On the validity of virtual reality applications for professional use: A case study on color vision research and diagnosis

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ABSTRACT

In recent years, there have been very important advances in graphic computing and technology related to the capture and representation of real objects in both 2 and 3 dimensions. One of these technologies is virtual reality, which can be incorporated into common tasks in research laboratories, especially in laboratories related to color vision and lighting research. To incorporate virtual reality devices into research tasks, newly developed applications must be validated with existing and known tests or techniques. The objective of this work was to study the validity of a commercial VR system for research and diagnosis in color vision. We carried out a comparative study on the behavior of these immersive systems for viewing 3D scenes in real time using a color vision test. In particular, we implemented a virtual version of the Farnsworth-Munsell 100 Hue test and compared the results obtained by 17 normal and 3 defective observers in both the physical and virtual tests. The results show that the functionality of both tests is very similar and that the diagnosis of both methods is equivalent. Detailed analysis of the results of both tests indicates that there is a slight difference in scale between the two tests. This difference in scale indicates a greater difficulty in the case of the virtual test but does not affect the final diagnosis. This could be due to the greater difficulty in using a head-mounted display (HMD).

INDEX TERMS

virtual reality, 3D scenes, computer vision, color research, color reproduction, color deficiency

I. INTRODUCTION

Technology is continuously evolving and offering new devices and/or techniques that professionals, researchers or end users try to incorporate into their daily lives, whether for professional, research or personal reasons, to obtain the possible benefits of the new technology. This integration process can be part of a long process in which the industry develops a new professional and specific device or service, and after several years of the refinement process, it finally reaches the end-user market. Another integration process is directly targeting new devices or techniques to the final end-user market, pursuing a generalization of their use, and after this generalization, several professional or specific applications can be developed by third-party researchers. The last case corresponds to the current state of evolution and development of virtual reality (VR) devices or services. The fact that virtual reality systems have been developed with the consumer market in mind does not invalidate their use for research or professional applications. It is only necessary to check the validity of this new technology against a well-known traditional tool or application.

In relation to the specific fields of color vision and lighting research, the introduction of virtual reality systems is not the first time that new commercial devices have been introduced in research laboratories to replace specific scientific devices such as visual colorimeters or anomaloscopes: image devices...
based on cathode ray tubes were first applied [1], [2], with LCD [3], [4] and OLED screens being launched later [5]. In all these previous cases, the chromatic characterization of these new types of devices has been a key point [6]–[11].

From a visual point of view, VR technology creates the visual sensation of immersion in a three-dimensional world. This 3D visual sensation is created using specific hardware and software components. The hardware component is always based on head-mounted displays (HMDs). There are two different types of hardware: devices that do not have their own graphic hardware and need a personal computer for this task and devices that use a mobile phone or other specific graphic hardware without a personal computer. There are significant differences in performance between the two types of devices. In this work, we will refer exclusively to the first type: those devices that are associated with a personal computer with a dedicated graphics card.

In terms of the software component of a VR system, there are two main commercial software platforms for developing virtual reality content: Unreal Engine and Unity Game Engine. In both platforms, mathematical functions are used as basic rules of internal functioning that try to reflect to a greater or lesser extent the real world through physical laws [12].

It is possible to obtain rendered scenes with a high degree of visual appearance fidelity when treating the light–matter interaction simulating the physical laws governing this phenomenon. To handle the lighting and shading conditions, the graphic engine uses a physical bidirectional reflectance distribution function model (BRDF) with four main components: diffuse, specular, normal, and smoothness. The diffuse component corresponds to material color, the specular component corresponds to surface color, and the normal and smoothness components correspond to surface texture.

In this study we research whether it is possible to use virtual reality technology for research tasks related to color vision and lighting. There are other examples of the utility of this new technology in other research fields [13]–[15]. We can approach this topic from different perspectives. On the one hand, we have the paradigm of classical colorimetry which characterizes the image device through spectroradiometric measurements, from which we can distinguish between absolute colorimetry or relative colorimetry. In both cases, the only relationship with human visual perception is through the standard observer CIE XYZ 1931 defined by the International Commission on Illumination (CIE) [16]. On the other hand, we have the paradigm of psychometry, where we would measure the effect of a scene shown on a VR device on the perception of the observer without having to be linked to any physical property [17]. Finally, the paradigm of psychophysics tries to relate the physical world with the perceptual world but this case has an intermediate processing layer dedicated to the simulation of a physical world in a virtual world, in such a way that we could call it virtual psychophysics [18], [19].

The objective of this work is to check the validity of a commercial virtual reality system to be used in research and diagnosis tasks in color vision and lighting laboratories. This validity arises from the point of view of what we have previously called virtual psychophysics, since it uses the simulation of the physical laws related to light-matter interaction. However, we have also studied the effect of this physical simulation on visual perception to check both aspects of psychophysics. Determining the validity of a specific use of this type of virtual reality system does not validate these systems for all uses in research tasks related to color vision research. However, if the result is positive, it opens the door to a wider future use in different fields provided each of its applications has been previously validated.

Specifically, in this study, a virtual version of the Farnsworth-Munsell 100 Hue test (FM 100) for color vision assessment has been implemented in a virtual reality environment. To verify its validity as a research and diagnosis tool, first, a relative colorimetric reproduction of the FM 100 test is necessary, and second, the results obtained with this virtual test are compared to those obtained with a real version of the mentioned test. This comparison is based on the analysis of the results obtained by both versions on the same population sample. These tasks try to answer the research questions posed previously: Is it possible to use virtual reality technology for research tasks related to color vision and illumination? What would be the validity of a commercial test implemented in a virtual reality environment?

In Section II of this paper, we review the state-of-the-art color vision testing methods and explain in detail how the FM 100 test works. In Section III, we describe the methodology used in this work, including the chromatic characterization of the VR system, the spectroradiometric measurements of the FM 100 test and the development of the 3D virtual scene. Finally, in Sections IV and V, the experimental results are analyzed and discussed, and conclusions are drawn.

II. TESTS FOR COLOR DEFICIENCY
Color perception depends on the light falling on the three types of cones of the retina. When a person suffers from color vision deficiency (CVD), it can limit his or her daily life, academic life or even work life.

Color vision tests play an important role in detecting visual deficiencies that may be related to pathologies such as optical neuritis, pituitary adenoma, glaucoma, and diabetes. In order to diagnose these pathologies very sensitive tests are required [20] which, on the one hand, allow the detection of small deviations from normal color vision, and, on the other hand, allow discrimination between different degrees of alterations in color vision.

The methods used in these tests for the detection of visual impairment can be grouped into three types:

- Pseudo-isochromatic tests: This type of test is based on the use of films composed of small colored surfaces (background) from which some colored areas stand out, forming a figure that will only be visible to normal observers on some occasions, while on others, it will
only be visible to abnormal or defective observers. This method provides a quick result (Ishihara, HRR, SPP, Ulloa, etc.).

Among the pseudoisochromatic tests, the Ishihara test, the first version of which appeared in 1906 [21], is the most widespread and used for the study of chromatic defects. The main objective of this test is to detect red-green type deficiencies and in its current configuration, it consists of thirty-eight plates (Fig. 1), twenty-five with numbers for observers who can read and thirteen with sinuous lines for those who cannot. For this type of test, we simulated the visual aspect in virtual reality [22].

- Tests were carried out using special instruments such as an anomaloscope. This device is essentially a colorimeter that produces a metameric pair from a mixture of two pure spectral colors of variable proportions to equal a reference color on a bipartite field. This device can be adapted to each problem.
- Tests for sorting colored caps in the natural order, from blue to red and various shades in between. They allow the detection of color perception deficiencies (Farnsworth-Munsell test, FM 100 and its reduced versions D-15, B-20 and H-16, Roth 28-Hue test, Lanthony test, etc.).

Ordering tests are currently one of the main tools for the diagnosis of congenital and acquired anomalies. They provide sufficient information while maintaining relative simplicity in the task to be performed by the subject compared to methods using an anomaloscope. Among the sorting tests, the most sensitive one is the 100-tone FM 100, although it actually consists of 93 (85 unfixed and 8 fixed) caps. This test is based on the notation system developed by D. Munsell [23]. It consists of a series of colored caps with constant saturation and clarity but different tones (Fig. 5). In this work, we develop a virtual scene with the FM 100 test applying color management techniques.

A. FM 100 TEST SCORING METHOD

The goal of this test is to place the color palettes in the correct order based on the color hue. Scores for the test are based on two factors:
- Frequency of the color caps are misplaced.
- The severity or distance of the misplacement.

The scoring tool provided with the test calculates the total error score (TES) and graphically represents the errors made by the observers (Figs. 2-4). A solid black line represents the observer’s response to the test. The further it moves away from the center circle, the larger the errors will be. The test results can be classified according to the following ranges:

1) Superior (Good) Score
Approximately 16% of the population makes 0 to 4 transpositions on the first test or has total error scores of zero to 16. This is a superior range of competence for color discrimination.

2) Average (Normal) Score
Approximately 68% of the population scores between 16 and 100 on the first tests. This is a normal range of competence for color discrimination.
3) Low (Weak) Score

Approximately 16% of the population has a total error score above 100. The first retest may show an improvement, but further retests do not significantly affect the score.

![FIGURE 4. Low (Weak) software Score.](image)

![FIGURE 5. Original Farnsworth-Munsell 100 Hue test samples divided into four rows.](image)

III. METHODOLOGY

The methodology applied in this work can be divided into six stages. The first stage describes the method applied for the chromatic characterization of the virtual reality device and the results obtained. The second stage shows how color management has been carried out within the VR software platform. In the third stage, the results of the spectroradiometric measurements performed on the FM 100 test are shown. Finally, each of the following are described: the virtual scene design, the graphics settings employed, the population sample used and the procedure followed to perform the test.

A. CHROMATIC CHARACTERIZATION OF HEAD-MOUNTED DISPLAY

The first step to use a virtual reality system in tasks related to color vision research is the chromatic characterization of head-mounted displays (HMDs). Each device of this type has its own specific characteristics in terms of the chromaticity of its primary colors and the white point, as well as for the relationship between the digital values of the analog-to-digital converter (DAC) and the associated tristimulus values. However, the main commercial devices currently on the market use two LCD or OLED screens (one for each eye) and Fresnel-Aspherical hybrid lenses to adapt the observer’s accommodation distance to infinity, even when the screens are at a short distance from the user’s eyes. With these lenses, the field of view (FOV) covered is close to 110° per eye. The authors of this paper have used the same methodology with different HMDs in other works [22], [24] and have developed a simple color characterization model for VR devices. This model is based on a typical linear transformation between the RGB\' values and the XYZ tristimulus values using a 3x3 matrix. RGB\' values are obtained after a gamma correction of the original RGB values that guarantee the linearity of the system.

For the specific HMD model used in this work (HTC Vive), the chromaticity values of primary colors and the white point and the gamma value of each chromatic channel are shown in Table 1.

![TABLE 1. Chromaticity coordinates of each primary channel and white point and gamma value of each channel.](image)

The color gamut associated with both HMD display types is similar to that of other displays with OLED technology, as shown in Fig. 6.

The measurements were performed in steps of 5 RGB values from 0 to 255 per channel. Then, we measured 50 random values to check the final error. Finally, we performed some systematic measurements. In total we have made 234 measurements. In the supplementary material, we have provided the RGB and XYZ values of these measurements. We obtained an average color error of 1.5 units in terms of CIEDE2000 with a standard deviation of 0.6.

B. COLORIMETRIC CALCULATIONS MODULE FOR VR

One of the main problems regarding color management in virtual reality devices is the high refresh frequency of images, between 90 and 120 Hz, due to the low latency in the interaction of the user with the environment. This high frequency reduces the time available for colorimetric calculations. For this reason, we have chosen a display characterization model that does not require complex calculations but only seeks to relate, as simply and accurately as possible, the values of the DAC with chromatic values of the stimulus in any reference color space. In this case, the most appropriate color space
FIGURE 6. Color gamut of different displays represented in the CIE 1931 chromaticity diagram. The evolution of the color gamut with different display technologies can be seen.

will be the tristimulus space associated with the CIE 1931 standard observer; the chromatic characterization approach is a classical matrix model connecting RGB and XYZ spaces, including a previous linearizing gamma correction of RGB values. This simplified color characterization model is widely used in color management software. In this case, the most appropriate color space will be the tristimulus space associated with the CIE 1931 standard observer; the chromatic characterization approach is a classical matrix model connecting RGB and XYZ spaces, as shown in Eqn. 2, including a previous linearizing gamma correction from Eqn. 1.

\[
\begin{align*}
R' &= R^{\gamma_1} \\
G' &= G^{\gamma_2} \\
B' &= B^{\gamma_3}
\end{align*}
\]

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} =
\begin{pmatrix}
X_{R_{\text{max}}} & X_{G_{\text{max}}} & X_{B_{\text{max}}} \\
Y_{R_{\text{max}}} & Y_{G_{\text{max}}} & Y_{B_{\text{max}}} \\
Z_{R_{\text{max}}} & Z_{G_{\text{max}}} & Z_{B_{\text{max}}}
\end{pmatrix} \ast
\begin{pmatrix}
R' \\
G' \\
B'
\end{pmatrix}
\]

\[
\text{C. FM 100 TEST: SPECTORADIOMETRIC MEASUREMENTS}
\]

In 1943, Deanne Farnsworth proposed the 'Farnsworth-Munsell 100 - Hue' test starting from 100 Munsell samples on matte paper, all of which had the same values of chroma and value (5/5) but had different tones (hues) varying in step constants from the perceptive point of view [25]. Subsequently, the test samples were reduced to 85, although the name of the test was maintained at FM 100. The FM 100 test is a sorting test with which two objectives can be achieved: distinguishing among people with normal color vision and those who have a high and low color discrimination ability and identifying different types of defective color vision. The FM 100 test has also been the subject of numerous specific scientific investigations over the past 50 years [26]–[31] and is a valid and well-known reference for any color vision laboratory.

FIGURE 7. Chromaticity of 85 FM 100 samples illuminated with CIE D65 illuminant (orange star) or LED D65 simulator (blue circle).

To implement the virtual version of this test in a virtual reality environment, we performed 3 independent spectroradiometric measurements for each of the 85 samples in a completely new FM 100 test. Specifically, the spectral reflectance of each sample and the CIE 1931 XYZ tristimulus values of each sample were measured. A Konica-Minolta CS-2000 spectroradiometer was employed. The spectroradiometer was inclined 45° to the horizontal, and a Spectralon diffuse reflectance pattern (LabSphere, USA) was used as a reference to measure spectral reflectance. All measurements were made using a D65 simulator as the light source, with which the LED viewing light booth was equipped (Just Normlicht, Germany). Fig. 7 shows the CIE 1931 chromaticity coordinates of each of the 85 samples of the FM 100 test under the CIE D65 theoretical illuminator and under simulator D65 of the light booth. Both power spectral distributions are shown in Fig. 8.

D. VIRTUAL SCENE

A virtual scene was created using the Unity Game Engine software platform in the software version 2019.1.5, which allows 3D scenes to be generated and displayed on virtual reality devices through their corresponding rendering. The scene simulates the Just NormLicht LED, available in our laboratory equipment (Fig. 9). This light booth is equipped with 12 LED spotlights and has been simulated both in physical and lighting geometry.

We simulated each of the 85 samples of the FM 100 test within this light booth. Each sample consists of a support
FIGURE 8. Spectral power distribution of the light sources employed in this work adjusted to a luminance value of 100 Cd/m²: CIE D65 (orange circles) and LED light booth D65 simulator (blue triangles).

FIGURE 9. Virtual light booth designed in this work.

part made of black Bakelite and another flat part, where the chromatic sample is located. The color of each sample was defined as a texture associated with a virtual material created in Unity, which allowed us to assign an RGB color to each sample.

To calculate the RGB color of each of the samples, a script that computes the tristimulus values of the FM 100 test samples under the SPD of the source used in the light booth was made. Subsequently, the corresponding RGB values were obtained through our colorimetric calculation module for VR.

We also measured every detail of the actual light booth. Details such as the angle of incidence of the lights or the separation between spotlights have been applied in the virtual scene. Next, in Fig. 10, an image of the lighting options is used to simulate the light booth.

Although the original recommendation was to use the C illuminant to perform the test, the CIE currently recommends using the D65 illuminant. However, it is not possible to use the D65 illuminant because of its theoretical nature. Many different D65 illuminant simulators exist on the market. A script has been introduced in the developed software that allows us to perform calculations on the RGB values for any light source so that it is possible to study the behavior of this test under different D65 simulators [32].

E. GRAPHIC SETTINGS

As we have described in the introduction section, the main objective of this work is to study the validity of commercial virtual reality systems to be used in professional tasks in color vision and lighting laboratories. From this perspective, our priority has been to carry out a visual impairment test with the greatest fidelity to reality, using hyperspectral textures as a new method for this purpose but without excessively penalizing the rendering and response time that virtual reality requires. For this reason, the standard render pipeline with deferred rendering has been used in our VR scenario. A previous work demonstrated the effectiveness of this configuration [12]. Light treatment is based on real-time lighting without baked global illumination light maps. Because of the simplicity of our scenario and the fact that there is no metallic material or transparency, we employ only the diffuse component of light reflected at the material surface (albedo color in Unity Terms). We did not include reflection probes or activate the HDR mode.

For the VR camera settings, we used a skybox with a black background. We have also performed the recommended VR default settings of field of view and stereo separation and convergence. The values used for the VR camera settings are shown in Fig. 11.
**F. OBSERVERS AND PROCEDURE**

The population sample was composed of 20 observers (14 men and 6 women) aged between 20 and 56 years old. Three of them demonstrated color vision deficiencies by means of other color blindness validation tests, such as an Ishihara test. Those observers who need glasses in their daily life used the glasses for both the physical and virtual tests. Each observer answered the test five times randomly in different sessions. The test requires two parts: one corresponding to the physical test and another corresponding to the virtual version. All sessions were carried out on different days and by varying the order randomly.

The methodology employed with the physical test (Fig. 12 above) follows the recommendations of the original author of the FM 100 test [25]. The methodology applied to the virtual test follows this sequence: first, all color samples correctly ordered are shown to the observer (Fig. 14 above). Subsequently, the test starts only showing the samples belonging to a single row. This row is chosen randomly, leaving the first and last caps at a fixed position in the same way that the physical test is applied (Fig. 14 bottom). The observer must place all the samples in the order he/she considers correct with a remote control for the VR device (Fig. 12 bottom). There is an equivalent remote control to the real one in the virtual scene, and the observers can see this remote control controlled by a virtual hand. Observers can modify the position assigned to each sample at all the times they consider necessary. After finishing each row, the next row is shown, and at the end of the test, the score obtained and the time spent are reported.

**IV. RESULTS**

The results of this work can be divided into two parts. The first part is related to the fidelity of the color reproduction of the virtual scene in relation to the original real scene. The second part deals with the comparison of the results obtained by means of both tests (physical and virtual tests). The results are described next.

**A. MEASURED COLOR DIFFERENCE BETWEEN THE PHYSICAL AND VIRTUAL TESTS**

The International Commission on Illumination (CIE) defines the metric distance $\Delta E'_{ab}$ (also called $\Delta E''$) as a basic color difference formula associated with the CIELAB color space standardized in 1976 [33].

There are known perceptual nonuniformities in the CIELAB color space; during recent decades, several new color difference formulas have been proposed and employed to correct these nonuniformities (as recommended by the CIE in 1994 and 2000 [34]). These nonuniformities are important because the human eye is more sensitive to certain colors than to others. A good metric should take this into account to...
associate the notion of a “just noticeable difference” (JND) to a unity of its metric in the whole color space. Otherwise, a certain $\Delta E^*$ may be insignificant between two colors in one part of the color space while being significant in some other part. With the concept of JND in mind, CIEDE2000 color difference values between 1 and 2 units are considered close to imperceptible for the human visual system. Values between 2 and 3 are considered an accurate representation of the color. Above these values, the result is considered to be inaccurate.

To obtain the average color difference between the real and virtual scenes of this work, we measured 12 FM 100 test caps (3 from each row, at both ends and at the middle) of the physical test, and measured the equivalent caps at the virtual scene for the virtual test. Table 2 shows the color difference between each pair of caps (virtual and real). The results showed an average color difference of CIEDE2000 = 1.5 and a standard deviation of 0.4. This value matches the chromatic characterization mean error limit and reflects the accurate behavior of our system in a faithful color reproduction of a real scene in a virtual scene.

### TABLE 2. Color difference values.

| Row- Tablet | $\Delta E^*$ |
|-------------|--------------|
| 1-1         | 1.76         |
| 1-10        | 2.42         |
| 1-20        | 1.73         |
| 2-23        | 0.99         |
| 2-32        | 1.38         |
| 2-41        | 1.44         |
| 3-46        | 1.18         |
| 3-55        | 1.43         |
| 3-62        | 1.36         |
| 4-64        | 1.36         |
| 4-75        | 1.60         |
| 4-83        | 1.42         |
| Mean Error (Standard Deviation) | 1.5 (0.4) |

Finally, in Fig. 14, we see the appearance of the virtual test, while if we look at Fig. 15, we see the appearance of the physical test. Although measuring the general appearance is not the main objective of this work, and we have only measured color values, we see that the appearance has many similarities.

### FIGURE 13. Chromaticity measurements (x,y) for the 12 FM 100 samples.

### FIGURE 14. (Top) Initial aspect of the virtual reality application in which the 93 test caps are shown. (Bottom) Screen capture during the development of one of the tests in which the virtual interface is used to order the samples.

### FIGURE 15. (Top) Initial aspect of the real scene application in which the 93 test caps are shown. (Bottom) Screen capture during the development of one of the tests in which the virtual interface is used to order the samples.

### B. SCORES OBTAINED BY THE OBSERVERS

As described in section II, the FM 100 test is a sorting test where a score is obtained according to the errors made in the
sorting of color samples with equal saturation and clarity and different hues. With this score, it is possible to quantify how accurate the color discrimination ability of the person taking the test is.

Although it is possible to carry out a comparative study capsule by capsule, an accurate indicator of the correct functioning of the virtual test versus the physical test is the comparison of the errors obtained by the same observers in both tests. Since each of the tests was carried out 5 times, this comparison should be made with the average of the scores obtained in the 5 sessions.

Table 3 shows the results obtained by the 17 observers previously classified as normal observers and the three observers classified as defective.

Table 3. Results obtained by the 17 observers previously classified as normal observers and the three observers classified as defective.

| Observer | Age | Sex | Physical Test | Virtual Test |
|----------|-----|-----|---------------|--------------|
| Normal 1 | 55  | W   | 35.2          |  68          |
| Normal 2 | 54  | W   | 26.4          |  47.2        |
| Normal 3 | 56  | W   | 19.2          |  34.4        |
| Normal 4 | 56  | M   | 29.6          |  43.2        |
| Normal 5 | 26  | M   |    4          |  19.2        |
| Normal 6 | 21  | M   |  13           |  25.6        |
| Normal 7 | 29  | M   |  5.6          |  21.6        |
| Normal 8 | 31  | W   | 13.6          |  29.6        |
| Normal 9 | 26  | M   |  4            |  16          |
| Normal 10| 24  | M   |  40           |  80          |
| Normal 11| 45  | M   |  14           |  23.2        |
| Normal 12| 26  | W   |  7.2          |  31.2        |
| Normal 13| 27  | W   |  1.6          |  28.5        |
| Normal 14| 56  | M   |  26           |  32          |
| Normal 15| 56  | M   |  22           |  46          |
| Normal 16| 26  | M   |  8            |  24          |
| Normal 17| 25  | M   |  16           |  52          |
| Defective 1| 59 | M   | 189           | 191          |
| Defective 2| 19 | M   | 133.6         | 155          |
| Defective 3| 25 | M   | 212           | 268          |

Mean (defective excluded) 16.8  37.7
Standard deviation (defective Excluded) 11.6  17.8
Upper limit for normals 51.5  91.3

Pearson Coef. 0.98

Figure 16 shows the correlations between the errors of the physical and virtual test.

Figure 16 shows the graphical representation of the results obtained and the expression of the linear relationship model between both sets of results. This figure clearly shows the difference between the observers classified as defective and normal. If we look at purely statistical criteria, a non-normal observer is one that is outside the normal probability distribution, which is usually defined as an observer who obtains a result that is more than 3 standard deviations away from the mean value of the population when calculating that mean value. This is what is known as the 99.9% confidence level. If we perform these calculations for the results obtained with normal observers, we can see how this upper limit would be marked by a score of 52 points for the physical test and 92 for the virtual test. In both cases, observers previously classified as defective are those who are outside these limits and would again be classified as defective.

No statistically significant differences were obtained after analyzing the data obtained according to the age and sex of the participants.
V. CONCLUSION

Virtual reality devices have been in constant evolution in recent years, allowing more diverse use. The general objective of this work was to contribute to the use of commercial virtual reality systems in professional tasks. Specifically, we have implemented a virtual version of a known arrangement test for color vision assessment, the FM 100 test, as an example of the use of this technology in research and diagnosis tasks at lighting and vision research labs. Our main objective was that the functionality of both tests (virtual and physical) would have the same behavior. The results obtained show that the functionality of both tests, the virtual and physical tests, are very similar. Furthermore, the diagnosis of both methods is equivalent. The scores obtained by real observers in both tests are slightly different in scale but have a clear linear relation. The small difference in scale does not affect the classification made of defective or normal observers and could be related to the greater difficulty in using an HMD as a display. The main limitation of this work lies in the dependence of a previous chromatic characterization of the virtual reality system (hardware and software). This limitation is identical for other types of electronic media used in research tasks (CRT, TFT, OLED). However, it is an advantage to use this technological support to perform color vision tests because there is no deterioration of the samples since the observers do not manipulate the samples. Another advantage is that we can control the illumination both in intensity and spatial distribution.

In view of the results, we conclude that this technology based on HMDs and virtual reality contents is valid for this research task. A future line of work could be to extend this type of generic tests based on virtual reality to other more specific types of tests such as visual evaluations carried out to obtain automobile driver or airline pilot licenses. This future work should be also oriented to deepen the improvement of the visual appearance of virtual 3D scenes. Despite the high quality of virtual reality systems, there is still room for progress both in the development of display devices and the improvement of the management of real-time rendering software. These improvements could expand the potential use of this virtual reality-based technology.

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REFERENCES

[1] P. Cavanagh, D. Maurer, T. Lewis, D. MacLeod, and G. Mather, “Computer-generated screening test for color blindness,” Color Research, vol. 11, pp. 63–66, 1986.
[2] A. Hoffmann and M. Menozzi, “Applying the ishihara test to a pc-based screening system,” Displays, vol. 20, no. 1, pp. 39–47, 1999.
[3] O. K. Ozgur, T. S. Emborgo, M. B. Vieyra, R. F. Huseid, and R. Banik, “Validity and acceptance of color vision testing on smartphones,” Journal of Neuro-ophthalmology, vol. 38, no. 1, pp. 13–16, 2018.
[4] P. Pardo, A. Perez, and M. Suero, “Validity of tft-lcd displays for colour vision deficiency research and diagnosis,” Displays, vol. 25, no. 4, pp. 159–163, 2004.
[5] E. A. Cooper, H. Jiang, V. Vildavski, J. E. Farrell, and A. M. Norcia, “Assessment of oled displays for vision research,” Journal of Vision, vol. 13, no. 12, pp. 16–16, 2013.
[6] R. S. Berns, R. J. Motta, and M. E. Gorzynski, “Crt colorimetry. part i: Theory and practice,” Color Research & Application, vol. 18, no. 5, pp. 299–314, 1993.
[7] J. A. Díaz, J. R. Jiménez, E. Hita, and L. J. del Barco, “Optimizing the constant-channel chromaticity and color gamut of crt color displays by control of brightness and contrast levels.” Applied optics, vol. 35, no. 10, pp. 1717–1718, 1996.
[8] K. Kam, Y. Tiantong, K. Behrman, Y. Caroline, and I. Kynissis, “57-3: Characterizing image retention for hrd oled displays;” in SID Symposium Digest of Technical Papers, vol. 51, no. 1, Wiley Online Library, 2020, pp. 850–853.
[9] D. Tian, L. Xu, and M. Luo, “The characterization of hrd oled display,” electronic imaging, vol. 2019, pp. 326–1–326–6, 2019.
[10] A. Almustanyir, J. Hovis, and M. G. Ghiholt, “Predicting the farnsworth–munsell d15 and holmes–wright–a lantern outcomes with computer-based color vision tests,” J. Opt. Soc. Am. A, vol. 37, no. 4, pp. A1–A10, Apr 2020. [Online]. Available: http://josaa.osa.org/abstract.cfm?URI=josaa-37-4-A1.
[11] J. S. Werner, B. Marsh-Armstrong, and K. Knothlaub, “Adaptive changes in color vision from long-term filter usage in anomalous but not normal trichromacy,” Current Biology, vol. 30, no. 15, pp. 3011–3015.e4, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960979220307417.
[12] P. J. Pardo, M. I. Suero, and A. L. Pérez, “Correlation between perception of color, shadows, and surface textures and the realism of a scene in virtual reality,” JOSA A, vol. 35, no. 4, pp. B130–B1315, 2018.
[13] M. A. Cohen, T. L. Botch, and C. E. Robertson, “The limits of color awareness during active, real-world vision,” Proceedings of the National Academy of Sciences, vol. 117, no. 24, pp. 13821–13827, 2020. [Online]. Available: https://www.pnas.org/content/117/24/13821.
[14] D. Kamińska, T. Sapinski, M. Kucharczyk-Pospiech, and M. Wilczyński, “Ishihara color test using a mobile virtual reality headset for immobilised patients,” 2017.
[15] K. Szczerurowski and M. Smith, “Emulating perceptual experience of color vision deficiency with virtual reality,” Studies in health technology and informatics, vol. 256, pp. 378–389, 01 2018.
[16] J. Schanda, Colorimetry: understanding the cie system, John Wiley & Sons, 2007.
[17] W. G. Backhaus, R. Kliegl, and J. S. Werner, Color vision: Perspectives from different disciplines, Walter de Gruyter, 2011.
[18] I. J. Koenderink, “Virtual psychophysics,” 1999.
[19] D. A. Gusev, D. M. Whittinghill, and J. Yong, “A simulator to study the effects of color and color blindness on motion sickness in virtual reality using head-mounted displays,” in Mobile and Wireless Technologies 2016. Springer, 2016, pp. 197–204.
[20] A. Fanlo Zarazaga, J. Gutiérrez Vásquez, and V. Puyo Royo, “Review of the main colour vision clinical assessment tests,” Archivos de la Sociedad Española de Ofthalmología (English Edition), vol. 94, no. 1, pp. 25 – 32, 2019.
[21] S. FMSA and S. Dain, “Clinical colour vision tests,” Clinical and Experimental Ophthalmoptometry, vol. 87, pp. 276 – 293, 04 2004.
[22] F. Diaz-Barrancas, H. Cwierz, P. J. Pardo, Á. L. Pérez, and M. I. Suero, “Spectral color management in virtual reality scenes,” Sensors, vol. 20, no. 19, p. 5658, 2020.
[23] D. Farnsworth, “The farnsworth-munsell 100-hue and dichotomous tests for color vision;” J. Opt. Soc. Am., vol. 33, no. 10, pp. 568–578, Oct 1943. [Online]. Available: http://www.osapublishing.org/abstract.cfm?URI=josa-33-10-568.
[24] F. Díaz-Barrancas, H. C. Cwierz, P. J. Pardo, A. L. Perez, and M. I. Suero, “Visual fidelity improvement in virtual reality through spectral textures applied to lighting simulations,” Electronic Imaging, vol. 2020, no. 15, pp. 259–1, 2020.
[25] D. Farnsworth, “The farnsworth-munsell 100-hue and dichotomous tests for color vision;” JOSA, vol. 33, no. 10, pp. 568–578, 1943.
[26] P. Kinney, “Proposals for scoring and assessing the 100-hue test,” Vision research, vol. 10, no. 5, pp. 423–433, 1970.
[27] K. Knothlaub, F. Saunders, M. Kasuda, R. Hynes, M. Podgor, K. E. Higgins, and F. M. De Monasterio, “Color and illumination effects in the
farnsworth-munsell 100-hue test," Applied Optics, vol. 26, no. 8, pp. 1441–1448, 1987.

[28] M. E. Breton, D. E. Fletcher, and T. Krupin, “Influence of serial practice on farnsworth-munsell 100-hue scores: the learning effect," Applied optics, vol. 27, no. 6, pp. 1038–1044, 1988.

[29] S. Ghose, D. Shrey, P. Venkatesh, T. Parmar, and S. Sharma, “A simple modification of the farnsworth-munsell 100-hue test for much faster assessment of color vision," Indian journal of ophthalmology, vol. 62, no. 6, p. 721, 2014.

[30] M. García-Romera, M. Grosman, M. Sánchez-Marañón, L. Gómez-Robledo, and M. Melgosa, “On the uniformity of the ‘farnsworth-munsell 100-hue’ test," Optica Pura y Aplicada, vol. 44, pp. 139–148, 01 2011.

[31] K. G. Foote, M. Neitz, and J. Neitz, “Comparison of the richmond hrr 4th edition and farnsworth–munsell 100 hue test for quantitative assessment of tritan color deficiencies," JOSA A, vol. 31, no. 4, pp. A186–A188, 2014.

[32] H. C. Cwierz, F. Diaz-Barrancas, P. J. Pardo, A. L. Perez, and M. I. Suero, “Application of spectral computing technics for color vision testing using virtual reality devices," Electronic Imaging, vol. 2020, no. 15, pp. 260–1, 2020.

[33] C. T. Committee et al., “Colorimetry, 4th edition," CIE publication, vol. 15, 2018.

[34] M. R. Lao, G. Cui, and B. Rigg, “The development of the cie 2000 colour-difference formula: Ciede2000," Color Research & Application: Endorsed by Inter-Society Color Council, The Colour Group (Great Britain), Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, The Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de la Couleur, vol. 26, no. 5, pp. 340–350, 2001.

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