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Emulating Perceptual Experience of Color Vision Deficiency with Virtual Reality

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Abstract. One of the major goals of Universal Design is to create experiences that are inclusive to all users, including those affected by Color Vision Deficiency. Color Vision Deficiency might have a significant impact on a users' perception of the content or the environment. There is a range of tools already available, that can be used to either aid or automate the process of readability testing for digital interfaces and content in respect to Color Vision Deficiency. Two different approaches to addressing this issue can be found. A brief review of such methodologies is provided in this paper. The first approach (user-end) attempts to solve the problem by altering mediation between the user and the content. The second (design-end) allows the designer to view an image, or color scheme altered to recreate the perceptual experience of a user affected by Color Vision Deficiency and asses the design from the perspective of a color-blind user. With an implemented proof-of-concept we investigate the potential use of Virtual Reality Head-Mounted Displays to employ similar methodology, to allow designers or interior decorators to experience physical environments (i.e.: classroom, library or a cafeteria) from the perspective of a color-blind person. Such tools might increase the designers' empathy towards color-blind users but also allow them to identify visual components, such as infographics or advertisement, in a physical environment that are poorly visible to color-blind users. Such tools could be developed by taking advantage of a modern Head-Mounted Displays six degrees of freedom tracking, a 360 camera and color processing filters applied during post-processing at run-time, allowing a designer to easily switch between different types of colorblindness emulation.

Keywords. Color Vision Deficiency; Color-blindness; Design; Virtual Reality; Head Mounted Display.

1. Introduction

Universal Design aims to create inclusive experiences for all users, including those suffering from Color Vision Deficiency (CVD). CVD might impact users' experience of a physical and virtual stimulus. We review methodologies used to date, aimed at increasing functionality or perception of the color for users affected by CVD, and tools for designers that can be used to increase their capacity design evaluation in the context of CVD. A taxonomy of such tools and the description of the proof-of-concept developed to allow designers of physical spaces to experience it through a perspective of a CVD affected user is provided. In the discussion section current approaches to increasing inclusiveness towards CVD users are critically analyzed to support the rationale behind proposed recommendations.

2. Color Vision Deficiency

Human perception of color is constructed from the composite of cones sensitive to different frequencies of the light spectrum: Short (S), Medium (M), and Long (L) [1].

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Normal color vision (trichromacy) requires all three of them to correctly respond to stimulation in one of the three bands of the light spectrum in the SML model [2]. However, a small percentage of female population and an even smaller percentage of male population are tetrachromats, enabling their cones to respond to four bands of the light spectrum [3]. In humans this additional band often overlaps with the other bands being a part of the standard SML model and as such a trichromatic model can be generalized to the whole population.

Color Vision Deficiency (CVD) is a broad term describing inability to detect differences between certain hues of color. This condition is colloquially known as 'color blindness'; however only a very small percentage of the population experiences a total loss of color vision (cone monochromacy). It is estimated that approximately 200 million people worldwide suffer from CVD [1]. Reported numbers on the percentage of the population affected by different types of CVD vary. This might be due to the fact that there seems to be differences in CVD occurrence in respect to different populations (at least in case of congenital CVD), and the widely reported 8% of male population seems to be applicable only to Euro-Caucasians while the Asian, African and Native populations seems to be less affected by congenital CVD [4]. Congenital CVD is less frequent in female population – 0.5% [5].

Anomalous Trichromacy results from an offset in the frequency the cones respond to creating an overlap between S, M or L cones:

- Protanomaly - reduced sensitivity to red,
- Deuteranomaly - reduced sensitivity to green (most common),
- Tritanomaly - reduced sensitivity to blue (most rare of the three conditions),

Dichromacy is a condition resulting from total absence of the cones sensitive to one of the bands (S, M or L) be it through replacement of the pigment in the cone or, in a less frequently observed condition, 'loss' of a cone class [6]:

- Protanopia - inability to perceive 'red' light
- Deuteranopia - inability to perceive 'green' light
- Tritanopia - inability to perceive 'blue' light

Complete achromatopsia (monochromatic vision) doesn't allow for any perception of color, this condition affects a small percentage of the population (approximately 1 in 33,000) – but being the most severe form of color blindness it can also have the strongest negative impact on the quality of life of people affected by it. Incomplete achromatopsia refers to a condition where under some special circumstances an interaction between cones and rods results in residual color discrimination [5]. Most common types of Color Vision Deficiency (CVD) are inherited (congenital) and result from mutation of the genes responsible for encoding the opsin molecules (light sensitive groups of proteins). However, even the most severe types of CVD can also arise as a result of brain fever, cortical trauma or cerebral infarction. Less severe forms of CVD can also be acquired through glaucoma, vascular, hematologic, optic nerve or central nervous system diseases, or even from consumptions of toxins such as lead, tobacco or alcohol [2].

3. Color vision, how important is it?

There is a range of activities where lack of color vision can have a negative impact on performance, the simplest example can be observed in translation of information often conveyed by the green and red colors (e.g.: traffic lights - be it for cars or pedestrians). Our society often uses the color green as a symbol for 'go ahead' or 'confirm' while the color red symbolizes 'stop' or 'cancel'. These two opposite concepts are represented by colors that are immediately distinguishable by the vast majority of the population, but might be problematic for users affected by CVD. This is probably why color is rarely used to convey this information without being supplemented by text, iconography and/or consistent spatial placement used to clarify any ambiguity, accessibility guidelines for game designers explicitly recommend that no essential information should be conveyed by color alone [7].

CVD became a subject of scientific inquiry during the industrial revolution, when color vision disorders started to hamper productivity at scale, as the growth of textile manufacturers require a uniform color perception of different threads used in production [8].

According to Changizi and his colleagues color vision has evolved primarily to support higher survival functions by allowing us to detect subtle changes in the blood flow through skin color, and identify potential risks associated to it [9]. This would suggest that individuals suffering from Color Vision Deficiency (CVD) are likely also impaired in their ability to recognize emotional states in others.

Furthermore, research conducted on students suggests that CVD could be a contributing factor in learning disabilities, as the CVD was found in "13.25 percent of EH" [Educationally Handicapped] students, compared to 5.04 percent of regular class students [10].

Color can be used to represent information. Given that we are living in the age of information it is plausible to assume that the role of color in the society will become increasingly prominent in the domain of information processing [11]. Our tendencies to utilize color to convey information are particularly prominent in the domain of science where we create pseudocolors to supplement dissemination of data, to make it easier to comprehend and quicker to process (e.g.: [40]). Therefore, individuals affected by CVD might be at a disadvantage while accessing knowledge relying on color for information transmission. Fortunately, color is often seen as a supplementary mode of conveying information so the data is still accessible through other means (usually text based source materials). However, this is likely a slower mode of processing information and as such it might have a negative impact on performance e.g.: [12]. This argument can also be used to support the notion of classifying CVD as a learning disability.

4. Technology available to assist color blind users

Over the years a number of attempts were made to help individuals affected by Color Vision Deficiency (CVD) by restoring their perceptual abilities or alleviating some of the issues arising from their condition. From 1850 when, James Maxwell designed the first glasses to help individuals affected by CVD [8], ongoing efforts are made to make all colors (or at least those perceived by an average human trichromat) accessible to everyone. There is a possibility that these efforts will result in an innovation that will allow us to alter our vision, potentially allowing us to expand the boundaries of visible light spectrum, similarly to the extra thumb that we can enjoy thanks to advancements and a pinch of thinking outside the box in the domain of prosthetics [13].

Meanwhile, researchers at 2AI Labs developed Oxy-Iso lenses claiming to improve red/green color discrimination for some users; the lenses were developed for the purpose of enhancing medical professionals' perception of veins and increase their ability to assess blood physiology, while the effect on color-blindness was a by-product [14]. Researchers at EnChroma took a different approach in designing their glasses and judging by the videos posted by some of their users, they did seem to achieve some impactful results [15]. However, as clinical research suggests, these results are unlikely to be applicable to a general population [5], [45]. A possible issue with such approach is that CVD effects can vary widely between subjects, so a solution that would address them all is unlikely going to be achieved through one set of corrective filters. This could explain anecdotal evidence demonstrating how different glasses can achieve a different degree of success depending on the user. There is also an interesting hypothesis being put forward (although hard to trace back to their source) suggesting that using corrective glasses might develop new color perception without wearing them, the effect seems to be based on the theory that the construct of the object is made within our minds, and as such if a color is learned and associated with an object, new color might be perceived based solely on the information derived from the mental model of it. However, this concept has to be explored further before any conclusions can be reached.

A range of applications is also available that alter the colors displayed on a mobile phone screen, to present a corrected live feed from the phone camera in order to increase capacity of CVD affected user to differentiate between colors in their immediate surroundings, (e.g.: [41], [42]). A similar methodology can be found in literature where Augmented Reality (AR) is used to overlay corrective filters on the physical environment registered by the camera to adjust the colors to match standard vision or even highlight the color range specified by the user [16].

Color pickers are also available for mobile phones equipped with a camera, that allow the user to identify the color that the camera is pointing at. These apps vary in functionality, some are aimed at a general user and provide detailed color description e.g.: "bold brown" e.g.: Color Blind Pal [17] or even RGB or HEX values. However, judging by feedback provided in the comments section for the Color Blind Pal app site on Google play store it seems that users are more interested in basic functionality that would enable them to distinguish between primary colors.

Color is an artificial construct created by our brains [18]. In the condition known as synesthesia color is often associated with a letter or a number or even a taste or a sound [19]. By utilizing different sensory modalities to translate missing perception of color into a different sensory channel, e.g.: haptic, auditory or olfactory [20], it might be possible to use different sensory channels to convey the color information.

In the domain of media, the chromatic contrast enhancement can be performed at the rendering level [21], which provides an exciting avenue that could potentially enable color-blind users to perceive the digital content as it was intended to be seen by the author. An example of such approach can be seen in a range of video games that allow the user to enable a color-blind mode after selecting a preset (usually compensating for dichromacy) to improve their color discrimination [43], [44].

From iOS 10, Apple iPhones also contain an accessibility feature that allow users to modify color intensity and tint manually or use presets for protanopia, deuteranopia and tritanopia [22]. Similar features can be found on Google Android devices from version 5.0 – Lollipop [23].

In October 2017 the "Fall Creators Update" for Microsoft Windows 10 introduced a set of functionality designed to increase accessibility for users affected by CVD. As such color-blind Windows 10 users are now able to use contrast enhancement filters to increase readability [24].

In November 2017, Samsung released an Android app for their QLED TVs with an accompanying app, that first performs a C-Test (developed by Dr. Wenzel Klára) to assess users color vision deficiency and applies corrective algorithms to the TV display to deliver an experience mimicking standard trichromatic vision to the user [25]. At present the SeeColors app has only been released on a limited range of Samsung mobile phones, so this feature is only available for those in possession of a limited combination of Samsung TV and high-end mobile phones.

Perhaps the most promising avenue for treatment of CVD is through gene therapy [5]. However, eradicating the problem of Color Vision Deficiency is outside the scope of this publication. The focus of our proposal is to aid designers in creating physical environments that are more inclusive towards the users affected by Color Vision Deficiency.

5. Existing technology assisting designers with catering for color-blind users' needs

CVD has been identified as one of the factors affecting the user experience of websites, and W3C standards include some guidance for designers in Web Content Accessibility Guidelines (WCAG). Starting from a general principle (#1 - Perceivable) stating that "Information and user interface components must be presentable to users in ways they can perceive" through more specific instructions: at the minimum for level AA compliance "The visual presentation of text and images of text has a contrast ratio of at least 4.5:1" (§1.4.3) and for higher compliance required for level AAA (§1.4.6) WCAG specify "The visual presentation of text and images of text has a contrast ratio of at least 7:1" [26].

W3C guidelines refer to quantitative analysis based on the contrast ratios between specified colors (e.g. background color evaluated against foreground text color). This can be a great starting point, but is unlikely to capture the actual perceptual experience of a color-blind user. Including color-blind users in the UX testing process seems like the most straightforward solution to the problem. However, given the range and differences in how CVD can affect perception, finding a group of testers who will be able to cover that spectrum fully may be problematic and expensive. Therefore, a range of tools has been devised to assist designers with increasing accessibility of websites they design by giving them a glimpse of the perceptual experience that a person affected by a CVD might have, while interacting with their content. By visually inspecting the designs and color schemes from the perspective of a color-blind user, designers can spot the issues that would normally be discovered only by color-blind users themselves.

At paletton.com designers can select the color schemes they would like to use in their design and see them applied to a mockup of a website. In itself this is a useful design tool, but the eye-opening feature can be found under the 'vision simulation' tab, allowing for visual inspection of the color scheme applied to a mockup with a filter emulating protanopia, deuteranopia, tritanopia, protanomaly, deuteranomality, tritanomaly, dyschromatopsia or achromatopsia. This filter can be used to visually inspect color themes but in its current form it is not possible to evaluate 'live' websites, gradients or images.

The color-blindness.com website has a tool that can be used for such purpose, by applying color correction transformation to the image supplied by the user, a simulation of color vision deficiency is achieved [27]. A number of other tools can be found online implementing a similar method to emulate CVD. However, to evaluate a 'live' website a screenshot has to be used.

Another web application developed specifically for testing websites by emulating CVD is fetching the content of the URL supplied by the user, and applies selected filter automatically [28]. An unaltered view of the page and a version with CVD filter applied can be seen and visually inspected by the designer in a side-by-side fashion [e.g.: Figure 1].

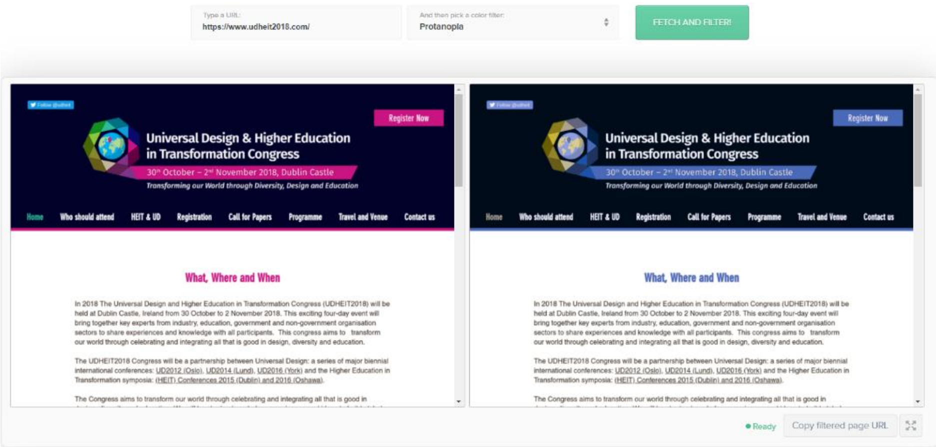

Figure 1. Screenshot of a side by side view of an unaltered website (left) and with a protanopia filter applied (right)

Some WYSIWYG tools that can be used for digital content creation, also come in with a built-in color proofing functionality that can be set to emulate perception of a CVD [29].

6. Taxonomy of available tools

Tools used to alter the perception of color to either emulate color blindness or correct for standard vision can be divided into four broad categories:

- Design-end,
- User-end,
- Screening,
- Support,

Design-end contain tools that are aimed at assisting designers and other practitioners in creating more inclusive content, this could include emulation of the CVD condition, or provide quantitative data for contrast analysis or even highlight the colors that can be confusing for different types of CVD disorders by highlighting the gamut.

The user-end category includes the tools designed to assist the color-blind user with their interaction with the world or digital content. From color pickers to an app altering the display settings of a TV set.

In screening category, we find tools designed to evaluate CVD, this can vary from pen and paper based tests through their digital counterparts to video games designed to diagnose CVD in children [30].

In the support category we can find tools such as ColorBlindVR [31] that aims at increasing awareness of the CVD among general population through gamification; the majority of members of the Design-end category can also be used for such purposes.

7. Modeling color blindness

In 1931 the International Commission on Illumination published one of the first mathematical models of a human vision color space known as CIE XYZ [32] based on the works of William David Wright and John Guild from late 1920s. The CIE XYZ model was derived from the CIE RGB color space model. The transformation between CIE XYZ and LMS color space is not universally accepted due to the complex nature of human color vision. Updated models such as Chromatic Appearance Models (CAMs) give basis to Chromatic Adaptation Transform (CAT) matrices which are the basis of modern CVD simulation models [33].

One of the first attempts at emulating CVD can be traced back to Meyer and Greenberg [34] who noticed that digital image processing can be used to emulate perception of the image as it appears to a dichromat while working on a digital version of the Farnsworth-Munsell 100-hue test, they have also described a potential application of such digital tests to customize interfaces to tailor to the user's ability of discriminating colors. Brettel and colleagues [35] further refined this concept and developed the algorithm and Machado et al [1] claims to be first to develop a version of the algorithm that consistently handles normal color vision, dichromacy and anomalous trichromacy.

8. Proof-of-concept

Lewis and colleagues developed a Virtual Reality application that used a replica of a physical location and a set of filters to emulate glaucoma, macular degeneration, cataracts, hemianopia, myopia and hyperopia vision impairments [36]. The vision loss simulator covers diabetic retinopathy, presbyopia, macular degeneration, cataract and glaucoma but uses a 360 photography [37] instead of a virtual environment as is the case with Unreal 3 engine based application developed by Lewis et al.

Following this approach, with a focus on CVD, our proof-of-concept has been developed on the Unity3d 2017 engine and use a third party plugin "Colorblind Effect" available through Unity asset store [38].

A JPG file obtained through an LG360 camera (although any other 360 camera should work just as well) is applied to a sphere with a custom unlit shader that flips its normal coordinates so that the texture appears on the inside of the sphere ignoring any dynamic lighting in the Virtual Environment. The final step involves selecting one of the three filters available from the dropdown menu to emulate protanopia, deuteranopia or tritanopia [see figures 2, 3 & 4].

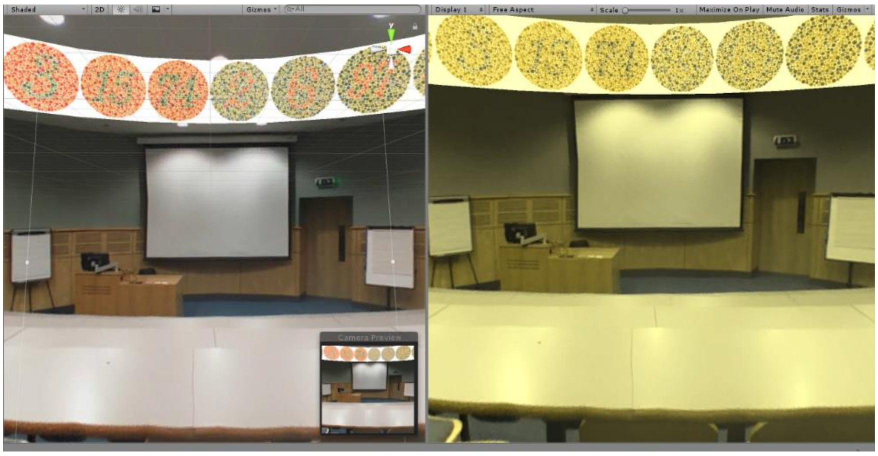

Figure 2. Unaltered 360 photography of a lecture hall (left) and the view of the same image rendered by the virtual camera with a deuteranopia filter applied (right). Ishihara plates used for validation are visible at the top of each image.

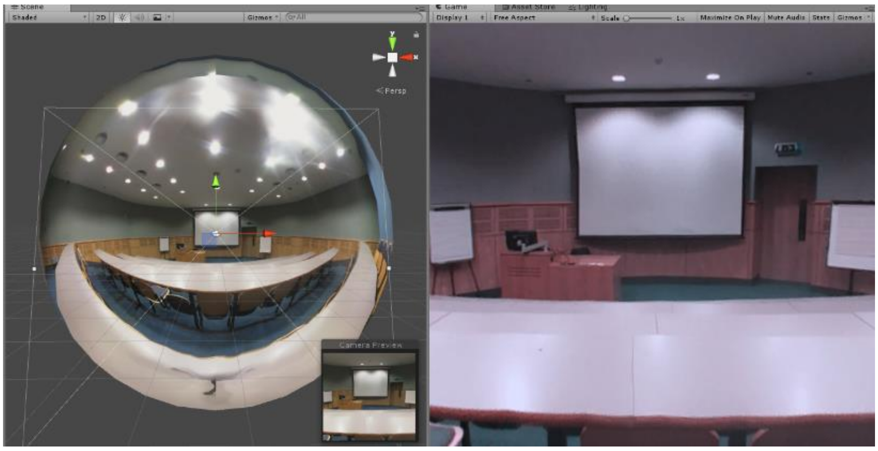

Figure 3. Unaltered 360 photography of a lecture hall (left) and the view of the same image rendered by the virtual camera with a protanopia filter applied (right). Ishihara plates used for validation are visible at the top of each image.

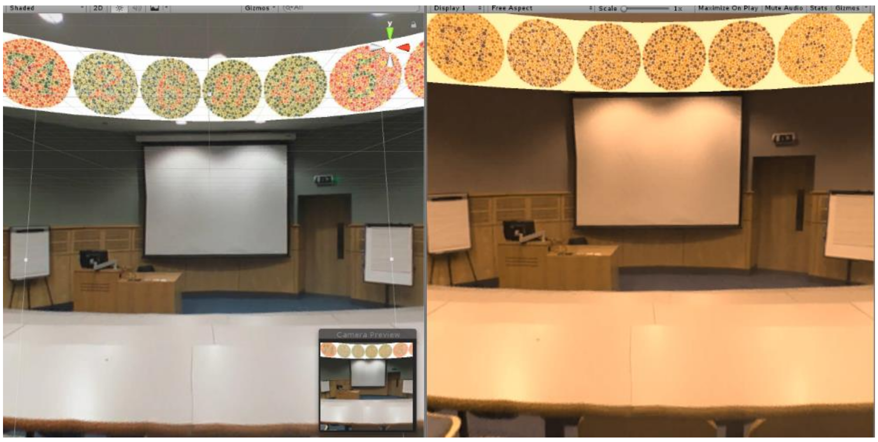

Figure 4. Spherical view of an unaltered 360 photography of a lecture hall (left) and the view of the same image rendered by the virtual camera with a tritanopia filter applied (right).

9. Proposed method to evaluate the proof-of-concept

To validate the filters and their accuracy in recreating the perceptual experience of CVD we propose to use Ishihara tests applied within the virtual environment with an active CVD filter [see figures 2, 3 & 4]. If the filter is working correctly our expectation would be that a standard trichromat user will fail to correctly identify the numbers on the Ishihara plates, similar approach to validation of a CVD filter (with a use of Fransworth-Munsell 100-Hue test) can be found in Machado, Oliveira, & Fernandes (2009). Alternatively, HRR test can be used to expand the coverage for tritanopia [39] [see figure 5].

Figure 5. 18 HRR plates [extracted from Figure 2 in [39]] rendered by a virtual camera with a tritanopia filter active.

A visual inspection of the graphical representation of the spectrum of light available to a CVD affected perceiver could also potentially be used to evaluate accuracy of the color transformation. In such approach the light spectrum band for the selected active filter should be indistinguishable from the representation of a trichromat spectrum of perceivable color [see figure 6].

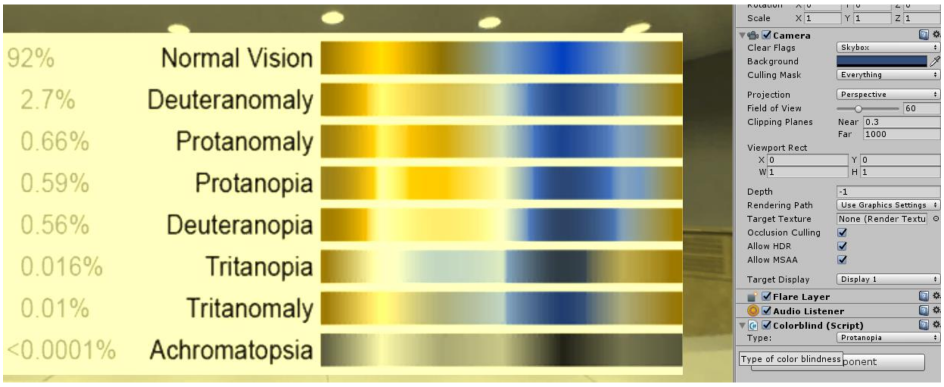

Figure 6. Image representing a color spectrum visible to different types of CVD as rendered by virtual camera with protanopia filter active.

10. Conclusion

The proof-of-concept presented in this paper might help the designers with understanding challenges that a color-blind user might have to tackle when navigating and interacting with a three dimensional space.

It might also accommodate higher empathy towards users affected by CVD and allow those with a normal trichromatic vision to learn more about the different experience of the world that such users might have. It might also widen our own perspective by demonstrating to us how unique and subjective the perception of reality is.

It seems that adjusting display settings (be it at the operating system, display device or in-game settings level) seems like the most effective solution for CVD in respect to Virtual Environments. Games are often experienced by multiple users using the same display hardware at the same time. As such, particularly in case of video games with a shared screen cooperation mode, it is still important to visually inspect the game from the perspective of a color-blind user to increase accessibility.

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