http://dx.doi.org/10.14236/ewic/BCSHCI2025.44

Simulating Visual Impairments in XR: Toward Virtual Player Models for Inclusive Design

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This work presents a novel approach to assessing accessibility in Extended Reality (XR) through the development of Virtual Player Models (VPMs) for simulating visual impairments. Grounded in qualitative insights from visually impaired users and informed by clinical vision parameters, each VPM encodes visual perceptual traits and adaptive strategies using a structured, JSON-based approach. These models can be integrated into XR design workflows to simulate user experiences in real time, supporting early-stage identification of accessibility barriers. We demonstrate the concept through a prototype VPM schema and outline its potential for extending accessible design practices in XR development.

Visual impairment, Extended Reality, User Modelling, Accessibility

1. INTRODUCTION

XR technologies - encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) - offer immersive, spatial experiences that are increasingly adopted in education, healthcare, cultural heritage, and gaming (Dudley et al. 2023; Pladere et al. 2022). However, these technologies are predominantly built for sighted users, marginalising people with visual impairments, who encounter barriers ranging from disorientation to inaccessible interaction mechanisms (Creed et al. 2023). While established guidelines and standards (W3C WCAG-EM 2020; WebAIM 2024; A11Y Project 2024; W3C ATAG 2023; W3C UAAG 2016; W3C ARIA 2024a; ISO 2019) help assess XR accessibility typically post-development, there is limited support for proactively designing XR experiences inclusively 'by-design' (Killough et al. 2024). Currently there are no fully-developed accessibility guidelines for XR, and those that currently exist tend to focus on the end user, lacking any meaningful technical guidance for XR developers(Killough et al. 2024).

In other fields, simulation tools have helped designers empathise with and accommodate different user needs (Lavoie and Clarke 2017; Krösl et al. 2020; Raviselvam et al. 2021; Barbieri et al. 2024). More relevant to this work, visual impairment simulators have been shown to be an invaluable tool (Krösl et al. 2020; Barbieri et al. 2024), however, these are often static and do not allow for adaptations in response to user behaviour and interactions. For instance, many simulators do not take into account natural gaze and head movement, or variations such as tunnel vision, central vision deficiencies, and changes in sight based on the external environment (Kasowski et al. 2023; Thevin and Machulla 2022) even though they can heavily influence user experience. As such, XR currently lacks standardised, dynamic approaches to simulate how vision impairments alter user perception and interaction in immersive environments. In addition, there is a reported lack in participation/inclusion of representative users in the design of immersive experiences (Schmidt et al. 2024), as most XR prototypes are tested in small groups, often with participants who have no visual impairments. This results in lack of feedback from the visually impaired community.

Accordingly, this work proposes the use of Virtual Player Models (VPMs) for XR, which are parametric user representations that encode visual impairment characteristics and behavioural traits to simulate user experience in real time. It must be noted that our proposed VPMs are not fictional personas, but structured data models that can be used to drive visual and interactional simulation in game engines such as Unity. Our framework draws on empirical insights from 42 visually impaired participants on their experiences of living with their condition, on barriers and challenges they encounter in both physical and digital settings, and on how they mitigate them (see Section 3.1). It is also informed by clinical characteristics of visual impairments, and established accessibility parameters.

2. BACKGROUND AND MOTIVATION

This section discusses the background and motivation for this work focusing on an overview of accessibility efforts in XR, simulation and user modelling.

2.1. Accessibility in XR

XR technologies remain largely inaccessible to users with visual impairments due to their fundamentally visual nature (Ahmetovic et al. 2021; Cañellas-Mayor and Aymerich-Franch 2023). Despite growing interest in inclusive XR, accessibility for users with visual impairments is still treated as an optional enhancement, not a crucial design component (**?**Kristensson 2024). Specifically, current XR experiences rely heavily on sight, with limited integration of alternative modalities such as haptics or audio (Wieland et al. 2022), which presents significant barriers, especially in navigation and interaction. For instance, common locomotion techniques in VR remain challenging or unusable for users with visual impairments unless enhanced with rich audio or haptic cues (Ribeiro et al. 2024). Moreover, XR hardware, such as headsets and hand controllers, is often uncomfortable or even completely unusable for people who wear glasses or have a physical impairment (Opoku-Baah et al. 2022).

Despite these challenges, research into multimodal interaction shows a lot of potential, as integrating sound, haptics, and speech has shown to improve user experience (Dang et al. 2023). For example, audio-based navigation tools, haptic music visualisation, and colour-to-sound mapping allowed to achieve more inclusive interaction (Robern et al. 2021). Yet, these adaptations rarely offer full equivalence to visual content and often struggle in noisy or complex environments (Xie et al. 2024).

While recent efforts have advanced accessibility in XR - such as introducing alternative input methods, spatial audio cues, and inclusive design guidelines - these approaches often assume a 'one-size-fits-all' approach that fails to reflect the diversity of user experiences, particularly among visually impaired individuals. Designing for this diversity requires more than universal features; it demands a deeper understanding of how different impairments affect perception and interaction. Simulation and user modelling offer a promising path forward by enabling designers to anticipate accessibility barriers through the lens of specific user profiles - bridging the gap between abstract guidelines and embodied user experience.

2.2. User modelling and simulation for visual impairments

User modelling, which is the abstract representation of user needs and characteristics, can be highly effective for improving general accessibility for users with impairments (Mohamad and Kouroupetroglou 2014), especially alongside simulations. The W3C's XR Accessibility User Requirements (W3C XAUR 2021) outline diverse user needs (e.g. immersive personalization, alternative inputs, magnification) to guide inclusive XR design, so it is not surprising that recent efforts in both academia and industry are advancing XR accessibility through user modelling and impairment simulation approaches. Specifically, developer toolkits have emerged to operationalise these guidelines – for example, Unity's XR Interaction Toolkit (XR Interaction Toolkit 2025) and the SeeingVR plugin (Zhao et al. 2019) provide prebuilt components (like magnifiers, high-contrast filters, and edge highlights) to improve virtual experiences for low-vision users. Researchers have also proposed comprehensive frameworks that integrate such features at the system level, offering customizable text, alternative image descriptions, multimodal controls, and scene adjustments (brightness, recolouring, etc.) to accommodate visually impaired users (Valakou et al. 2023).

In parallel, simulation tools now enable designers to experience XR through the eyes of people with visual impairments. Systems like XREye (Krösl et al. 2023) combine eye-tracking with real-time post-processing to mimic conditions such as refractive errors, cataracts, and macular degeneration within VR/AR environments. Such simulators help uncover accessibility barriers and foster empathy, which helps participants to show significantly greater understanding and awareness of visually impaired users' challenges.

However, to ensure the usefulness of these approaches, it is important to keep in mind the wide spectrum of characteristics, such as visual acuity, central and peripheral vision loss, field of view, etc. (Krösl et al. 2020), as well as the variety of coping strategies and approaches. Modelling and simulation approaches of visual impairments for XR need to therefore move past static and overly simplistic representations towards making them more dynamic, where effects are able to adapt based on user interaction and on environmental changes, as well as ensuring that they are developed based on visually impaired people's characteristics and realistic expectations, making them compatible with principles of user-centred design (Krösl et al. 2020; Barbieri et al. 2023).

To address this need, we propose the development of Virtual Player Models - structured, data-driven representations of users with visual impairments that can be used to simulate perceptual and behavioural characteristics within XR environments. Unlike generic simulation tools or static personas, our VPM approach encodes measurable parameters such as visual acuity, field of view, and contrast sensitivity, alongside spatial parameters, and typical navigation strategies derived from empirical research. This enables designers to explore how specific user profiles experience virtual spaces, and to iteratively test accessibility during development. Our work presents an early-stage framework for defining and implementing VPMs in XR, grounded in qualitative insights.

3. VIRTUAL PLAYER MODELS FOR XR

This section presents our proposed VPM framework alongside its empirical foundation, structure, and an example use case to inform further work.

3.1. Empirical foundation

The development of our Virtual Player Models is grounded in relevant literature and qualitative research involving 42 visually impaired participants who were interviewed following a semi-structured approach between February and May 2025 to explore their perceptions, challenges, and adaptive strategies. The participants varied in age (24-86), gender identity (26 female, 16 male), and severity level of the impairment (9 - mild, 18 - moderate, 15 - severe). The inclusion criteria were broad: (1) being partially sighted, (2) being over 18 years old at the time of the interview, (3) being able to speak and understand English, and (4) being able to give consent. The sample included individuals who used screen readers, magnifiers, and other assistive technologies. While some participants reported having experience with XR, it was not a requirement for this study. Ten participants had limited experience, but shown interest in XR. Twelve had no experience with XR (in many cases due to accessibility barriers), but were interested in it and would like to be able to use it. The rest of the interviewees had no experience in XR. The recruitment was done through relevant organisations such as Macular Society and Visionary, social media, and via snowballing approach. The study was closed once the point of saturation was reached.

The participants were asked to describe their experiences and their insights were used to inform the design of the proposed framework. The participants were encouraged to share their thoughts on accessibility features in technology they use or would like to have.

The interviews were carried out online or on the phone, depending on participants' preferences and accessibility needs. Each interview lasted between 40 min to 1.5 hrs. The participants were asked to sign a consent form, or to give their consent verbally if text format was inaccessible. The interviews were recorded and transcribed with all identifying information removed to ensure confidentiality. Ethical approval for this study was gained via the institutional Ethics Committee.

A reflexive thematic analysis (Braun and Clarke 2019, 2021) was chosen due to its data-driven nature: there were no pre-imposed pre-existing categories. A number of challenges and barriers were revealed, which are not reported here as they are not in the scope of this paper. Beyond these challenges, the analysis also uncovered a range of coping strategies, including use of magnification, alternative colour schemes, and custom contrast and brightness levels. The detailed analytical process followed cannot be discussed due to the limited nature of this paper. Using these findings, we designed our proposed VPM framework which consists of two main components. Specifically, the identified coping strategies were used to inform the design of the second component of our VPMs - Adaptive Strategies - which can include information on how visually impaired users might behave under certain conditions. Similarly, the first component of our VPMs - Visual Characteristics - was designed based on findings from relevant literature and can include certain visual parameters that should be simulated, including visual acuity, field of view, and contrast sensitivity, as well as characteristics related to the spatial distribution of visual perception. We then embedded these empirically derived findings into a VPM schema (see also next section), which helped to move beyond perceptual simulation alone and offer a more holistic model of visually impaired user experience in XR. This foundation ensures that our VPM approach is not just clinically plausible, but also behaviourally realistic - capturing how real users may navigate immersive spaces despite visual limitations. These insights provide a critical bridge between lived experience and simulation-based accessibility evaluation in XR design workflows.

3.2. Model structure

The VPM framework is built around a structured, JSON-based schema designed to flexibly represent key visual and behavioural characteristics of visually impaired users, as discussed in the previous section. This format was chosen for its readability, interoperability, and ease of integration with XR development environments, such as Unity. The VPM includes fields for clinical visual parameters (e.g. logMAR, fieldOfView, contrast), spatial characteristics (e.g. scotomaData), and adaptive strategies (e.g. outlineThickness, textScalingFactor). This is shown in Fig. 1 below along with relevant pseudocode for simulation logic.

This structure enables two important functions. First, it supports modular simulation, as individual parameters can be mapped to specific visual effects (e.g., tunnel vision to a vignette shader). Second, it encodes user adaptive strategies, derived from our empirical study, allowing simulation of not just what a user perceives but how they can behave in response to their impairment.

Figure 1: *Virtual Player Model JSON schema and pseudocode*

Finally, the JSON-based VPM model is both extensible and configurable, enabling developers and researchers to define new profiles or dynamically adjust parameters during runtime (Fig.1). This offers a pathway toward adaptive XR systems that tailor content based on user characteristics, and lays the groundwork for standardised virtual user testing across accessibility-focused XR design tools.

3.3. Use case: Evaluating XR accessibility through VPM-based simulation

To demonstrate the potential of our VPM framework, we next present an example use case involving the hypothetical design of a virtual museum experience intended for a diverse public audience. As Fig. 2 demonstrates, using our VPM framework, XR designers can load a selection of JSON-defined VPMs representing common visual impairment profiles, for example, a model simulating severe tunnel vision can trigger a circular vignette shader in Unity, restricting peripheral field of view, and simulating increased head movement during navigation to reflect compensatory behaviours. Another model representing low contrast sensitivity could apply global desaturation and increase reliance on audio landmarks, emulating a visually impaired user's coping strategy of auditory landmarking. The XR designers can toggle between different VPMs to assess how various users perceive and interact with the virtual space. Designers can identify problematic areas - such as unreadable signage, overly dark corridors, or visually indistinct objects - and iterate based on these insights. Whilst a detailed walkthrough cannot be provided due to the limited nature of this paper, this use case illustrates how VPMs can function as a bridge between abstract player personas and concrete, testable design decisions, supporting early-stage, simulation-based accessibility evaluation in XR workflows.

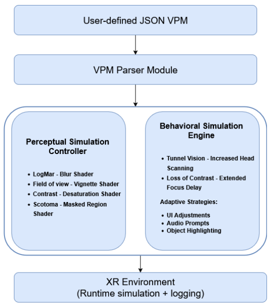

Figure 2: *VPM Workflow Architecture*

4. CONCLUDING DISCUSSION

This work introduces a novel approach to accessibility evaluation in XR through Virtual Player Models, which combine relevant clinical and spatial visual parameters and empirically grounded user adaptive strategies in a structured, simulation-ready format. We propose that by encoding visual impairments and adaptive behaviours in a JSON-based schema, VPMs can enable designers to simulate diverse user experiences and identify accessibility barriers early in the XR development process, ensuring therefore that XR experiences are 'accessible by-design'. Unlike traditional personas or static simulations, our VPM models integrate both perceptual and behavioural realism, offering a more holistic view of interaction. As immersive technologies become more prevalent, tools like VPMs are essential for embedding inclusive design practices at the core of XR workflows. Overall, this paper builds the groundwork for developing evaluation frameworks and tools that are tailored to people with visual impairments. Future work will focus on validating the simulation outputs with visually impaired users and experts, as well as on expanding the framework to encompass other impairments and adaptive profiles.

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