Exposing Blind Spots in XR Accessibility With Simulated Vision Impairments

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1 Motivation

One in four people in the United States of America has some form of disability [8]. Yet this large portion of the population is unable to use extended reality (XR) head-mounted displays (HMDs) due to their inaccessible designs. Both head-worn augmented reality (AR) displays like the Microsoft HoloLens and virtual reality (VR) displays like the Oculus Rift fall under the umbrella of XR HMD products. Accessibility groups, like XR Access [14], have recently emerged to disseminate best known practices for developing accessible applications in extended reality. However, best practices for accessibility in immersive XR HMDs are still a nascent area of research.

Because XR HMDs are not yet a mature or widespread technology—developers, designers, and researchers alike have the rare opportunity to make immersive XR accessible from the outset [7]. A barrier to this goal is that most software developers and designers do not know how to make their applications accessible, and they often do not have access to user testers with disabilities to evaluate their products.

My dissertation research will create and evaluate the efficacy of a testbed that will give developers the ability to design better XR experiences for those with vision disabilities, whom account for 4.6% of the U.S. population [8]. I will create an eye-tracked, data-driven visual impairment simulation with flexible input parameters that allows people to experience visual impairments firsthand. Furthermore, I will conduct a robust evaluation of the system with low vision patients, those with simulated low vision, and those with normal vision.

1.1 Visual Impairments

The visual impairments expressed by low vision, in which vision is impaired to the degree that it cannot be corrected with glasses alone, are often the result of a *scotoma*—or a blind spot in one's visual field. Scotomas vary in size, intensity, number, and placement within a person's visual field. As such, low vision conditions are heterogeneous and vary widely between conditions and even between patients with the same condition. Two of the most common types of visual field loss that can affect people's vision are: central and peripheral field loss. An example of simulated peripheral vision loss, which may be caused by glaucoma or retinal detachment, can be seen in Figure 1. Low vision conditions interfere with one's ability to interpret visual information, making everyday tasks like reading, driving, or walking down the street challenging. Tasks like driving may even become dangerous.

1.2 Disability Simulations

If developers are to design accessible products that people with disabilities can use, then they must understand how affected populations interact with their surroundings. Disability simulations allow individuals to experience what it is like to have a specific impairment. These simulations are not only informative for product and application design, but they can also help caregivers or medical professionals better understand the needs of those whom they care for.

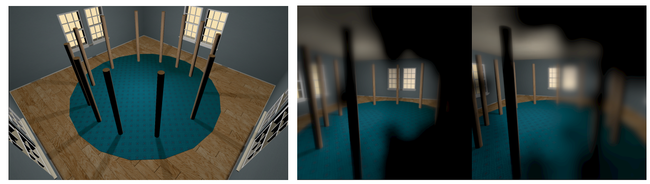

Figure 1: An overhead view of a virtual environment (left) and the environment as viewed stereoscopically by someone with simulated peripheral field loss (right)

Extended reality (XR) provides a particularly unique opportunity for disability simulation. Within XR people may experience firsthand how specific disabilities, like visual impairments, affect the strategies that one employs to interact with their surroundings. Some immersive low vision simulations already exist. However, most are based on simplified symptoms of eye diseases [12] and are unable to produce the irregular scotomas that individuals experience in reality. Even fewer of these simulations have been implemented with eye tracking [6, 13]. Yet the biggest obstacle for the adoption of immersive low vision simulations for design may be that there are no rigorous evaluations of their efficacy. In short, there are no complete, empirical studies that evaluate the ability of low vision simulations to replicate the impairments of those with low vision. This dearth of evaluations is likely due in part to the low latency demands of eye-trackers for effectively simulating low vision and to the difficulty of recruiting a sufficient number of people with visual impairments for system evaluations. As a result, most researchers have either only been able to conduct preliminary analyses [12, 6] or they have focused on applying their simulation to applications [13].

2 Project Framework

2.1 Research Objectives

Accessible design allows a large portion of the population, which would otherwise be neglected, to have access to products. However, not all product development teams have access to disabled test users for feedback. Reliable disability simulations may allow these teams to better design their products for accessibility, especially in the absence of real user testers.

My dissertation research presents an immersive, low vision simulation testbed to evaluate how design decisions affect user experience for those with visual deficits. This testbed uses a data-driven approach to empower XR developers to design for low vision individuals—even when they do not have access to real low vision test users. I will validate the testbed by analyzing behavioral responses across real low vision patients, simulated low vision patients, and normally-sighted individuals.

I will also demonstrate how to employ this testbed to evaluate accessibility by conducting user studies with both normally-sighted and simulated low vision participants to assess how specific rendering techniques affect spatial perception in XR. By the end of my dissertation research, I will have generated developer guidelines that improve spatial perception for both normally-sighted and low vision users in XR. And I will create a testbed for future investigations into how design decisions affect those with low vision in XR.

2.2 Vision Disability Simulation

My immersive simulation will map data from visual field tests, such as Humphrey or Goldmann, to calibrated blur and opacity maps in a stereoscopic head-mounted display (HMD). By employing HMDs equipped with eye trackers, I may map foveal deficits correctly to the foveal regions of a user's vision. The field of view of these devices is limited, so I am unable to model far peripheral field deficits. User-specified scotomas and blur fields can also easily be mapped. An example of the simulator output using patient data is shown in Figure 1.

How to best render scotomas for simulation is an active area of research [9]. However, the simulation of central vision loss is particularly challenging since intrasaccadic perception might occur [5], which would result in a misalignment between the simulated field and fovea. Misalignment could allow "peeking" at the percepts that are supposed to be masked. To prevent this effect, a low vision simulation that attempts to mask central vision should have an overall latency of 25 ms or less; higher latencies can be tolerated for peripheral field loss [10]. This overall latency is independent of the display update rate but instead derives from the time between eye movement event and display event. Recent work on commodity-level head-mounted displays suggests that system latency remains the primary concern but that commodity eyetrackers perform well at simulating peripheral field loss [11]. The low vision simulator proposed in this grant will be built on equipment that has significantly lower overall latencies than those tested in Sipatchin et al. [11]. If necessary, the field of foveated rendering has developed fast gaze prediction techniques [4] that can be used to further reduce latencies.

2.3 System Evaluation

There is little published research validating the ecological validity of immersive low vision simulations. My primary evaluation will be conducted within virtual reality (VR) for experimental control. I intend to thoroughly assess my system by observing behavioral responses across three groups: people with low vision, people with simulated low vision, and people with normal vision. Low vision participants will be recruited through Vanderbilt University Medical Center. All three groups will undergo a training period to acclimate to the VR environment. A training period is particularly important for those in the simulated low vision group, since people with low vision develop compensatory techniques over time to successfully navigate their environment.

2.4 XR Design Testbed

After the initial evaluation, I intend to extend the testbed to encompass both video see-through and optical-see through augmented reality HMDs. The HoloLens 2 is of particular interest for low vision simulation since it provides an unobstructed view of the real world outside of any augmentations. This feature makes visual impairment simulation within the HoloLens desirable for the evaluation for physical products. I will additionally make the simulation publicly accessible for other developers and researchers to use. For a design case study, I will evaluate the effects of non-photorealistic rendering techniques on perception in XR, which is motivated by my prior work in which I found that non-photorealistic renderings of cast shadows improved surface contact perception in immersive augmented reality displays [2, 3].

3 Conclusions

Although many consider extended reality to be one of the next major computing platforms, current head-mounted displays do not easily accommodate for consumers with disabilities—a population that constitutes one fourth of the U.S. population. Robust toolkits for enhancing accessibility in XR for people with low vision like those presented by Zhao et al. [15] are rare. Effective disability simulations, like the system proposed in the current work, may allow accessible design tools to be developed more rapidly and iteratively, especially for groups without ready access to user testers with disabilities. My simulation, when extended to immersive augmented reality, can even inform the accessible design of physical products. Given my prior research findings in which high contrast shading was demonstrated to improve spatial perception [2, 3], I hope to extend my research to enhance depth perception for both normally-sighted individuals [1] and those with low vision.

References

[1] H. Adams. Resolving cue conflicts in augmented reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 547–548. IEEE, 2020.

[2] H. Adams, S. Creem-Regehr, J. Stefanucci, and B. Bodenheimer. Stay in touch! shape and shadow influence surface contact in xr displays. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR) [Submitted]*, volume 0, page 0, 2021.

[3] H. Adams, J. Stefanucci, S. Creem-Regehr, G. Pointon, W. Thompson, and B. Bodenheimer. Shedding light on cast shadows: An investigation of perceived ground contact in ar and vr. *IEEE TVCG [Accepted with Minor Revisions]*, 0(0):0, 2021.

[4] E. Arabadzhiyska, O. T. Tursun, K. Myszkowski, H.-P. Seidel, and P. Didyk. Saccade landing position prediction for gaze-contingent rendering. *ACM Transactions on Graphics (TOG)*, 36(4):1–12, 2017.

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[6] K. Krösl, C. Elvezio, L. R. Luidolt, M. Hürbe, S. Karst, S. Feiner, and M. Wimmer. Cataract: Simulating cataracts in augmented reality. In *2020 IEEE ISMAR*, pages 682–693, 2020.

[7] M. Mott, E. Cutrell, M. G. Franco, C. Holz, E. Ofek, R. Stoakley, and M. R. Morris. Accessible by design: An opportunity for virtual reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 451–454. IEEE, 2019.

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[9] E. Peli, J.-H. Jung, and R. Goldstein. Better simulation of vision with central and paracentral scotomas. *Investigative Ophthalmology & Visual Science*, 61(7):3370–3370, 2020.

[10] D. R. Saunders and R. L. Woods. Direct measurement of the system latency of gaze-contingent displays. *Behavior research methods*, 46(2):439–447, 2014.

[11] A. Sipatchin, S. Wahl, and K. Rifai. Eye-tracking for low vision with virtual reality (vr): testing status quo usability of the htc vive pro eye. *bioRxiv*, 2020.

[12] F. Werfel, R. Wiche, J. Feitsch, and C. Geiger. Empathizing audiovisual sense impairments: Interactive real-time illustration of diminished sense perception. In *ACM Augmented Humans*, pages 1–8, 2016.

[13] H. Wu, D. H. Ashmead, H. Adams, and B. Bodenheimer. Using virtual reality to assess the street crossing behavior of pedestrians with simulated macular degeneration at a roundabout. *Frontiers in ICT*, 5:27, 2018.

[14] XR Access. https://xraccess.org, 2020.

[15] Y. Zhao, E. Cutrell, C. Holz, M. R. Morris, E. Ofek, and A. D. Wilson. Seeingvr: A set of tools to make virtual reality more accessible to people with low vision. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2019.

Budget Proposal:

Exposing Blind Spots in XR Accessibility With Simulated Vision Impairments

Expenditure Category	Quantity	Cost	Total Amount
Equipment Expenses			
Microsoft HoloLens 2	1.00	$3500.00	$3500.00
Pupil Labs Binocular Add-on	1.00	$2100.00	$2100.00
MSI GE76 Raider 10UG-232 Laptop	1.00	$2299.00	$2299.00
VIVO Stand Up Height Adjustable Desk Riser	1.00	$159.99	$159.99
Seagate Desktop 8TB External Hard Drive HDD	1.00	$144.99	$144.99
Subtotal			**$8203.98**
Personnel Expenses			
Underrepresented Undergrad Research Assistant	1.00	$6000.00	$6000.00
Vision Simulation Experiment Participants	40.00	$30.00	$1200.00
Accessible Design Experiment Participants	40.00	$30.00	$1200.00
Subtotal			**$8400.00**
Miscellaneous			
IEEE Open Access Publication Fees	2.00	$2045.00	$4090.00
Conference Attendance Costs	1.00	$4300.00	$4300.00
Subtotal			**$8390.00**
Total Requested			**$24993.98**

The requested funds will go towards progressing & disseminating the proposed research. Equipment purchases will allow research to be completed faster, and the HoloLens 2 will be essential for porting the simulation to optical see-through display. I have requested personnel expenses to equitably compensate those who volunteer for our experiments, as well as funds for supporting an undergraduate researcher from an underrepresented group in computer science to join my lab in 2022. I am actively involved with CS outreach & mentorship programs with younger students. To dissemenate my research, I have allocated a portion of the budget towards open access publication fees, & I have set aside funds for conference attendance at venues including IEEE VR & ASSETS.

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Research Interests

Perception | Virtual & Augmented Reality | Human-Computer Interaction | Visualization

Education

PhD in Computer Science
Vanderbilt University | Nashville, TN, USA — 2016 - present
Advisor: Bobby Bodenheimer

BSc in Computer Science
Rhodes College | Memphis, TN, USA — 2011 - 2015
Advisor: Betsy Williams Sanders

Exchange Student in Information and Communication Technology
Griffith University | Southport, QLD, Australia — 2014

Research Experience

Research Assistant — Vanderbilt University
Department of Electrical Engineering and Computer Science — 2018 - present
- Project 1: Assessed what visual properties of holograms affect depth perception and action affordances in the Microsoft HoloLens
- Project 2: Developed a deep learning walking-in-place system for infinite locomotion in VR

Graduate Researcher — Vanderbilt University
Department of Electrical Engineering and Computer Science — 2016 - 2018
- Project 1: Revealed behavioural differences in children's motor recalibration after VR exposure
- Project 2: Simulated vision impairments from patient data using a head-mounted display
- Project 3: Designed an interface for visualization of ear anatomy in medical training

Undergraduate Research Assistant — Rhodes College
Department of Math and Computer Science — 2015 - 2016
- Integrated Oculus Rift DK2 and WorldViz PPT Tracking System to create collaborative experience
- Evaluated how virtual reality affects collaboration when users are unable to meet their collaborators in person prior

Undergraduate Research Assistant — University of Minnesota
Department of Computer Science — 2013
- Conducted preliminary work on a VR application for neurocognitive assessment

Publications

Journal & Conference Proceedings

Haley Adams, Sarah Creem-Regehr, Jeanine Stefanucci, and Bobby Bodenheimer. "Stay in Touch! Shape and Shadow Influence Surface Contact in XR Displays". *IEEE Transactions on Visualization and Computer Graphics (TVCG)*. 2021. [Submitted]

Haley Adams, Jeanine Stefanucci, Sarah Creem-Regehr, Grant Pointon, William Thompson,and Bobby Bodenheimer. "Shedding Light on Cast Shadows: An Investigation of Perceived Ground Contact in AR and VR". *IEEE Transactions on Visualization and Computer Graphics (TVCG)*. 2021.

Haley Adams. "Resolving Cue Conflicts in Augmented Reality". *IEEE Virtual Reality Abstracts and Workshops* . 2020.

Gayathri Narasimham, **Haley Adams**, John Rieser, and Bobby Bodenheimer. "Encoding Height: Egocentric Spatial Memory of Adults and Teens in a Virtual Stairwell". *Symposium on Applied Perception.* 2020.

Hansen Wu, **Haley Adams**, Grant Pointon, Sarah Creem-Regehr, Jeanine Stefanucci, and Bobby Bodenheimer. "Danger from the Deep: A Gap Affordance Study in Augmented Reality". *IEEE VR Workshop on Perceptual and Cognitive Issues in AR (PERCAR).* 2019.

Carlos Salas-Rosales, Grant Pointon, **Haley Adams**, Sarah Creem-Regehr, Jeanine Stefanucci, and Bobby Bodenheimer. "Distance Judgments to On- and Off-Ground Objects in Augmented Reality ". *IEEE Virtual Reality.* 2019.

Sara Hanson, Richard A. Paris, **Haley Adams**, and Bobby Bodenheimer. "Improving Walking in Place Methods with Individualization and Deep Networks". *IEEE Virtual Reality.* 2019.

Haley Adams, Justin Shinn, William G Morrel, Jack Noble, and Bobby Bodenheimer. "Development and evaluation of an immersive virtual reality system for medical imaging of the ear". *SPIE: Image-Guided Procedures, Robotic Interventions, and Modeling.* 2019.

Noorin Asjad, **Haley Adams**, Richard Paris, and Bobby Bodenheimer. "Perception of Height in Virtual Reality — A Study of Climbing Stairs". *In Proceedings of the ACM Symposium on Applied Perception (SAP).* 2018.

Haley Adams, Gayathri Narasimham, John Rieser, Sarah Creem-Regehr, Jeanine Stefanucci, and Bobby Bodenheimer. "Locomotive and Prism Recalibration of Children and Teens in Immersive Virtual Environments". *IEEE Transactions on Visualization and Computer Graphics (TVCG)*. 2018.

Haojie Wu, Daniel Ashmead, **Haley Adams**, and Bobby Bodenheimer. "3D Sound Rendering in a Virtual Environment to Evaluate Pedestrian Street Crossing Decisions at a Roundabout". *IEEE VR Workshop on Sonic Interactions for Virtual Environments (SIVE)*. 2018.

Haojie Wu, Daniel Ashmead, **Haley Adams**, and Bobby Bodenheimer. "Using Virtual Reality to Assess the Street Crossing Behavior of Pedestrians With Simulated Macular Degeneration at a Roundabout". *In Frontiers in Virtual Environments*. 2018.

Hannah Chipman, **Haley Adams**, Betsy Williams Sanders, D Brian Larkins "Evaluating Computer Science Camp Topics in Increasing Girls' Confidence in Computer Science". *Journal of Computing Sciences in Colleges*. 2018.

Erin Mindell Cannon, Priya Chawla, Katherine Lo, and **Haley Adams**. "igniteCS: Addressing Undergraduate CS Retention". *In Proceedings of the 47th ACM Technical Symposium on Computing Science Education (SIGCSE)*. 2016.

Presentations

Haley Adams. "A Strange View: Using Perception to Improve XR". *Hi5 Seminar Series, University of Mississippi.* 2020. *https://www.youtube.com/watch?v=ZbPsKN4H_nw*

Haley Adams, Jack Noble, William G. Morrel, Alejandro Rivas, Justin Shinn, Robert Labadie, and Bobby Bodenheimer. "Play it by Ear: An Immersive Ear Anatomy Tutorial". *In Proceedings of IEEE VR.* 2019.

Gayathri Narasimham, **Haley Adams**, John Rieser, Sarah Creem-Regehr, Jeanine Stefanucci, and Bobby Bodenheimer. "Spatial Memory of Children and Teens in Immersive Virtual Environments". *In Proceedings of the ACM Symposium on Applied Perception (SAP)*. 2018.

Alex Ayris, Richard Paris, and **Haley Adams**. "STEManism: Current and Future Horizons of Interdisciplinary Collaboration between the Humanities, Digital Humanities, and STEM". *In Proceedings of Humanities, Arts, Science, and Technology Alliance and Collaboratory (HASTAC)*. 2017.

Haley Adams, Chelsey Thompson, David Thomas, Farah Sharis, Catherine Grace Jernigan, Corrie Moore, and Betsy Williams. "The Effect of Interpersonal Familiarity on Cooperation in a Virtual Environment". *In Proceedings of the ACM Symposium on Applied Perception (SAP)*. 2015.

Haley Adams, Alyssa Crider, and Victoria Interrante. "Virtual Reality Implementation for Neurocognitive Assessment". *In Proceedings of Grace Hopper Celebration of Women in Computing*. 2013.

Teaching & Mentorship Experience

Graduate Teaching Assistant — Vanderbilt University
Department of Electrical Engineering and Computer Science — 2016 - 2018

- Evaluated assessments and provided meaningful feedback to 50-100 student classes in short time frames for Discrete Structures and Algorithms (CS 2212)
- Guest lectured on inductive proofs to sophomore undergraduates for Discrete Structures and Algorithms (CS 2212)
- Guest lectured on 3D modeling for Virtual Reality for Interdisciplinary Applications (UNIV 3279)
- Guest lectured on Virtual Reality and Visualization for Introduction to Visualization (CS 5891)
- Instructed multiple class sessions for Augmented Virtual Reality (CS 8395)
- Served as Experienced TA Panelist at Teaching Assistant Orientation, 2017

Graduate Research Mentor — Vanderbilt University
School of Science and Math — 2016 - 2019

- Dictated project milestones and facilitated communication with research faculty
- Guided development of fundamental research and software development skills in C# of high schoolers

Students Mentored

Carlos Salas · High school student in School for Science and Math — 2018 - 2020
Hansen Wu · Undergraduate in Vanderbilt University — 2018 - 2019
Priya Rajan · Undergraduate in Vanderbilt University — 2018 - 2019
Nidhi Mehta · Undergraduate in Vanderbilt University — 2018 - 2019
Peter Cho · Undergraduate in Vanderbilt University — 2018 - 2019
Noorin Asjad · Undergraduate in Vanderbilt University — 2017 - 2018
Taylor Nye Smith · High school student in School for Science and Math — 2016 - 2017

Leadership & Service

Student Volunteer Chair
IEEE VR — 2020

Unity Development Workshop Leader
Vandy Hacks — 2018

Founding Member and Officer
ACM-W Student Chapters — 2013 - 2018

- Managed resources and mediated between students, faculty, and the ACM-W
- Provided opportunities for advancement and organized events with diverse speakers and recruiters

Event Organizer
Emerge - Emerging Technology Symposium — 2017

- Handled event logistics for half-day symposium, including food, advertisement, and audio/video
- Recruited and arranged accommodation for keynote speakers

Director, Instructor
CAMP CODETTE 2015 - 2016

- Founded a persisting summer coding program for middle and high school girls
- Formulated curriculum, led team of undergraduate counselors, and instructed learning sessions
- Provided insights to Google Education and conferred pedagogical strategies for student retention in computer science

Technical Skills

Programming Languages | C# · PYTHON · MATLAB · LATEX · C++ · HTML5 · CSS

3D and 2D Design | UNITY GAME ENGINE · PHOTOSHOP · BLENDER

Honors & Awards

Microsoft Research Dissertation Grant, **Microsoft** 2021 - present
Academic Merit Scholarship, **Vanderbilt University** 2016 - present
Vanderbilt IBM Fellowship, **Alumni Association** 2016 - 2020
Presidential Scholarship, **Rhodes College** 2011 - 2015
Best Poster, **ACM Symposium on Applied Perception (SAP)** 2015