Understanding the Impact of Glaucoma Severities Through Virtual Reality Simulations

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Abstract

Glaucoma is a visual impairment that presents a significant global challenge due to limited access to routine screenings. In this study, we explore glaucoma by creating a virtual reality (VR) simulation of peripheral vision loss. Initial interviews (N=3) indicated that traditional darker peripheral visualizations do not accurately represent the experiences of individuals with glaucoma. To address this, we developed an innovative visualization that simulates varying severities of glaucoma, aligning more closely with the descriptions provided by interviewees. In a subsequent user study (N=24), we examined the impact of different glaucoma severities using our visualization in high-fidelity VR environments, which helped maintain contextual cues. Specifically, we analyzed how glaucoma affects visual search tasks and investigated correlations between eye movement patterns and the severity of the simulated condition. Our results revealed significant differences in both eye movement metrics and task performance. These findings provide a foundation for future simulation studies on glaucoma.

CCS Concepts

• **Human-centered computing → Empirical studies in accessibility**; *Human computer interaction (HCI).*

Keywords

Glaucoma Simulation, VR, Eye Movement

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1 Introduction

Visual impairments become more prominent with every passing year. As most of them are age-related and the average age of humans keeps increasing, the WHO estimated 2.2 billion people worldwide will be affected by visual impairment in 2040, of which 1 billion could have been prevented or has yet to be addressed [6]. Glaucoma is one of these prevalent visual impairments, with 76 million of the global population affected in 2020 [15] and an estimated 111.8 million individuals affected by 2040 [52]. While not as common as refractive errors and cataracts, glaucoma is the leading cause of irreversible global blindness. In contrast to refractive errors, glaucoma requires regular monitoring and treatment once diagnosed. However, as the progression of glaucoma happens slowly and in a generally older population, individuals might only realize they experience the effects of glaucoma in a far-advanced stage.

Simulation experiments are standard and have contributed to advancing our understanding of the capabilities of visually impaired users [34, 57]. Furthermore, simulations have played a key role in examining the impact of visual impairments on task performance [24, 56, 58] as well as in evaluating assistive technologies [43]. Lastly, simulations have played a role in understanding how various eye conditions affect eye movements [14, 20]. As such, previous research aimed at increasing understanding of visual impairments by allowing individuals without impairments to experience them and by evaluating accessibility (e.g., emergency signage [30]). Thus, researching and utilizing simulations to investigate visual impairments is essential for advancing accessibility studies and understanding the impact of these impairments on day-to-day activities, as well as for investigating and developing mitigation strategies.

Our work examines the impact of simulated glaucoma in VR on eye movements during a visual search task for household items. This progressive disease can go unnoticed for an extended period, where ubiquitous eye movement monitoring might provide a way for early detection. Thus, we developed a comprehensive visual impairment pipeline that includes two independently adjustable parameters: the remaining central field and a fading effect around the central field. We designed the parameters based on semi-structured interviews with three individuals experiencing glaucoma, which provided insights into their perceptual experiences. This approach enabled us to create a virtual reality (VR) simulation of glaucoma that accurately reflects the conditions reported by the participants. With the simulation, we conducted a user study (N=24) to understand the effect of glaucoma on eye movements. We used our glaucoma simulation to systematically vary the severity of glaucoma during a search task for household items in VR environments. This approach aims to maintain contextual cueing and better understand the effect of glaucoma on eye movements and task performance.

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2 Related Work

Next, we review simulations to analyze invisible phenomena, focusing on their application to vision impairments. Then, we highlight the real-world relevance of them. Lastly, we cover previous research on the effect of glaucoma on eye movements.

2.1 Simulations to Enhance Understanding

VR devices enable enhanced experiences and understanding through immersive simulations. For example, ElectroVR [18] allows users to explore electrostatics through a shared VR environment and leverages the capability of VR to offer insights into an invisible phenomenon. Similarly, CrystalVR [19] allows the explanation of complex crystal structures, which are difficult to visualize. Finally, Knierim et al. [28] augments objects to visualize their temperature using an overlay directly onto the object. Thus, previous systems leverage immersive capabilities to make complex or invisible phenomena more accessible and comprehensible for concepts that are often challenging to grasp.

In the context of accessibility, simulations are used extensively to evaluate designs and inform designers. Rousek and Hallbeck [40] used simulation goggles for various visual impairments to investigate the existing wayfinding design in a healthcare facility and used the simulation goggles to identify design flaws. Väyrynen et al. [56] simulated various visual impairments while participants navigated a virtual world in an architectural design setting. Thus, using VR as a tool allows designers to uncover challenges faced by those affected. Juniat et al. [26] used goggles to have medical students understand and appreciate the challenges of living with visual impairments. These visual simulation works help identify design flaws and foster empathy.

Simulations have been used to assess designs and foster empathy, and also to simulate glaucomatous visual field loss in various ways. Banks and McCrindle [2] explored how simulating visual impairments can improve the design of public buildings and homes for better accessibility, allowing designers to see spaces as visually impaired users would. Lewis et al. [35] developed a visual impairment simulator. Testing with opticians, a visually impaired consultant, and students revealed that the simulation increased users' awareness and understanding of visual impairments. Stock et al. [48] showed that perimeter data can effectively be used in a VR platform to simulate glaucomatous visual field loss. Their study found that VR provided a clearer representation of vision loss than traditional methods, though it did not fully match individual perceptions.

Thus, we see that impairment simulation has multiple benefits: it helps to foster awareness, it helps to understand design flaws, and it helps to understand the underlying phenomenon. Establishing an underlying understanding of impairment, especially its progression over long periods, will help build early detection strategies, which may reduce the severity.

2.2 Real-World Relevancy of Simulations

Lam et al. [32] explored VR technology to assess vision-related disabilities in glaucoma patients by simulating daily activities (e.g., navigation, shopping) under different conditions. They showed that glaucoma patients had longer search times, made more incorrect object selections, and had higher collision rates than healthy individuals, linking it to binocular visual field loss, which suggests visual field defects affect search efficiency. This aligns with Sippel et al. [45], who found glaucoma patients took longer to complete visual searches in real-world supermarket tasks than controls. Moreover, Smith et al. [46] found glaucoma patients had slower search performance, especially when locating objects in complex scenes, suggesting restricted peripheral vision reduces search efficiency. Sun et al. [50] studied text-based searches, finding that more severe visual field loss in glaucoma patients resulted in longer search times. Ogata et al. [38] examined visual crowding, showing that glaucoma patients had more trouble identifying objects in cluttered environments due to peripheral vision defects. Lastly, Lee et al. [33] studied driving performance in glaucoma patients, revealing that drivers with glaucoma had impaired scanning abilities and poorer driving performance, reinforcing the link between glaucoma and real-world task difficulties. Lam et al. [32] explored the use of VR technology to assess vision-related disabilities in glaucoma patients by simulating daily life activities such as city navigation and shopping under different conditions. Their findings showed that those affected by glaucoma had significantly longer search times, made more incorrect object selections, and had higher collision rates compared to healthy individuals. The impact of glaucoma was lined to the degree of binocular visual field loss, suggesting that visual field defects impact search efficiency. The findings of Lam et al. [32] directly correlate with the real-world findings of Sippel et al. [45], where they showed that glaucoma patients took longer to complete visual searches than controls in a real-world supermarket task.

Additional work has reinforced the findings. For instance, Smith et al. [46] showed that glaucoma patients had slower visual search performance, particularly when locating target objects in complex daily life scenes, suggesting that restricted peripheral vision limits its search efficiency. Sun et al. [50] focused on text-based search tasks, finding that greater visual field loss in glaucoma patients corresponded with longer search times. Ogata et al. [38] examined visual crowding, showing that glaucoma patients experienced more difficulty identifying objects in cluttered environments due to their peripheral defects. Lastly, Lee et al. [33] investigated driving performance in glaucoma patients, finding that older drivers with glaucoma showed impaired visual scanning and poorer driving performance compared to healthy peers, reinforcing the link between glaucoma and real-world task difficulties.

2.3 The Effect of Glaucoma on Eye Movements

Glaucoma induces eye movement dynamics alterations due to retinal cell degeneration and degeneration of visual processing pathways [36, 37]. Those affected by Glaucoma exhibit elongated saccadic reaction times across all disease stages [27], and saccadic trajectories with abnormal departure and arrival angles during vertical target pursuit [59]. Compensation behavior includes increased saccadic reversal rates when viewing pictures [1] and directional saccade amplitude asymmetries when performing video free-viewing tasks [16]. These compensation processes are linked to functional visual field loss severity [17, 59]. New eye-tracking assessments like saccadic trajectory angles [59] and fixation spread analysis [1, 17] promise to detect preclinical glaucoma progression.

3 Structured Interviews

From the simulations mentioned in the related work, we found that peripheral vision loss from glaucoma is mostly visualized with dark visualizations obscuring the periphery with a gradient towards the middle of images. We held semi-structured interviews with individuals who experience glaucoma to verify the current quality of the visualizations. The interviews all followed the same structure, namely, demographic questions and, following this, questions about how they perceive the world. We conducted all interviews over video call or in person.

3.1 Procedure

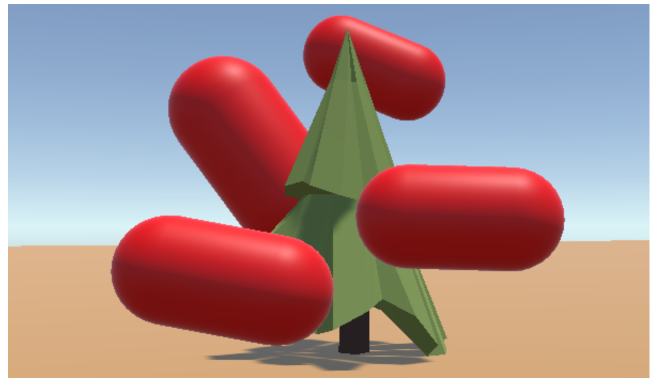
Before the interview, we provided participants with consent forms and a detailed description of the procedure to ensure they had sufficient time to review the materials. At the beginning of each interview, we gave participants the opportunity to ask any questions regarding the consent form and the procedure. The interview commenced with a series of demographic questions pertinent to the study. Once the demographic information was collected, the interview proceeded with questions about their perception of the world (see Supplemental Materials). Examples of guiding questions are: "How does glaucoma impact your everyday life? What are the challenges?" and "Do specific lighting conditions have influence on your perception? And if can you describe how/what changes?"

3.2 Participants

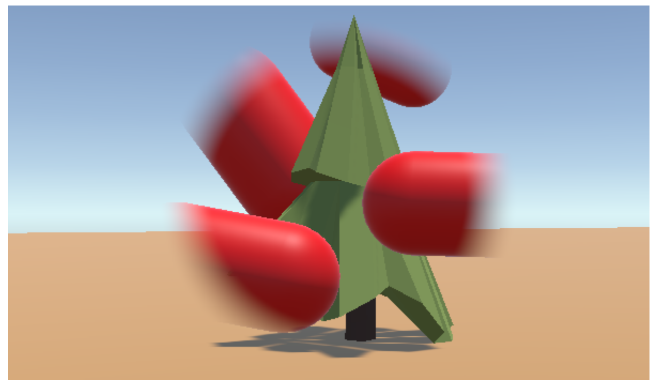
In total, we interviewed four individuals who currently have glaucoma. One participant was excluded as they reported having other visual impairments as well, which are more influential to their vision. For the remaining three participants, P1 (female, 68 years old) reported no effect in her central vision and 20-30% remaining peripheral vision. P2 (male, 52 years old) reported 40% remaining vision. P3 (female, 74 years old) reported 30% remaining vision. It is important to note that each of the participants reported having normal vision earlier on in life, which allows them to comment on the loss of vision.

3.3 Results

During the interviews, we found that not all participants experienced glaucoma as it is usually visualized, i.e., a dark periphery with a gradient fading towards their central vision. All of our interviewees reported similar experiences. P1 said "The first sign that something was off was when I noticed I was bumping into things more often." P2: "I just noticed things were missing; I wouldn't see them until I basically tripped over them." Furthermore, P3 states, "I can see the road, but I cannot see the bike coming." (If participant statements were not made in English, quotes have been translated by a native speaker with full professional proficiency in English). When we showed them how glaucoma is often visualized, they mentioned the following. P2 stated, "The periphery of my vision isn't just dark; I can't see what's there, but it's not completely black either. It is more like things fade away into nothingness." During the interviews, we talked about and showed different visualizations of the effect, i.e., the visualization used by Stock et al. [48] and Lewis et al. [35].



(a) Without Glaucoma Simulations



(b) With Glaucoma Simulations

Figure 1: A low-poly landscape without (a) and with (b) any of the glaucoma simulations applied. In this image, the red capsule-shaped objects have a custom shader material that hides these items if they are not obscured by our simulation. This simulation is gaze-contingent.

4 Glaucoma Simulation

For our pipeline for simulating glaucoma, we use two parameters, namely, the peripheral field loss and fading around the periphery. It is important to note that we assume the periphery to be obscured evenly and in a circular shape. This is oversimplified as there are indefinite variations of how the peripheral loss exactly manifests.

4.1 Peripheral Field Loss

We simulate the peripheral vision loss using a spherical shape of size S (diameter of the sphere) at a fixed distance (d) from the camera for each eye in VR while being gaze-contingent, $NC_{degrees}$ is the degrees of central vision to be not obstructed by our glaucoma simulation. We determine the size of the sphere using the following the angular diameter formula: $S = 2 \times d \times tan(NC/2)$. This allows us to manipulate the area of the vision that is not obstructed by our glaucoma simulation.

4.2 Fading

To prevent the peripheral field loss from resulting in a hard cut-off, we implemented a fading effect on the inside of the sphere determined by the peripheral field loss as described above. Our fading implementation is an adaptation and modification of the `smoothstep` function[1]. The modified `smoothstep'` function has three parameters: the lower edge (e_0), the upper edge (e_1), and the source variable for interpolation (x). If x is less than or equal to e_0, it outputs 1; if x is greater than or equal to e_1, it outputs 0; and if x is between e_0 and e_1, it interpolates between e_0 (start edge) and e_1 (end edge) according to the Hermite interpolation. The source variable for interpolation (x) is the normalized distance of the objects' texture fragment concerning the sphere's central position in the screen space. Finally, we use the output of `smoothstep'` as alpha values of the objects' texture to control the objects' visualization.

$$\texttt{smoothstep'}(x) = \begin{cases} 1 & \text{if } x \leq e_0 \\ 1 - (3(\frac{x-e_0}{e_1-e_0})^2 - 2(\frac{x-e_0}{e_1-e_0})^3) & \text{if } e_0 < x < e_1 \\ 0 & \text{if } x \geq e_1 \end{cases} \quad (1)$$

By applying this combination of the peripheral field loss and fading as a custom shader effect in Unity, we were able to simulate the loss of peripheral vision where objects treated with a custom material disappear when they are not obstructed by the sphere. This, while leaving the rest of the Unity scene unaffected, see Figure 1. We chose to have the fading dynamically adjust to the size of the sphere, namely, being 20% of the sphere. If our sphere is 40°, our fading starts at 40° with items treated with the material being completely invisible, and ends at 32° where items would be completely visible.

5 User Study

Next, we will present the user study performed with 24 participants. We chose to simulate eight conditions of glaucoma, all Latin Square balanced, 100°, 90°, 80°, 70°, 60°, 50°, 40°, 30° of remaining vision. These were chosen to keep the interval between conditions equal. Furthermore, we decided to not have our simulation affect more than 30° of remaining vision to stay outside of the near periphery [49] and on the basis of the reported vision loss of our interviewees, see Section 3. Our starting visualization of 100° is larger than what a single display shows using the HTC Vive Pro Eye headset; as such, there is no visualization during this condition, and it will be our control condition.

5.1 Apparatus

We use a visual search task to evaluate the effects of the glaucoma simulation on participants' eye movement behavior and task performance. Visual search tasks are commonly used to investigate the impact of visual impairments, both in patients with actual impairments [10, 39] and in simulations of visual impairments [11, 25, 31]. Pollmann et al. [39] demonstrated that patients with visual impairments performed significantly better in search tasks within realistic environments, such as rooms in a home, compared to those in non-realistic scenes, due to the availability of contextual cues. This finding highlights the importance of using realistic environments to accurately assess the deficiencies caused by visual impairments during search tasks. Accordingly, we implemented realistic virtual environments. Following the approach of David et al. [11],

Figure 2: Items participants were tasked with searching for, listed from left to right and top to bottom, are Eraser, Sticky Notes, Glass, Medicine bottle, Tape Dispenser, Hole Puncher, Duck, Apple, First Aid kit, Screwdriver, Pencil Sharpener, Smartphone, Calculator, Hair Dryer, Highlighter, Kettle, Flashlight.

we designed eight high-fidelity virtual environments representing different rooms in a household, see Figure 3. We ensured that luminance in all rooms was consistent.

The search items included common household objects such as a medicine bottle, screwdriver, calculator, and flashlight, among others, see Figure 2. The rooms and items were carefully selected to preserve contextual cueing throughout the task.

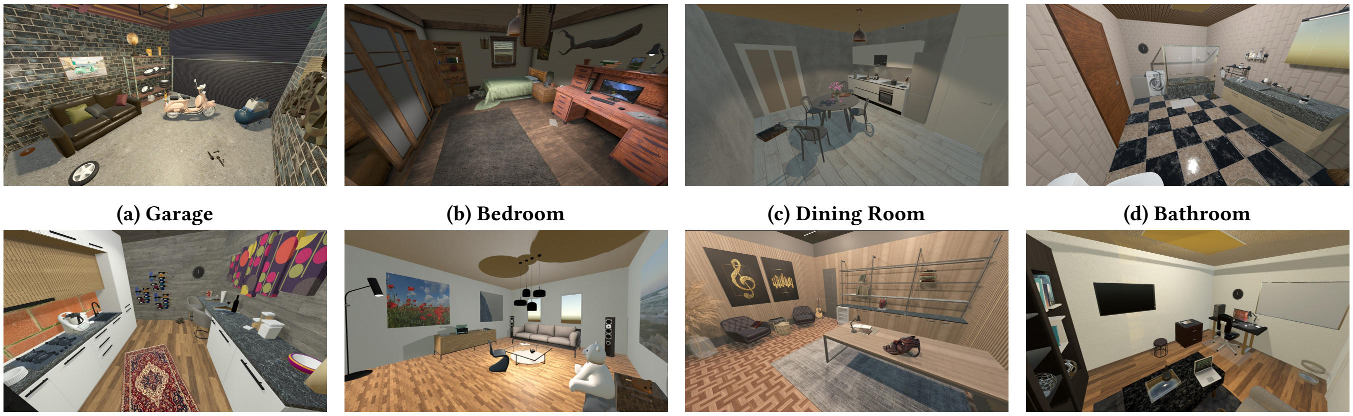
We developed the experiment using Unity on a desktop equipped with a Ryzen 9 7900X3D processor, 64GB of RAM, and an NVIDIA RTX 4080 Super graphics card. The setup included an HTC Vive Pro Eye headset with an integrated Tobii eye tracker. We accessed the eye tracker at a 120 Hz via the Vive SRanipal SDK. For our analysis, head direction, eye-in-world direction, and other 3D directional vectors were converted into 2D Fick angles using the Fick-gimbal method [23]. These 2D Fick angles for head and eye directions served as the foundation for our subsequent analysis. We concentrated on eye-tracking data for each trial, and given the relatively short trial durations ($M = 4.95$, $SD = 3.63$ seconds), our analysis was performed at the trial level rather than on individual behaviors within each trial.

5.2 Procedure

In the beginning, the coordinator welcomes participants and provides an overview of the study. After participants had signed the consent form, we asked them to fill out a brief demographic questionnaire. Before entering VR, the coordinator explained the necessary hardware and controls to ensure participants were comfortable with the setup. Once participants put on the VR headset, they were guided through eye-tracking calibration. Following this, each participant completed four practice trials without any visual impairment simulation to familiarize themselves with the task.

During the experiment, an item to be located was presented on a gray background at the start of each trial. After the participant confirmed, the item was randomly placed in the virtual room, with

[1] http://www.thebookofshaders.com/ last accessed: August 27, 2025)



(a) Garage (b) Bedroom (c) Dining Room (d) Bathroom

(e) Kitchen (f) Living Room (g) Meeting Room (h) Office

Figure 3: All rooms used in the user study.

adjustments made to avoid collisions with other objects. Participants completed a total of 15 trials per room. We balanced eight different conditions, ranging from no simulated peripheral vision loss to 30° of remaining central vision in equal increments, using a Latin square design. After each room, we applied a drift correction following the method of Sipatchin et al. [44], compensating for the known issue of eye-tracker drift caused by participant movement in VR [8]. This correction ensured the accuracy of gaze-contingent simulations of peripheral vision loss throughout the study.

5.3 Participants

We recruited 27 participants for the evaluation. However, we had to exclude three participants (one for technical issues and two who did not follow the experimenters' instructions). The remaining 24 participants had a mean age of 23.7 ($SD = 2.6$), 13 identifying as female and 11 as male. Two participants had corrected to normal vision using contacts, and all others had normal vision.

6 Results

Next, we outline the results of our preprocessing. We then present the findings on how varying severities of our glaucoma simulation influenced participants' eye movements and task performance.

6.1 Preprocessing

We analyzed fixations and saccades using pymovements [29]. Specifically, we employed its implementation of the ID-T algorithm [41], using a minimum fixation duration threshold of 83 ms and a maximum dispersion threshold of 1.8°, based on previous studies [4, 55]. This enabled the extraction of key fixation metrics, including total fixation duration, average fixation duration, fixation count, and the time between the start of a trial and the last fixation. For saccades, we utilized pymovements' microsaccade detection algorithm [13], which allowed us to compute saccadic amplitude (the angular distance between saccade onset and offset) and saccade frequency (the number of saccades per trial normalized by trial duration). Pupil dilation was averaged across both eyes, and standard deviations were calculated to facilitate trial-level analysis. We computed the Index of Pupillary Activity (IPA) using the method of Duchowski et al. [12].

Across all conditions and participants, 2880 trials were collected (120 per participant). Trials with excessive head movement, defined as head displacement greater than 15 cm above or below the participant's average, were excluded, as our focus was on gaze behavior. To determine whether participants visually engaged with the target object, we calculated the maximum angular diameter using the formula $\delta = arctan\left(\frac{d}{2D}\right)$, where d is the object size, and D is the distance to the object. We compared the absolute gaze angle to the object's center during the trial, and if over 50% of the final ten gaze samples fell within 180% of δ, the trial was retained. Additionally, trials exceeding 20 seconds in duration were discarded. After applying these filters, 2438 trials remained for analysis. 320 trials in the control condition, 319 with 90°, 325 with 80°, 310 with 70°, 298 with 60°, 303 with 50°, 294 with 40°, and 270 with 30° of vision remaining. To examine whether the filtering process introduced bias in trial retention across conditions, a Bayesian repeated measures ANOVA was conducted using JASP with default prior scales. The analysis yielded a Bayes Factor of $BF_{10} = 0.031$, providing strong evidence against any condition-related effect on trial retention.

6.2 General Linear Mixed Model Results

To analyze the data from our complex experimental design, we employed generalized linear mixed-effect models (GLMMs), which are well-suited for accounting for random effects due to individual differences, room variability, object placement, spawning locations, and potential learning effects. This approach is particularly effective for handling non-normal data and repeated measures designs [7, 42]. The general formula used for each dependent variable was $DV \sim condition + (1|Room) + (1|Object) + (1|Location) + (1|TrialNr) + (1|Pid)$, where DV represents the dependent variable. We conducted the analysis in R using the lme4 package [3]. We report conditional R^2 as R_c^2 and marginal R^2 as R_m^2.

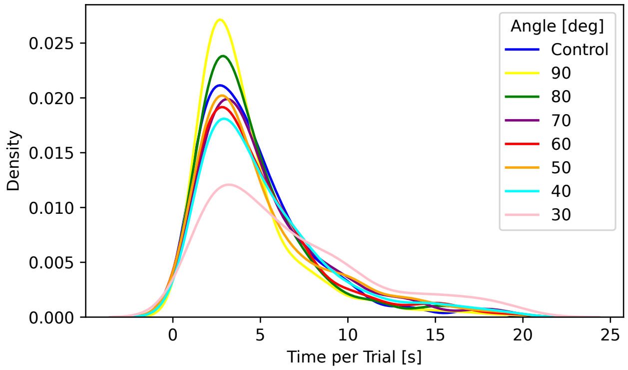


Figure 4: Kernel Density Estimate of Time per Trial for each of the different peripheral vision loss simulations.

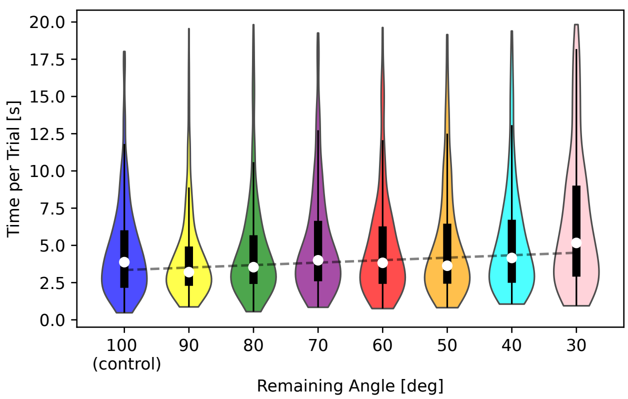


Figure 5: Time per Trial for each of the different peripheral vision loss simulations.

6.3 Time Per Trial

Our model for time per trial as a function of peripheral vision loss condition exhibits substantial explanatory power, with a conditional $R^2 = .80$ and a marginal $R^2 = .50$ related to the fixed effects using an inverse Gaussian family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 4.63 ($t = 13.06$, $p < .001$). We found that participants took longer to complete their tasks with a higher area of their peripheral vision affected by the peripheral vision loss (see Figure 4 and Figure 5). The time required for each trial was largest in the case of the 30° of vision remaining, as confirmed by the GLMM analysis ($t = 7.93$, $p < .001$), we further found significant differences for 40° ($t = 3.13$, $p = .002$), 50° ($t = 2.38$, $p = .018$), and 70° ($t = 2.06$, $p = .040$). We found no significant differences in time per trial for the three lowest peripheral vision loss simulations, namely 60° ($t = 1.47$, $p = .141$), 80° ($t = 1.00$, $p = .316$), and 90° ($t = -0.40$, $p = .690$) of vision remaining.

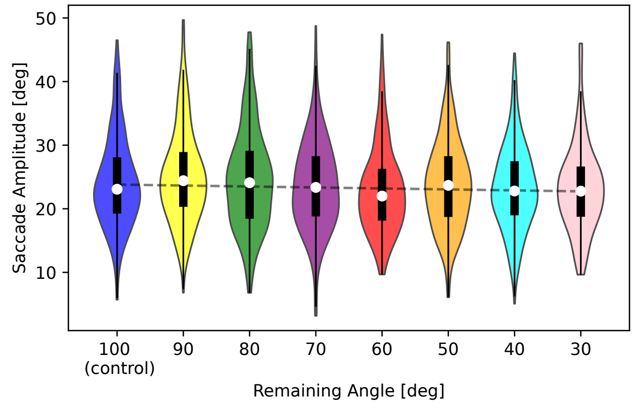


Figure 6: Saccade amplitude for each of the different peripheral vision loss simulations.

6.4 Fixations

Fixation Rate. We did not find significant differences for fixation rate with an $R^2 = .59$ and a marginal $R^2 = .18$ related to the fixed effects using a Gamma family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 3.67 ($t = 23.72$, $p < .001$). We found no significance between conditions. 30° ($t = 0.21$, $p = .836$), 40° ($t = 1.75$, $p = .079$), 50° ($t = 0.10$, $p = .918$), 60° ($t = 0.45$, $p = .653$), 70° ($t = -0.09$, $p = .926$), 80° ($t = 0.05$, $p = .963$), and 90° ($t = 0.79$, $p = .428$) of vision remaining.

Mean Fixation Duration. We did not find significant differences for mean fixation duration with an $R^2 = .09$ and a marginal $R^2 < 0.01$ related to the fixed effects using an inverse Gaussian family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 0.16 ($t = 23.03$, $p < .001$). We found no significance between conditions. 30° ($t = 0.25$, $p = .804$), 40° ($t = -0.08$, $p = .936$), 50° ($t = -0.77$, $p = .441$), 60° ($t = 1.35$, $p = .176$), 70° ($t = 0.97$, $p = .332$), 80° ($t = -0.95$, $p = .343$), and 90° ($t = -0.60$, $p = .548$) of vision remaining.

6.5 Saccades

Saccade Amplitude. Our model for saccade amplitude as a function of peripheral vision loss condition exhibits substantial explanatory power, with a conditional $R^2 = .92$ and a marginal $R^2 = .42$ related to the fixed effects using a Gamma family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 25.74 ($t = 16.24$, $p < .001$). We found that participants made smaller saccades complete their tasks with a higher area of their peripheral vision affected by the peripheral vision loss (see Figure 6). The time required for each trial was largest in the case of the 30° of vision remaining, as confirmed by the GLMM analysis ($t = -3.09$, $p = .002$), we further found significant differences for 40° ($t = -2.51$, $p = .012$), 60° ($t = -2.97$, $p = .003$). We found no significant differences in saccade amplitude for four peripheral vision loss simulations, namely 50° ($t = -0.76$, $p = .450$), 70° ($t = -1.33$, $p = .182$), 80° ($t = 0.45$, $p = .652$), and 90° ($t = 1.08$, $p = .279$) of vision remaining.

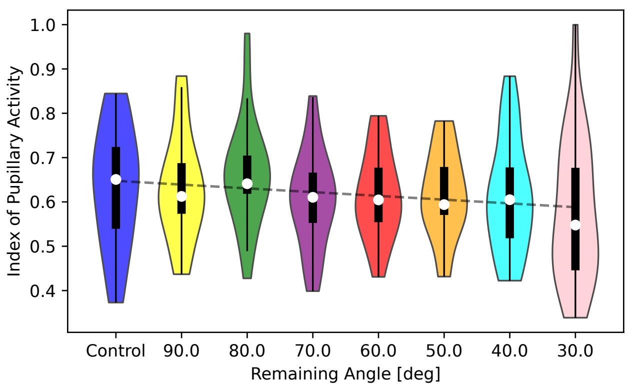


Figure 7: Index of pupillary activity for each of the different peripheral vision loss simulations.

Saccade Frequency. We did not find significant differences for saccade frequency with an $R^2 = .40$ and a marginal $R^2 = .17$ related to the fixed effects using a Gamma family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 2.71 ($t = 23.20$, $p < .001$). We found no significance between conditions. 30° (−0.07, $p = .940$), 40° ($t = 0.87$, $p = .383$), 50° ($t = 0.15$, $p = .878$), 60° ($t = 0.37$, $p = .712$), 70° ($t = -0.22$, $p = .827$), 80° ($t = -0.93$, $p = .353$), and 90° ($t = -0.94$, $p = .348$) of vision remaining.

6.6 Pupillometry

Index of Pupilar Activity. Our model for the index of pupillary activity as a function of peripheral vision loss condition exhibits moderate explanatory power, with a conditional $R^2 = .19$ and a marginal $R^2 = .03$ related to the fixed effects using a Gamma family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 0.65 ($t = 17.38$, $p < .001$). We found a lower index of pupillary activity while completing the tasks, with a higher area of peripheral vision affected by the peripheral vision loss (see Figure 7). The pupil size during each trial was largest in the case of the 30° of vision remaining, as confirmed by the GLMM analysis ($t = -3.32$, $p < .001$). We found significant differences for 40° ($t = 2.39$, $p = .017$). We found no significant differences in saccade amplitude for four peripheral vision loss simulations, namely 50° ($t = -0.99$, $p = .320$), 60° ($t = -1.00$, $p = .315$), 70° ($t = -1.35$, $p = .177$), 80° ($t = 0.99$, $p = .322$), and 90° ($t = -0.45$, $p = .654$) of vision remaining.

Pupil Size. Our model for pupil size as a function of peripheral vision loss condition exhibits substantial explanatory power, with a conditional $R^2 = .90$ and a marginal $R^2 = .32$ related to the fixed effects using a Gamma family with an identity link. The intercept of the model, representing no peripheral vision loss simulation, was estimated at 4.37 ($t = 20.22$, $p < .001$). We found that participants had larger pupil sizes while completing their tasks with a higher area of their peripheral vision affected by the peripheral vision loss (see Figure 8). The pupil size during each trial was largest in the case of the 30° of vision remaining, as confirmed by the GLMM analysis ($t = 4.31$, $p < .001$), we further found significant differences for 40° ($t = 3.59$, $p < .001$), 50° ($t = -2.97$, $p = .003$) and 60° ($t = 2.08$, $p = .037$). We found no significant differences in saccade amplitude for four peripheral vision loss simulations, namely 70° ($t = -0.86$, $p = .390$), 80° ($t = 0.14$, $p = .892$), and 90° ($t = -1.56$, $p = .119$) of vision remaining.

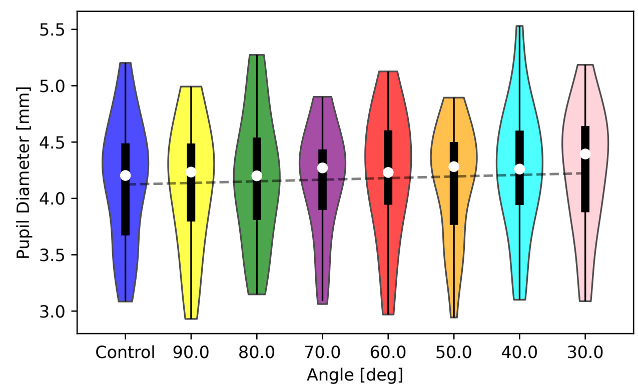


Figure 8: Pupil size for each of the different peripheral vision loss simulations.

7 Discussion

In this work, we held semi-structured interviews with individuals affected by glaucoma to understand their perception of the world and how realistic past visualizations are compared to their perception. By doing so, we found that dark visualizations are unrealistic and that those affected by glaucoma describe it more similarly to the blind spot. However, they do not directly mention it. Following this, we built a simulator for glaucoma in Unity that allows for precise manipulation of two parameters: the remaining central vision and the fading effect. We used this simulator in a Latin square-balanced user study to investigate the effect of peripheral vision loss on task performance and eye movements.

The results of this study demonstrate a significant difference in task performance over different simulation severities in comparison with the control condition, with the more severe glaucoma simulation having a direct impact on task performance, making the visual search task take longer, see Section 6.3. We could not find a significant difference in fixation rate or mean fixation duration; however, there was a significant decrease in saccade amplitude (see Section 6.5), differences in index of pupillary activity (see Section 6.6), as well as a significant increase in pupil dilation (see Section 6.6). Though participants made more errors in the higher-severity glaucoma simulations, we found strong evidence against any condition-related effect on trial retention.

Previous studies have also demonstrated the impact on task performance, where simulation made it more difficult to find objects and took longer [32] as well as in work where they investigated the search time in a visual search task by glaucoma patients [38, 45, 46, 50]. In line with our findings, previous studies have also demonstrated altered eye movements in patients with glaucoma [9, 33, 51, 53]. In our task, participants made smaller saccades to, unconsciously or otherwise, "compensate" for their restricted field of view. Since a lowering in the visual field reduces the amount of visual information available, previous work suggested a decrease in eye movements [47], but this was not the case in our visual search task. Our research indicated no significant changes in fixation rate or mean fixation duration, while others have reported changes such as an increase in fixation duration and a decrease in fixation rate in patients [9]. While we did find an increase in pupil size and differences in the index of pupillary activity, we did not find any previous work echoing these results. As such, these might be artifacts from our work, being a simulation study, as these are often linked to mental workload.

Crabb et al. [9] proposed that information from eye movements might be useful for detecting glaucoma. Tatham et al. [51] investigated if the latency of saccades adds value to glaucoma detection when compared to the threshold sensitivity values from visual field tests, but only found little value. They suggest that further research is needed to explore whether changes in eye movements occur before changes in visual sensitivity. Here, our work adds value to future research, allowing controlled environments to test how changes in eye movements develop over time, particularly before detectable changes in visual sensitivity occur. By simulating various stages of glaucoma progression, we allow researchers to explore different scenarios and early detection mechanisms before clinical trials are needed.

Disability simulations, including those for Glaucoma, provide insights into task performance but have significant limitations. They often fail to capture adaptive strategies developed by individuals with disabilities, such as scanning routines or systematic object placement [54]. Simulations should be complemented with participatory methods, involving individuals with Glaucoma to explore their strategies and inform supportive designs [5]. Though eye-tracking is not without its challenges [21, 22], we believe that this work has paved the groundwork for further investigation to have eye-tracking serve for potential early detection of Glaucoma. As such, future research should refine glaucoma simulations to include varied patterns of vision loss and diversify tasks beyond visual search, and validate the results found in this work with the eye movements of those affected by Glaucoma, as our participants might not necessarily represent the general descriptives of those affected. Validating simulations with glaucoma patients is critical to ensure their accuracy and relevance. Patient feedback and real-world data will enhance simulation realism, aiding in the development of eye-tracking tools for early detection and improving our understanding of glaucoma's progression.

8 Conclusion

In this work, we built a novel glaucoma simulation based on structured interviews with individuals affected. We have then employed this simulation in a user study with several severities of the glaucoma simulation in a visual search paradigm. From this user study, we have identified significant differences in eye movements and task performance between the control condition and several severities of the novel glaucoma simulation. Those affected by the more severe conditions of the glaucoma simulation took longer to complete the visual search task and made smaller saccades.

Open Science

We encourage readers to reproduce and extend our results and analysis methods. Therefore, our simulation scripts, collected data, and analysis scripts are available at https://osf.io/b6xpu/.

Author Contributions

Jesse W. Grootjen: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Sairam Narsimha Reddy Yadla**: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft; **Sven Mayer**: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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