

EduColorVR: A Virtual Reality Serious Game for Enhancing Color Vision Deficiency Awareness in Educational Settings

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Abstract: Color vision deficiency (CVD) impacts approximately 300 million individuals globally, yet it remains significantly overlooked within educational environments. Preliminary consultations with primary and secondary educators reveal that colorblindness is rarely documented in students' educational backgrounds, and proactive classroom discussions regarding the condition are virtually nonexistent. Currently, accommodations are implemented on a strictly ad hoc, reactive basis, highlighting a critical pedagogical gap and a stark lack of standardized guidelines for teachers. To address this systemic challenge, we introduce the design and development of EduColorVR, an interactive virtual reality (VR) serious game designed to raise awareness, foster pedagogical empathy, and provide an experiential understanding of CVD for both students and educators. Developed using the Unity engine and the XR Interaction Toolkit, the application implements a highly optimized, real-time color transformation based on the Brettel-Viénot-Mollon model. This computational approach utilizes a per-pixel separation test and precomputed matrices to simulate the three main CVD phenotypes - Protanopia, Deuteranopia, and Tritanopia - using a scientifically grounded approach. This technically rigorous method significantly surpasses traditional desaturation filters, offering a more physiologically plausible representation of dichromatic vision in a VR environment. Within this immersive digital learning environment, users engage in a series of targeted, gamified pedagogical tasks. These activities include an interactive Ishihara screening test, a concentration-based memory card matching game, a color-sorting exercise, and a navigable maze. These specific game-based learning mechanics are strategically designed to translate the abstract challenges of dichromatic vision into memorable, lived interactions. By bridging immersive VR technology with digital pedagogy, EduColorVR serves not merely as an experiential learning platform, but as a critical conversational tool. The project demonstrates the profound capacity of serious games to support the early detection of visual learning barriers, encourage peer empathy through playful exploration, and promote the proactive, inclusive design of future educational materials.

Keywords: Virtual reality, Color vision deficiency, Serious games, Inclusive pedagogy, Game-based learning

1. Introduction

Color vision deficiency (CVD) impairs the ability to distinguish certain colors. Normal color vision relies on three retinal photoreceptors (L, M, and S cones) sensitive to long, medium, and short visible spectrum wavelengths. Protein variations can shift cone sensitivity, causing anomalous trichromacy. The most common CVD manifestations involve L and M cones, known as red-green deficiencies. Globally, approximately 300 million people are affected by colorblindness (Simunovic, 2010).

Despite its high statistical prevalence, understanding and proactively addressing CVD remains fundamentally overlooked within educational settings (Blackstone et al., 2021; Diasse & Kawai, 2024). Qualitative consultations conducted with a small sample of educators reveal that colorblindness is rarely explicitly addressed or documented in a student's educational background unless a specific problem emerges. While orthoptic examinations conducted during early school years (first and second grade) may occasionally include checks capable of identifying visual deficiencies, schools generally do not provide specific, specialized examinations for CVD. Instead, there is a prevalent expectation among educators that parents should be the first to detect these visual difficulties and notify the institution (Smith et al., 2004; Memarzadeh & Ganji, 2019). This dynamic creates an environment where the burden is often inadvertently placed on young children to articulate their visual discomfort to peers and teachers.

Furthermore, educational accommodations for CVD are implemented on a strictly ad hoc, reactive basis. While teachers express a general willingness to adapt classroom materials, for instance by avoiding problematic colors in math graphs, fractions, or histograms, they simultaneously highlight a complete absence of standard institutional guidelines or dedicated professional training regarding how to accommodate colorblind students. Discussions or awareness initiatives concerning colorblindness within classrooms, among faculty colleagues, or through professional development courses are sparse or entirely non-existent. Consequently, teachers often underestimate the complexity of the condition, assuming they can quickly adapt school materials without first possessing a foundational background on the various types of dichromacy.

To address these systemic shortcomings, this paper introduces EduColorVR, an interactive virtual reality (VR) application designed to bridge this knowledge gap. By leveraging the perspective-taking effect of immersive VR, EduColorVR aims to elicit stronger, longer-lasting empathetic reactions than traditional media (Herrera et al., 2018). Targeted at elementary and middle school cohorts and their educators, the project utilizes game-based elements with simulated dichromatic perception, raising awareness of CVD's impact on learning and empowering teachers to proactively promote classroom inclusivity. This paper is framed as a design-and-development study complemented by a preliminary qualitative needs assessment. The primary research questions guiding this work are: (1) What needs concerning CVD awareness emerge from an exploratory consultation with primary and secondary teachers? and (2) How can a scientifically grounded simulation of color vision deficiency be translated into VR game mechanics to address these educational needs?.

Through these questions, we present the design and development of the EduColorVR prototype, establishing a foundation for future empirical evaluation of its educational effects.

2. Background

To fully understand the pedagogical necessity of EduColorVR, we contextualize the current landscape of color vision deficiency (CVD) accommodations. This encompasses traditional school approaches, the accessibility of digital media, the evolution of video game design, and existing attempts at virtual reality simulations.

2.1 Traditional School Approaches and Digital Media

In traditional educational settings, systemic methodologies for addressing CVD remain scarce. As digital media becomes increasingly integrated into modern classrooms, new accessibility barriers arise. Digital educational tools frequently rely on color-coded information, utilizing distinct hues to differentiate data charts, graphs, and interactive UI components. This color reliance disadvantages individuals with CVD in both academic and private environments (Schwabish, J., 2021).

Efforts to standardize digital accessibility do exist: broad User Experience (UX) design principles and specific digital accessibility frameworks, such as the Web Content Accessibility Guidelines (WCAG) (Peters, C., & Bradbard, D. A, 2010; Alim, S., 2021), have been established to guide developers toward colorblind-accessible designs. However, despite the availability of these guidelines, they are inconsistently applied and frequently overlooked in the development of educational software. Consequently, the pedagogical burden falls back onto ad hoc teacher interventions (who are often untrained in CVD accommodations) rather than relying on systemic, accessible-by-design digital infrastructure

2.2 The Evolution of CVD Accessibility in Video Games

While video games traditionally relied heavily on color to convey essential mechanics and narrative (presenting historical barriers for colorblind players), the industry has recently shifted toward inclusive design. Modern games increasingly incorporate customizable palettes and alternative visual indicators to support accessibility. Academic research underscores this necessity: Mazur, Hovis, and Ramaswamy (2025) detail the specific challenges gamers with CVD face, while Kerac, Milic, and Dedijer (2022) emphasize the critical role of accessible user experience design in digital environments. To formalize these practices, the Game Accessibility Guidelines (GAG) suggests that essential information must not be conveyed by color alone (Sloan, D., et al., 2006; Heilemann, F. et al., 2021). By implementing secondary cues like shapes, patterns, or text (as successfully demonstrated in games like *FTL: Faster Than Light* and *Hue*), developers can effectively mitigate these visual barriers.

2.3 Existing VR and Simulation Attempts

Within the realm of Virtual Reality and serious games, there have been preliminary attempts to simulate colorblindness to foster empathetic understanding. A notable example is *eXPerience: Colorblindness*, released in 2018 for the Oculus Rift, which served as an early inspiration for immersive CVD simulation. Additionally, various "colorblind filter" plugins are commercially available to developers on platforms like the Unity Asset Store.

However, these existing tools exhibit technological and educational limitations. While some digital algorithms intentionally distort colors to act as visual aids rather than true simulations (Elrefaei, L. A. , 2018), accurately simulating what a colorblind person perceives requires a strict transformation into long-medium-short (LMS) color space, as simplified filtering methods yield approximate results (Jones, P. R., & Ometto, G., 2018).

Moreover, achieving this physiological accuracy in modern VR environments requires overcoming the lack of native color management systems in standard 3D rendering engines (Díaz–Barrancas, F. et al, 2020).

These shortcomings in the current state of the art underscore the necessity for a more rigorous tool. EduColorVR addresses this gap by moving away from generic visual overlays and instead utilizing a validated scientific model (Brettel, H., Viénot, F., & Mollon, J. D., 1997) to provide a pedagogically focused, physiologically accurate representation of dichromacy in an educational context.

3. Design and Development of EduColorVR

This section presents the design and development of the application. First, a small cohort of teachers has been interviewed, highlighting the need for awareness of the condition. Then, the application was designed and implemented.

3.1 Teachers' Interview

Understanding CVD in educational settings ensures suitable learning experiences for all students. To expand insight into how colorblindness impacts students in classroom activities and to assess teacher awareness regarding this issue, short targeted questions were asked to educators in the form of a very short structured interview. The following section presents the questions used, along with a summary and discussion of the responses provided by teachers.

To conduct an exploratory qualitative needs assessment, we selected four primary and secondary school teachers through convenience sampling. The educators follow the local cantonal curriculum in Switzerland, therefore the findings are context-specific and are not intended to represent broad generalizations. The structured interviews were conducted in Italian, translated into English, and analyzed using preliminary thematic analysis to identify common pedagogical gaps and current classroom practices regarding CVD.

Q1. Is colorblindness mentioned in the student's educational background?

Q2. Is any examination done to check for students with colorblindness?

Q3. Are there any changes in school materials to support students with colorblindness? If yes, which ones?

Q4. Have there ever been any discussions within the class in the past or present regarding this condition?

A thematic synthesis of the exploratory interviews revealed three primary operational realities within these educational settings. First, CVD is rarely documented proactively; it is only addressed if a specific learning disruption makes it apparent. Second, while educators express a strong willingness to adapt materials, accommodations are implemented on a strictly ad-hoc, reactive basis due to a complete absence of standardized institutional guidelines. Finally, proactive classroom discussions or professional development training regarding dichromacy are virtually non-existent. These exploratory findings highlight a distinct need for accessible tools that can build pedagogical awareness and support educators in understanding the visual barriers their students may face.

3.2 Pedagogical Framework

To ground EduColorVR in established educational theory, its design applies principles of experiential learning, serious games, and empathy education. Users engage in active experimentation and reflective observation (core components necessary for fostering pedagogical empathy and inclusive learning design) rather than passively receiving information. The application utilizes specific game mechanics, such as restricted perception, time-pressured tasks, and immediate feedback loops, to simulate the cognitive load and daily frustrations experienced by students with color vision deficiency. By confronting these barriers firsthand, followed by active reflection within the virtual environment, educators can better conceptualize the necessity of accessible pedagogy.

Table 1: Pedagogical Framework Mapping of EduColorVR Activities

Game Activity	Learning Objective	Game Mechanic	Feedback & Reflection	Anticipated educational outcome
Educational Ishihara Demonstration	Experience information loss when visual assessments are inaccessible.	Filtered visual decoding; numeric keypad input.	Immediate HUD results; reflecting on failure states caused by color reliance.	Proactive design of visual assessments that avoid color-only cues.

Game Activity	Learning Objective	Game Mechanic	Feedback & Reflection	Anticipated educational outcome
Dichromatic Memory Game	Understand how CVD collapses distinct hues into identical shades.	Flipped visual memory matching with dynamic material swapping.	Audio cues for matches; active reflection phase to guess true colors before vision resets.	Avoidance of color-coding as the sole differentiator in learning materials and handouts.
Color Sorting Exercise	Recognize the cognitive friction between textual labels and perceived reality.	Time-pressured object sorting and categorization.	Post-task performance assessment canvas; iterative exploration of different CVD filters.	Implementation of secondary cues (e.g., shapes, patterns) alongside color in classroom organization.
The Hidden Maze	Experience the frustration of relying on flawed or inaccessible visual instructions.	Spatial navigation using deceptive, color-coded directional arrows.	Encountering dead-ends; arrows reverting to confusing colors when off-route.	Enhanced pedagogical empathy and commitment to clear, accessible instructions and signage.

3.3 Environment Design

Because educators and normotensive peers struggle to conceptualize the visual reality of a dichromat, developing empathetic pedagogical strategies remains difficult. By leveraging immersive VR, EduColorVR aims to shift the pedagogical approach from theoretical explanation to active, lived experience.

To maximize the educational impact of the colorblindness simulation, the virtual environment was intentionally designed to provide a highly saturated, visually stimulating baseline. Natural elements such as grass, flowers, and trees were heavily utilized, as these familiar objects provide users with an intuitive, recognizable benchmark for normal color perception. When the dichromatic simulation is activated, the contrast against the baseline shows the perceptual loss.

The virtual world is segmented into distinct zones, each serving a specific pedagogical and interactive purpose. The first explorable area is the classroom, shown in Figure 1, that acts as the central hub and onboarding area to familiarize the user with the VR controls and mechanics. Pedagogically, it helps contextualize the simulation within a standard educational setting. The walls are decorated with maps and posters, allowing users to directly experience how inaccessible standard school materials can be when viewed through a colorblind lens. The authors placed exact maps found in most classrooms in the area: old topographic maps of Switzerland and world maps that were not colorblind-friendly.



Figure 1: The classroom area, where users can familiarize themselves with VR controls and mechanics

By exiting the classroom, users can explore an expansive outdoor environment populated with vegetation, reinforcing the natural color baseline required for effective comparative learning. Figure 2 shows a bird's-eye view of part of the outdoors. We stressed the importance of creating an immersive world that encourages the user to explore, understand the game mechanics, and enjoy the surroundings. In one outdoor area, we opted to have trees appear in bright, distinct colors to highlight the comparison with different colorblind conditions. The

rest of the area implements natural colors to let users experience how colors in nature are perceived under different conditions.

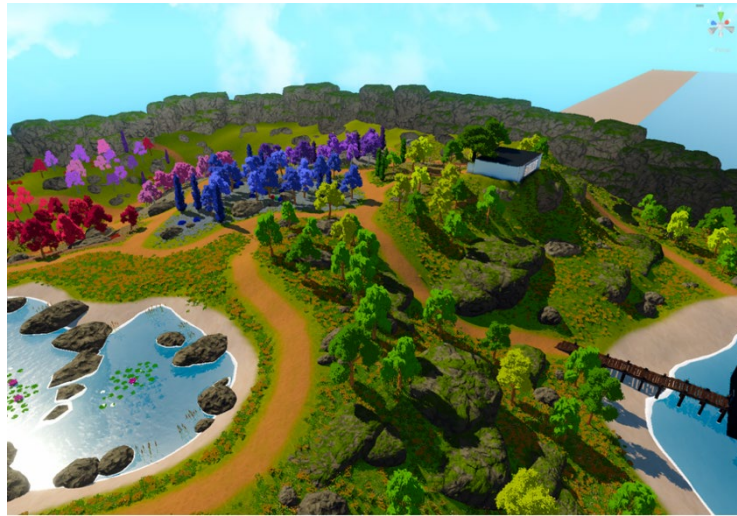


Figure 2: Outdoor environment from a bird's eye view, showing the classroom and the museum's entrance

By walking to the docks, users can explore the museum portion of the experience. This dedicated visual stimulation area features a gallery of images from around the world, taken by the paper's authors. The gallery is systematically divided by chromatic schemes, as shown in Figure 3, allowing users to observe how specific color spectrums are uniquely affected by Protanopia, Deutanopia, and Tritanopia without the distraction of gamified tasks.

3.4 System Architecture and Optimization

The project was developed with Unity 2022.3 LTS and the Universal Rendering Pipeline (URP). URP helped create a more appealing aesthetic and was critical to the development of custom-made colorblind shader graphs. The VR's user actions are elaborated via the XR Interaction Toolkit (XRI) 2.5, which allows locomotion (DynamicMoveProvider), grab/interact, and UI input module for world-space canvases. The XRI's action-based input keeps controller mappings clean across different brands of headsets.

To balance high visual fidelity with strict frame-rate requirements, the development process incorporated several aggressive optimization strategies, including baking lighting, single directional light for sun simulation, and conservative shadow distances and cascade counts.

To manage the polygon count of the natural environments, static GameObjects extensively utilize Level of Detail (LOD) systems, which dynamically reduce triangle counts as the user moves further away. Repeated environmental assets share meshes and materials via GPU instancing and static batching, which drastically reduces draw calls.

Because the Brettel-Viénot-Mollon full-screen pass shader and the highly saturated color palettes demand significant processing power, deploying the application as a standalone mobile VR build would have compromised the visual clarity necessary for the educational tasks. Consequently, EduColorVR targets PC-rendered VR streamed to a Meta Quest headset. Virtual Desktop was explicitly chosen over the default Air Link for this streaming process.



Figure 3: The museum section of the application, showing pictures from around the world

3.5 The Colorblind Simulation Model

To achieve a physiologically informed representation of color vision deficiency, EduColorVR avoids simple desaturation in favor of the Brettel-Viénot-Mollon algorithm. Implemented in Unity via a full-screen pass renderer, the simulation converts the rendered frame into LMS cone space before projecting it onto a dichromatic color plane. An important feature of this implementation is the per-pixel separation test: the shader calculates a dot product between the pixel's RGB value and the deficiency's boundary plane to dynamically select between two precomputed 3x3 color-mixing matrices. This dual-matrix approach prevents the severe visual artifacts that a single-matrix approach would cause, ensuring a fast, stable transformation across all three simulated CVD phenotypes. While VR hardware constraints required minor compromises, such as fixed-matrix approximations, occasional gamut clamping, and the exclusion of partial dichromacy, this method provides a robust and reliable empathetic tool.

4. Interactive Games

To translate visual impairment into a tangible learning experience, the application challenges users to apply active problem-solving skills within a series of interactive, color-based puzzles. By tying the abstract concept of dichromacy to concrete, goal-oriented tasks, users are forced to confront the cognitive load and daily frustrations experienced by students with color vision deficiency.

4.1 The Ishihara Educational Demonstration

One of the first interactions within the virtual classroom is an educational demonstration inspired by the Ishihara test (Birch, 1997), shown in Figure 4. While the traditional Ishihara test is a clinical screening tool used for diagnosis, this virtual activity is intended strictly for educational demonstration rather than clinical screening. The test is a clinical screening tool consisting of plates made of colored dots arranged to obscure a central number. The dots are calibrated to share identical brightness levels, isolating hue perception and preventing users from relying on luminance to solve the puzzle.

For users without a diagnosed deficiency, the plates (inspired by designs from Enchroma, Almutairi et al., 2024) are presented while the VR headset applies specific dichromatic filters. As the Brettel matrices collapse the distinct hues into a narrow spectrum, the hidden numbers become difficult or impossible to distinguish. This immediate loss of visual information serves as an empathy-building mechanism, allowing educators to directly experience the failure states their students might encounter during poorly designed assessments that include visuals. At the end of the test, the HUD displays the results of the test.

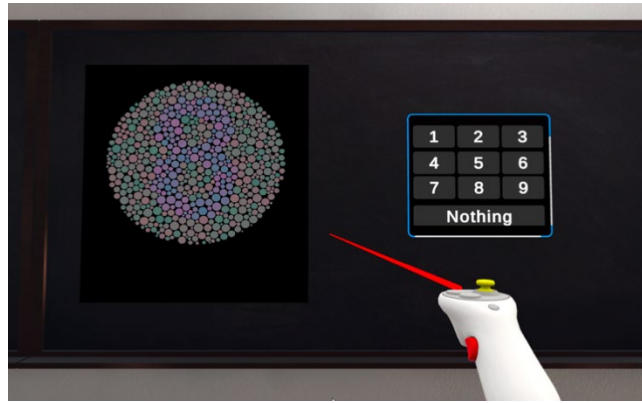


Figure 4: The Ishihara test, which can be administered in the classroom environment

4.2 Dichromatic Memory and Concentration

In this game, users are tasked with matching pairs of cards based entirely on their material color. To highlight colorblindness difficulties, the deck is designed with materials that use similar underlying color schemes.

The pedagogical value of this game lies in the flipped standard visual memory mechanics. The application dynamically swaps the color materials based on the selected colorblind mode. Users must attempt to solve the concentration puzzle while looking "through the eyes" of a person affected by CVD. Furthermore, the game incorporates an active reflection phase, challenging users to guess the original, true color of the cards before switching back to normal vision. Audio cues provide immediate feedback for correct and incorrect matches, reinforcing the learning loop without relying on visual indicators.

Figure 5 shows the game played in two different modalities: the normal version and the deutan efficiency version. The deutan deficiency version demonstrates how two different colors may appear identical to an individual with CVD.

4.3 Color Sorting and Categorization

In a corner of the classroom, users can find the ball-sorting exercise, which directly addresses the cognitive friction between textual labels and perceived reality. Users face a basket containing variously colored balls and a row of empty bins, each marked with a specific color name, as shown in Figure 6. The objective is to quickly reorganize the balls into their corresponding bins.

When played under a dichromatic filter, the user must grapple with the uncertainty of categorizing objects when their primary identifying feature has been obfuscated. Upon completing the task, a UI canvas displays a performance assessment detailing the number of correctly sorted items. The user can then restart the exercise using a different simulation filter, allowing for iterative exploration of how Protanopia, Deuteranopia, and Tritanopia uniquely impact simple sorting mechanics.

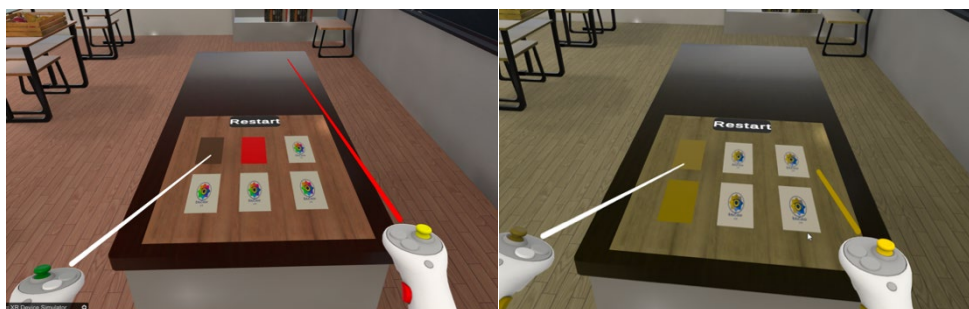


Figure 5: The Dichromatic Memory and Concentration game. The left panel displays the matching cards in a normal vision scenario with distinctly contrasting hues. The right panel demonstrates the same cards under a deutan-deficient simulation, illustrating how these distinct colors collapse into indistinguishable shades, forcing the user to experience the loss of primary visual cues

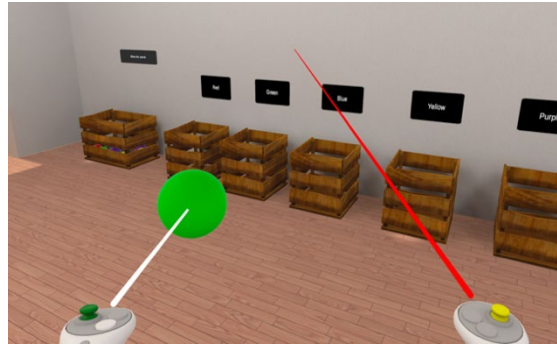


Figure 6: The ball-sorting exercise displayed in a normal vision baseline. Users are tasked with matching vividly colored balls to their corresponding text-labeled bins, establishing a baseline experience that becomes cognitively demanding once a dichromatic filter obscures the primary visual identifiers of the objects

4.4 The Hidden Maze

Hidden within the outdoors, a teleportation device brings users into a labyrinth, where they must find the exit by following a trail of colored directional arrows.

To ensure replayability and consistent challenge, the maze is dynamically generated at runtime utilizing a recursive backtracker algorithm, guaranteeing a solvable maze with a single, unbroken path between the entrance and the randomly assigned exit. Once the shortest route is calculated, the application strategically places UI canvases at junctions where the path branches.

At these intersections, the game uses color against the player. The arrow pointing toward the correct route and the dead-end are different. They are not random, but deliberately paired to create realistic physiological confusions based on the active deficiency. For instance, if the Deuteranopia mode is active, the arrows rely on a vivid green versus an orange tone: two colors that collapse into near-identical shades under the Brettel simulation. Protanopia mode utilizes brown versus saturated red, while Tritanopia utilizes yellow versus pink. If a user is not on the shortest route, all arrows revert to the "wrong" confusing color, further punishing incorrect navigation. This forces the player to rely entirely on flawed visual data. Figure 7 shows the navigational arrows found within the maze in a normal scenario (left) versus in a deutan deficiency scenario (right).

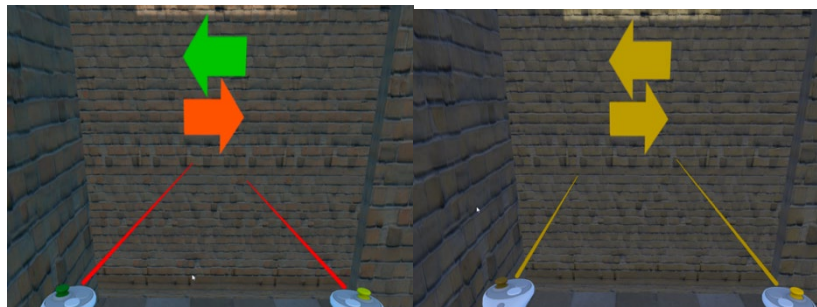


Figure 7: The hidden maze: on the left, the navigational arrows display distinct green and orange hues in a normal vision scenario. On the right, the deutan-deficient simulation demonstrates how these specific hues collapse into nearly identical shades of gold, forcing navigational errors

5. Discussion

The exploratory interviews highlighted a critical gap in current educational practices: while teachers demonstrate a strong willingness to accommodate students with CVD, their interventions are hindered by a lack of standardized institutional guidelines. EduColorVR directly addresses this (systemic) shortcoming by shifting the pedagogical approach from theoretical instruction to experiential learning. By immersing educators in a visually saturated baseline and obfuscating primary visual cues during targeted tasks, the application forces users to confront the exact cognitive friction CVD students experience. This design choice ensures that the resulting empathy is not merely sympathetic, but relevant on an operative level, equipping teachers to recognize and revise poorly designed, color-reliant learning materials.

The affordances of immersive VR combined with game-based learning mechanics provide a distinct advantage over traditional awareness media. 2D simulation filters can demonstrate color confusion, but they often fail to capture the frustration and cognitive load of attempting a task with compromised visual data. By integrating game mechanics, the application transforms the abstract concept of dichromacy into a goal-oriented challenge. This gamified approach relies on active experimentation and immediate feedback loops, critical for long-term pedagogical empathy and driving the proactive adoption of accessible instructional design.

6. Conclusion, Limitations, and Future Work

The EduColorVR application was developed to communicate the lived experience of color vision deficiency to teachers and students. By immersing users in an aesthetically rich environment coupled with gamified activities, the project transforms an abstract understanding of visual impairment into actionable interactions. The implementation of the Brettel-based two-matrix projection provides a rigorous balance of physiological plausibility and performance, aiming to capture characteristic color confusions in a scientifically grounded manner compared to generic accessibility tweaks or simple desaturation.

This project addresses a critical pedagogical gap. Teacher feedback collected during our preliminary studies suggests that awareness of CVD remains limited, and educational responses are almost exclusively reactive rather than planned. EduColorVR is designed to serve as a foundational conversational tool, with the anticipated benefit of providing educators and students with the experiential empathy required to support inclusive design of learning materials. While the current prototype requires empirical validation, its design demonstrates a promising approach to translating the abstract challenges of visual impairment into actionable game-based learning interactions.

6.1 Limitations

The current version of the project already delivers a compelling, high-fidelity simulation, while offering clear opportunities for further improvement. To achieve the intended visual richness, the full-screen simulation uses advanced shaders that currently work best with PC rendering and streaming (via Virtual Desktop), rather than running natively on lower-power standalone VR headsets; addressing this will enhance portability for resource-constrained educational settings. The simulation presently models full dichromacy and can be extended to represent the broader and more common range of anomalous trichromacy (partial color-vision deficiencies).

An important next step is empirical validation in real classroom contexts. Early consultations with educators confirm a strong pedagogical need for the tool; piloting the application with student cohorts will enable the collection of quantitative evidence on its effects on classroom dynamics, peer empathy, and teaching practices. These planned developments will both broaden accessibility and strengthen the project's demonstrated educational impact.

Furthermore, while EduColorVR provides an immersive activity into specific visual challenges, a brief VR experience cannot reproduce the full nuanced experience of individuals with color vision deficiency. Disability simulation carries the risk of oversimplifying complex conditions. Therefore, future iterations of the design process would benefit significantly from the direct involvement and reflective feedback of other people with CVD, ensuring the application remains respectful and grounded in actual lived realities.

6.2 Future Work

Future development will address these limitations across both technical and pedagogical dimensions. On a technical level, migrating the project to the newer Unity 6 stack aims to unlock engine-level optimizations, such as render graph improvements and updated SRP Batchers paths. Additionally, the color simulation model will be expanded to include a "severity" control, allowing users to blend between the original frame and the transformed one to accurately simulate anomalous trichromacy.

Pedagogically, future iterations of the game will incorporate more specific classroom scenarios, focusing on exposing standard teaching activities that inadvertently confuse students affected by CVD. Finally, our immediate priority for future work is to deploy EduColorVR in middle school environments. Conducting structured in-class testing with experimental and control groups will allow us to empirically measure the application's impact on fostering peer empathy and observe how experiential VR alters educators' approaches to inclusive instructional design.

Ethics Declaration: The exploratory educator interviews described in this paper were conducted in accordance with the institutional guidelines for qualitative needs assessments at our institution.

AI Declaration: AI tools were used for grammatical checks during the proofreading of this paper.

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