataract surgery patient's did not make any mistakes and showed normal color vision sensitivity. HRR test did not demonstrate sensitivity to detect color vision sensitivity shift for cataract patients.

4. COLOR VISION TEST RESULT CORRELATION WITH COLOR VISION QUESTIONNAIRE

4.1. Introduction

In order to gain a deeper understanding of patients subjective color vision, we investigated patient's subjective questionnaire score and its connection to Farnsworth-Munsell 100 Hue test. [87] In the literature, similar studies have not been conducted. The aim was to evaluate if patients cap arrangement sequence influence changes on subjective color vision. [dis3] The study's findings will enable health care specialists to determine whether there is a correlation and proof to patient's subjective experiences with daily life activities related to color vision. The research findings could give an answer if color vision questionnaires can be used to detect color vision sensitivity shift to monitor cataract progression, and give better understanding – what do cataract patients feel after cataract surgery.

4.2. Method

Research analysed the cap arrangement results of each participant and categorized them into five groups based on their before the surgery cap arrangement sequence: normal (n = 39), unspecific (n = 6), *tritan* (n = 25), and *protan* and *deutan* deficiency combined (n = 10). [dis3] We employed the Pearson correlation coefficient (r) to examine whether there was a relationship between a patient's subjective questionnaire responses and their confusion index (C index). We evaluated the questionnaire score and C index values separately for each time period and determined the correlation coefficient. A correlation coefficient between 0.7 and 1.0 was considered a strong positive correlation, 0.5 to 0.7 was moderate, 0.3 to 0.5 was weak positive, and 0 to 0.3 was regarded as negligible correlation.

4.3. Results

Overall group (n = 80) results showed that before and after the cataract surgery, there was a moderated positive correlation between the C index and answers to the first, second, third and fourth question (see Table 6). The questionnaire score and the C index correlation coefficient was the strongest positive correlation at the 2 weeks follow up (r = 0.79), indicating a strong steadiness between patient complaints and the results of the color vision test. It is observed that corelation decreased with follow up time. Question no.8 showed the smallest positive correlation compared to other questions.

Before the cataract surgery patients who had normal cap arrangement sequence (n = 39) showed moderated positive correlation to the first four questions. The patients answers matched color vision test findings and showed strong positive correlation to the seventh (before) and first (6 months after) question. At the 6 month follow up there were a weak correlation to fourth, fifth, sixth and seventh question.

Before the cataract surgery the FM100 cap arrangements of 25 participants showed similarities with the *tritan* color vision deficiency The cap arrangement sequence had a strong positive correlation with second question before, sixth question 2 weeks and first question 6 month after cataract removal. Before the surgery results demonstrate that color vision test sequence matches questionnaire score to the first three questions, but correlation decreases dramatically afterwards, except mentioned questions before. The first three questions can be used in an optometrist's practice to evaluate patients with a similar ossicular sequence to *tritan*.

Due to the limited number of participants with *protan* and *deutan* deficiencies, we combined their data in our study. To the first question there was a moderately positive correlation at the 2 week and 6 month follow ups. The correlation coefficient between the questionnaire score and the C index was negative in the second and eighth questions, indicating that although patients reported subjective changes ($p < 0.02$), there was no statistically significant change in the C index ($p > 0.15$). In general, the results indicated that the strongest positive correlation between the questionnaire score and the confusion index occurred in the *protan* and *deutan* group during the 2-week follow-up after the surgery.

Table 6. Correlation Coefficients (r) between Subjective Questionnaire Scores and the C Index for Each Question at the Different Time Periods. [a]

Before	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Normal ($n = 39$)	0.65	0.64	0.68	0.64	0.22	0.43	**0.71**	0.47
Unspecific ($n = 6$)	0.61	**0.94**	**0.94**	−0.61	0.41	0.33	0.13	0.41
Tritan($n = 25$)	0.64	**0.70**	0.54	0.28	0.28	0.04	0.03	0.37
Protan/Deutan ($n = 10$)	0.14	−0.18	**0.76**	0.54	0.40	0.63	0.57	0.32
All ($n = 80$)	0.58	0.59	**0.76**	0.60	0.43	0.61	0.50	0.43
2 weeks	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Normal ($n = 39$)	0.64	0.62	0.58	0.55	0.50	0.49	0.21	0.23
Unspecific ($n = 6$)	**0.73**	0.18	**0.75**	**0.89**	**0.80**	0.21	0.53	−0.07
Tritan($n = 25$)	0.39	0.001	0.15	0.36	0.13	**0.72**	0.29	−0.14
Protan/Deutan ($n = 10$)	0.54	−0.26	**0.82**	**0.70**	**0.72**	0.34	0.60	−0.45
All ($n = 80$)	0.60	**0.77**	**0.72**	**0.79**	0.67	0.44	0.39	0.20
6 months	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Normal ($n = 39$)	**0.73**	−0.09	0.54	0.25	0.30	0.32	−0.06	0.38
Unspecific ($n = 6$)	0.61	**0.78**	0.38	−0.25	−0.67	0.20	NA	−0.37
Tritan($n = 25$)	**0.72**	0.19	0.21	0.59	−0.07	0.68	0.12	0.19
Protan/Deutan ($n = 10$)	0.57	0.02	**0.77**	0.65	**0.88**	0.34	−0.43	**−0.81**
All ($n = 80$)	0.68	0.67	0.66	0.52	0.23	0.01	0.01	0.14

[a] Strong positive correlations are marked in bold.

Six patients showed similarities with unspecific color vision deficiency before the surgery. The first three questions showed a strong positive correlation between observers before and after the cataract surgery, as shown in Table 6. However, in the fourth question regarding subjective color appearance, the correlation coefficient showed a negative relationship between both parameters before and at the 6-month follow-up.

METHODOLOGY FOR EVALUATING CATARACT AND ITS INDUCED VISION CHANGES

The methodology has been developed based on the results obtained in the doctoral thesis. Health care professionals can use the obtained results to evaluate the dynamics of cataracts or to recommend cataract surgery. The decision on cataract surgery is made by the ophthalmologist, based on the patient's willingness to undergo the surgery and the obtained results.

Determining cataract and its type using objective light scattering index (OSI):

If OSI:

1) < 2 units → cataract is not diagnosed;
2) 2 to 3 units → cortical cataract;
3) 3 to 4 units → posterior subcapsular cataract;
4) > 4 units → nuclear cataract.

If the patient has cataract, but <u>no complaints</u>:

1. Visual acuity (Snellen chart):
   a) > 1.00 decimal units → ophthalmologist control after 1 year;
   b) 1.00 – 0.63 decimal units → ophthalmologist control after 1 year;
   c) < 0.63 decimal units → ophthalmologist control after 6 months.

   Visual acuity lower than 0.63 decimal units does not correspond to the functional vision required by a person (driving a B category car, working with a computer).
2. Questionnaire: Visual function questionnaire (VF-14):
   a) 99 to 100 points→ no complaints observed, control after 1 year;
   b) 75 to 98 points → mild complaints, control after 1 year;
   c) < 75 points → moderated or severe complaints, reduced quality of life. An ophthalmologist's consultation is recommended to the patient.
3. Objective light scattering index test (OSI):
   a) ≥3 units → an ophthalmologist's consultation is recommended to the patient (functional visual acuity is affected due to light scattering);
   b) ≤3 units → ophthalmologist control after 1 year.

The assessment of visual acuity, objective light scattering index measurements, and questionnaire results can assist vision care specialists in comprehending the progression of cataracts. In routine clinical practice, a primary care physician (family doctor) can administer a visual acuity test and questionnaire to patients, thereby monitoring changes in both healthy and affected individuals over time. The responsibility of the vision care specialist is to educate the patient about the anticipated symptoms associated with cataract progression, with consideration of the specific cataract type (refer to section 1.1. for details)

If patient was complaints:

1. Visual acuity test (Snellen chart): regardless of visual acuity, ophthalmologist's consultation is recommend.
2. Contrast vision test at high spatial frequencies: 12 and 14 cycles/degree, at a brightness level of 60–100 cd/m^2. The brightness level of the test depends on the patient's complaints. For example. If the patient has complaints about vision functions in the dark, the test is performed at a background brightness of 60 cd/m^2.
   a) > 10 % → ophthalmologist's consultation is recommended to the patient;
   b) < 10% → control after 6 months.
3. Questionnaire – assessment of visual functions (VF-14): Irrespective of the questionnaire score, it is advisable to seek an ophthalmologist's consultation. The questionnaire outcomes serve as a valuable tool for assessing cataract progression. Subjective experiences of patients with various cataract types are detailed in Section 1.1.
4. Color vision test: *Farnsworth-Munsell* 100 hue test or *Farnsworth-Munsell* D15 color vision test.
   a) Normal color vision: Errors not more than 2 (D15); 16 errors (FM100);
   b) If the patient commits more than 2 errors in the D15 test and more than 16 errors in the FM100 test →an analysis of the cap arrangement sequence is conducted to assess its similarity to patterns associated with color vision deficits → subsequently, the Color Vision Sensitivity Questionnaire (questions 1-4th) is administered to gain a better understanding of complaints related to changes in color vision.

If the cap arrangement sequence shows a similarities with *tritan* color vision deficiency → the responsibility of the vision care specialist is to apprise the patient that they may experience more pronounced changes in color vision following the surgery.

SUMMARY

Two weeks following cataract removal surgery, patients experience a significant improvement in their quality of life, particularly related to near work. Among the different types of cataract, patients with cortical cataracts report the greatest subjective improvement in quality of life after surgery, followed by those with posterior subcapsular and nuclear cataracts. Before the surgery, patients with nuclear cataracts were not as severely affected in their daily activities. Patients with posterior subcapsular cataracts experienced the most complaints about daily activities related to objects with reflections, such as traffic signs. However, there was no significant difference in the questionnaire scores related to reading large print, books, recognizing faces, and doing sports activities before or after the surgery, regardless of the type of cataract. Similarly, before and after cataract surgery there was no significant difference in the cataract group's answers related to visual tasks, such as seeing steps and driving. Questions no. 1; 6; 7; 8; 9; 12; 13 can be used to diagnose the type of cataract, as the results showed differences between the responses of patients with nuclear, cortical, and posterior subcapsular cataracts.

Following cataract surgery, there is an improvement in FM100, D15 hue performance, and subjective perception. However, the questionnaire scores before surgery are significantly different when compared to the 6-month follow-up results, indicating that subjective changes can only be noticed at longer periods after the surgery. It is expected that color-vision-related complaints will decrease starting from two weeks after the surgery. Patients before surgery reported mild problems with color naming, feeling that the colors appear different, and everything becoming bluer. Color confusion and distinguishing were the most significant problems that patients dealt with in daily life situations before the surgery, but these complaints are not extensively studied in current literature. Two weeks after cataract surgery, patients did not feel a difference in color confusion, distinguishing, color naming, and food preparation compared to before the surgery. Color appearance and everything becoming bluer showed a dramatic increase in subjective scores, noted at all follow-ups after surgery. Yellowing of daily life objects and brightness changes were noted right after surgery, but this effect had disappeared by the 6-month follow-up. The overall results suggest that vision care professionals should inform patients that after cataract surgery, subjective sensations of color vision will not change sooner than 2 weeks after surgery.

Overall, patient-subjective color sensitivity feeling corresponds well to the color vision test cap arrangement before and 2 weeks after surgery. The results show that subjective patient feelings are consistent with color vision test findings. However, the reliability of this method decreases after longer time periods, depending on the question asked. The first (color confusion), second (color naming), third (color distinguishing), and fourth question (color feels

different) results showed a strong positive correlation with the C index. But the results were not reliable at the 6-month follow-up for the fifth (everything appearing bluer), sixth (food preparation), seventh (yellowing of daily objects), and eight (brightness changes) questions. The first four questions can be used in optometrist practice as a characterization tool for color vision changes due to cataracts.

Color vision tests like FM100 and D15 hue are sensitive to detect color vision sensitivity changes after cataract surgery and can serve as an additional method to monitor cataract in dynamic. The D15 test was able to detect changes in color vision sensitivity 1 week after cataract surgery Before cataract surgery, 30 % of patients experience similarities with the *tritan* cap arrangement, which changes to normal after time. Color vision sensitivity shifts can be observed to occur beyond a period of 6 months following cataract removal.

Regarding other factors that could influence questionnaire scores, the results demonstrate that cataract-induced light distribution significantly decreases contrast sensitivity at all spatial frequencies. Before surgery, the worst contrast sensitivity was seen at high spatial frequencies in the darkest background. There are no significant differences between the Weber constants when the background brightness level increases in the group before cataract surgery and the control group. At a lighting level of 60 cd/m^2, cataract surgery provides a significant improvement at the medium spatial frequencies, but at a background lighting level of 85 cd/m^2 and 100 cd/m^2, an improvement in contrast sensitivity is obtained at high.

Health care professionals can benefit from our findings by using this questionnaires as a valuable tool to better understand the subjective feelings of patients and to monitor their color vision sensitivity changes and progression of cataracts. Moreover, our research provides health care professionals with a better perspective regarding nuclear cataract patient experiences, both before and after cataract surgery, related to color vision. Day-to-day color cap matching tests can serve as additional tools in the evaluation of cataracts.

THESIS

1. A questionnaire for evaluating color vision sensitivity has been developed to assess patients' subjective feelings prior to cataract surgery. The subjective assessment of quality of life has been found to correlate with contrast sensitivity, visual acuity and color vision test results. The use of questionnaires can be a valuable tool to monitor cataract progression.
2. Experimental evidence supports the notion that subjective color vision sensitivity changes occur in cataract patients within a time frame ranging from 2 weeks to 6 months following surgery.
3. Based on empirical evidence, it has been demonstrated that cap arrangement color vision tests exhibit greater sensitivity in detecting changes in color vision sensitivity in cataract patients before and after surgery as compared to the Hardy Rand Rittler tests. Consequently, the implementation of color vision tests can be utilized as an additional technique for assessing the progression of cataracts.
4. The objective light scattering index can be employed as additional diagnostic tools for identifying different types of cataracts.

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ADDITIONAL INFORMATION

Scientific publications not included in this dissertation

1. **Jansone Langina, Z.,** Ozolinsh, M. (2023) Cataract type dependence on lens thickness parameter, *Perception, 52* (5), 354–355. https://doi.org/10.1177/0301006623115753
2. Truksa, R., **Jansone-Langina, Z**., Fomins, S. & Dzenis, J. (2023) Modelling D15 test sequences in red-green anomalous trichromacy, *J. Opt. Soc. Am. A, 40* (3), A85-A90. https://doi.org/10.1364/JOSAA.479848
3. Truksa, R., Fomins, S., **Jansone-Langina, Z**., Fomins, S., Dzenis, J. (2023) Software based solution to improve colour rendering accuracy, *Perception, 52* (5), 362–636. https://doi.org/10.1177/03010066231157537
4. **Jansone-Langina, Z.,** Mikelsone, R. and Gertnere, J. (2022) Differences of corneal biomechanical parameters for keratoconus patients, Proc. SPIE 12146, Clinical Biophotonics II, 121460B. https://doi.org/10.1117/12.2617095
5. **Jansone Langina, Z.,** Ozolinsh, M., Truksa, R., Fomins, S. (2022) Contrast sensitivity changes at different background brightness levels in patients before and after cataract removal surgery, AVA Virtual Christmas, December 20 2021, *Perception, 5* (21), 360–361. https://doi.org/10.1177/03010066221091992
6. Karitans, V., Ozolinsh, M., **Jansone-Langina, Z**., Paulins, P. (2021) Tolerance of observers vision during misusing of light protective goggles, *Perception, 50* (1), 216. https://doi.org/10.1177/03010066211059887
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ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor, Professor *Dr. habil. phys.* Maris Ozoliņš, for involving me in the field of color vision and providing valuable opportunities to advance my scientific career. I extend my thanks to the supportive colleagues at the Optometry department (Gatis, Jānis, Varis, Evita, Aiga, Tatjana) for their scientific advice, suggestions, assistance with programming and technical issues, as well as their friendship, understanding, and support. I am especially grateful to Sergejs Fomins and Renārs Trukša for fostering an excellent work atmosphere and encouraging me to persevere. I would also like to express my appreciation to my family for their unwavering support and understanding throughout my studies. A special acknowledgment goes to my husband, Aigars Langins, for his invaluable help, advice, encouragement, and strength during the final stages of writing my dissertation. Furthermore, I would like to extend my gratitude to the following international colleagues for their advice and confidence, which played a crucial role in completing my thesis: Jasna Martinovic (The University of Edinburgh), Michael Webster (University of Nevada), and Christoph Witzel (University of Southampton).

The development of this doctoral thesis has been made possible through financial support from several international and national projects, including the "SAM project (8.2.2.2./18/A/010, registration nr. ESS2018/289)" and the SPIE student scholarship program. Without their assistance, I would not have been able to complete my dissertation.