ICthroughVR: Illuminating Cataracts through Virtual Reality

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Figure 1: In our VR simulation of cataracts, users experience cortical cataracts (left), posterior subcapsular cataracts (second from left) and nuclear cataracts (middle), and the influence of different lighting setups on their perception with these simulated vision impairments. In a user study, we also measured maximum recognition distances of escape-route signs with simulated nuclear, cortical (second from right) and posterior subcapsular cataracts (right).

Abstract

Vision impairments, such as cataracts, affect the way many people interact with their environment, yet are rarely considered by architects and lighting designers because of a lack of design tools. To address this, we present a method to simulate vision impairments, in particular cataracts, graphically in virtual reality (VR), using eye tracking for gaze-dependent effects. We also conduct a VR user study to investigate the effects of lighting on visual perception for users with cataracts. In contrast to existing approaches, which mostly provide only simplified simulations and are primarily targeted at educational or demonstrative purposes, we account for the user's vision and the hardware constraints of the VR headset. This makes it possible to calibrate our cataract simulation to the same level of degraded vision for all participants. Our study results show that we are able to calibrate the vision of all our participants to a similar level of impairment, that maximum recognition distances for escape route signs with simulated cataracts are significantly smaller than without, and that luminaires visible in the field of view are perceived as especially disturbing due to the glare effects they create. In addition, the results show that our realistic simulation increases the understanding of how people with cataracts see and could therefore also be informative for health care personnel or relatives of cataract patients.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computing methodologies—Computer Graphics—Graphics systems and interfaces—Perception; Applied computing—Life and medical sciences—Health informatics

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1 Introduction

Vision impairments affect 1.3 billion people worldwide, according to the *World Health Organization* (WHO), with cataracts being one of the leading causes [18]. However, this significant portion of the population is hardly ever taken into account in architectural or lighting design, because architects and designers lack the tools to evaluate design concepts with regard to their accessibility for people with vision impairments. Conducting user studies of these designs can be extremely difficult since such studies currently require participation by many people with the same form of vision impairment to allow for statistical analysis of sufficient power.

We present a novel approach to simulate cataract vision in virtual reality (VR) and introduce a methodology to conduct user studies for evaluating architectural design concepts with regard to vision impairments, illustrated in Figure 1. Together with experts in ophthalmology, we developed simulations of different forms of cataracts, using eye tracking for gaze-dependent effects. Furthermore, we use these simulations to demonstrate how our approach creates new possibilities to investigate maximum recognition distances (MRDs) of escape-route signs, prescribed by international norms and standards, for people with different types of cataract.

In architectural design and lighting design, concepts for escape-route signposting and lighting are developed during the planning phase of a building, by experts in the respective fields. In addition to the information given by international standards and norms, designers have to rely on their own expertise to take visually impaired people into account when planning emergency lighting and signage. To be able to develop truly accessible designs for the majority of the population, architects and lighting designers need clear guidelines and tools to help them evaluate the suitability of their design for people with vision impairments.some researchers [11] are working on compensating for vision impairments to allow for better focus of the physical structure of the environment by augmenting the physical environment, using *ChromaGlasses*. An important factor for the development and improvement of such assistive technology, and also for the development of guidelines for architects and designers, is to determine the exact influence of vision impairments on perception and the effects of different lighting scenarios on perception by people with vision impairments.

One way to do this would be to perform user studies in real-world situations. Wood et al. [25], for example, conducted a user study on the effects of cataracts and refractive blur on nighttime driving, by using modified goggles. The problem with such experiments is that the different vision capabilities of the study participants can influence the results. Increasing the reliability of the statistical analysis requires increasing the number of participants with the same form of vision impairment, and getting larger samples can be difficult. Moreover, for eye diseases such as cataracts, diabetic retinopathy, glaucoma or macular degeneration, it is difficult to determine exactly how a person experiences the visually degrading effects caused by the disease, other then to ask them for a verbal description. Some participants might have an eye disease with similar extent (e.g., a similarly clouded lens) as estimated by eye exams, but since the experience of the individual symptoms is highly subjective, it is unlikely that two people experience the exact same form of vision impairment and difficult to even find out if this is the case. This makes it infeasible for real-world user studies to determine the exact effects of eye diseases such as cataracts on perception.

When conducting user studies in VR with simulated vision impairments, it is important to recruit participants with normal sight to avoid degrading a user's vision more than intended by the simulated impairments. However, even people with normal sight have varying vision capabilities that need to be accounted for. Furthermore, the resolution of VR headsets is lower than that of the human eye. Therefore, users already experience a form of vision impairment when wearing a VR headset. In our previous work [10], we introduced a methodology to calibrate the vision of users to a specific level of reduced visual acuity (VA), taking into account the actual vision of users and the hardware constraints of the VR headset. We build upon this methodology to simulate and calibrate not only reduced VA, but also loss of contrast. This is then combined with a simulation of a clouded lens, a color shift, and a simulation of light sensitivity. In combination, these symptoms create a form of impaired vision corresponding to a disease pattern associated with cataracts. In contrast to previous work on cataract simulation [7, 12, 13, 25], we achieve a more detailed and adjustable simulation of this eye disease by simulating and combining multiple symptoms and are able to simulate different forms of cataracts: nuclear cataracts, cortical cataracts, and subcapsular cataracts, as shown in Figure 1.

Different illumination levels cause the pupil of the human eye to get wider or narrower, allowing more or less light to enter the eye. This also affects the area of the lens that is exposed to light entering the eye. For some forms of cataracts that exhibit a nonuniform clouding of the lens, the area of the pupil that is exposed to light affects the way vision is impaired. Therefore, our simulation adapts to different lighting conditions to simulate these effects, making it possible for the first time to conduct experiments on the effects of illumination on perception under simulated cataract vision.

Our simulation of cataract vision gives a more complete impression than previous work of the perception experienced by people with cataracts. We calibrate reduced VA in the manner described in our previous work [10], together with a new approach to contrast calibration, to allow calibrating the vision of each user to the same level of impairment, making it possible to conduct user studies with people with normal sight and graphically simulated cataracts. Our tool can be used by architects and designers to evaluate their concepts for people with vision impairments, or by relatives of cataract patients to get a better understanding of the problems and challenges people with cataracts face every day.

The main contributions of this paper are:

- *More extensive simulation than in previous work of different forms of cataracts in VR, using eye tracking for gaze-dependent effects.* Our simulation comprises multiple effects representing different symptoms that are simulated separately and then combined to form certain disease patterns of cataracts. Hence, instead of simple approximations of cataract vision, our approach is the first to plausibly simulate different forms of cataracts.

- *Simulation of the influence of light on the visual perception of people with cataracts.* We simulate intensified blinding effects when looking into bright lights, as well as brightness-dependent widening and contraction of the pupil that exposes more or less area of a clouded lens to light and therefore influences vision differently. This can aid in architectual design.

- *Improved methodology for conducting user studies in VR using participants with normal sight.* In addition to reduced VA, we also calibrate contrast loss to the same level for every user-study participant, taking into account the actual vision of the user and the hardware constraints of the VR headset. This is an important prerequisite to studying cataracts with normal-sighted participants.

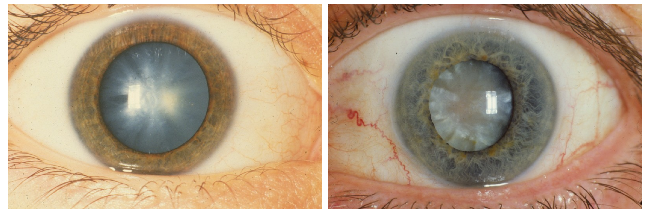


Figure 2: White congenital cataract (left) and hypermature age-related cortico-nuclear cataract with brunescent (brown) nucleus (right). Images taken from the *National Eye Institute* [16].

This paper is organized as follows: In Section 2, we provide background information on types of cataracts and present related work on simulating vision impairments. Section 3 explains how we simulate, calibrate, and combine different cataract symptoms to form certain disease patterns of cataracts. We describe our user study in Section 4 and present its results in Section 5. We then discuss and summarize the results in Section 6 and point out limitations of our work and possible approaches for improvement. Finally, Section 7 presents our conclusions and an outlook on future work.

2 Background and Related Work

The leading causes of vision impairment worldwide, as identified by the WHO, are uncorrected refractive errors and cataracts. VA is usually expressed relative to 6/6, the Snellen fraction for the test distance of 6m, or 20/20 in feet, or the decimal value of these fractions. The WHO distinguishes between mild (VA worse than 6/12 or 20/40), moderate (VA worse than 6/18 or 20/60), and severe (VA worse than 6/60 or 20/200) vision impairment, and blindness (VA worse than 3/60 or 20/400). The global estimates of the number of visually impaired people, given in the WHO report on global data on visual impairments [18] show that about 14 percent (186.203 million people) of the world population over the age of 50 (1340.80 million) have a moderate to severe vision impairment (154.043 million) or are blind (32.16 million), with cataracts being the major cause of blindness. Figure 2 shows two examples of cataracts.

2.1 Cataract Types

Depending on their characteristics cataracts are categorized as *nuclear*, *cortical*, or *subcapsular* cataracts.

Nuclear Cataract Nuclear cataracts are characterized by a clouding of the lens due to an accumulation of yellow-brown pigment or protein in the central area (nucleus) of the lens. This creates a homogeneous clouding of the lens, often with a yellowish/brownish tint and results in increased light scattering [14].

Cortical Cataract Cortical cataracts are caused by an opacity forming at the lens cortex, due to protein aggregation or damage to the fibres in this area. People with cortical cataracts experience dot-like opacities, radial shades or spoke-shaped opacities in the periphery of their vision. The latter is the most common form of cataracts [14].

Posterior Subcapsular Cataract Posterior subcapsular cataracts are caused by defective fibre production in the lens and result in opacities at the posterior pole of the lens, perceived as dark shadows in the center of the field of view of affected people [14].

2.2 Impact of Cataracts on Vision

The effect of lens opacities on vision depends on their location and on pupil size. In daylight, when the pupil diameter is small, only opacities within the pupillary zone are likely to affect vision. If ambient light is further reduced and the pupil diameter becomes larger, vision is further affected as an increasing amount of straylight (light that is scattered by parts of the eye, due to optical imperfections like particles in a clouded lens [22]) falls on the retina. Intraocular straylight is better correlated to cataract severity than both visual acuity and contrast sensitivity and is worst in mixed cataracts [15].

2.3 Related Work on Simulating Vision Impairments

There has been much work in simulating visual impairments across different display modalities. Hogervorst and Van Damme [5] found a linear correlation between a just recognizable threshold for blurring an image and visual acuity, which forms the basis of our simulation of reduced visual acuity.

Wood et al. [25] and Zagar et al. [26] simulated typical effects of visual impairments such as glaucoma or cataracts, by creating actual sets of modified goggles. Using VR, Lewis et al. [12, 13] presented predefined simulations of vision impairments, where symptoms were not adjustable in severity. Their goal was not to conduct user studies or evaluate designs, but to raise awareness and increase the understanding of the effects of vision impairments. Jin et al. [7] provided a more complex simulation of vision impairments, by using a scotoma texture, created from perimetry exam data of real patients, to define regions of degraded vision. Banks and Crindle [2] also combined different image-processing effects to achieve particular eye disease patterns on 2D images, but not in VR and without eye tracking or calibration to participants. Werfel et al. [24] developed an augmented reality (AR) and VR system for empathizing with people with audiovisual sense impairments, which also includes a cataract module, but also did not do eye tracking or user calibration.

To create a setup for accessibility inspection, Ates et al. [1] simulated vision impairments in AR, based on photos from the National Eye Institute (NEI) [17] and using a stereoscopic VR media player. Väyrynen et al. [23] targeted their research towards giving architectural designers an idea of the challenges with which visually impaired people are often confronted. They used Unity3D and standard effects provided by the game engine to simulate vision impairments, based on images of online simulators or hardware-based simulations. Recent work by Jones and Ometto [8] aims not only at creating a teaching or empathy aid, but also a tool for accessibility evaluations. Their VR simulation of different visual impairments allows adjusting symptoms, integrates eye-tracking data, and achieves near real-time rendering. However, none of this research takes into account the actual vision capabilities of the user or the constraints imposed by the VR headset.

3 Simulating Cataracts

Taking the VA of users and the hardware constraints of the VR headset into account by calibrating our effects appropriately, we used Unreal Engine (UE) 4.0 (on a PC with an AMD Ryzen 7 1800 CPU, 32GB RAM and an NVIDIA GTX 1070 GPU) and an HTC Vive Pro headset with Pupil Labs binocular eye tracker add-on to develop simulations for three different types of cataracts: nuclear cataracts, cortical cataracts, and subcapsular cataracts. We simulate separately each of five symptoms (blurred vision, contrast loss, color shift, clouded lens, and sensitivity to light) and combine them for a simulation of the whole disease pattern.

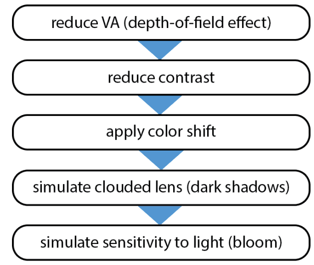


Figure 3: Combining effects to simulate cataract: reduce VA by using UE built-in depth-of-field effect; reduce contrast; apply color shift; use alpha texture to simulate dark shadows (clouded lens) for cortical or subcapsular cataracts, and modify clouded-lens effect according to brightness of virtual environment the user is currently viewing; and add UE bloom effect to achieve glare, simulating sensitivity to light.

3.1 Effects Simulating Cataract Symptoms

For each frame, the image that is to be displayed on the VR headset is modified in several ways by applying different effects in sequence, as outlined in Figure 3.

3.1.1 Blurred Vision

Blurred vision caused by reduced VA is a very common symptom for many eye diseases and vision impairments. In our recent work [10] we simulated reduced VA by applying a Gaussian blur to the image. Following the findings of Hogervorst et al. [5], we used a sigma parameter for the Gaussian blur that was related to the level of VA to be simulated. We now use the same principle in this work, but go one step further by also taking distance-dependent effects into account. For example, people with myopia (nearsightedness) do not have a VA that is the same for every viewing distance. They often see very well at close distances and the reduced VA only has an effect at longer distances. We simulate this factor by using a depth-of-field effect and adjust its effect size with the sigma parameter, as described in our previous work [10]. The resulting image C_{rVA} with reduced VA is then reduced in contrast in the next step.

3.1.2 Contrast Loss

A loss of contrast is often experienced as faded colors, which may be implemented in a number of different ways in VR. Using an approach that shrinks the histogram of a frame by using min and max values of the image is not feasible, because intensity changes from one frame to the next could change the color and intensity distribution in the image. This could yield very sudden changes of the histogram and introduce flickering artifacts. Instead, we need a way to reduce contrast that is consistent over multiple frames. Furthermore, our simulation needs to run in real time, which means we need to avoid expensive calculations. For these reasons, we chose to use a simple histogram remapping. We use a contrast reduction value, which we determine in our contrast calibration phase (see Section 3.2.2), to modify the pixel values in every frame:

$$C_{rContrast} = C_{rVA}c + 0.5(1 - c).$$

The constant c is the contrast reduction value, a value between 0 and 1, independent of the pixel values in the image. Scaling the color values with c shrinks the histogram and therefore reduces the

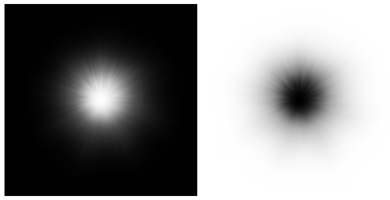


Figure 4: Alpha texture used to create shadows for cortical cataracts (left) and subcapsular cataracts (right) by scaling the image values with the alpha value of this texture. Dark pixels represent an alpha value of 0, while white pixels represent a value of 1.

contrast. At the same time this operation reduces the intensity of each value by $(1-c)$. Adding $(1-c)$ would then shift all values, so the maximum intensities would be preserved. However, this would mean darker regions would be perceived a lot brighter after the contrast reduction. In order to preserve the average intensity in the image, we only add $0.5(1-c)$.

This operation is essentially an interpolation between the current image and a uniformly grey image, weighted by the contrast reduction value. In future work, we plan to investigate more elaborate ways (e.g., tone-mapping methods) to efficiently simulate contrast loss. Next, we apply a color shift to the image.

3.1.3 Color Shift

As described in Section 2, a common symptom of cataracts is tinted vision. We simulate this yellowish/brownish tint by applying a color shift to the contrast-reduced image $C_{rContrast}$ in the direction of a predefined target color C_{target}:

$$C_{colorShift} = C_{rContrast}t + C_{target}(1-t).$$

The amount of the color shift is controlled by the parameter t. Both the target color and the parameter t can be adjusted. The target color $C_{target} = (1.0, 0.718461, 0.177084)$ (in RGB color space) and the parameter $t = 0.8$ were selected for our user study, after some iterations together with experts in ophthalmology to achieve a plausible depiction of this symptom. Note that this form of color shift further reduces the contrast of the image. This additional contrast reduction is in the same amount for every participant. If we wanted to avoid further reducing the contrast we could perform a color shift in the HSL or HSV color space.

3.1.4 Clouded Lens

Cataracts lead to a clouding of the eye lens. While for nuclear cataracts, this clouding is uniform over the whole lens, cortical cataracts also produce dark shadows in the periphery of the lens, and subcapsular cataracts create a dark shadow in the center of the lens. We simulate these shadows with an alpha texture that is used to darken the image, either in the periphery (for cortical cataracts) or in the center (for subcapsular cataracts), by linearly interpolating between the image color $C_{colorShift}$ of the image after the color shift and a shadow color C_{shadow}:

$$C = C_{colorShift}\alpha + C_{shadow}(1-\alpha),$$

where α has values between 0 and 1. In our user study, we used black $(0,0,0)$ (in RGB color space) as the shadow color C_{shadow}. The amount to which these dark shadows appear in the visual field of the user also depends on the light intensity in the scene (see Section 3.1.5).

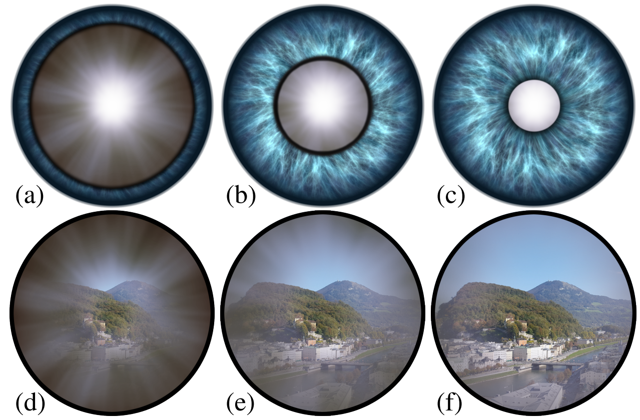


Figure 5: Changes in pupil size (a,b,c) can affect the influence of dark shadows, experienced (d,e,f) with cortical cataracts, on human vision. For demonstrative purposes other effects were omitted in this image. (a,d): Vision with large pupil. (b,e): Vision with smaller pupil. (c,f): Vision with very small pupil, where the darkening of the shadows is hardly noticeable anymore.

3.1.5 Sensitivity to Light

We simulate sensitivity to light in two ways. The clouded lens of cataract patients scatters in many directions onto the retina. Images become blurred and bright lights become especially problematic, because they create intense glare. We simulate this by post-processing the image to apply a bloom effect. The threshold for the bloom is set to a value below the intensity of the light sources in the scene, but above the rest of the geometry. This avoids the blooming of white walls, for example. The intensity and width of the effect can be adjusted and we plan to test different values with cataract patients in future work.

The second way in which light affects the vision of people with cataracts is the widening and contracting of the pupil when we look at dark areas or into bright lights, respectively. For cortical cataracts, the clouding of the lens creates dark shadows in the periphery, but the center of the field of view is less affected (see Figure 5). This means when the pupil is wide open, light enters the eye also through parts that are heavily clouded and the shadows in the periphery become more apparent for the person. When looking into bright lights, the pupil contracts and light can only enter the eye through the central area of the lens. This area is less clouded, and dark shadows in the periphery are less visible or might disappear altogether. We simulate this behavior by scaling the texture that creates these peripheral shadows. We calculate the average intensity value of the current field of view and use it to scale the texture so it gets bigger (extending the less clouded area in the center of the field of view) when the user looks at bright areas and smaller (pushing more of the shadows into the center of the field of view) when the user looks at dark areas. The extent of this effect can be adjusted.

The influence of subcapsular cataracts increases when the pupil becomes smaller, since less of the unaffected area of the lens is exposed to light in this case. Consequently, the dark shadows in the center of the field of view become more prominent and more disturbing. We implement this effect the same way as for cortical cataracts, by scaling the texture that creates the shadows.

3.2 Calibration with Eyesight Tests in VR

To statistically analyze and be able to generalize our findings, we need to control independent variables such as the actual vision capabilities of our user study participants and the hardware constraints imposed by the VR headset, or at least take these variables into account when simulating cataract vision. We do this by calibrating

Figure 6: The *Landolt C*, or *Landolt ring* is a common optotype for medical eye exams. It has a gap at one of eight possible positions: top, bottom, left, right, or 45° in between.

the reduced VA and the reduced contrast to the same levels for all our participants in a calibration step before the MRD tests. We do not calibrate our clouded-lens effect or color shift or sensitivity to light, because we would only expect significantly different perception of these effects from users that already have an eye disease. In contrast, we can expect even people with normal sight to have slightly different levels of VA and contrast sensitivity. Hence, we need to account for these factors.

3.2.1 Calibrating Reduced Visual Acuity

We use an eyesight test in VR to calibrate all our users to a specific level of reduced VA, an improved version of the eyesight test presented in our recent work [10]. We use a set of five Landolt rings (see Figure 6) as described by the international standard *ISO 8596:2017* [6]. If the user recognizes the direction of the gap in the ring correctly for at least three out of five rings, the next set of smaller Landolt rings is used. The standard states that as soon as the user cannot correctly identify the direction of the gaps for at least three out of five, the tests ends and the VA is recorded as the VA of the last correct row of Landolt rings.

In our VR simulation, we do not have an ophthalmologist pointing at one Landolt ring after another on a chart of optoypes. Therefore, we display only one Landolt ring at a time at a fixed distance to the VR headset. Instead of changing the size of the rings every five optotypes, we fix the size (and distance) of the Landolt ring. We select the size and distance of the Landolt ring such that a person who cannot identify the gaps at this fixed size and distance correctly anymore is classified as having a VA of 6/36 or ~ 0.167 decimal acuity. Then we add a Gaussian blur to the image, and increase its effect stepwise (without altering size or distance of the rings), as described in our previous work [10], until the user can no longer recognize the gaps in the rings and therefore now has a simulated reduced VA of 0.167 decimal.

We improved our previous version of this method by not just applying a Gaussian blur to the whole image, but using the UE depth-of-field effect to account for the near vision that is usually not blurred for shortsighted people. The test value of 0.167 decimal, or 6/36 VA was chosen as one example, that represents a moderate vision impairment (VA between 6/18 and 6/60) as defined by the WHO [18], which is well beyond the VA limit of 0.5 decimal for driving, as prescribed by most international standards [3].

3.2.2 Calibrating Contrast Loss

We use the same methodology as for calibrating reduced VA also to calibrate the perceived loss of contrast. We use the *Pelli–Robson contrast sensitivity test* [19], but with Landolt rings as optotypes. For this test, optotypes are displayed at a large size (equivalent to 20/60 acuity) in groups of three with decreased contrast for each group. According to the test protocol of this standardized test, the participant has to correctly recognize two out of three optotypes to proceed with the next group. If the participant cannot recognize two out of three optotypes correctly anymore, the contrast sensitivity (CS) is recorded as the *log CS* value of the last correct group. For our simulation, we display groups of three Landolt rings, one after the other and decrease the contrast, as described by Pelli et al. [19] after each group until the direction of the gaps in two out of three Landolt rings cannot be recognized correctly anymore. The contrast is reduced by applying the following calculations to the image during this calibration procedure:

$$C = C_{original}\, c + (1 - c),$$

where c is the contrast reduction value. Scaling the color values with c shrinks the histogram. Adding $(1 - c)$ then shifts all values, so the maximum intensities are preserved by this operation. This allows us to reduce the contrast of the Landolt ring in relation to the background, while keeping the background color white. This can be seen as an interpolation between the image and a uniformly white image, weighted by the contrast reduction value.

In contrast to the original Pelli–Robson test, we already start with a reduced contrast, corresponding to a log CS 1.0, which is a remaining contrast of 10 percent. It should be noted that the UE post-processing pipeline reduces the remaining contrast noticeably. We estimate the actual remaining visual contrast to be around 5%. Further investigations are necessary to determine the influence of UE and also of the VR headset display on visual contrast. However, the additional degradation caused by UE is constant and the same for every participant. While we are aware that this constant might be unknown, we find that it should not impact the assessment of our results, since it only changes the start value of the contrast calibration.

As soon as the participant cannot recognize the Landolt rings anymore, our simulation has calibrated the vision of the participant to the same perceived level of contrast loss as for every other participant. The *contrast reduction value* of the last group of correctly recognized optotypes is then used to simulate the same amount of contrast loss as part of cataract vision (see Section 3.1.2).

3.3 Eye tracking for Gaze-Dependent Effects

In contrast to nuclear cataracts that result in a uniformly clouded lens, cortical cataracts and subcapsular cataracts produce dark shadows in the periphery or in the center of the lens, respectively. To correctly simulate vision affected by these gaze-dependent symptoms, we need to track the gaze of the user and adjust our effects to it. We use the 120Hz HTC Vive binocular eye tracking add-on from *Pupil Labs* [21], integrating it in our UE project. The Pupil Labs software uses the same coordinate system as OpenGL, with the origin (0,0) in the bottom left and (1,1) at the top right corner. The eye tracker cameras track the pupils of the user's eyes and provide us with 2D coordinates (X and Y positions in the eye image frame in normalized coordinates) as well as a confidence value between 0 and 1 that indicates how sure the eye tracker is about the measurement. According to the Pupil Labs documentation [20], values greater than 0.6 are reliable and values of zero should be ignored. Our proof-of-concept eye-tracking integration exhibits a noticeable lag. However, users testing our simulation during the user study were still impressed by the gaze-dependent effect. For future work, we plan to test newer Pupil Labs software and improve our own implementation to attempt to further decrease noticeable lag.

4 User Study

We conducted a user study with 21 participants, 8 participating in a pilot study and 13 in the final study, which included some adjustments. For more details on demographics see Section 5.4.

4.1 Methodology and Experiment Design

In our recent work [10], we conducted MRD tests at the beginning and again at the end of each experiment session with a user. We compared these measurements statistically and could not find any evidence for a learning effect. We use the same experiment setup again for our MRD test in this study, but omit a second round of MRD tests to stay within a maximum time of half an hour per participant. Because we did not expect a learning effect and wanted to keep our participant pool small, we use a within-group design

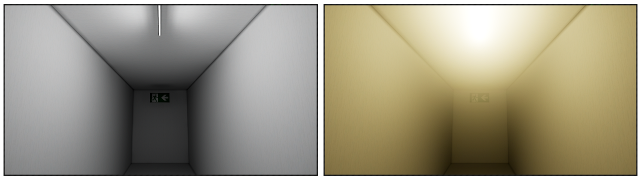


Figure 7: Escape-route sign at the end of the corridor during MRD tests with clear vision (left) and nuclear cataract (right).

Figure 8: VE with lighting setup 1 (left), consisting of four luminaires on the ceiling and a torchiere in the corner of the room, and lighting setup 2 (right) featuring small spotlights under the kitchen cupboards and on the ceiling.

for our user study, so that every participant experiences each of our experimental conditions.

4.1.1 Maximum Recognition Distance Tests

The MRD tests constitute our quantitative experiment. Participants are placed in a virtual corridor with an escape-route sign at the end (Figure 7). They then have to advance along the corridor until they can recognize the direction to which the sign is pointing and indicate this through trackpad input on the HTC Vive controller. In this experiment, we are investigating one independent variable (vision) with four conditions (clear vision and three types of cataracts). The task is to recognize the direction on the sign. We took three measurements per condition (and one extra for the subcapsular cataract vision), resulting in 13 trials per participant.

4.1.2 Environment Exploration

In the second experiment, participants are asked to explore a virtual environment (VE) and rate its lighting setup. In this qualitative experiment, users are placed in a virtual kitchen with two different lighting setups (see Figure 8). The individuals are then asked to try to identify different details in the environment and comment on how well or badly they can recognize objects. We again investigate one independent variable (vision), but with two *experimental objects* (two different lighting setups) and three conditions (cataract types). While exploring and comparing both lighting setups with each cataract type, the researchers write down comments by the participants for use in qualitative analysis.

4.2 Pilot Study

While we used the same methodology for MRD testing as in our previous work, we also wanted to analyze how various lighting setups would impact a person's ability to recognize objects in the environment. We first conducted a pilot study with eight participants to test the simulation and experiment setup, which led to two changes:

- Participants were told not to "cheat" the eye tracker with fast eye movements after it became apparent that exploiting eye tracker delay made it possible to recognize escape-route signs early.
- Participants wanted to be able to switch back and forth between both lighting setups in the environment exploration experiment, to be able to better compare the lighting setups. This functionality was added after the pilot study.

4.3 User Study Protocol

The participant was first welcomed by the study coordinator and asked to answer a few demographics and computer literacy questions.

The coordinator then introduced and explained the procedures for the study. After the introduction, the participant was asked to sign a consent form. Then the participant moved into the HTC Vive tracking space and was outfitted with the equipment. Once the participant was ready, the study began, with the following flow:

1. (Calibration) Eye-tracker calibration. To ensure proper functionality, the eye tracker needed to be calibrated for each user. This was done by asking the participant to focus on a green point that would move about their field-of-view, to calibrate different eye-to-screen poses.
2. (Baseline Test) Eyesight test for visual acuity (VA) using Landolt Cs to test VA of participants (capped by HTC Vive Pro resolution), as described in Section 3.2.1.
3. (Calibration) Eyesight test for visual acuity (VA) using Landolt Cs to calibrate to predefined level of reduced VA (constant size of Landolt C, stepwise increasing the blur applied to the image, using the UE depth-of-field effect).
4. (Calibration) Eyesight test for contrast sensitivity using Pelli–Robson contrast-sensitivity test (as described in Section 3.2.2), but with Landolt Cs, to calibrate to predefined level of loss of contrast.
5. (Baseline Test) Eyesight test with full nuclear cataract simulation to measure the VA of the combined effects.
6. (Quantitative Experiment) Test MRDs of an escape-route sign, with both clear vision and different cataract simulations (measurements taken for illuminated signs).
7. (Qualitative Experiment) Environment Exploration
   - After the previous step, users are placed in a VE and are asked to look around and perform some tasks (e.g., reading aloud brand names and looking at a clock).
   - Two different illumination scenarios (for the same VE) are tested (Figure 8).
   - The investigator changed scenarios manually.
   - Participants were asked to compare both illumination scenarios when looking at the scene with (1) cortical, (2) nuclear, and (3) subcapsular cataract.
   - The investigator wrote down observations (while participants—still in VR—were talking and commenting on the quality of the different illumination scenarios).
8. Questionnaire. After the VR experiment, participants were asked to fill out a questionnaire, consisting of questions for each cataract simulation and some additional questions about their experience with the simulation.

Note that the order of conditions during the environment exploration was not taken into account in the evaluation, because participants could ask the investigator to switch back and forth between cataract types and illumination scenarios any time. Furthermore, we did not conduct any analyses regarding learning effects, because participants were presented with different random tasks by the investigator. These tasks only served to make participants look more closely at the VE before giving their subjective opinion on which lighting system they preferred with which type of cataract. In future work, one could also implement search tasks and measure completion times for a quantitative analysis.

5 Results

During our user study, we measured VA without and with simulated cataracts. Then we conducted our quantitative experiment and measured MRDs under different vision conditions. The environment-exploration experiment yielded qualitative feedback on two different lighting setups, experienced with all three types of cataracts.

Through our questionnaire and a look at the data recorded by the eye tracker, we gained additional insights for our analysis.

5.1 Eyesight Tests in VR

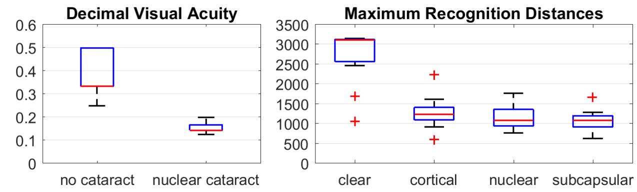
We tested the VA of all participants when they first put on the Vive Pro headset used in our study. We used an eyesight test using Landolt rings as described in Section 3.2.1. After reducing their VA and contrast in our calibration procedure, we tested their VA again with simulated nuclear cataract (combining all effects described in Section 3.1). The results are shown in Figure 9a. We do not show the few outliers we removed here as they fall significantly outside of range, and did not occur due to normal operating procedure. Even without simulated vision impairment, none of the participants managed to achieve a higher decimal VA than 0.5 (or 6/12), which is considered "mild vision loss" according to the *International Council of Ophthalmology* [4]. Hence, the HTC Vive Pro headset alone induces a mild vision loss of 0.5 decimal VA. This is slightly better than previously reported for the original HTC Vive (0.4), presumably because of the higher resolution of the HTC Vive Pro.

While VA varied without simulating vision impairment (with a variance of ~ 0.0093), for nuclear cataracts, we achieved simulated VA levels with a very small variance of ~ 0.0004. (Note that outliers were removed for the variance calculations of VAs.) Considering that eyesight tests (in VR or in reality) are never completely accurate (patients are asked to guess when they can no longer recognize the stimulus), this gives us a realistic baseline to investigate MRDs with cataract vision.

5.2 Measured Maximum Recognition Distances

In our quantitative experiments, we measured MRDs under different visual conditions as described in Section 4.1.1. These tests were error-prone, as participants sometimes touched the the trackpad of the Vive controller too far on the rim and the controller would not register their input. This led users to believe their input was wrong and made them move much closer to the escape-route sign than necessary (before realizing how to properly press the trackpad), yielding a very small MRD value in the results. Since these input problems caused at least one skewed MRD value for almost every participant, we decided to take the median of each group of samples (1 group = 3 samples under 1 condition) instead of all samples or the mean of these groups. Figure 9b shows the distributions of median values per vision condition. The first boxplot represents the measurements with clear vision and no simulated cataracts. Participants achieved higher MRDs than we anticipated and sometimes recognized the sign's direction from the starting point. For future studies, we recommend placing the starting point much farther from the sign to avoid capping the MRD values.

Knezevic [9] states that "[i]f two statistics have non-overlapping confidence intervals, they are necessarily significantly different." Figure 9b shows that MRDs with cataract vision are significantly lower than with clear vision. Paired t-tests comparing the distribution of MRDs of clear vision to MRDs of each cataract type also show that these distributions are significantly different, rejecting the null-hypothesis at a 0.05 significance level, with $p < 0.001$ and effect sizes of 2.43, 2.46 and 2.56, calculated with *Cohen's d* for MRDs with cortical, nuclear and subcapsular cataracts, respectively. Our statistical evaluation yields that a sample size of four or five participants is required to achieve a statistical power of 0.9 for these tests. All of our tests have a power of ~ 1 with our sample size of 13 participants. With outliers removed, the p-values are still below 0.001. The outliers that are shown as red plus-signs in Figure 9b can be attributed to three participants. After investigating our data, we found that for at least one of these participants the VA calibration did not work, causing errors in the remaining measurements of this participant.



(a) Decimal VA measured without (left: 0.25 to 0.5 VA), and with (right: 0.125 to 0.2 VA) simulated nuclear cataracts.

(b) MRD (in cm), measured with clear vision, and simulated cortical, nuclear, and subcapsular cataracts.

Figure 9: Measurements of (a) VAs and (b) MRDs.

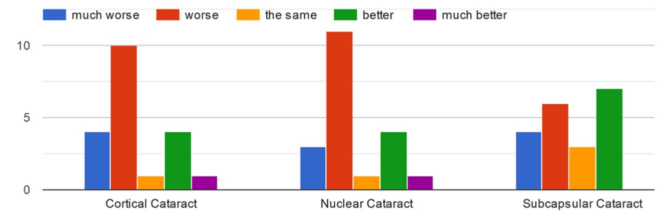


Figure 10: Answers to the question, "Compared to the previous illumination, does this second one feel better or worse regarding perception? (Is it easier or harder to see objects?)".

5.3 Environment Exploration Results

During our qualitative experiment (Section 4.1.2), participants were asked to comment on the illumination in the scene and their perception with the three different cataract simulations. For each cataract type, they were shown lighting setup 1 (Figure 8 left) and then lighting setup 2 (Figure 8 right), and could switch back and forth between them. They were asked to compare the second to the first lighting setup, first with cortical cataracts, then with nuclear cataracts, and finally with subcapsular cataracts.

Figure 10 shows that most participants rated the second lighting setup worse when compared to the first, with cortical or nuclear cataracts. Some participants complained in the second setup that they did not like having this many spotlights in their field of view, since the simulated glare was blinding their vision. Interestingly, three taller participants preferred the second lighting setup over the first one, since they experienced a smaller grazing angle to the spotlights and therefore a less severe blinding effect. Most participants also mentioned that the first setup illuminated the whole scene better, instead of primarily illuminating the work surface. Overall, participants liked a well-illuminated work space (as in the second setup), but in general disliked luminaires in their field of view, due to blinding effects.

5.4 Questionnaire Data

We had 21 user study participants in total, 8 of them for the pilot study and 13 for the final user study. The participants' ages ranged from 24 to 56 years old, with $\sim 85\%$ male and $\sim 15\%$ female. 19% wore glasses and another 19% wore contact lenses during the experiments, mostly due to myopia. Since we expected glasses to interfere with the eye tracker, we were specifically looking for people with normal sight or wearing contact lenses for our study, but did not exclude any participants who volunteered to take part in our study (even when they were wearing glasses). All participants were proficient in using computers and except for one participant, all had had at least some previous experience with VR. After the experiments, participants were asked to answer a questionnaire about their experience with the simulation. Figure 11 shows that all partici-

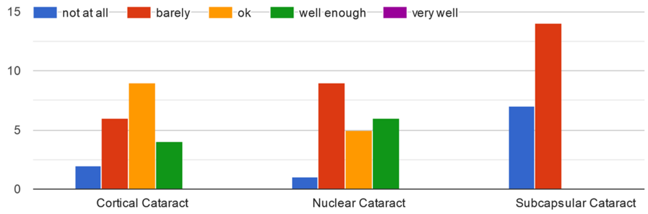


Figure 11: Answers to the question, "How well did you feel you were able to read the escape-route signs with cortical cataracts, nuclear cataracts or subcapsular cataracts?".

pants felt they could barely read escape-route signs with subcapsular cataracts or not at all. Our data (see Figure 9b) does not show such an apparent performance difference between different cataract types. All participants answered the question of whether they thought they gained a better understanding for the problems people with cataracts face every day, after testing this simulation, with "yes."

5.5 Eye Tracking Data

During the whole study (for the MRD tests as well as the environment exploration), we recorded the eye movements picked up by the eye tracker. The more data it recorded for a participant, the better it worked. When using the eye tracker with users wearing glasses, the performance and accuracy of the tracker, as well as the amount of recorded data, decreased. Another interesting observation we made was that for one participant in our user study, dark mascara irritated the eye tracker, causing it to sometimes track eye lashes instead of the pupil (Figure 12).

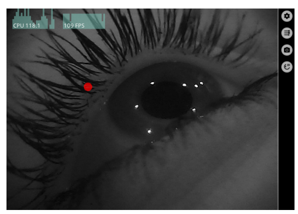


Figure 12: Eye tracker showing poor performance for user with dark mascara, mistaking eye lashes for pupil.

6 Discussion and Limitations

The results of our VA tests in VR suggest that our simulation is able to calibrate the vision of every participant with simulated cataracts to a similar level of impairment. This is achieved by using a calibration step for VA (as introduced in our previous work [10]) and our novel calibration for loss of contrast. Both calibration procedures are based on a medical test and follow the respective protocols as outlined in the international standard ISO 8596 [6] and the work of Pelli et al. [19]. For future work, it may be worth considering deviating from these protocols and instead using a psychophysical approach to possibly increase the accuracy of these tests.

Regarding the color shift and bloom effect, we cannot claim that our simulation correctly simulates exactly how cataract vision appears. The different symptoms of cataracts, including tinted vision and glare, vary among affected patients. In future work, we plan to conduct a study with cataract patients to better verify the faithfulness of each of our simulated symptoms, comparing simulated cataract vision seen with an unaffected eye with actual cataract vision in the other eye. Furthermore, it should be noted that the lenses and brightness of the particular VR display (HTC Vive Pro) affect the perception of what is rendered on the display. With other types of displays, we would expect to get different values from our calibration procedures and might need different calculations for some effects.

The results of our quantitative experiments show that people with simulated cataracts achieve significantly lower MRDs than people with clear vision. For future work, conducting a user study with a larger number of participants and more measurements per vision condition could allow us to also investigate possible differences between types of cataracts.

In our qualitative experiment, we found that different lighting setups achieve different quality ratings when experienced with cataract vision. Our present methodology can allow architects or lighting designers to qualitatively evaluate their designs by importing them into UE and conducting experiments with our cataract simulation. To demonstrate this approach, we did a brief experimental evaluation of two different lighting setups (Figure 8) for a 3D model of a kitchen with our system. During these tests, looking at direct lights was reported as especially uncomfortable.

Future work should test lighting setups designed by a professional lighting designer, featuring more indirect illumination, to find suitable lighting designs for people with cataracts. Using our calibration techniques also shows how user studies can be conducted to quantitatively evaluate different aspects of architectural design, like emergency signage (as shown in Section 4.1.1). While planning the design of a building, architects can use our methodology to make determinations of where to place constructions, such as lighting fixtures, in order to maximize accessibility for users with limited visual acuity.

Our current integration of the Pupil Labs eye tracker has a noticeable delay, but still made it possible to show gaze-dependent effects. Even if our simulation is not perfect yet, participants were impressed by the simulated cataract vision and our questionnaire shows it succeeded in increasing their understanding of what people with cataracts experience.

7 Conclusions and Future Work

We have presented the most complete simulation of cataracts in VR to date. In particular, three different types of cataract are simulated through an appropriate combination of individual effects, the severity of symptoms can be interactively modified, and the simulation reacts to eye tracking. This allows a realistic simulation of this type of visual impairment in diverse immersive settings. For the first time, we also support simulating the influence of light on the visual perception of people with cataracts. Through a calibration procedure that takes contrast loss into account, we provide a methodology to conduct user studies of cataract vision with normal-sighted participants. Further, we explored a methodology that might be helpful to architects and designers, when designing spaces that are accessible to people with visual impairments.

In the future, we would like to conduct experiments with cataract patients who have already been operated on one eye and ask them to adjust our cataract simulation, which they observe with their corrected eye, to match the VE as seen with their not yet corrected eye (without any graphically impaired vision). This would allow us to create presets for all effect parameters to simulate disease patterns as experienced by real patients. We would also like to extend our simulation to other visual impairments, such as glaucoma, macular degeneration or diabetic retinopathy. Finally, we believe that our findings on the influence of light on cataract patients could be used to design smart lighting systems that provide more comfort to these patients.

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