electronics

Article

The Optimal Color Space for Realistic Color Reproduction in Virtual Reality Content Design

Hyun-Suh Kim [1], Eun Joung Kim [2,*] and JungYoon Kim [3,*]

[1] School of Photography and Videography, Kyungil University, Gyeongsan-si 38428, Republic of Korea; hyunsuh@kiu.ac.kr
[2] Culture Contents Technology Institute, Gachon Universirty, Seongnam 13120, Republic of Korea
[3] Department of Game Media, College of Future Industry, Gachon University, Seongnam 13120, Republic of Korea
* Correspondence: eunjoungkim97@gachon.ac.kr (E.J.K.); kjyoon@gachon.ac.kr (J.K.)

Abstract: In the emerging era of the Metaverse in which virtual reality (VR) is used for various purposes such as product demonstration, marketing, and online commerce, it becomes essential to reproduce colors accurately not only for gaming but also for brand recognition and product representation. In this regard, this study investigated the optimal color space to minimize the difference between the intended colors for the VR device and the colors selected on the designers' monitor during the development process. To this end, this study conducted measurements and provided technical demonstrations to highlight the color differences between three different color spaces of sRGB, AdobeRGB, and DCI-P3. Through this approach, we discovered that designing the VR content using the DCI-P3 color gamut yields the most ideal results currently available.

Keywords: virtual reality; content color space; VR headset display; designers' monitor display; DCI-P3

check for updates

Citation: Kim, H.-S.; Kim, E.J.; Kim, J. The Optimal Color Space for Realistic Color Reproduction in Virtual Reality Content Design. *Electronics* **2023**, *12*, 4630. https://doi.org/10.3390/electronics12224630

Academic Editor: Stefanos Kollias

Received: 5 October 2023
Revised: 7 November 2023
Accepted: 9 November 2023
Published: 12 November 2023

1. Introduction

With the advancement of technologies associated with the Metaverse in the fourth industrial revolution, there has been a gradual expansion of virtual reality (VR) content produced through Headset Mounted Displays (HMDs) [1]. Initially, VR was primarily utilized for digital gaming purposes, but with the growth of Metaverse platforms, a new type of display that incorporates VR is being employed to enrich immersive storytelling. Unlike traditional one-way content, VR-mediated content facilitates two-way communication through various user interactions. This opens up countless possibilities for direct user experiences with products and services in the fields of online commerce and marketing.

Color fidelity is a crucial aspect that significantly impacts the realistic presentation of VR experiences. This significance becomes particularly pronounced when VR is employed to introduce new branded products, as the level of immersion in virtual reality should accurately mirror the product's real-life counterpart. Achieving brand recognition and accurately depicting the product's colors are essential attributes in this context. It is imperative to faithfully reproduce the company logo's color and display the color of a car in a manner precisely matches its appearance in reality.

Recent research has been conducted with the focus on color-related aspects of HMDs [2,3]. In particular, an accurate color calibration of the VR HMD, both in terms of luminance and chromaticity, received attention because due to the large field of view of the HMD or the software implementation used for scene rendering, the color constancy present significant new challenges [4]. For example, Kim conducted experiments to measure color reproduction on VR displays with three contents using different color spaces. It also aimed to evaluate the quality of VR runtime color space calibration on VR HMDs [5]. Furthermore, recent technological advancements have enabled the analysis of VR users' perceptions through techniques such as EEG or eye tracking in order to provide valuable insights for VR product design and development [6–8]. However, there has been little attention given to VR color representation research from the designers' perspective during the content creation process. Thus, the primary objective of this study is to identify the optimal color space for a VR graphic designers' PC monitor in a workplace, which is distinct from the previous research that addressed color reproduction on VR HMDs.

As shown in Figure 1, there is a noticeable disparity between the product color observed in a color-controlled environment and that seen in a color-uncontrolled environment when VR 3D product that designers create in a workplace. This difference can be attributed to the difference between the designers' PC display and characteristics of VR displays, where the achievable color range varies depending on the built-in panel, even within headsets released by the same brand [9].

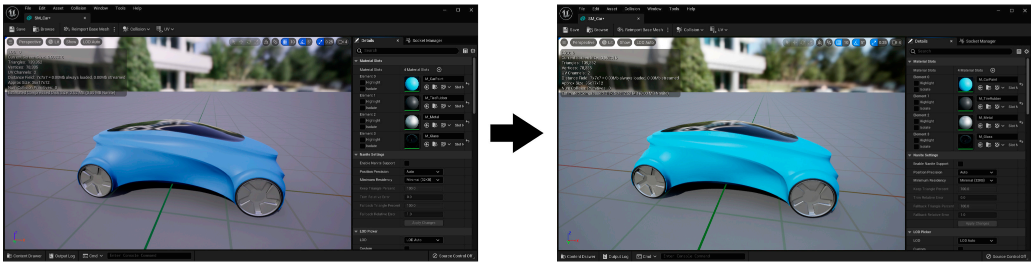

Figure 1. Examples before and after applying color management in the design stage in the virtual reality.

In the case of flat-panel monitor displays (LCD), color management system (CMS) technology has been developed based on the International Color Consortium (ICC) standards. According to ISO 15076-1 [9], this CMS can also be applied to VR headsets in a similar manner [4]. For videos and images displayed on these monitors, the BT. Rec.709 standard is used for high-definition television while the BT. Rec.2020 standard is utilized for ultra-high-definition television. Both of these standards have been defined by the International Telecommunication Union (ITU) and serve as color-reference standards. In the film industry, DCI-P3, designed as a digital-cinema standard, is widely employed in mobile devices as a next-generation display standard for technologies such as OLED and Micro LED [10–12]. Figure 2 shows a color comparison between the abovementioned three-color gamut.

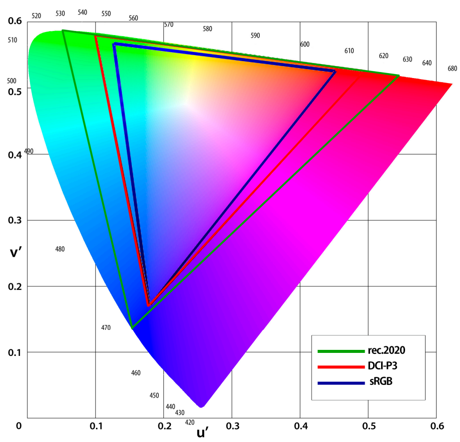

Figure 2. Comparison between the DCI-P3 color gamut and sRGB and Rec.2020.

The standard for color management, ISO 15076, plays a crucial role as a reference point and provides the necessary basis for accurately reproducing colors in videos and images [13]. When creating VR content using software such as Adobe Photoshop and

Unreal Engine, which run on platforms such as Microsoft's Windows or Apple's macOS, incorporating ISO 15076 in a controlled manner can yield improved color results. ISO 15076 defines the profile standard format specified by ICC [14].

In this study, ISO 15076 was implemented to minimize the difference between the intended colors for the VR device and the colors selected on the designers' monitor during the development of a VR contents [15,16]. By adhering to the principles of ISO 15076, this study aimed to ensure that the colors in the VR experience closely matched the designer's intent, thus enhancing the overall quality and immersion of the VR content. The objective of this study is to investigate the optimal color space to minimize the difference between the intended colors for the VR device and the colors selected on the designers' monitor during the development process. To this end, this study conducted measurements and provided technical demonstrations to highlight the color differences between three different color spaces of sRGB, AdobeRGB, and DCI-P3.

2. Relative Studies

2.1. VR Headsets' Color Presentation

Generally, image quality is closely influenced by factors such as the illuminance or color temperature of the ambient light, viewing distance, and viewing angle. However, VR circumvents some of these concerns because they block out all light [17]. Rather, the main concern is ensuring accurate color representation. Pouli et al. presented a workflow for producing VR contents as described in Figure 3 [18]. In this production process, the visual data undergo multiple transformations and combinations, followed by a re-encoding process. At each step of the workflow, the color space, container, and encoding attributes are applied differently, and this determines how the color contained in each pixel is mapped. Thus, evaluating the quality of color reproduction becomes challenging without knowledge of the device information and the final VR display built-in panel [19].

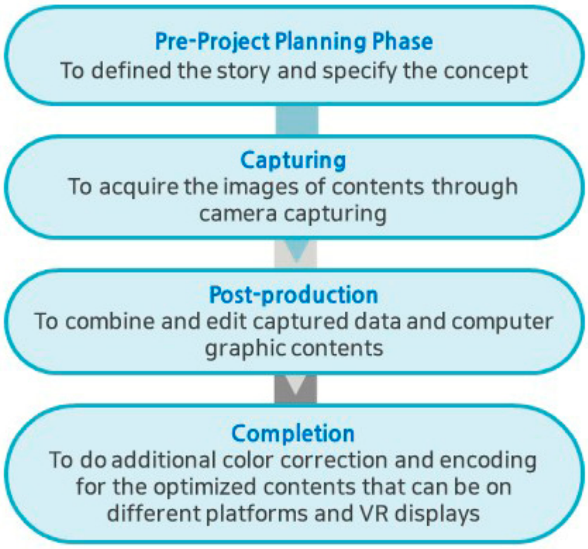

Figure 3. VR content production workflow.

In addition, due to the use of display panels from different vendors in the production of VR headset devices like Oculus Go, there may be instances where the finished product exhibits variations in the color reproduction area including different RGB primary colors or discrepancies in the color temperatures of the white point. To address this issue and align the color reproduction characteristics of the display with standard values, a color space conversion was performed by mapping the ITU Rec.709 color space based on the white point D65 when implementing the program on Oculus Go [20]. However, in the case of Oculus Quest 1, when comparing the color gamut with the color spaces of the standard color space ITU BT Rec.709, it was observed that the OLED panel in Oculus Quest 1 displayed more areas in green and blue. Additionally, the color gamut exhibited an intermediate value between Rec.709 and Rec.2020 [21]. The differences in color reproduction gamut for each color gamut can be observed in Figure 4. This indicates that the color reproduction of Oculus Quest 1 falls between the two standard color spaces, displaying a broader range of colors than Rec.709 but not as extensive as Rec.2020.

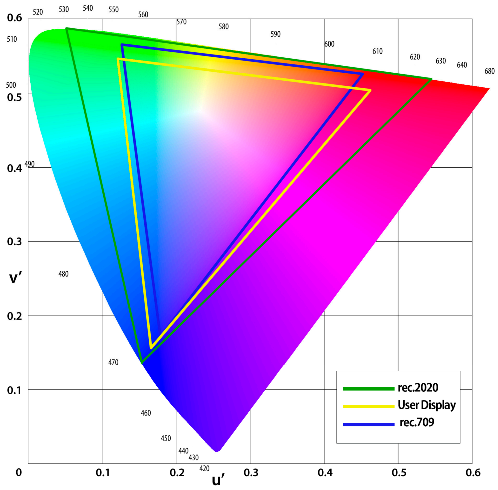

Figure 4. Oculus GO's display color gamut.

To prevent variations in the color gamut, a standardized color space is established, even for devices from the same brand, such as Oculus Go. However, when upgrading to Oculus Quest 1, these standards undergo alterations and make it complicated to maintain consistency in the color gamut of VR content.

2.2. Color Conversion on VR

To convert the color space of VR headsets, it is necessary to map the three-primary colors and white points from the color space applied to the VR application to the color space of the panel installed in the headset [22]. If the device employs individual display panels for each eye, color space conversion can be performed separately on both panels to mitigate differences in brightness, color, and white point between the displays [23].

Color space standards such as DCI-P3 and sRGB define display lightness separately. For instance, sRGB specifies a screen lightness level of 80 candela assuming a surrounding viewing environment of 200 lux [24]. However, since VR operates in a no-ambient-lighting situation, the lightness standard defined by the color space standard is often disregarded [25]. When using individual display panels for each eye, lightness is adjusted according to the panel with the lower lightness [26].

In the case of the Oculus Quest, a 3 $\times$ 3 color correction matrix is utilized to enable the mapping of RGB primary colors and white points as target values through a color space correction pipeline in the VR runtime. The flow of color information within the VR application is depicted in Figure 5, while the rendering process within the VR application can be observed in Figure 6 [27–29].

Figure 5. VR application flow.

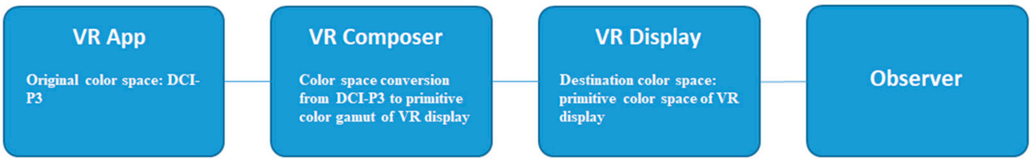

Figure 6. VR rendering flow.

The color space rendering flow was initially implemented to address color space discrepancies arising from multiple suppliers. While the Oculus Go was calibrated using Rec.709 as the standard, which generally produced satisfactory results, it led to unexpected outcomes in the Oculus Quest due to its wider color gamut [21]. To mitigate such issues and ensure compatibility with all future HMD color spaces, Oculus has adopted Rec.2020, the widest standardized color space, as the new standard.

However, despite the existence of a standard value, there is still a deviation from this value due to the nature of the display. Obtaining XYZ values corresponding to all RGB values in order to fully characterize the display is impractical. Figure 7 shows the difference in lightness between the DCI-P3 and sRGB color gamut at L* = 50 and L* = 10. Characterizing colors becomes more complex when the lightness varies between color gamuts. In addition, Figure 8 shows the color shift in saturation when adjusting gamut range from sRGB to P3 to highlight the challenges in maintain color fidelity.

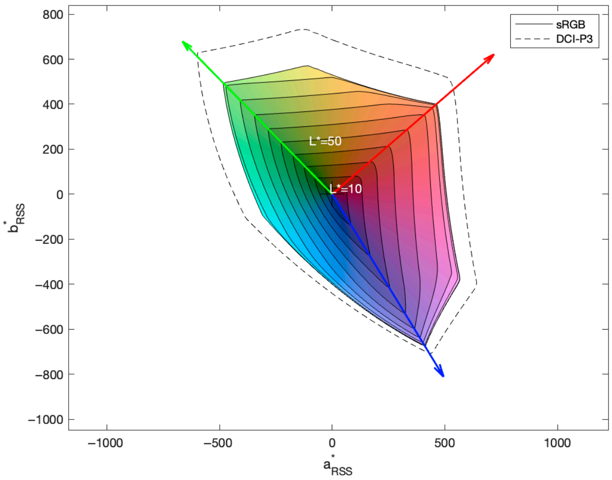

Figure 7. Lightness differences between DCI-P3 color gamut to sRGB.

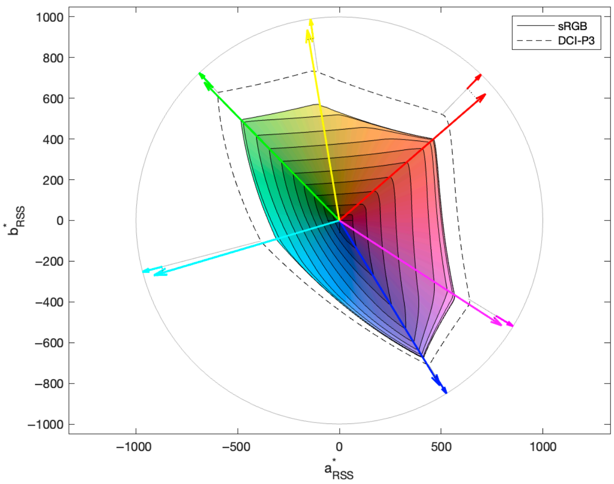

Figure 8. sRGB to P3 saturation shift.

Consequently, various methods are employed to simplify the characterization process [30]. One common method involves completely isolating the color channels of the display to ensure that the emission of light from one channel does not interfere with the other channels [31]. Given this assumption, display characterization can be established by calculating the conversion value between the RGB display value and the XYZ tristimulus value [32].

2.3. Color Reproductionon VR Headsets and Designer Monitor Displays

As shown in Table 1, VR headsets (HMDs) and designer monitor displays have different color reproduction characteristics because they are designed for different applications. VR headsets are intended for VR experiences, gaming, and simulation training, while designer monitor displays are often used for tasks such as 2D or 3D design work, image editing, and coding. VR headsets typically use OLED panels, which feature high contrast, high screen refresh rates, and fast response times. This is focused on providing an immersive 3D experience, so the headset's panel does not necessarily have to have a wide color gamut. In contrast, for graphic designer monitor displays, IPS panels are often preferred because they support a wide range of color spaces, from the basic sRGB color space to Adobe RGB and DCI-P3, and allow for consistent color accuracy and high-resolution display.

Table 1. Properties of VR headset and designers' monitor displays.

Properties	**Display**	
	VR Headset	**Designers' Monitor**
Main purpose	VR experience, gaming, simulation training	2D or 3D designs, image editing, coding
Main requirements	high contrast, high screen refresh rates, fast response times	Wide color space, color accuracy and consistency
Commonly used panels	OLED, LED	IPS, OLED, VA

According to Kim's research, it was observed that Oculus Quest 1, equipped with OLED panels, displays more areas in green and blue than the standard color space Rec.709. Namely, the color gamut falls somewhere between Rec.709 and Rec.2020 [5]. Rec.709 closely aligns with the sRGB gamut, whereas Rec.2020 encompasses a broader color space, including both AdobeRGB and DCI-P3. Thus, it implies that designers should consider using a monitor display with a color space wider than sRGB to create content intended for VR headset devices like Oculus Quest 1.

The disparity in color reproduction between VR headsets and VR content designers' monitors can make VR content look different to users than what the designers initially intended. In other words, depending on the working color space configured in the graphics application on the monitor, there may be a color discrepancy between the content displayed on the VR headset and the designer's original creation. This is a pertinent consideration for enhancing the color consistency and overall quality of VR content and, ultimately, the user experience.

To prevent these color discrepancies as shown in Figure 9, it is important to closely review the color space settings on the designers' monitor. Hence, this study aims to investigate the most suitable color space for the designers' monitor display in a VR development setup.

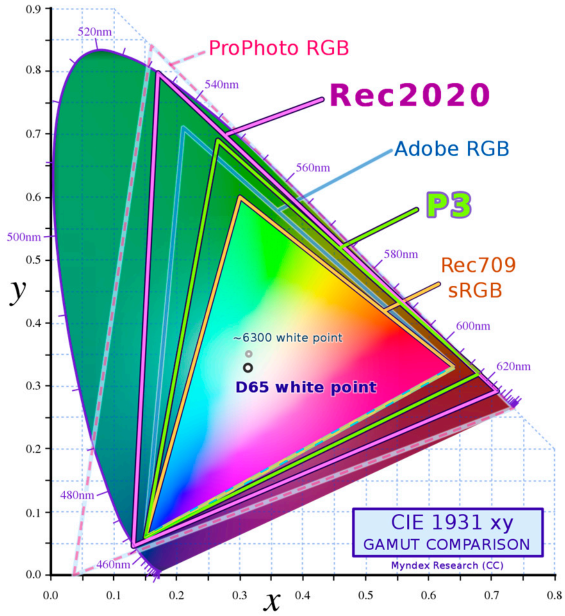

Figure 9. CIE 1931 chromaticity diagram, overlaid with outlines of the color gamuts of sRGB, DCI-P3, Rec2020, AdobeRGB, and ProPhoto.

3. Experiment

Applying the general color management method to designers' monitor displays poses challenges, especially when utilizing an Android OS with a closed architecture for the color pipeline. In such cases, there are limitations in controlling color in VR headsets [33]. To overcome these challenges, this study aimed to incorporate the colors obtained through VR display characterization onto the monitor of VR content designers and allow them to predict the colors that would be reproduced in the VR environment more accurately.

The process of VR display characterization involves defining the visual characteristics, such as color and lightness, reproduced on the device as device-independent values including CIE XYZ tristimulus values. This characterization process follows similar principles as the characterization of general monitor displays. Pre-defined RGB color patches were displayed on the VR device and the spectral distribution of the reproduced colors was measured so that it could enable the calculation of corresponding XYZ values display as shown in Figure 10.

Characterizing VR headset displays differs from general monitor's displays and requires additional considerations. While various software options exist to define and display color patches on VR displays for spectrophotometer measurement, native integration with VR headsets presents challenges. In particular, popular VR headset such as Oculus devices operate on an Android-based VR operating system and cannot be utilized as designers' conventional monitor displays. VR devices introduce the possibility of color difference errors in the output color patches. Therefore, this study aimed to establish a framework that ensures the most stable color output within the Android VR platform. Figure 11 shows the color working environment in Unreal Engine from a designer's perspective. It uses a color checker (reference targets) with standard colors and grayscales for measurement.

To evaluate the quality of the color space calibration in the VR runtime on the VR, measurements were carried out on the colors reproduced both in the VR display and the designers' monitor display using sampling colors. The color measurements were performed using X-rite's i1 Display Pro Plus and the VR headset used for the testing was Oculus Quest 2. The sampling process includes a total of 175 colors that consists of 50-phased grayscale patches, 120 color patches with a multidimensional structure, and 5 white and black patches as shown Figure 12.

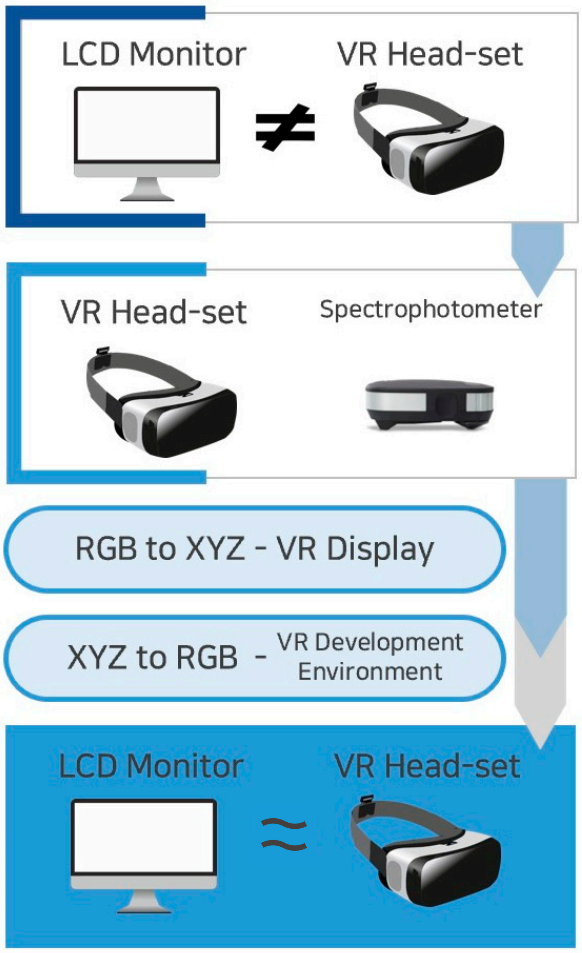

Figure 10. Color matching with a design display through the characterization of VR displays.

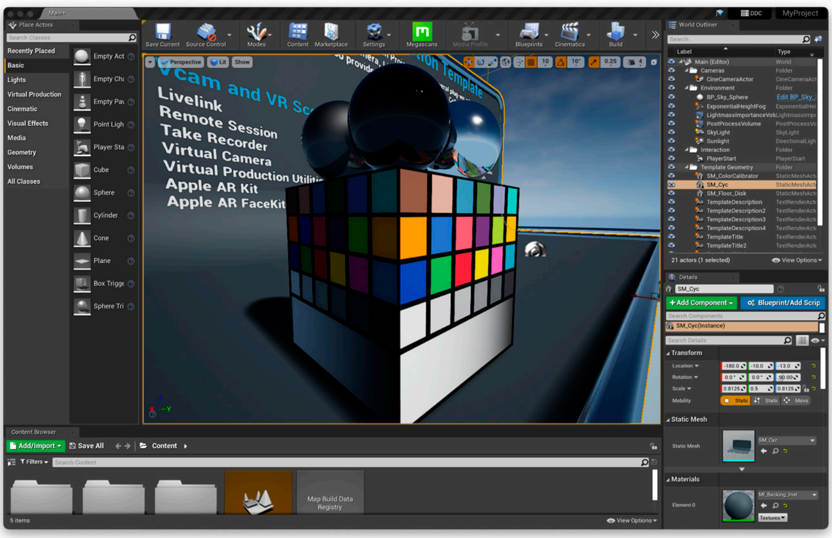

Figure 11. Color working environment in Unreal Engine as visualized from a designer's perspective.

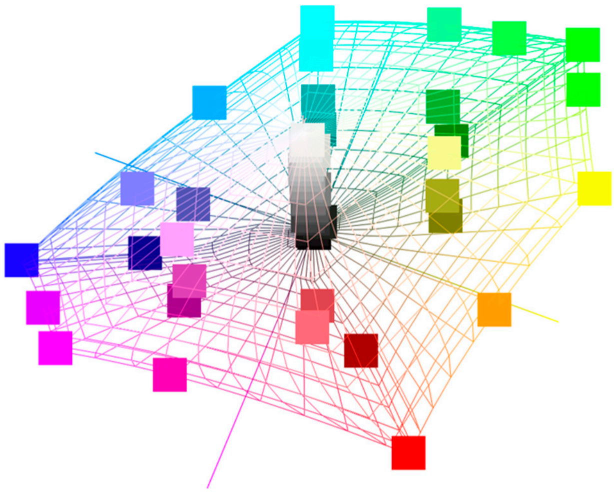

Figure 12. Sampling color used for VR display measurements.

Color measurement was performed through the calculation of CIE XYZ stimulus. The calculation of CIE XYZ stimulus values plays a critical role in ensuring accurate color representation. First, the spectral radiance data of the VR and monitor display across the visible spectrum were acquired. This was performed using a spectroradiometer of X-rite's i1 Display Pro Plus. Then, the acquired data were normalized so that they can fall in a manageable range. The CIE XYZ tristimulus values were calculated through the below equations.

$$X = \int_{\lambda_{min}}^{\lambda_{max}} x(\lambda)L(\lambda)d\lambda$$

$$Y = \int_{\lambda_{min}}^{\lambda_{max}} y(\lambda)L(\lambda)d\lambda$$

$$Z = \int_{\lambda_{min}}^{\lambda_{max}} z(\lambda)L(\lambda)d\lambda$$

$x(\lambda), y(\lambda), z(\lambda)$ are the color matching functions, and $L(\lambda)$ is the spectral radiance and λ_{min} and λ_{max} define the range of the visible spectrum [34–36].

For the experiment, this study compared three color spaces of sRGB, AdobeRGB, and DCI-P3 on the designers' monitors. The reason why sRGB was chosen is to set the benchmark for color representation because it is widely accepted as the standard color space for web content and consumer devices. Both AdobeRGB and DCI-P3 were selected because with the ongoing evolution of display technology, broader color gamut like AdobeRGB and DCI-P3 are becoming more prevalent, not only in professional contexts but also in consumer devices. Both AdobeRGB and DCI-P3 offer a more extensive color gamut than sRGB. AdobeRGB is the preferred choice in professional photography and graphic design as it excels in representing green and blue hues. DCI-P3 offers a broader spectrum of colors and it has gained increased significance as VR content creation ranging from digital games to films.

4. Results

Prior to commencing our experiments, this paper replicated sRGB, AdobeRGB, and DCI-P3 content on a VR headset (Oculus Quest 2) to assess the quality of the VR runtime's color space calibration on the VR display. When sRGB was employed as the content color space, the average color difference was measured at 1.94 with the maximum color difference reaching 3.35. For content using AdobeRGB, the average color difference was 2.10, and the maximum color difference was observed at 4.28. Notably, when DCI-P3 was utilized as the color space for the content, the average color difference was 1.02 and the maximum color difference was recorded at 2.90. Thus, DCI-P3 led to the most satisfactory results in terms of color accuracy [5].

Then, this study measured color differences between the above VR headset and the designers' monitor when reproducing the sampled colors according to the three color spaces on the designers' monitor. To ensure the objectivity of quantitative evaluation, two different monitors were employed. Profiling is essential for accurate color reproduction and consistent matching across various devices. Yet, not all graphic designers have access to professional calibration tools for monitor characterization. To address this practical constraint, this study conducted a comparative analysis under two conditions: without and with profiling. The first experiment involved sRGB monitors, both before and after profiling, with the results presented in Tables 2 and 3, respectively. In the second test, a DCI-P3 monitor was utilized, and the test was conducted both before and after profiling, with the results available in Tables 4 and 5, respectively.

Table 2. sRGB, AdobeRGB and DCI-P3 contents color accuracy on an sRGB-rated designers' monitor without the profile.

Item	Content Color Space		
	sRGB	**AdobeRGB**	**DCI-P3**
Average color difference (ΔE*00)	1.47	3.14	2.54
Neutral color difference (ΔE*00)	0.747	0.94	1.09
Maximum color difference (ΔE*00)	6.09	12.64	7.98
Standard deviation (ΔE*00)	1.51	3.72	2.52

Table 3. sRGB, AdobeRGB and DCI-P3 contents color accuracy on an sRGB-rated designers' monitor with the profile applied.

Item	Content Color Space		
	sRGB	**AdobeRGB**	**DCI-P3**
Average color difference (ΔE*00)	0.74	3.44	2.39
Neutral color difference (ΔE*00)	0.64	1.61	2.07
Maximum color difference (ΔE*00)	2.28	10.79	6.12
Standard deviation (ΔE*00)	0.53	3.35	2.02

Table 4. sRGB, AdobeRGB and P3 contents color accuracy on a DCI-P3-rated designers' monitor without the profile applied.

Item	Content Color Space		
	sRGB	**AdobeRGB**	**DCI-P3**
Average color difference (ΔE*00)	4.49	3.42	1.67
Neutral color difference (ΔE*00)	4.32	3.23	1.54
Maximum color difference (ΔE*00)	7.95	4.12	3.46
Standard deviation (ΔE*00)	5.32	3.97	2.23

Table 5. sRGB, AdobeRGB and DCI-P3 contents color accuracy on a DCI-P3-rated designers' monitor with the profile applied.

Item	Content Color Space		
	sRGB	**AdobeRGB**	**DCI-P3**
Average color difference (ΔE*00)	0.84	1.56	0.93
Neutral color difference (ΔE*00)	0.78	1.34	0.82
Maximum color difference (ΔE*00)	2.12	4.98	3.71
Standard deviation (ΔE*00)	1.73	3.54	1.98

4.1. Color Accuracy on an sRGB-Rated Designers' Monitor

The results can be shown in Table 2 on sRGB-rated displays in the designers' monitor without profiling. First, average color differences measure the perceived disparity between the displayed color and the target color. AdobeRGB color space exhibit the highest average color differences at 3.14 followed by DCI-P3 at 2.54. In contrast, the sRGB color space show the lowest value at 1.47. However, this is likely attributed to sRGB's narrower color space. To make a more meaningful comparison, it is essential to consider AdobeRGB and DCI-P3, especially concerning VR headsets with broader color reproduction capabilities compared to sRGB. Second, for the Maximum color difference, the AdobeRGB color space once again leads with the highest value at 12.64, suggesting a greater likelihood of displaying significant color inaccuracies. Third, standard deviations measure the variability in color differences, with the AdobeRGB having the highest variability at 3.72, followed by the DCI-P3 at 2.52.

In summary, the results indicate that AdobeRGB color space are prone to both inaccuracies and variability, so it may have difficulty in maintain uniform color reproduction, particularly for contents that require precision in color representation. In contrast, DCI-P3 provides a color reproduction spectrum that aligns effectively with the demands of VR headset usage.

The results on sRGB-rated displays in the designers' monitor with ICC profiling can be shown in Table 3. After applying the profiles, there can be seen differences between using the profiles and not using them. Firstly, when considering the average color difference, AdobeRGB color space had the highest average color difference at 3.44, followed by DCI-P3 at 2.39, and sRGB with the lowest value at 0.74. This is because sRGB represents a narrower color space compared to the color reproduction capabilities of the VR headset. Secondly, in terms of the Maximum color difference, AdobeRGB exhibited the most significant difference among the color spaces at 10.79. Applying the profile resulted in a slight improvement in the neutral color difference within AdobeRGB, but minimal changes in other aspects. This suggests that when working in AdobeRGB as the chosen color space, color representation errors may still occur [37].

4.2. Color Accuracy on a DCI-P3-Rated Designers' Monitor

The color difference results displayed on an unprofiled DCI-P3-rated monitor are presented in Table 4. Notably, the color accuracy for content within the same color space, DCI-P3, is the highest, while the variation in color difference for the AdobeRGB color space is attributed to differences in the green primary color. As for the sRGB color space, the largest color difference was shown with a relatively high deltaE measurement. This can be interpreted that sRGB content, when displayed on a DCI-P3-rated monitor without a profile, may appear oversaturated in terms of color saturation. In summary, DCI-P3 produces the most favorable results even when the monitor is in an unprofiled state. It is likely due to the fact that DCI-P3 content closely aligns with the color gamut range of the monitor's display.

The color difference results for displaying sRGB, AdobeRGB, and DCI-P3 content on a monitor with the profile applied are presented in Table 5. These results show that sRGB as the working color space exhibits the lowest color difference, which is a notable improvement from the unprofiled environment as shown in Table 4. However, it is worth noting that the difference between DCI-P3 and sRGB is not that significant. This is primarily attributed to the fact that DCI-P3 monitors typically reproduce only 90–95% of the entire DCI-P3 color space.

In summary, after considering both the results without the profile in Table 4 and with the profile in Table 5, it can be determined that DCI-P3 provides better color accuracy. Furthermore, sRGB coverage for the color space of Oculus VR HMD is not consistent depending on the manufacturer and device version. Therefore, establishing a working environment for virtual reality content using DCI-P3 as the reference working color space can be better on a DCI-P3-class monitor

Based on the results of both experiments in this paper, we believe configuring the working content color space of a designer's monitor display to DCI-P3 is more advantageous in terms of achieving consistency and accuracy in color reproduction compared to selecting sRGB or AdobeRGB

4.3. Technicla Demonstration of the Original Input Image and the Monitor's Output Image

In addition to the above quantitative comparison results, qualitative comparison was also included by technical demonstrations of the three color spaces in Figures 13–15. In these figures, the left image represents the original input image, while the right image illustrates the results when specifying sRGB, AdobeRGB, and DCI-P3 as the working color space.

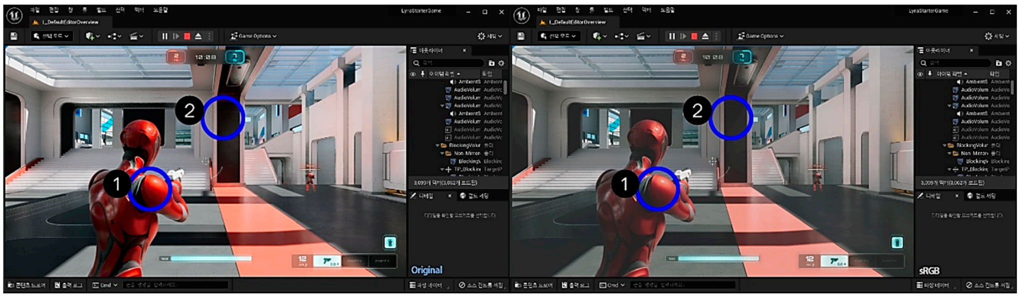

Figure 13. Technical demonstration of the original input image (**left**) and the designer's monitor working image in the sRGB color space (**right**).

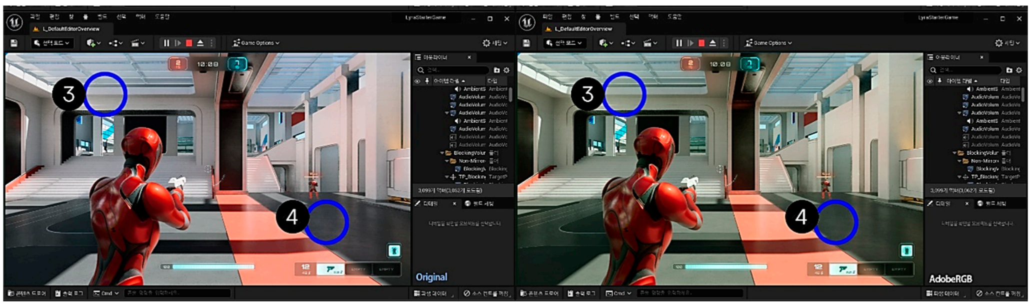

Figure 14. Technical demonstration of the original input image (**left**) and the designer's monitor working image in the AdobeRGB color space (**right**).

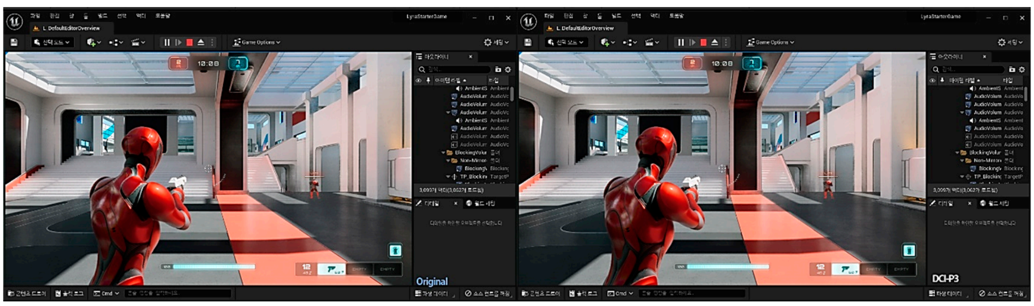

Figure 15. Technical demonstration of the original input image (**left**) and the designer's monitor working image in the DCI-P3 color space (**right**).

As shown in Figure 13, the sRGB working color space results in more desaturation compared to the original image, particularly in areas 1 and 2. As shown in Figure 14, the white walls (area 3) and gray floor (area 4) in the AdobeRGB image exhibit green and yellow color casts, differing from the original image. Lastly, Figure 15 demonstrates that the DCI-P3 color space effectively covers a substantial portion of the color gamut present in the original target image, in line with the quantitative evaluation results.

5. Discussion

The purpose of this study was to investigate the optimal color space to minimize the difference between the intended colors for the VR device and the colors selected on the designers' monitor during the development process. The ISO 15076 characterization method, commonly used in traditional color management, was applied to measure and compare color representation on VR HMD displace and designers' monitor display. Both quantitative and qualitative results demonstrated that selecting the appropriate color space for content creation and adopting DCI-P3 as the color space within the VR API and engine yielded the most stable and accurate color reproduction on popular VR displays, such as Oculus Quest. This study revealed that using an sRGB color space for HMD content in the designers' monitor may result in faded colors when reproduced on a VR device, as high-chroma colors are targeted in the VR application. The Oculus Quest runtime primarily sets the Rec.2020 color space. When AdobeRGB is employed as the color space for HMD content, errors in the working colors are more likely to occur. When designers utilize the sRGB color space for VR content creation, they work within a restricted color space. sRGB is the standard for many web and desktop applications, but it does not encompass as wide a range of colors as the DCI-P3 color space. In the VR game contents, this can lead to certain elements being less visible or indistinguishable than the VR game developer or designer intended, which potentially disrupts users' immersive experience. Moreover, it may cause users to overlook crucial UI elements or gameplay cues. In cinematic or artistic VR productions, the inability to convey the intended emotions or moods through color changes or fading can also be a significant concern.

On the other hand, using DCI-P3 as the color space for content yielded the most stable results. The findings suggest using a display that can cover 100% of the DCI-P3 color space in the VR development environment. It may also be advantageous to select the DCI-P3 color space within the VR API and engine to achieve more accurate colors. According to the results, the monitor displays utilizing the Android OS offered a wide color gamut ranging from DCI-P3 to Rec.2020. These displays, incorporating OLED and the latest display technologies, demonstrated a stable level of color accuracy. The evolution of VR content production is expected to follow a workflow similar to standard digital cinema practices.

As shown from the results in this study, employing a broader color space such as DCI-P3 is advantageous but it comes with its own set of issues. Most of all, adjusting the color space will increase computational requirements, in particular, if it involves dynamic color adjustment or real-time color mapping. In addition, implementing adjustments for a wider color space can cause compatibility issue with older devices. Although adjusting color space in VR development can enhance the visual quality for users, it is necessary for developers to strike a balance between visual fidelity, computational demands, and compatibility.

In addition, challenges still remain in color management for VR, particularly with different VR devices, display types, and operating systems. This is attributed to the fact that various VR devices utilize different display resolutions, field of view, refresh rates and other technical specification. Also different display types such as OLED, LCD, pentile, or RGB stripe displays offer distinct color reproduction capabilities. Furthermore, the operating system can exert an influence on color reproduction, particularly if it incorporates software-based color calibration or enhancement features. In spite of these disparities in color reproduction arising from the multitude of VR devices. there is a notable absence of standardized recommendations or universally accepted standards for the color space of VR HMDs.

This study has a limitation with only a focus on sRGB, AdobeRGB, and DCI-P3, so future study can be conducted with different color spaces including ProPhoto RGB with its very wide color gamut. Another color space will be Rec. 2020, commonly used in ultra-high-definition TVs, which has gained more relevance as VR and Augmented Realty (AR) technologies intersect with broadcast and cinematic experiences. Recently, the latest display panels are transitioning from LCD to OLED. Thus, further study can extend to examine the contrast range differences between OLED-type and LCD-type displays in relation to the development workflow. The future of VR lies in the creation of genuinely immersive experiences with precise color accuracy. For this, convergence research can be used to possibly create a more immersive VR experience by blending not only color but also haptic feedback, 3D sound, and olfactory experiences. For this, it is needed to focus on adaptive technologies capable of automatically adjusting VR content according to the specific color profile of the display.

Based on the findings in this study, accurate and lifelike color reproduction in VR expects to revolutionize how users interact with VR contents and it will eventually increase user satisfaction and shape the future of immersive experiences in virtual reality. This advancement in color management will have wide-ranging applications in diverse industries, including gaming, education, health care, architecture, and travel. Thus, this study expects to contribute to the growth and expansion of the VR market by offering new prospects for both developers and users in the ever-evolving field of VR.

Author Contributions: Conceptualization, H.-S.K., E.J.K. and J.K.; methodology, H.-S.K. and E.J.K.; software, H.-S.K.; validation, H.-S.K. and J.K.; formal analysis, H.-S.K.; data curation, H.-S.K.; writing—original draft preparation, H.-S.K. and E.J.K.; writing—review and editing, E.J.K. and J.K.; visualization, H.-S.K. and J.K.; supervision, J.K.; project administration, J.K.; funding acquisition, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Culture, Sports and Tourism R&D Program through the Korea Creative Content Agency grant funded by the Ministry of Culture, Sports and Tourism in 2023 (Project Name: Cultural Technology Specialist Training and Project for Metaverse Game, Project Number: RS-2023-00227648), Contribution Rate: 100%.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Forecasts VR Market Shipments at 5 Million Units in 2018. Available online: https://press.trendforce.com/press/20180108-3045.html (accessed on 14 August 2023).
2. Toscani, M.; Gil, R.; Guarnera, D.; Guarnera, G.; Kalouaz, A.; Gegenfurtner, K.R. Assessment of OLED Head Mounted Display for Vision Research with Virtual Reality. In Proceedings of the 2019 15th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS), Sorrento, Italy, 26–29 November 2019. [CrossRef]
3. Díaz-Barrancas, F.; Cwierz, H.; Pardo, P.J.; Pérez, A.L.; Suero, M.I. Improvement of realism sensation in virtual reality scenes applying spectral and colour management techniques. In Proceedings of the 12th International Conference on Computer Vision Systems (ICVS), Thessaloniki, Greece, 23–25 September 2019; pp. 5–9.
4. Gil Rodríguez, R.; Bayer, F.; Toscani, M.; Guarnera, D.; Guarnera, G.C.; Gegenfurtner, K.R. Colour Calibration of a Head Mounted Display for Colour Vision Research Using Virtual Reality. *SN Comput. Sci.* **2022**, *3*, 22. [CrossRef] [PubMed]
5. Kim, H.S. Design environment corresponding to the color of virtual reality headset display. *J. Digit. Art Eng. Multimed.* **2022**, *9*, 105–111. [CrossRef]
6. Wang, Z.Y.; Cho, J.Y. Older Adults' Response to Color Visibility in Indoor Residential Environment Using Eye-Tracking Technology. *Sensors* **2022**, *22*, 8766. [CrossRef] [PubMed]
7. Jimenez, I.A.; Marcolin, F.; Ulrich, L.; Moos, S.; Vezzetti, E.; Tomincasa, S. Interpreting Emotions with EEG: An Experimental Study with Chromatic Variation in VR. In Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing, JCM 2022, Ischia, Italy, 1–3 June 2022. [CrossRef]
8. Roy, S.; Banerjee, A.; Roy, C.; Nag, S.; Sanyal, S.; Sengupta, R.; Ghosh, D. Brain response to color stimuli: An EEG study with nonlinear approach. *Cogn. Neurodynamics* **2021**, *15*, 1023–1053. [CrossRef] [PubMed]
9. *ISO 15076-1:2010*; Image Technology Colour Management-Architecture, Profile Format, and Data Structure. Specification ICC.1: 2004-10; Profile version 4.2.0.0. International Color Consoritum: Reston, VA, USA, 2004.
10. Masayuki, S.; Choi, S.Y.; Wood, D. Ultra-high-definition television (Rec. ITU-RBT.2020): A generational leap in the evolution of television [standards in a nutshell]. *IEEE Signal Process. Mag.* **2014**, *31*, 170–174. [CrossRef]
11. *SMPTE ST 431-1*; D-Cinema Quality-Screen Luminance Level, Chromaticity and Uniformity. SMPTE: White Plains, NY, USA, 2006.
12. Fairchild, M.; Wyble, D. *Colorimetric Characterization of the Apple Studio Display (Flat Panel LCD)*; Munsell Science Laboratory Technical Report; Munsell Science Laboratory: Rochester, NY, USA, 1998.

13. Sharma, G.; Wu, W.; Dalal, E.N. The CIED2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations. *Color Res. Appl.* **2005**, *30*, 21–30. [CrossRef]
14. Nielsen, M.; Strokes, M. The Creation of the sRGB ICC Profile. *Color Imaging Conf.* **1998**, *6*, art00054. [CrossRef]
15. Kim, H.; Kim, D.H. Display Characterization Method for Accurate Color Representation Quality. *J. Digit. Art Eng. Multimed.* **2022**, *9*, 85–92. [CrossRef]
16. Kim, H.; Kim, D.H. OLED Display Color Characterization with Deep Learning Method. In Proceedings of the Next-Generation Convergence Information Service Society Conference, Jeju, Republic of Korea, 29–30 December 2021.
17. Pouli, T.; Morvan, P.; Thiebaud, S.; Orhand, A.; Mitchell, N. Color Management for Cinematic Immersive Experiences. *SMPTE Motion Imaging J.* **2019**, *128*, 25–31. [CrossRef]
18. Pouli, T.; Morvan, P.; Thiebaud, S.; Mitchell, N. Color Management for VR Production. In Proceedings of the VRIC '18: Virtual Reality International Conference—Laval Virtual VRIC '18, Laval France, 4–6 April 2018. [CrossRef]
19. Worldwide Augmented and Virtual Reality Spending Guide. Available online: https://www.idc.com/getdoc.jsp?containerId=IDC_P34919 (accessed on 14 August 2023).
20. Dessai, P.R.; Desai, P.N.; Ajmera, K.D.; Mehta, K. A Review Paper on Oculus Rift-A Virtual Reality Headset. *Int. J. Eng. Trends Technol.* **2014**, *13*, 175–179. [CrossRef]
21. Meta Quest. Color Management in Oculus Headsets. Available online: https://developer.oculus.com/resources/color-management-guide/ (accessed on 14 August 2023).
22. Hainich, R.R.; Bimber, O. *Displays Fundamentals & Applications*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2016.
23. Sridharan, S.K.; Hincapié-Ramos, J.D.; Flatla, D.R.; Irani, P. Color correction for optimal see-through displays using display color profiles. In Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology, Singapore, 6–9 October 2013. [CrossRef]
24. Anderson, M.; Motta, R.; Chandrasekar, S.; Stokes, M. Proposal for a Standard Default Color Space for the Internet-sRGB. *Color Imaging Conf.* **1996**, *4*, 238–245. [CrossRef]
25. Itoh, Y.; Dzitsiuk, M.; Amano, T.; Klinker, G. Semi-Parametric Color Reproduction Method for Optical See-Through Head-Mounted Displays. *IEEE Trans. Vis. Comput. Graph.* **2015**, *21*, 1269–1278. [CrossRef] [PubMed]
26. Dempsey, P. The teardown: HTC Vive VR headset. *Eng. Technol.* **2016**, *11*, 80–81. [CrossRef]
27. Matthews, S.L.; Uribe-Quevedo, A.; Theodorou, A. Rendering Optimizations for Virtual Reality. In Proceedings of the 2020 22nd Symposium on Virtual and Augmented Reality (SVR), Porto de Galinhas, Brazil, 7–10 November 2020. [CrossRef]
28. Aksoy, V. Color Management in Meta Quest Headsets. 2021. Available online: https://developer.oculus.com/blog/color-management-in-oculus-headsets/ (accessed on 1 November 2023).
29. Soneira, R.M. Display color gamuts: NTSC to Rec.2020. *Inf. Disp.* **2016**, *32*, 26–31. [CrossRef]
30. Berns, R. Methods for characterizing CRT displays. *Displays* **1996**, *16*, 173–182. [CrossRef]
31. Reinhard, E.; Khan, E.A.; Akyüz, A.O.; Johnson, G.M. *Color Imaging: Fundamentals and Applications*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2008.
32. Argyll Color Management System Home Page. Available online: http://www.argyllcms.com (accessed on 14 August 2023).
33. Baveye, Y.; Urban, F.; Chamaret, C.; Demoulin, V.; Hellier, P. Saliency-Guided Consistent Color Harmonization. In *Computational Color Imaging*; Springer: Berlin/Heidelberg, Germany, 2013; Volume 7786, pp. 105–118.
34. Wyszecki, G.; Stiles, W.S. *Color Science: Concetps and Methods, Quantitative Data and Formulae*; Wiley: Hoboken, NJ, USA, 2000.
35. Fairchild, M.D. *Color Appreance Models*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
36. Zhang, X.; Wnag, Q.; Li, J.; Zhou, X.; Yang, Y.; Xu, H. Estimating spectral reflectance from camera responses based on CIE XYZ tristimulus values under multi-illuminants. *Color Res. Appl.* **2016**, *42*, 68–77. [CrossRef]
37. Smith, E.; Heckaman, R.L.; Lang, K.; Penszek, J.; Bergquist, J. Measuring the color capability of modern display systems. *J. Soc. Inf. Disp.* **2020**, *28*, 548–556. [CrossRef]