Color blind: Can you sight?

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ABSTRACT

Virtual 3D conferences are emerging communication channels as a substitution for face-to-face fashion due to the advancement of technologies and the covid-19 pandemic. Current efforts focus on bringing contents into 3D virtual space while delivering them to the color vision deficiency have not been taken into account. To alleviate the stated issue, this paper presents a *prototype* for color-blind people to simulate the same experience as normal ones. Our method helps users: 1) understand the presented content through adjusted color filtering in such a way that similar colors can be differentiated by the brightness, 2) apparently-identical colors can be varied by the color transformation. Our proposed prototype is demonstrated through three use cases setup in three conditions such as traffic lights, fruit color differentiation, and graph reading in a virtual meeting room. A pilot study conduct with 29 participants shows that our proposed method can improve color differentiation and accuracy for color-blind.

CCS CONCEPTS

• **Human-centered computing → Visualization design and evaluation methods**.

KEYWORDS

Color Blind, Color filter, Virtual Reality

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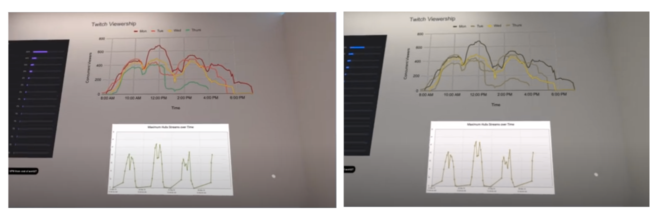
1 INTRODUCTION

The explosion of covid-19 has dramatically transformed the ways of communication, with shifting from face-to-face conversation to an online fashion, where all communications will be conducted via emails, forums, video calls, or even 3D virtual meetings [6]. For example, one of the leading VR conferences (i.e., IEEE VR [11]) took place in Atlanta in March 2020 organized the event over the internet with a special venue for the 3D virtual room. In this regard, attendees or participants can immerse themselves in a shared virtual space and be capable of experiencing authors' work synchronously. This new kind of emerging medium provides a unique perspective of how we perceive the world while being quarantined. It allows participants to have the feelings of being 'present' at the event [6]. The absence of physical sense demands heavier needs on other communication channels, such as visual and auditory inputs/outputs. However, does anyone have an equal opportunity to experience VR content? Especially for those who are visually impaired by color differentiation [13]. It is because literature work has contributed extensively to increase the fidelity of the virtual world, meaning that to construct or reconstruct the 3D environment as similar to the physical world as possible [19, 23]. To get this work done, many different techniques are used, such as manually building the meshes, carefully designing the textures/materials, iteratively setting up the lighting conditions, and supporting haptic feedback. Yet, when designing a VR application, it is assumed that users have a full capability of enjoying the proposed apps. However, a small population of VR enthusiasts can not have the same experience as others. Figure 1 illustrates this point where normal people can fully read the graph contents presented by the speaker in the 3D setting, but it is challenging for color-blind users to interpret the information or differentiate the colors of the graph [16].



(a) (b)

Figure 1: Information presented in the IEEE VR room [11]: (a) Normal vision, (b) Colorblind view where orange and green curves are inseparable.

Not being able to read the information correctly could potentially pose a negative impact on color blindness enthusiasts. Globally, one in 12 males and one in 200 females are color-blind. Color blindness is a disability of not being able to see colors in a normal way, and it is classified into three types [17]: *protanopia*, *deuteranopia*, and *tritanopia*. The first type of color deficiency is *protanopia*, where users cannot distinguish between colors in the green-yellow-red region of the spectrum. In the second type, *deuteranopia*, the cone cells sensitive to green light are absent. The *tritanopia* is the lack of blue cones, and a *tritanopia* can not distinguish colors in the blue-green region of the spectrum.

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Many efforts have been attributed to equalize the users' experience between normal and visually impaired people [14, 20]. For example, in Apple and Samsung products, users have the ability to filter colors (or select type of color-blind) in their handheld devices. These visual features are supported in modern TVs, especially in the gaming sector. In line with manufacturing markets, research work also conducted experiments or proposed methods to help visually impaired people to carry out better some given tasks with the help of assistive means such as sound, blinking, or patterns [1, 9, 22]. However, most of the studies were conducted by using a Head Mounted Display (HMD) along with the IDE tools such as UnReal Engine, and Unity which poses another challenge of not being able to see the text clearly or the frame rate significantly reduces when deploying the VR app on mobile devices. Part of the problem is due to the rendering mechanism of the scene engine (e.g., multi-pass rendering), and thus the motivation of using VR for color-blind people could be impacted.

Motivated by the increasing number of virtual 3D conferences and unresolved issues in existing work, this paper presents a *prototype* for visually impaired people to achieve the best VR experience as normal visions. Our proposed prototype works at the post-processing level; it only involves the final rendered image. The contributions of this paper can be listed as follows:

- We propose an adaptive color filter method to help color deficiency people differentiate colors in the scene.
- We present transformation method to distinguish colors of a number of different color blindness conditions
- We demonstrate our prototype through three use cases in different environment settings
- We assess our proposed prototype by conducting a descriptive analysis with 29 users

The rest of this paper is organized as follows: Section 2 summarizes related research. Section 3 presents methods for color filtering and color transformation in detail. Section 4 demonstrates our proposed prototype via use cases in different environment settings. Section 5 presents user feedback of domain experts. Section 6 concludes our paper with future work direction.

2 RELATED WORK

In the research community, Gusev et al. [10] investigated whether a color-blind person can suffer from motion sickness while watching a spinning sphere. Ates et al. [5] introduced an augmented reality simulator, SIMVIZ, that enables visually impaired people to convey information from the display better. In their research, media streams achieved from the head-mounted are processed in each frame; the image processing technique is for color filtering at the camera. Craddock et al. [8] presented the proof-of-concept on the perpetual design for color-blind people in Virtual Reality. In their research, the authors reported that adjusting display settings directly from the operating system or display devices seems to be the most effective solution for visually impaired users with respect to Virtual Environment, although the possibility of using HMD is potential and promising. The research also laid out some available tools that enable researchers to design and conduct experiments for color-blind people, ranging from design-end, user-end, screening, and support. ColorBlind VR [3] is a Google Cardboard game that aims to raise awareness of designing VR applications for color vision deficiency people through gamification; in this work, the creators challenge normal users to pick up fruits such as apples through the lens of a color-blind person. In this project, low poly 3D models are downloaded from the Unity Assets Store, and the two libraries (i.e., ColorBlind Effect, ColorBlindness Simulator) are adapted. ColorBlind Effect [21] is a Unity package that enables developers to impose a color filter on the camera so that when users put the HMD on their head, they can see the 3D environment through the lens of a visually impaired person. This package is adapted in a variety of research experiments. However, the limitation of this package is the lack of some image processing features. As such, users face difficulty in differentiating similar regions or the texts displayed are often blurred. ColorBlindness Simulator [7] is another Unity package that allows 3D developers to verify how their projects may be perceived by color deficiency people. However, this package supports only two types of color blindness (i.e., *protanopia* and *deuteranopia*). Previous studies reported the limitations of using the available Unity packages that differentiation of similar regions and blurred texts are the most common drawbacks of the experiments. Our research overcomes these issues by imposing color transformation on the rendered image and apply adaptive color filters to simulates different color blindness conditions.

3 METHODS

We process and impose our adaptive color filter after the scene is rendered in each rendering cycle. Algorithm 1 gives pseudo-code at a high level. Our approach is straightforward: First, we capture the rendered image from the scene (line 3), then we perform image modification by subtracting (on line 4) and transforming (line 5).

Algorithm 1: Adaptive color filter algorithm

```
  Result: Filtered Images
1 initialization;
2 while scene is rendered do
3     img = getImage(scene);
4     applyColorFilter(img);
5     applyColorTransform(img);
6     putImage(img, scene);
7 end
```

Algorithm 2 demonstrates the processing of the extracted image in detail. In this step, we adjust the image color pixel by pixel with respect to *protanopia*, *deuteranopia*, and *tritanopia*. We apply color matrix transformation to each pixel based on the following formula:

$\varphi_{tritanopia} = \begin{bmatrix} 1.0 & 0.0 & 0.09 \\ 0.19 & 0.95 & 0.35 \\ 0.0 & 0.16 & 0.88 \end{bmatrix}$ After the color of each pixel is modified, the RBG value is used again to adjust the brightness level for each data point (Algorithm 2 - line 4). In this step, color values are clamped into bins (the number of bins is defined manually or automatically based on the distance between color values), and the alpha is adjusted based on the bin each pixel belongs to. This step ensures that when two regions have a similar color that can not be distinguished, then brightness can be imposed to supplement color differentiation. While Algorithm 2 can help users to differentiate color regions based on the intensity of each pixel, it is vulnerable to image homogeneity - meaning that the color values are similar. To overcome this issue, we apply color transformation in which colors in the connected-region are transformed into another spectrum. In this regard, we impose a color transformation in such a way that the color distance between two given groups is far enough for distinguishing them [15]. Our approach is similar to the Gaussian Blur [18], but it differs in a way that instead of updating pixels in each iteration, we update the group of pixels in each loop. This process ensures that colors in the same region are consistent. The distance to the centroid is first calculated, then the transformed_values function checks which components the current pixel belongs to then it applies the transformation correspondingly.

Algorithm 2: Color filter algorithm

```
Result: Color Filter
initialization;
for each pixel in image do
    pixel = adjusted_values(pixel);
    alpha = adjusted_alpha(pixel);
end
```

Algorithm 3: Color transformation algorithm

```
Result: Transformed color
initialization;
for each pixel in image do
    dist = distance_to_threshold(pixel);
    pixel = transformed_values(dist);
end
```

4 USE CASE

This section demonstrates our prototype through three use cases in different environmental settings: traffic light recognition, fruit color differentiation, and graph readings. Our prototype is implemented in Unity with Oculus Rift headset; the application is exported in both in-app and web browsers to check the performance.

4.1 Traffic lights

Figure 2 illustrates the traffic lights use case where we apply our adaptive filtering algorithm. The upper row shows the results of ColorBlind Effect filtering techniques [21] while the lower row is generated by our filtering technique on *protanopia*, *deuteranopia*, and *tritanopia* respectively. In Figure 2–*protanopia*, the person with a *protanopia* is unable to recognize the differences between the red and green. In contrast, we can identify the three colors separately in our improved results. Similarly, color transformation is applied in Figure 2–*deuteranopia* where the orange color is transformed to another spectrum. However, there is only a slight change (brightness) of the colors in Figure 2–*tritanopia* due to the distinctive color bands in the original image. The modified color spectra are also displayed at the corner of each image.

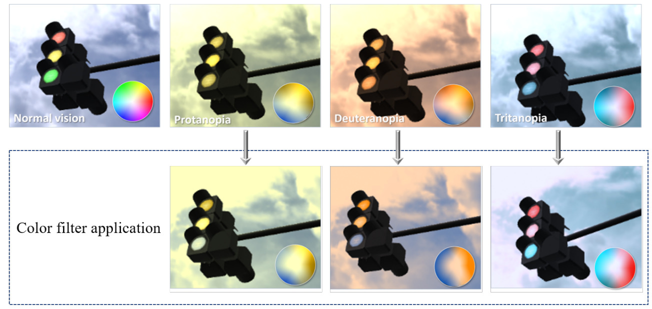

Figure 2: Traffic light recognition with different color filters.

4.2 Fruit color differentiation

Though the color-blind is a small part of the population, they should still be considered in designs, especially when their safety could be compromised [4]. In particular, color differentiation is not only essential for fruit identification but also crucial in recognizing fruits at different stages. For example, green bananas change to yellow/orange when they are ripe and to gray when they are rotten. While their shapes are almost unchanged, recognizing significant color changes is important for color blind people to avoid uneatable food. Figure 3 demonstrates our color transformation techniques to help people with *deuteranope* disability to recognize there are three types of apples on the table. As depicted, the yellow and green apples look almost identical for *deuteranope* color-impaired users.

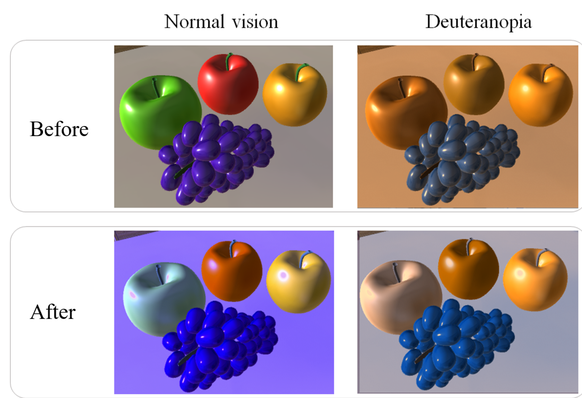

Figure 3: An example of normal vs. *deuteranope* views for fruits: Before vs. After applying our proposed color filter.

4.3 Graph reading

While the two previous focus on daily activities, this use case supports viewers to convey information presented on computer displays. Figure 4 shows a typical circumstance where a presenter embeds the PowerPoint presentation directly into the 3D space at IEEE VR 2020 [11]. Users with *tritanopia* disability find it difficult to identify countries in a certain group. Our prototype alleviates this issue by modifying the *tritanopia* spectrum. As shown at the bottom row of Figure 2, our new color filters do not expand color spectrum of *protanopia*, *deuteranope*, or *tritanopia* (or no treatment is applied color blinds). Instead, we modify their color space so that important colors are still visually distinguishable.

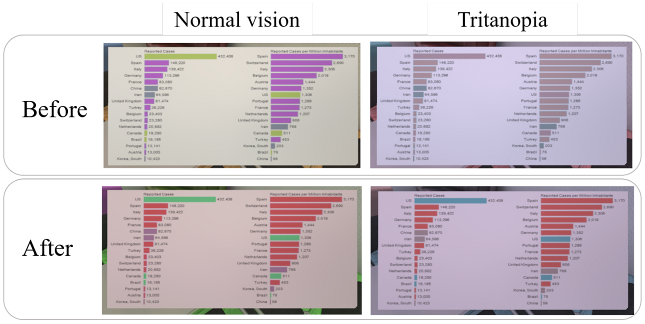

Figure 4: Normal vs. color blind views of *tritanopia* when visualizing a bar chart in a 3D virtual meeting: Before vs. After applying our proposed color filter.

5 USER STUDY

Two typical design approaches to design a VR application attributed to vision deficiency people include user-end and design-end [8]. While the first approach focuses on altering the mediation between users and the media content, the second approach addresses the design by allowing developers to view an image and color scheme altered and emulate perceptual experience from the perspective of a color-blind user. We follow the second approach in our study. The purpose of the pilot study is to assess the usability of our *prototype* before delivering it into an actual online VR room or asset store. To remove the ambiguity of the interpretation result, the Ishihara test of color deficiency was administered to all subjects before performing the actual test [12].

5.1 Participants and Apparatus

There are a total of 29 users taking part in the experiment, including 17 males and ten females, and two prefer not to say. Albano [2] suggested that the number of subjects should be as five times as the number of questions being asked in the pilot study. Thus, our sample size meets this requirement.

5.2 Tasks

The actual test was carried out by asking subjects to answer three questions related to the number of colors presented in an image. We hypothesize that the proposed approach outperforms existing tools/packages on these questions. The images given for each question are randomly ordered. Three main questions are as follows:

- **Question 1**: How many colors are there in these traffic lights?
- **Question 2**: How many colors can you see in the fruits?
- **Question 3**: How many colors are presented in the given graph?

The purpose of this test is to assess whether our *prototype* can help color-blind people distinguish there is a difference in color in each area.

5.3 Results

Accuracy: Overall, participating subjects have no color vision deficiency as they answered Ishihara's plates questions correctly. The average time taken for each question is 3 seconds, and the total time for the pre-test is 2 minutes. Figure 5 reported the results of the test: our prototype outperforms the existing filter method in terms of accuracy, except for users with *tritanopia* disability when administering traffic lights set. Specifically, users with *protanopia* disability would find it difficult to differentiate colors in all three conditional settings: traffic lights (13.8%), fruit (6.9%), and charts (13.8%) when using the normal color blind filter. However, when applying our filter methods, their performance has increased significantly (traffic lights (68.9%), fruit (62.0%), and charts (65.5%)). For *deuteranopia* visually impaired users, the accuracy is increased from traffic lights 48.3%, fruit 48.3%, and charts 24.1% to 79.3%, 79.3%, and 55.2% respectively. Meanwhile, *tritanopia* color-blind people also benefit from our color filter with a high achievement as of from traffic lights 79.3%, fruit 82.8%, and charts 51.7% to 79.3%, 89.7%, and 62.1%. In addition, we can observe a consistent result for the *deuteranopia* type where the subjects not only experience the same level of difficulty with traffic lights and fruits by using the normal color filter but also achieve similar performance with our prototype. Our results for the charts gained the least accuracy, around 60% compared to the other settings, part of the issue is due to the complexity of the given graph (e.g., the number of categories to be plotted). This forces users to make more mental efforts to link the differences. We can create a simple graph with few categories as shown in traffic lights and fruit examples. However, we want to simulate the scenario as close to the real-world setting as possible. In this regard, although the performance is moderate, the result implies that multiple approaches to improve the accuracy should be investigated further.

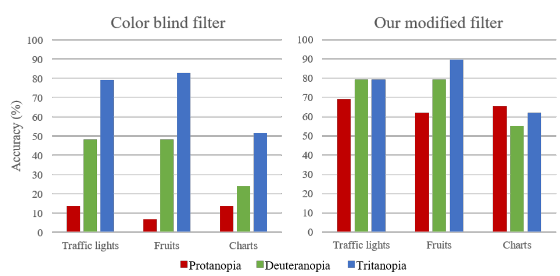

Figure 5: Accuracy results of the three questions in our user study.

Completion Time: Figure 6 depicted time taken for simulated color-blind people per question. Overall, it takes a maximum of 30 seconds and a minimum of 2 seconds to answer a question for both comparing methods. As depicted, users have to spend more time with the normal filter compared to our prototype. *Protanopia* users seem to spend most amount of time in extracting color differentiation in both settings compared to that of *tritanopia*, and *deuteranopia* users. However, this group seems to benefit from our filter as we see the biggest reduction in time taken (from an average of 15 to 10.8 seconds per question). Overall, the majority of users take lesser mental efforts when answering the question. This conclusion is also aligned with the accuracy results when this group's performance has increased significantly on our modified filters.

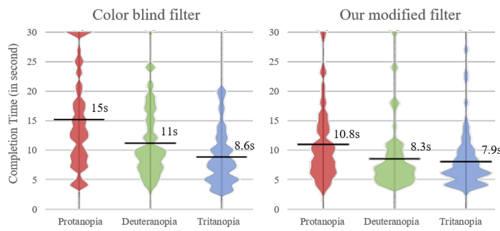

Figure 6: Average time spent for each question from 29 participants: The black horizontal lines are the medians in each case.

6 CONCLUSION

This paper presents a new color filtering method attributed to color-blindness. We demonstrated our proposed method's usability through different use cases and then evaluated it with 29 participants using the design-end method. Results showed that our method outperformed existing color filtering packages in terms of color differentiation. Since our method works at the post-processing stage, it is independent of tools and hardware and can be adapted to an online setting. Our prototype can give good performance when the 3D environment is not so complex, or in other words, contains low poly mesh and minimal animations. This issue is due to an additional image processing step after the scene is rendered, thus in one cycle of rendering, if the amount of work required for 3D rendering is huge, the frame rate may be dropped taken into account processing the extracted image. Therefore, our method may best fit for an online setting where low poly meshes are often used. This is aligned with our intention of bringing VR to color-blind people in remote virtual VR meetings. Future work will be focusing on porting our prototype to Unity Package and as an extension in the Chrome browser so that visually impaired enthusiasts in VR can install it directly on their devices. We believe that our prototype could potentially increase the motivation of color-blind people to be involved in the VR community.

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