CatARact: Simulating Cataracts in Augmented Reality

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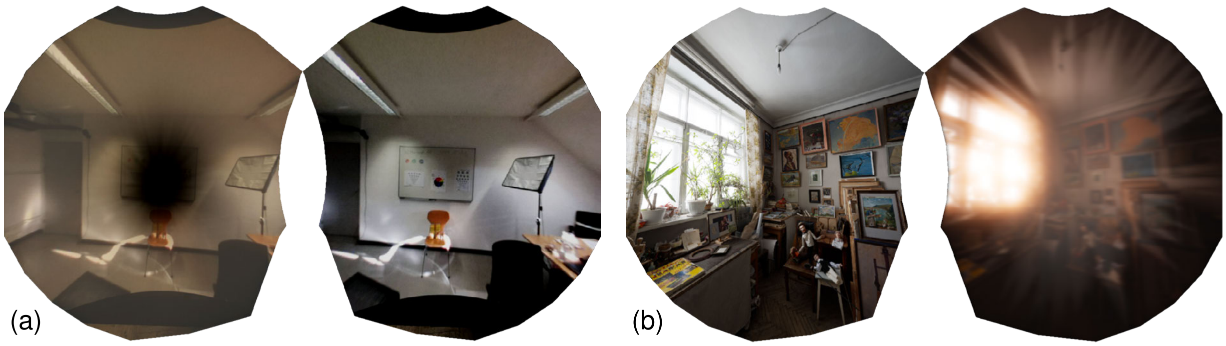

Figure 1: Simulation of cataract vision in eye-tracked stereoscopic head-worn display. Study participants were cataract patients with one corrected eye and one uncorrected eye. (a) Posterior subcapsular cataract simulated for corrected left eye and no modification for uncorrected right eye, viewing live stereoscopic video. (b) Cortical cataract with glare simulated for corrected right eye and no modification for uncorrected left eye, viewing 360° image.

Abstract

For our society to be more inclusive and accessible, the more than 2.2 billion people worldwide with limited vision should be considered more frequently in design decisions, such as architectural planning. To help architects in evaluating their designs and give medical personnel some insight on how patients experience cataracts, we worked with ophthalmologists to develop the first medically-informed, pilot-studied simulation of cataracts in eye-tracked augmented reality (AR). To test our methodology and simulation, we conducted a pilot study with cataract patients between surgeries of their two cataract-affected eyes. Participants compared the vision of their corrected eye, viewing through simulated cataracts, to that of their still affected eye, viewing an unmodified AR view. In addition, we conducted remote experiments via video call, live adjusting our simulation and comparing it to related work, with participants who had cataract surgery a few months before. We present our findings and insights from these experiments and outline avenues for future work.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Perception; Applied computing—Life and medical sciences—Health informatics; 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; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality

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1 Introduction

The *World Health Organisation* (WHO) reported in 2019 that at least 2.2 billion people globally were affected by vision impairments or blindness [30]. This number is expected to continuously increase due to different factors such as aging of the population, urbanization, or behavioral and lifestyle changes. Many eye conditions, such as presbyopia, cataract, glaucoma and age-related macular degeneration, show a higher prevalence with age. [30]. Cataracts were identified as one of the leading causes for vision impairments (33%) and blindness [23].

A *cataract* is a clouding of an eye's lens and the visual symptoms it produces include, among others, blurred vision, glare, and fading colors. Standardized tests for each symptom have been established to characterize the severity of visual impairment, and verbal descriptions from patients can give some insight into the quality of vision impairment. However, verbal descriptions can be inaccurate or incomplete, since vision impairments secondary to cataracts progress slowly over time; therefore, affected people do not notice these symptoms, especially if both eyes are affected and they lack a healthy eye for reference. While there are some existing simulations of cataract vision that work with live camera imagery, they are inadequate, overly simplifying the effects that are experienced. This can make it difficult for a healthy person to comprehend how a person with cataracts sees the world, experiences light, or accomplishes crucial tasks such as reading escape-route signs.

To address this, we developed a system to simulate cataract vision interactively in augmented reality (AR), using eye tracking to model gaze-dependent effects (Figure 1). We then evaluated the realism of our simulation with actual cataract patients. Our pilot study yielded sets of parameter values that can be used to create a realistic simulation of cataract vision in AR or virtual reality (VR), as experienced by these patients. Our system presents a number of cataract symptoms (in one or both eyes) to a user wearing a stereoscopic head-worn display (HWD), integrating the symptoms with either the user's live binocular camera view of the real world, previously recorded video footage, 360° images, or live virtual environments. We support a number of modifiable parameters that control the simulated symptoms. Using a binocular eye tracker, gaze-dependent effects of the cataract simulation respond to the user's gaze.

Cataract symptoms are highly subjective and can vary individually depending on the kind and severity of lens opacity. At the same time, individual demands on visual function and its impact on quality of life also differ vastly, depending on the individual lifestyle. Therefore, we designed a pilot study to evaluate the simulation with people who actually have cataracts. Our participants recently had cataract surgery on one eye, and were awaiting surgery on their other eye, and thus could do a side-by-side comparison of our simulation, seen through their post-operative eye, with their own cataracts. In subsequent remote experiments, we showed our simulation through video calls to people who had cataract surgery a few months before and asked them to compare our simulation to related work.

Our system simulates and includes parameterized control for the characteristics and intensity of the following cataract symptoms:

- Reduced visual acuity,
- Reduced contrast,
- Color shift,
- Dark shadows, and
- Increased sensitivity to light.

To maximize the potential applicability of our system, we worked closely with ophthalmologists to refine both this set of symptoms and their depiction. Their expertise informed our development process and provided valuable insights that helped us understand how these diseases impact a person's vision, allowing us to identify and represent the core symptoms. This kept us from including uncommon symptoms in the core simulations.

We make the following contributions:

- We present the first system to simulate symptoms of cataracts in AR using an HWD with eye-tracking technology and parameterized visualizations that are informed by ophthalmology professionals.
- We describe a methodology to generate realistic simulations of eye diseases, such as cataracts, via per-symptom adjustment and comparison of real cataract vision to simulated symptoms observed with healthy eyesight.
- We extend our previous work in this area [14] with more sophisticated and perceptually accurate simulations and compare our newer system to the previous one.
- We test our methodology and evaluate the realism of our simulation through a pilot study with participants who are post-operative cataract surgery in one eye, and awaiting surgery for their second eye.

The aim of our work is to create a system that provides a more complete, accurate and immersive simulation than previous work, to help people without cataracts to better understand how people with cataracts view their environment. Our simulation can be used to train medical personnel, as well as to increase the understanding and empathy of relatives of cataract patients. Our methodology and the framework defined here form the basis for many other vision impairment simulations in AR. Our system also makes it possible to import 3D models of architectural scenes and can therefore be used to inform architectural planning to create more inclusive designs and support investigating how well different lighting conditions work for people with cataracts.

2 Background and Related Work

While highly treatable, cataracts represent one of the leading causes of vision impairment worldwide. Approximately one in six people with vision impairment have cataracts [11], and one in three people who are blind suffer from blindness caused by cataract.

stage	Snellen fraction		decimal acuity
mild	$<$20/40 ft	$<$6/12 m	$<$0.5
moderate	$<$20/60 ft	$<$6/18 m	$<$0.3
severe	$<$20/200 ft	$<$6/60 m	$<$0.1
blind	$<$20/400 ft	$<$3/60 m	$<$0.05

Table 1: Stages of visual impairment, as defined by the WHO [30], shown as Snellen fraction (in feet and meters) and decimal acuity. Smaller VA values correspond to more severe impairments.

2.1 Vision Impairment and Blindness Caused by Cataracts

Ophthalmologists have a number of tools available for defining impairments to visual acuity (VA). VA is often quantified using the Snellen fraction, which uses the reference value set of 20/20, expressed in feet (or 6/6, expressed in meters), indicating the distance a person needs to be (first value) to see what a standard person with normal eyesight can see at the distance specified by the second value. The World Health Organization (WHO) defines three stages of visual impairment and one for blindness, as shown in Table 1.

Intraocular straylight (light scattered by optical imperfections in an eye [25]) is closely correlated with cataract severity, more so than VA. As ambient light incident on the eye is reduced, and the pupil dilates, the amount of straylight that falls on the clouded lens increases and vision is reduced [19].

2.1.1 Cataract Types

There are three forms of cataract: nuclear, cortical, and posterior subcapsular. *Nuclear cataracts* manifest as a ubiquitous yellow tinting (or clouding) in one's vision, with increased straylight. This is due to build-up of protein in the nucleus of the lens [19]. *Cortical cataracts* appear as peripheral radial opacities (called "shades"), or spoked opacities starting near the periphery. These are caused by protein aggregation or fiber damage at the lens cortex [19]. *Posterior subcapsular cataracts* appear as shadows, smudges, or a general darkening at the center of one's vision. This is due to defective fiber production in the lens, with opacities forming at the posterior pole [19]. These three forms of cataract can develop to different extents within the same eye, and their severity can be graded in a slit-lamp examination or lens photography in *mydriasis* (dilation of the pupil) [5].

2.1.2 Pre- and Post-operation VA Comparisons

Most cataract surgeons do not perform bilateral same-day surgery [1]. Although same-day surgery is preferable in certain situations, there is a remaining risk of bilateral complications and sometimes the first eye's outcome is used as a reference to better plan the second eye surgery [6].

2.2 Simulating Vision Impairments

A number of systems have been developed to simulate and assess visual impairment across the ophthalmological diagnostic spectrum, using both physical instruments and virtual effects. While Hogervorst and Van Damme [8] evaluated the relationship between blurred imagery and VA, Fidopiastis et al. [7] examined reduced VA when using a projective HWD. Later, Banks and Crindle [3] attempted to recreate the visual effects of several ocular diseases by creating overlays and filters for 2D images (viewed on a desktop display, without calibration for individual users). Utilizing effects created in Unreal Engine 3 (later XNA), Lewis et al. [16, 17] simulated several types of visual impairments to help spread awareness of them. The simulated impairments were presented in a 3D game or explorable environment on a desktop screen, and were fixed in severity and effect size.

Using physical goggles, Wood et al. [29] attempted to recreate visual impairments in order to understand their potential effect on night-time driving. Zagar and Baggarly [31] used a set of physical goggles in order to help student pharmacists understand how patients with various ocular diseases and visual impairments might interact with medication. Physical goggles designed to simulate the decreased VA and increased glare of generic cataracts are available commercially [27], but with the express disclaimer that they are not intended to replicate a specific user's visual impairment.

Jin et al. [9] tried to recreate the effects of age-related macular degeneration, glaucoma, diabetic retinopathy and color vision deficiency *protanopia* (an absence of red cones) in a virtual environment. They used a scotoma texture, created from perimetry exam data from real patients to define regions of degraded vision, and a database associating colors perceived with normal vision and and those with protanopia. The texture and simulation is the same for every user and does not account for a user's vision capabilities. Later, Väyrynen et al. [26] used Unity and a VR HWD to approximate multiple visual impairments, including a cataract simulation consisting only of a flare-layer component in each virtual camera and a lens-flare component for each scene light source. Werfel et al. [28] modeled audiovisual sensory impairments using real-time audio and visual filters experienced in a video–see-through AR HWD. Visual impairments, such as macular degeneration, diabetic retinopathy, and retinitis pigmentosa were modeled according to information and illustrations from the German Association for the Blind and Visually Handicapped (DBSV). They simulated cataracts with blur, decreased saturation, and modified contrast and brightness, but without trying to replicate an individual user's impaired vision, which we do in our system. Ates et al. [2] also simulated visual impairments on a video–see-through AR HWD; however, their cataract simulation was restricted to a Gaussian blur. Furthermore, none of the above mentioned systems supported eye-tracking to model gaze-dependent effects.

There are also commercial smartphone applications that simulate vision impairments. For example, the Novartis ViaOpta Simulator [21] for Android and iOS processes the live smartphone camera feed to address a broad set of impairments, including vitreomacular traction syndrome, diabetic macular edema, glaucoma, and cataract. However, the provided cataract simulation affects only VA and color vision, can be adjusted only in severity and not per symptom, and supports just one generic cataract type. In addition, while smartphones are ubiquitous and thus can reach a broad audience, they have a far smaller field of view than current VR HWDs when held at a comfortable distance, are monoscopic, and do not support eye tracking for simulating gaze-dependent effects.

Jones and Ometto [10] also focused on simulating the effects of visual impairments on VR HWDs, introducing both near real-time rendering and eye-tracking to this type of visualization, although not targeting cataracts. More recently, we expanded upon our earlier work [13] by creating simulations of three types of cataracts in VR, also using eye tracking, but taking into account the visual capabilities of the user and limitations of the VR HWD [14].

The system we present in this paper is a more advanced version of our previous system ICthroughVR [14] (see Table 2 for comparison), improving its effects to make them more perceptually correct, and also replacing its bloom effect by a very advanced glare simulation. Furthermore, we adapted our whole simulation to work in video–see-through AR. In contrast to most prior work, we collaborate with ophthalmology experts to achieve a plausible simulation and each of our simulated effects is highly adjustable and can be applied to one or both eyes. This allows us to introduce a new methodology for finding parameters for realistic cataract simulations by conducting experiments with cataract patients.

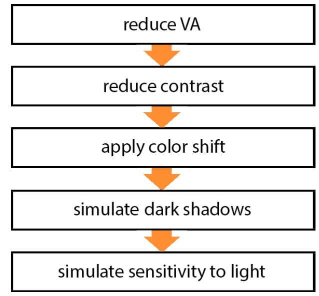

Figure 2: Our effects pipeline follows the effects pipeline we introduced in ICthroughVR for our VR simulation of cataract vision, but introduces changes to each stage. The simulation of dark shadows is only done for posterior subcapsular or cortical cataract.

3 Cataract Simulation

Our system builds upon our previous work ICthroughVR [14], adapts the original effects pipeline (Figure 2) for AR, and extends parts of it with improved techniques. As shown in Table 2, we now use a Gaussian blur instead of a *depth of field* (DOF) effect to reduce VA, since it more accurately simulates reduced VA caused by cataracts. In our new simulation, we use a histogram compression of luminance values to achieve a perceptually correct contrast reduction. Our new color shift more accurately simulates the physical process of light passing through a tinted lens than our previous color-interpolation. When simulating dark shadows, we enhance our original technique by making the influence of light (and therefore interactive scaling of the shadow textures) dependent on the distance of a light source to the center of the gaze. Furthermore, we exchange our previous simple bloom effect for a glare, based on human perception and medical expertise. In addition to VR, we can now also apply our simulation to an AR video stream or a 360° image and apply it selectively to one or both eyes. More details on our new effects can be found in the following subsections.

Our implementation is built using Unreal Engine 4.0. Stereoscopic output is displayed on an HTC Vive Pro HWD with built-in RGB stereo cameras to support video–see-through AR, outfitted with a Pupil Labs binocular eye tracker with 200Hz update-rate cameras. The order in which we apply each effect remains roughly the same and starts with a simulation of reduced VA. Ideally, each of the simulated symptoms would be optimized to take into account the particulars of the chosen display technology. In the case of near-eye optical–see-through displays, additional considerations related to accommodation should be observed [12]. Each of our simulated symptoms was tuned by adjusting the respective effect parameters. We started the program with 0 as the default value per-parameter, as adjustment was a requirement of the system.

3.1 Reduce VA

Similar to our earlier work [13], starting with the original image (Figure 3a), we apply a Gaussian blur (Figure 3b) to simulate reduced VA. In ICthroughVR [14], we chose to use the Unreal Engine 4 DOF effect instead of a Gaussian blur. Creating a realistic simulation of nearsightedness can easily be achieved with a DOF effect and also inverted to simulate farsighted vision, as described in our recent work [15]. However, in cataracts, reduction of VA is caused by an accumulation of yellow-brown pigment or protein in the lens and not by a deformation of the eyeball (unlike myopia/hyperopia). Therefore, the VA of people with cataracts mainly depends on the visual angle of an object in the field of view and does not necessarily improve with close or far distance. Hence, a Gaussian blur simulates the reduced VA caused by cataracts more accurately. We could have used Unreal's DOF effect, configuring it to blur the whole visible

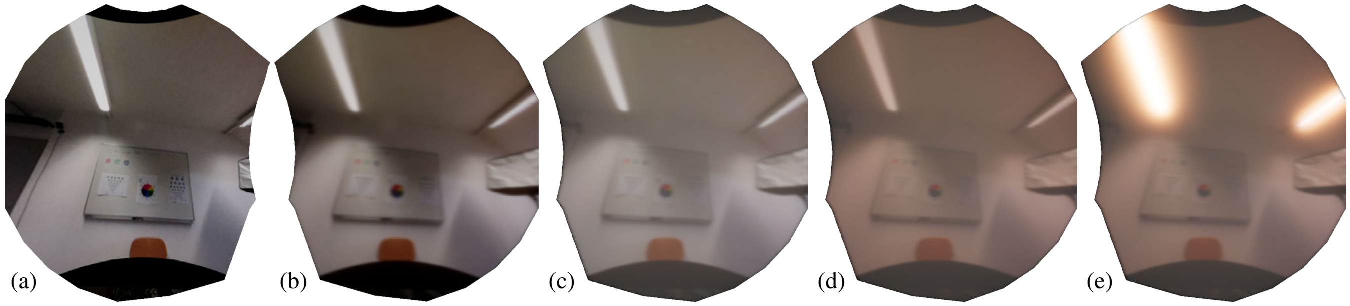

Figure 3: Application of the effects pipeline. (a) Original AR video with (b) reduced VA, (c) reduced contrast, (d) applied color shift, and (e) glare.

Simulation of	**ICthroughVR** [14]	**CatARact (this paper)**	***Comments***
reduced VA (Sec. 3.1)	Unreal's DoF effect	Gaussian blur	*more accurate for cataracts*
reduced contrast (Sec. 3.2.1)	interpolation with one fixed gray value in linear RGB	histogram compression of luminance values in CIELAB	*perceptual contrast reduction*
color shift (Sec. 3.2.2)	interpolation with one fixed target color in linear RGB (*reduces contrast further*)	multiplication with complementary color of cataract particles	*simulates physical process of light passing through a tinted lens*
dark shadows (Sec. 3.3)	average image brightness to scale shadow texture	Gaussian-weighted image brightness of eye-tracking view	*influence dependent on distance to gaze center, reduces artifacts*
sensitivity to light (Sec. 3.4)	Unreal's bloom effect	glare, based on Luidolt et al. [18]	*based on human perception and medical expertise*
works in	VR	VR, AR, 360° image (Sec. 3.5)	*applied to one or both eyes*

Table 2: Comparison to our previous work ICthroughVR [14]. Details of our implementation are explained in the respective sections.

depth region to the same amount of reduced VA. However, this would work only if depth information were available. Therefore, we decided to switch to a Gaussian blur to support 360° images/video without depth information.

3.2 Reduce Contrast and Apply Color Shift

In our previous system [14], we apply a color shift by interpolating between the pixel color of the image and a predefined *target color* in the linear RGB color space. This is a fast and easy way to perform a color shift, but it has the disadvantage of also reducing contrast in the process. The separate contrast-reduction stage is also done by interpolating between a pixel color and a gray value in linear RGB space. Transformations in a linear color space do not correspond to perceived color or contrast changes. One possibility would be to perform these operations in HSV or HSL color space. However, these color spaces are based on saturation, and their *luminance* ("L" in HSL) or *value* ("V" in HSV) do not match colors as perceived by the human eye. Color spaces such as CIELAB or Hue-Chroma-Luminance (HCL), on the other hand, are based on human perception and have perceptual uniformity. This means the Euclidean distance between two colors, represented as 3D locations in the color space, is proportional to their perceived distance.

3.2.1 Reduce Contrast

There are different formulas to calculate contrast, based on differences in luminance between pixels. We perform our contrast reduction by doing a histogram compression of luminance values. Linear changes of the three channels of RGB colors would not yield linear contrast changes. The lightness value ($L \in [0,100]$) in the CIELAB space, on the other hand, represents the perceived luminance of a pixel and is perceptually uniform. Therefore, we modify the L value of a pixel in CIELAB space to reduce contrast. We compress the histogram of lightness values L_I using a factor $0 < p < 1$ to control how much the histogram should be compressed:

$$L = L_I \cdot p + 50 \cdot (1 - p). \quad (1)$$

Of course, the p value can be adjusted during the simulation. This histogram compression results in a perceptual contrast reduction of the whole image (see Figure 3c).

3.2.2 Apply Color Shift

The yellowish/brownish tinted vision that people with cataracts sometimes experience is caused by particles in the lens that absorb parts of the incoming light falling onto the retina. The lens often appears blueish white. This part of the incoming light does not fall onto the retina. Hence, the resulting color shift that a person with cataracts experiences can be simulated by multiplying the image color C_I with the complementary color of the cataract particles:

$$C = C_I \cdot (1 - C_{particles}). \quad (2)$$

Since this is a physical and not a perceptual process, we do our calculations in linear RGB and not in a perceptual color space. We have two options to determine a color for the color shift. We could measure the color of the particles in the lens of a cataract patient and calculate the complementary color for our color shift. This works for patients who still have cataracts, and if the right equipment to examine the eyes is available. For practical reasons, the preferred option is often to ask a person about the color shift they are experiencing or had experienced before their cataract surgery. Our implementation allows both variants, but uses the color described by the patient (C_{target}) as input for our color shift during the pilot study. Additionally, we added a weight α to be able to also control the amount of color shift for the image colors C_I:

$$C = C_I \cdot C_{target} \cdot \alpha + C_I \cdot (1 - \alpha). \quad (3)$$

The result of this operation can be seen in Figure 3(d).

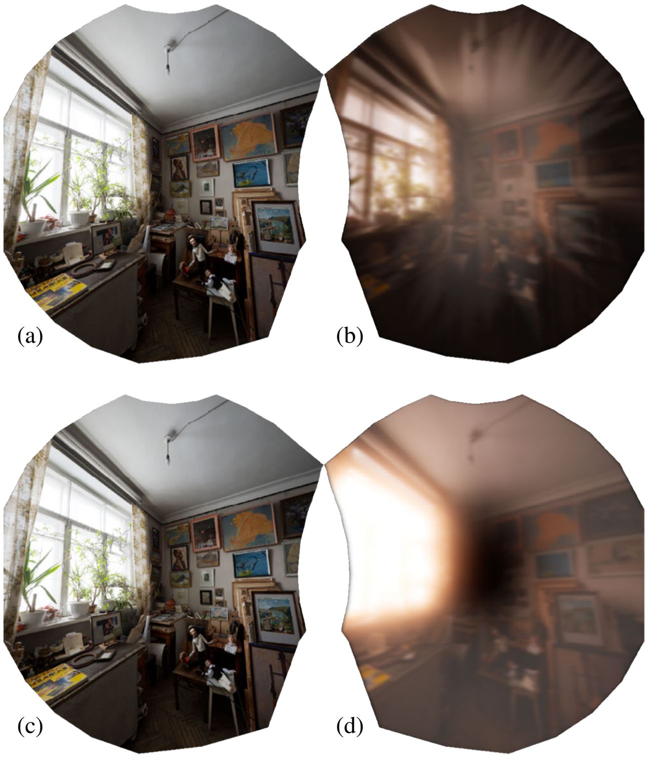

Figure 4: (a,c) Unmodified 360° image. (b) Dark shadows of cortical cataract added to the VA-reduced, contrast-reduced, and color-shifted image. (d) Posterior subcapsular cataracts with glare.

3.3 Simulate Dark Shadows

People with cortical or posterior subcapsular cataracts experience dark shadows in the periphery or center of their field of view (depending on the cataract type), due to protein aggregation or damage to fibers in the lens, which form an opacity that casts these shadows. Our simulation builds upon our previous approach [14] to simulate these dark shadows. A semi-transparent shadow texture is overlaid over the image. If a person with cataracts looks at bright areas, the pupil shrinks. Because of the smaller pupil, less light passes through the periphery of the lens. Consequently, shadows caused by opacities in the periphery of the lens become less apparent, while shadows in the center of the visual field become more prominent (see Figure 4 for examples). To simulate the influence of the contraction and dilation of the pupil, the shadow texture is scaled according to the average brightness of the image. We improve on our previous approach by making this step view-dependent and using a Gaussian distribution as weights (127×127 kernel with $\sigma = 38$, multiplied onto a down-sampled part of the current view), centered at the gaze point, to give more importance to the area on which a person is currently focusing. This also avoids sudden changes in pupil size caused by bright pixels entering the field of view.

One thing to take into account is the hardware camera's auto exposure settings and the potential impact to the overall image brightness and consequently the user's pupil size. While we partially account for pupil contraction as a part of the simulation above, we don't currently adjust the effect to account for the brightness change caused by the Vive Pro front-facing cameras' auto exposure. This is a minor concern in our current system, as we don't average over the whole image, as described above. However, we will explore this further in future work.

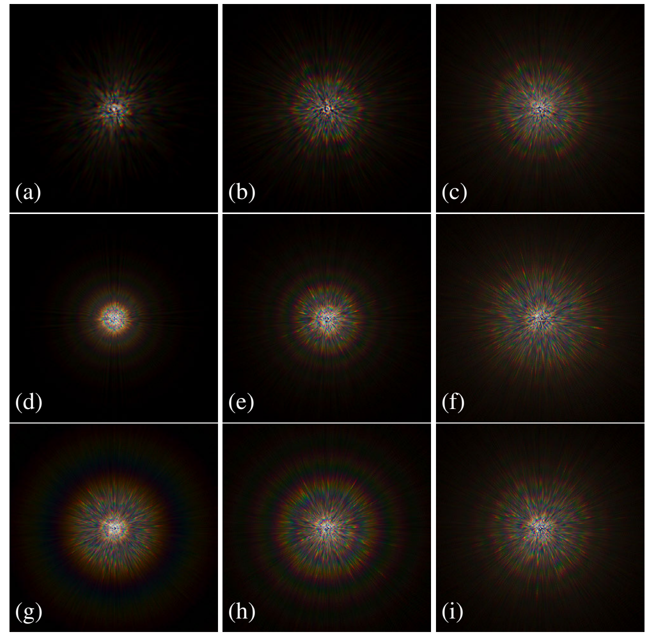

Figure 5: Glare kernels with different parameter values. Pupil sizes: (a) 2 mm, (b) 5 mm, (c) 8 mm. Number of particles: (d) 10, (e) 100, (f) 1000. Particle radii, using a scale of: (g) 1/3, (h) 2/3, (i) 1 (representing an average particle radius of 0.74 µm).

3.4 Simulate Sensitivity to Light

To simulate sensitivity to bright light sources such as sunlight or bright lamps, we apply a glare effect, adapted from Luidolt et al. [18]. This glare effect is a simplified version of the bloom proposed by Ritschel et al. [24], where only the most important influences for the scattering of light are taken into account. A glare kernel is generated based on the anatomy of the human eye and the scattering of light inside the eye, using data obtained from studies of normal, healthy eyes. Particles inside the lens are simulated by generating a user-defined number of particles at random positions and projecting them onto a plane. The resulting image is then converted to the spectral domain. Using this method, a spectral point-spread function is obtained, which can be used as a glare kernel (see Figure 5).

The glare presented by Luidolt et al. includes only the size of the pupil and the static particles in the lens, since the influence of the vitreous humor and the collagen fibrils of the cornea were deemed negligible according to a consulted optometrist. Computing the glare kernel every frame to simulate the slight pulsation of the pupil, as done by Luidolt et al., is still expensive for an interactive VR or AR application that also features other performance-intensive effects. Therefore, we assume a static pupil size and compute the glare kernel only once and then use it in our simulation. The kernel is applied to the image using a convolutional *Fast Fourier Transformation* (FFT) bloom, where both image and kernel are transformed to the frequency domain and multiplied. The result is then transformed back into linear RGB image space. Since we need two FFTs per eye (forward and inverse), this results in four FFT transformations per frame, which is very costly and not well suited for real-time VR or AR applications. Therefore, the effect is applied according to the viewing direction in a smaller window (in our case, a 1024×1024 window). This results in reasonable run times and the borders of this window are hardly visible for the user, since they are almost outside the visible field of view. We further improved performance for our pilot study by reducing the number of FFTs to only two, since we apply the cataract simulation, including this glare effect, to only one eye. The glare effect (Figure 3e) can be adjusted by changing various parameters, such as the size of the pupil, the number of particles in the eye, and the radius of the particles.

3.5 Adjustments for an AR Study

In recreating the approach described in our previous work [14], we needed to make a number of modifications to properly adapt the visualizations for video–see-through AR (see Figure 3), and to prepare the system for an AR pilot study whose participants are patients who have undergone cataract surgery on one eye and will soon have cataract surgery on the other eye. In our in-person experiments, we ask participants to view one channel of the video stream, captured by the built-in Vive Pro stereoscopic RGB cameras, and modified with our simulation, with their post-operative corrected eye. With their pre-operative other eye, which still has cataracts, they will view the unaltered video stream from the other channel. This allows them to compare our simulation (as seen with the corrected eye) to their own cataract vision.

To better compare both images, users need to close one eye at a time if both images were displayed. However, this is not very comfortable and the resulting facial movement could easily move the HWD a bit, affecting the calibration of the eye tracker. Therefore, we provide a comparison mode, where we render the view for only one eye at a time and show a black screen to the other eye. We let users switch between left and right eye, using the Vive controller trigger, while we adjust the parameters of our effects according to their feedback. At the conclusion of the experiment, all adjusted parameters are saved and can be used as a parameter set to simulate the cataract vision of that participant as closely as we could match it. Our study yielded three parameter sets from the in-person experiments and two parameter sets from remote experiments, where participants looked at both images (left and right) while one was being modified with our simulation.

For future experiments (when parameters cannot be adjusted with patients), we recommend parameters in the following ranges: blur sigma: 0.8–5; contrast reduction: 0.05–0.2; color shift intensity: 0.35–0.7; glare particles: 500–800 with radius: 15–25 µm.

4 User Study

To develop our simulation, we consulted experts from the field of ophthalmology and optometry. To evaluate our simulation and the methodology behind it, we consulted cataract patients, who are uniquely qualified to tell from first-hand experience what vision with cataracts looks like and who are able to do a side-by-side comparison of our simulation to their own cataract vision. We conducted a pilot study that was registered and approved by the ethics committee of the Medical University Vienna (EK 1737/2019) and adhered to the tenets of The Declaration of Helsinki. A subsequent larger quantitative study with in-person experiments had to be postponed (see Section 6.3). To gather additional feedback, we decided to conduct remote experiments, showing our simulation to participants on a 2D screen via video call.

Our primary goal for this pilot study (and the subsequent remote experiments) was to test how well our methodology works for parameter adjustment of simulated symptoms during the experiments. Furthermore, we wanted to investigate how realistic each of our simulated symptoms can be in comparison to the effects of real cataracts on vision. Finally, we wanted to determine the overall realism of the simulation.

4.1 Study Design

We designed a qualitative study with a very specialised population: cataract patients after their first operation on one eye and before the operation on their other eye. This allows us to compare the clear vision of a corrected eye viewing the environment through our cataract simulation to the vision of a cataract-affected eye viewing the unmodified environment. Since cataract patients often get surgery on their second eye a few days or weeks after their first operation, there is a very limited time frame in which they qualify as participants for our study. Furthermore, cataracts predominantly affect elderly people [30] and this age group is, in general, not as technically knowledgeable as younger adults. Consequently, finding volunteers for such a study was challenging because of the lack of motivation: Many initially recruited participants dropped out right before starting the single-session experiment. Therefore, we decided to work with fewer participants and try to obtain more qualitative feedback, during semi-structured interviews. We used a between-subjects design for our pilot study and no randomization or counterbalancing was done, since each patient experienced a simulation adjusted to their own specific vision impairments.

Additionally, we conducted two remote experiments with people who recently had cataract surgery. During these experiments, we showed the participants our simulation as well as related work during a video call. This enabled us to compare results from our simulations (after parameter adjustment with participants) to simulations presented in related work. We counterbalanced the order in which simulations were shown.

4.2 Participants

We recruited five participants, three male and two female, aged 63, 64, 74, 64, and 71. Most of our participants had only a mild degree of vision impairment secondary to cataract because surgery was available to the population from which we recruited before severe symptoms could develop. We would like to emphasize that our five patients are not representative of all different manifestations of cataract. Hence, our small subset cannot represent the entire spectrum of what people with cataracts experience. However, a clouded lens results in distinct symptoms (e.g., a change in color vision), so participants were expected to give us valuable feedback on the realism and adaptive options of our simulation.

The following three cataract patients were recruited at the Department of Ophthalmology and Optometry, Medical University Vienna, after their first cataract surgery (a few days prior to our experiments), with diagnosed cataract scheduled for surgery in the other eye:

P1 (male, 63 years old) was nearsighted (-6 diopters) with astigmatism (+3/90°) and diagnosed with cataract in both eyes. An introcular lens was chosen that left him with -3 diopters in the left, post-operative eye. The right eye, that served as reference was also nearsighted (-5.5 diopters) with astigmatism (+2.75/89°) and had early signs of cataract with a VA of 20/30.

P2 (female, 64 years old) was also nearsighted (-5 diopters) before surgery and had her refractive error corrected during surgery on the left eye. An examination of the background of this eye showed *drusen*, a sign of aging or dry age-related macular degeneration, which could potentially impact the VA. The patient's right eye was also nearsighted (-7.25 diopters), had astigmatism (+2.75/86°) and early stage cataract, with 20/30 vision.

P3 (male, 74 years old), was nearsighted (-3.25 diopters) in his left eye before surgery, which was corrected with an implanted intraocular lens. His right eye had early-stage cataract, and was farsighted ($+1.75$ diopters) with a VA of 20/25.

The following two participants, acquaintances of the research team, agreed to participate in our remote experiments:

P4 (female, 64 years old), was farsighted ($+2.25$ diopters) in her left eye before surgery, which was corrected during surgery, about two month before the remote experiment. Her right eye still had early-stage cataract, with no noticeable symptoms at this time.

P5 (male, 71 years old) was farsighted ($+0.1$ diopters) before surgery, which was corrected during surgery about three month prior to the remote experiment. His right eye had early stage cataract.

Figure 6: 360° image[1] shown to participants.

Figure 7: 360° image[1] of a low-light scene shown to participants.

4.3 Pilot Study Protocol

The in-person experiments were conducted in our lab, after cataract surgery on the first eye, with participants P1, P2 and P3.

Patient information and consent form. Before the experiment, the study, its purpose and the study protocol are explained in detail and written informed consent is obtained. Patients are also advised to refrain from fast head movements to avoid VR sickness that could be caused by the lag of the AR video.

AR simulation. Before starting the experiment, the eye tracker is calibrated for each participant in VR. The video stream of the surrounding environment, captured by the Vive Pro cameras, is displayed unaltered in the HWD. Then the view for one eye is turned off. Using the Vive controller, the user is able to switch between eyes (one is always looking at a black screen, the other at the AR video) to simulate closing alternating eyes.

Iterative parameter adjustment. The participant is asked to compare the vision of their pre-operative eye with cataract (looking at the unaltered video stream) to the vision with their post-operative eye on the AR video and tell the researchers about the differences. The researchers then activate and adjust one effect at a time and apply it only to the former unmodified clear vision of the post-operative eye. Meanwhile, the patient switches back and forth between the view of the left and right eye to compare both AR videos. Each effect is adapted according to the patient's feedback to achieve a simulation that matches the patient's cataract vision as closely as possible.

360° image. After the parameter adjustment in AR, patients are also shown a 360° image (Figure 6) and are again asked to point out differences between simulated cataract vision and actual cataract vision in the other eye. Parameters are further adjusted if necessary. This 360° image view serves as a fallback in case the parameter adjustment in AR does not work well. Especially for patients who have just a mild form of cataract, the quality of the AR video might be too low for them to easily tell differences between the view with their post-operative eye and the view with their cataract.

Environment exploration and semi-structured interview. While the patients look around and explore (either in AR or in the 360° image), they are asked to rate the (adjusted) parameters and the overall impression of the simulation in terms of realism (on a Likert scale from 1 to 7) and are asked a few questions regarding the simulation, in a short semi-structured interview (which may continue after the patient takes off the HWD). At the end of the study, patients are asked to fill out or dictate answers to several questions regarding demographics as well as their own severity of symptoms and experience living with cataracts.

Breaks are possible at any time on demand and are recorded accordingly. The experiment is stopped if a patient starts to feel uncomfortable.

4.4 Remote Experiments Protocol

We conducted further experiments with participants P4 and P5, using Jitsi[2] to stream live images and communicate with participants via voice chat. Participants are specifically asked to compare the presented cataract simulations to their memory of their cataract vision before the surgery, noting the protocol components particular to this experiment:

Related work simulations. Two images are shown in a side-by-side view: the unmodified original image and an image with simulated cataracts (using 2D images of related work [2,20,26]). The participant is asked to compare both images and tell the experimeter to adjust the cataract simulation until it best reflects their memory of their cataract vision before surgery. Adjustment is done by adjusting the opacity of the cataract image when blending it over the original.

CatARact simulation in 360° image mode. The participant is asked again to compare the unmodified image to the simulation, which is adjusted, one effect at a time, each tweaked with input from the participant until it best matches their memory of their cataract vision before surgery. The video displayed in the Vive Pro (for both eyes) is mirrored on the desktop and streamed via Jitsi video call to the participant. The position of the HWD is fixed and shows a static part of a 360° image (Figure 6), to create a fair comparison to the related work images, and avoid revealing which is our simulation. A second image (Figure 7) is used to test a low-light scene.

Final ratings and semi-structured interview. Images of all four adjusted simulations with reference images are shown to the participant (at the same time) and rated in terms of realism.

5 Results

We first conducted our pilot study with in-person experiments. After evaluating the results, we conducted two more remote experiments to gain further insights and compare our simulation to related work.

5.1 Pilot Study

Figure 8 shows examples of simulated cataract vision after parameter adjustment for P1, P2, and P3, compared to their unaltered views.

For each participant, we simulated only their individual symptoms experienced with their cataract-affected eye. For example, P3 did not experience any blinding or glare effects and none of the three participants in our pilot study experienced dark shadows, which are caused by cortical or posterior subcapsular cataracts. All three participants experienced reduced VA and color shift with their cataract vision. P3 did not notice any difference in contrast vision, when comparing his post-operative eye to his cataract vision.

Figure 9 shows the results of simulated symptoms comparisons. All symptoms were rated as more similar than not, except for glare,

[1]Image taken from https://hdrihaven.com/

[2]https://jitsi.org/

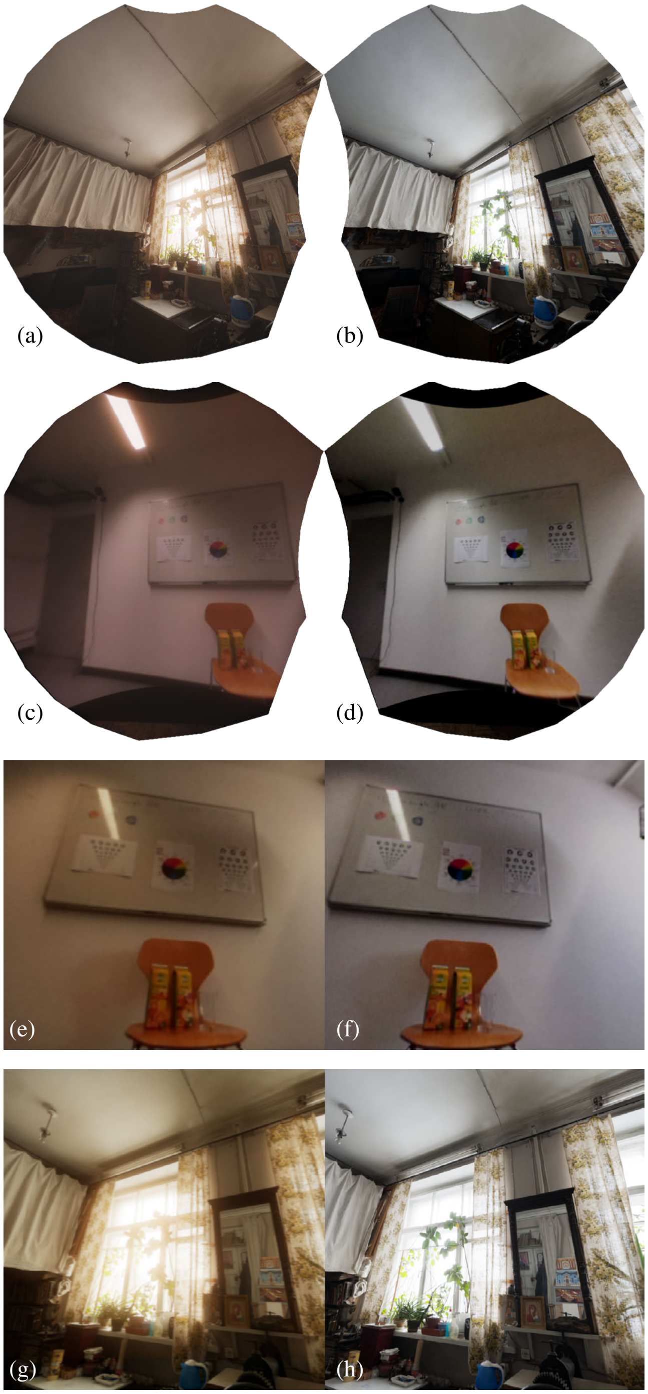

Figure 8: Simulated cataract vision of (a) P1 with (b) unmodified 360° image, (c) P2 with (d) unmodified live AR video and close-ups of (e,g) simulated cataract vision of P3 and unmodified (f) AR video and (h) 360° image.

which was rated as 7 by P1 and as 2 by P2 (in terms of similarity). With an average score of ~ 3.7, the overall impression of the simulated cataracts was that they were not perceived as very similar to the vision participants experienced with their own cataracts. P3 was overall very satisfied with the simulated cataract, which involved just the simulation of reduced VA and a color shift, because he did not experience any other symptoms.

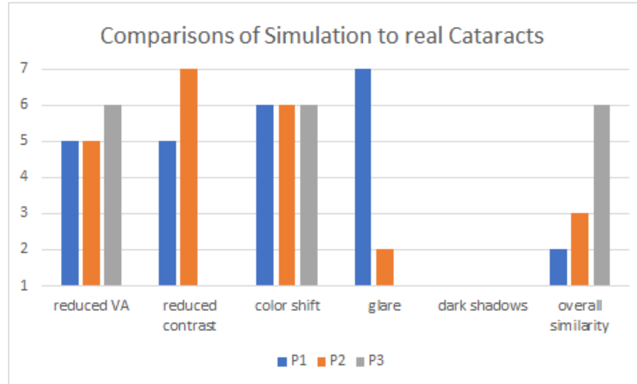

Figure 9: Participants P1, P2 and P3 compared each simulated effect, as well as the overall impression of our simulation, to their own cataract vision on the pre-operative eye, on a 7-point Likert scale (from 1 — does not look similar, to 7 — looks exactly alike).

5.1.1 Observations and Qualitative Feedback

For P1, it took a long time to adjust the parameters for all effects in the AR mode. The visual impression for this patient seemed to vary over time. The experiment was continued in the 360° image view, where he had an easier time distinguishing between his own cataract and the simulation and could give more precise feedback, which allowed adjusting the parameters with less variance. Although P1 rated each of our effects above average up to very good (see Figure 9), he rated the overall impression of the simulation as 2 out of 7.

P2 participated in our study just two days after her first cataract surgery. She often tilted her head backwards in order to be able to look downwards. (This behavior can be explained by her astigmatism, where looking down makes it easier for her to recognize objects.) Unfortunately, her neck became sore, which resulted in an early termination of the experiment before the 360° image view could be tested. This participant did not experience very disturbing glare effects with her cataract, which could explain why she gave a rather low rating for the glare effect. She mentioned impaired vision especially in dark environments.

P3 noticed only a slight blurriness and color shift in his vision when his cataracts started to become noticeable. Therefore, we focused on these effects with this participant. He also told us that he first noticed his eyesight was deteriorating when driving a car, because his peripheral vision had gotten worse.

5.2 Remote Experiments

P4 rated the result of our simulation of the low-light scene, including reduced VA, reduced contrast and glare, as 7 on the Likert scale, since it best resembled her experienced cataract vision, especially with the blinding effects (see Figure 10). She also liked (6 on the Likert scale) our simulation of the interior scene, since it showed the faded colors well, which she had experienced. The participant further rated the adjusted image of Väyrynen et al. [26] as 7 regarding the blinding effect as well as the adjusted image of Ates et al. [2] regarding the blur alone. She did not like the adjusted image of the NEI [20] (rated as 2), since she could not recall experiencing such color changes.

P5 also preferred our simulated cataract for the low-light scene (rated as 7), and the indoor scene (rated as 6) shown in Figure 11. The simulation included reduced VA and contrast, a very subtle glare, as well as a dark shadow in the center of the field of view. P5 rated the simulated effects of Ates et al. and the NEI [20] as 7 and 6 respectively (even though he mentioned not having experienced any color shift). Furthermore, he could not recall experiencing intense blinding effects as simulated by Väyrynen et al. (no rating).

Figure 10: (a) Simulated cataract vision of P4 and (b) unmodified 360° image.

Figure 11: (a) Simulated cataract vision of P5 and (b) unmodified 360° image (right).

6 Discussion

The results of our user study experiments allowed us to gain insight into the complexity and subjectivity of visual perception with cataract vision.

6.1 Interpretation of Results

Through our first qualitative pilot study, we learned that parameter adjustment for our simulation is not trivial and multiple factors can influence the perception of patients with their operated eye.

Varying visual impressions. For some patients, it can take up to a few weeks for the operated eye to fully heal. An unstable tearfilm, small injuries of the cornea, elevated intraocular pressure, or mild inflammatory response are frequently seen early after surgery. Each of these conditions could have an impact on VA and might explain the varying visual impressions of P1. In future studies, experiments should be conducted a few weeks after the surgery if possible (noting that our protocol did not allow postponing surgery on the other eye). Additionally, auto-focus AR eyeglasses, as described by Chakravarthula et al. [4], could be used to compensate for a remaining reduced VA that could not be fully corrected through cataract surgery, as in the case of P1.

Overall Ratings. The individual components (effects) are rated by participants during environment exploration, while experiencing the simulation as a whole (including all adjusted effects combined). Individual effects got good, but not perfect, ratings. We suspect that these small differences of each effect (comparing simulated to real symptoms) add up, which explains why the overall simulations received lower ratings than the individual effects.

Light intensity. People with cataracts often experience uncomfortable blinding or glaring effects caused by bright light sources, as described by P5 during one of our remote experiments. Although light is needed, very bright light like sunlight can be dazzling. The VR HWD we used limits our ability to simulate very bright, dazzling light, let alone sunlight. Furthermore, even if we could, we would not want to expose our study participants to uncomfortable and potentially harmful light intensity.

Blur. In this study, we applied our blur uniformly to the whole image to simulate reduced VA. In future work, we plan to blur the periphery of a user's visual field independently to an adjustable amount, so we can simulate early cataract symptoms such as blurry peripheral vision, as described by P3.

Subjective feedback. Even when conducting a study with a very specialised population such as cataract patients between surgeries, who can simultaneously compare our simulation to their cataract vision, it may be useful to conduct medical vision tests (e.g., for VA or contrast sensitivity) in the simulation. This would help acquire more objective feedback: Vision impairments such as cataracts can be experienced very differently and it can be hard to explain how cataract vision looks or even accurately describe the difference between cataract and clear vision when comparing both. As an extreme example, Pamplona et al. [22] describe a procedure for capturing and modeling the visual effects of a participant's cataract-affected eye with a smartphone augmented with special optics, and then rendering an image with the model (without real-time constraints).

6.2 Runtimes

We measured the GPU runtimes of our simulation on a Schenker XMG Ultra 15 notebook with NVIDIA RTX 2080 graphics card. Except for the reduced VA (Gaussian blur) and the glare, all other stages are implemented in one Unreal Engine post-processing material called *Cataract Material* in Table 3.

We also measured the glare on the same PC as Luidolt et al. [18], with an NVIDIA GTX 1070 graphics card. On the same system, our adapted glare runs in 1.2 ms, compared to 1.47 ms per eye, as reported by Luidolt et al., and is applied to only one eye.

Overall	$\sim$ 7.5 ms
Post Processing (both eyes combined)	$\sim$ 2.5 ms
Gaussian Blur (one eye)	$\sim$ 0.55 ms (for σ = 3)
Cataract Material (one eye)	$\sim$ 0.07 ms
Glare (one eye)	$\sim$ 0.66 ms
Other Post Processing	$\sim$ 1.22 ms
Other operations	$\sim$ 5 ms

Table 3: GPU runtimes for relevant parts of our simulations. (Runtimes for the Gaussian blur depend on σ and corresponding kernel size.) Times for other calculations done by Unreal Engine 4.0 are omitted for readability. Note that most of our effects (except for the expensive FFTs of the glare and the Gaussian blur) are calculated for both eyes and only applied to one. This could be optimized for future work.

6.3 Limitations

We note that all our participants had a refractive error beside their cataracts, which potentially interfered with their visual perception. In addition, our calibrations might not reflect the impact of a clouded lens alone. However, refractive errors can easily be corrected with glasses or contact lenses, which could be worn with the VR HWD.

Mitigating the effects of COVID-19 on research. After the presented pilot study, we planned to conduct a quantitative study with cataract patients, which would also include medical data such as slit-lamp images of eye lenses of patients and Lens-Opacity-Classification-System (LOCS) III gradings of these images. However, the prepared study with already scheduled experiments with patients had to be postponed at the last minute, due to the COVID-19 pandemic. With hospitals that could only be entered by medical personnel or patients whose procedures could not be delayed, elderly people (our primary target group) who are supposed to stay at home, and social distancing rules in place, it was impossible for us to conduct further in-person experiments. We plan to run our quantitative user study as soon as it is safe to do so for our participants, even though we cannot predict when this will be the case.

In the meantime, we were able to recruit two participants for remote experiments. This allowed us to test an alternative form for conducting such studies, which turned out to be a viable option to gather more information and gain more insight when in-person experiments are not possible. However, we need to keep in mind that simulated symptoms are experienced very differently in a VR HWD, as compared to looking at a computer screen. Furthermore, the quality of the internet connection can have a significant impact on the visual quality of the images shown and on communication with the researcher. Changes are sometimes only visible after a perceptible delay, which makes parameter adjustments difficult. Even if we are not able to create a controlled test environment and show a high-quality simulation for the whole field of view, this format at least allows us to compare our simulation to related work. We chose images from the National Eye Institute [20], Väyrynen et al. [26] and Ates et al. [2] to compare with our simulation, since cataract images as well as the corresponding original images were available (or easy to reconstruct). Since patients in our pilot study mentioned experiencing blinding effects, especially when driving at night, we added a low-light scene for our remote experiments, which turned out to yield the best results.

Evaluation. Even though we could not test every simulated symptom during our in-person experiments (since none of the three participants experienced dark shadows caused by their cataracts), they showed that our methodology, involving comparisons of simulated cataract symptoms to real cataract vision, proves useful. While parameter adjustments cannot be done as accurately in our remote experiments, they enabled us to also test one simulation with dark shadows (for P6) and participants preferred our simulation when compared to related work.

We acknowledge that our pilot study has a very small number of participants. However, our simulation builds upon our previous work [14], was developed in close collaboration with medical experts, and our experiments yielded encouraging feedback of each individual effect. Even though our study cannot fully validate the accuracy of our simulation, we believe that our methodology and framework already provide timely and valuable insights for the research community and create a base for future studies.

Hardware. Using the low-resolution Vive Pro cameras is not ideal, as it results in reduced VA for both eyes. We then add additional blur in one eye to reduce the VA further for our cataract simulation, to match the vision of the other (cataract-affected) eye. The limited resolution does not directly interfere with the VA simulation, but as a result, our simulation will match the blurred vision of the cataract-affected eye including the reduced VA caused by the HWD alone. It is unclear at this point if the overall VA experienced with cataracts (when looking at the unmodified AR stream) equals the person's VA in the real world, or if it equals the sum of the VA reduction caused by the HWD and the cataract. Still, we need to use video–see-through AR for our simulation, since it uses post-processing effects that cannot be applied to conventional optical–see-through AR. We have also tried a Stereolabs ZED Mini stereo camera, which has higher resolution and lower latency, but at the expense of a smaller field of view. The Varjo XR-1 video–see-through AR HWD meets our resolution needs, but is an order of magnitude more expensive and weighs much more—an important concern when deploying to an elderly population.

7 Conclusions and Future Work

We presented a system to simulate cataracts in AR. We tested our methodology and evaluated the realism of our simulation in a pilot study with three participants, each of whom had cataract surgery on one eye, while they still had cataracts in the other eye. Our preliminary results (Figure 9) show that the individually adjusted symptoms were deemed to be close to our participants' perception of the environment with cataract vision in the majority of cases. However, the overall impression of our simulation was rated worse than the individual symptoms by P1 and P2. We also conducted two remote experiments, adjusting our effects with participants via video call and comparing our simulation to images of simulated cataracts in related work. Qualitative feedback and Likert-scale ratings from our participants indicate that our complete simulation of cataract vision is superior to related work, which often only features one or two symptoms. The individual setting of each parameter adjusted during our experiments was saved for use in future experiments, to start with more realistic simulation parameters.

By conducting a pilot study, we have shown the feasibility of our methodology and gathered qualitative feedback. Our remote experiments demonstrate an alternative to in-person experiments and served as a way to compare our simulation to related work. We conclude that our methodology proved useful for creating more realistic simulations of cataracts and could also be used for simulations of other vision impairments. In future work, we also want to provide a statistical analysis of quantitative data, evaluating the realism of our simulation. To that end, we already obtained ethics-committee approval for a quantitative study with cataract patients, which will run over a longer period of time and also include patient medical data. Although there is potential for improvement, our work already has advantages over 2D images, physical goggles or other existing 3D, VR or AR simulations with very simple depictions of cataract vision, due to its immersiveness and complete simulation of cataracts, developed together with ophthalmology experts.

Our experiments emphasized that different lighting conditions influence the perception of cataract symptoms. Therefore, simulated effects should also take lighting conditions into account. The impact of different lighting conditions on the individual perception of a visually impaired eye presents an interesting topic for future investigation. We have started to explore other vision impairment simulations [15] and intend to integrate them with our cataract simulation and open-source our framework (at `https://xreye.io/`) with all implemented simulations in the near future.

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Appendix

COMPARING CATARACT AND ICTHROUGHVR IMAGES

The following figures show a VR scene with simulated subcapsular cataract, done with (left) our new *CatARact* simulation, compared to (right) our previous work *ICthroughVR* [14].

Figure 12: Original image.

Figure 13: Reduced VA.

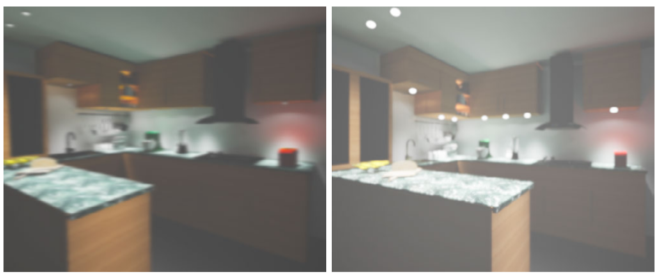

Figure 14: Reduced contrast.

Figure 15: Applied color shift.

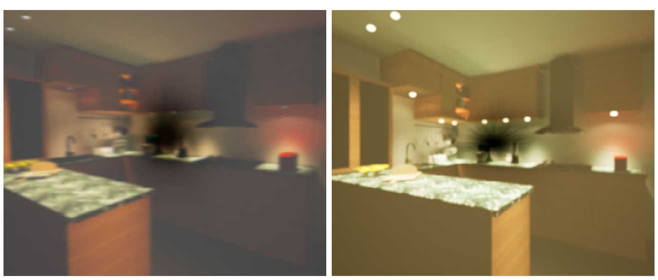

Figure 16: Simulated dark shadows.

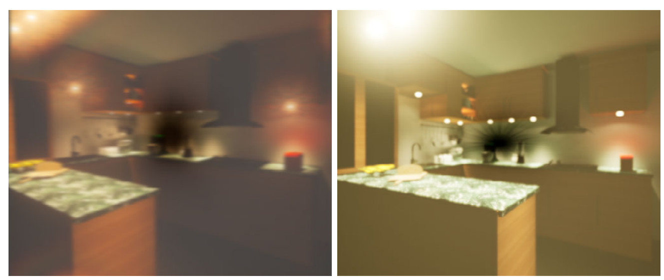

Figure 17: Simulated sensitivity to light (glare/bloom).