

ANALYZING PERCEPTUAL COLOR DIFFERENCES OF 3D STRUCTURES IN CIVIL ENGINEERING: REAL VS VIRTUAL ENVIRONMENTS

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ABSTRACT

This study explores the perceptual color differences of 3D objects in real and virtual environments to improve color accuracy in civil engineering applications. Experiments were conducted using real-world objects under controlled D65 lighting and virtual objects displayed on LDR and HDR monitors. The grey scale method, involving fifteen color-normal observers for real-world tests and twelve for virtual tests, revealed that surface glossiness and lighting direction significantly affect color perception. Glossy surfaces exhibited smaller color differences, while combined diffuse and spot lighting further minimized these differences. Virtual experiments showed that HDR displays more accurately replicate real-world color differences, with a correlation of $r = 0.461$ compared to $r = 0.301$ for LDR displays. However, discrepancies between real and virtual environments remain, suggesting that further advancements in rendering techniques are needed. These findings highlight the value of HDR technology in virtual simulations for achieving more precise color representation, ultimately enhancing design accuracy and decision-making in civil engineering.

1. INTRODUCTION

In the realm of civil engineering, the use of 3D modeling has revolutionized the way structures are designed, visualized, and communicated. With the increasing accessibility and affordability of 3D scanning and color printing technologies, there is a growing emphasis on accurately reproducing the colors of these models. This accuracy is crucial not only for aesthetic and design

purposes but also for functional aspects, such as safety markings and material identification (Chi et al., 2020; Wang et al., 2021). As the integration of 3D models in civil engineering projects becomes more widespread, understanding the perceptual color differences between real-world and virtual representations of these models has become essential.

Various factors, including glossiness, lighting direction, and the shapes of objects, can

significantly affect how colors are perceived (Luo & Rigg, 1987; Reinhard et al., 2010). These perceptual differences are crucial for developing models that accurately represent real-world structures. The CIEDE2000 color difference formula, which quantifies perceptual color differences more accurately, provides a foundation for this analysis (Luo, Cui, & Rigg, 2001).

Research has shown that display technologies significantly impact color perception in virtual environments. Sun and Lai (2017) investigated the appearance differences of 3D objects when viewed through an RGB camera, highlighting the challenges of maintaining color fidelity across different viewing conditions. Similarly, Lai and Sun (2017) focused on the conversion techniques from Low-Dynamic Range (LDR) to High-Dynamic Range (HDR) images, concluding that simpler conversion methods often yield better perceptual results than complex models. These studies emphasize the importance of choosing appropriate display and conversion techniques to ensure accurate color representation in virtual simulations (Mantiuk et al., 2011; Wang et al., 2019).

In civil engineering, accurate color reproduction is critical for visualizing design elements, safety features, and material characteristics (Chen et al., 2020; Smith et al., 2018). Hung et al. (2018) conducted visual evaluations of color differences between 3D objects in real-world settings and virtual simulations, emphasizing the need for optimized color difference formulas tailored to 3D structures. Their findings suggest that while HDR displays offer better color accuracy than LDR displays, there are still noticeable discrepancies between virtual and real-world color perceptions. This discrepancy highlights the ongoing challenge of achieving true color

fidelity in virtual representations of civil engineering models (Gomes et al., 2018; Li et al., 2020).

This study aims to compare the perceptual color differences of 3D objects in both real and virtual environments within the context of civil engineering. By conducting three visual experiments—one with real-world objects and two with virtual objects displayed on LDR and HDR monitors—we aim to determine how closely virtual models can replicate the color perception of real-world objects. The objective is to identify the optimal conditions for achieving the most accurate color representation in virtual environments. By understanding these perceptual color differences, this research aims to improve the fidelity of virtual models used in civil engineering, ultimately contributing to better design accuracy, enhanced visualization, and more effective communication among engineers, architects, and stakeholders.

Researchers have extensively examined the precise reproduction of colors in 3D models within the realms of computer graphics and visual perception, revealing substantial implications for diverse fields such as civil engineering. Numerous studies have investigated the factors that affect perceptual color discrepancies between real-world and virtual environments. The development of the CIEDE2000 color difference formula serves as a foundational study in this field, striving to quantify perceptual color differences with greater precision (Luo, Cui, & Rigg, 2001), and it establishes a framework for assessing color variations across diverse applications, including digital imaging and printing.

In virtual environments, research demonstrates that display technologies profoundly influence color perception; Sun and Lai (2017) examined the variances in the

appearance of 3D objects observed through an RGB camera, illuminating the difficulties of preserving color fidelity under diverse viewing conditions, thereby underscoring the necessity for precise color reproduction in virtual simulations.

Lai and Sun (2017) focused on the conversion techniques from Low-Dynamic Range (LDR) to High-Dynamic Range (HDR) images, concluding that simpler conversion methods often yield better perceptual results than complex models. Their research suggests that HDR displays can better simulate real-world lighting conditions, thereby improving color fidelity in virtual environments.

Hung et al. (2018) conducted visual evaluations of color differences between 3D objects in real-world settings and virtual simulations, emphasizing the need for optimized color difference formulas tailored to 3D structures. Their findings indicate that while HDR displays offer better color accuracy than LDR displays, discrepancies between virtual and real-world color perceptions persist. This highlights the ongoing challenge of achieving true color fidelity in virtual representations of civil engineering models.

Additionally, Luo and Rigg (1987) developed the BFD(1) color-difference formula, which considers factors such as glossiness, lighting direction, and object shape in color perception. These factors can significantly alter the appearance of colors and must be carefully managed to achieve realistic visualizations. Understanding how these variables impact color perception is crucial for creating models that faithfully replicate real-world appearances.

While significant progress has been made in understanding and quantifying perceptual color differences, there remains a gap in applying these findings specifically to civil engineering. This study aims to bridge this gap by comparing

perceptual color differences of 3D objects in real and virtual environments, with a focus on optimizing the conditions for achieving accurate color reproduction in civil engineering models. By addressing these issues, we can improve the fidelity of virtual models, enhancing their utility in design, visualization, and communication within the field of civil engineering.

2. METHODOLOGY

The methodology for both real-world and virtual experiments involved several key steps. For real-world objects, preparation began with printing the objects using a color-managed inkjet printer on thick paper to ensure accurate color reproduction. A lightbooth with D65 lighting was then set up to create controlled lighting conditions, including diffuse and spotlight configurations. Fifteen color-normal observers were selected based on standard vision tests to participate in the experiment. The grey scale method was employed to rate the color differences between pairs of 3D objects, and the data collected from the observers' ratings were analyzed to determine the perceptual color differences.

For virtual objects, the real-world objects were replicated in 3D using Autodesk 3dsMAX. These virtual objects were displayed on a 42" HDR display, with images scaled to simulate LDR conditions (200 cd/m²). A simple knee function was applied for the tone expansion from LDR to HDR, as illustrated in Figure 3(c). A Matlab interface was used to randomize the order of test images to prevent bias. Twelve color-normal observers participated in the virtual experiments. The grey scale method was again used to assess the visual color differences, and the collected ratings were analyzed to compare the perceptual differences between LDR and HDR displays.

Data from both the real-world and virtual experiments were analyzed using statistical methods to compare the perceptual color differences. The correlation between the results from real-world objects and virtual objects (both LDR and HDR) was calculated to assess the fidelity of virtual simulations in representing real-world color differences.

Real-world Objects

The first experiment was designed to investigate the perceptual color differences of 3D objects in real-world settings. The setup involved using a lightbooth equipped with D65 lighting to ensure consistent and standardized lighting conditions. The objects used in this experiment were made from thick paper printed using a color-managed inkjet printer to maintain high color accuracy. Five reference colors were selected, each exhibiting a constant color difference in lightness, chroma, and hue (Luo & Rigg, 1987). These reference colors were crucial for accurately evaluating the perceptual differences.

The properties of the experimental factors, such as the shape of the objects, surface glossiness, and lighting direction, are detailed in Table 1. The viewing environment setup is illustrated in Figure 1. The grey scale method, a well-established technique for evaluating visual color differences, was employed in this experiment. This method involves presenting pairs of 3D objects to observers and asking them to rate the color differences. A total of fifteen color-normal observers participated in this experiment to ensure reliable and statistically significant results. The reference color-difference pairs used in the experiment are shown in Figure 2.



Figure 1. Viewing geometry for the grey scale method (diffuse and spot lighting)



Figure 2. Reference color-difference

Table 1. Properties of experimental factors

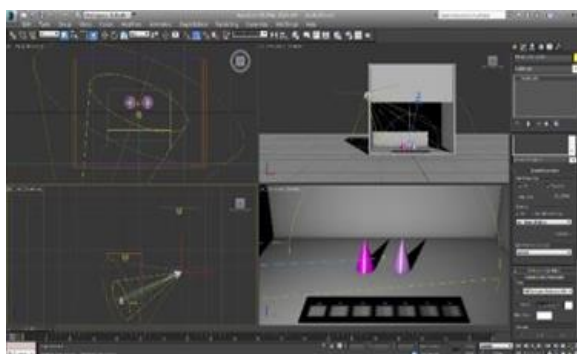
Factor	Property
1. Shape of the object	1. Cone, 2. Cube
2. Glossiness of the surface	1. Matte, 2. Glossy
3. Lighting direction	1. Diffuse lighting (topdown) 2. Diffuse lighting + spotlight

Virtual Objects

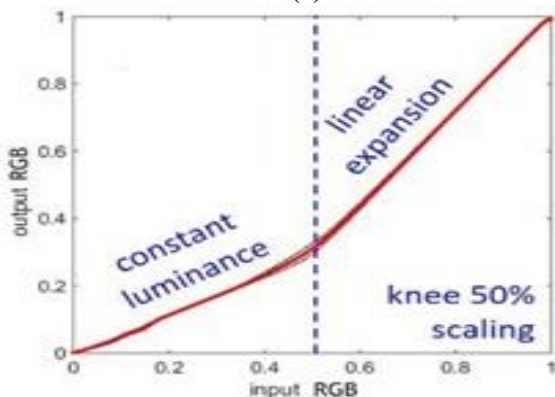
The second and third experiments aimed to simulate the real-world conditions using virtual objects. Autodesk 3dsMAX 2014 was utilized to create accurate 3D models that replicated the real objects used in experiment of real-world objects. These models were displayed on a 42" HDR display with an sRGB color gamut, capable of high dynamic range imaging, to test the perceptual color differences in virtual environments.

To mimic a typical LDR display environment, the images were scaled in linear sRGB space to 200 cd/m², as the maximum luminance of the HDR LCD display is close to 800 cd/m². The conversion from LDR to HDR was based on findings from Sun and Lai (2017), which demonstrated that a simple knee function for tone expansion provided superior results compared to more complex models. This conversion process is illustrated in Figure 3

The virtual images were displayed using a Matlab-written graphic interface, which randomized the order of test images to prevent observer bias. The grey scale method was again employed to assess the visual color differences of the 3D object pairs. Twelve color-normal observers participated in these experiments to provide a robust comparison between LDR and HDR displays.



(a)



(b)

Figure 3. Simulate real-world objects: (a) 3D model created by 3dsMAX. (b) Knee function for LDR to HDR image conversion

3. FINDINGS AND DISCUSSION

3.1 Real-world Objects

The results from the real-world object experiments provided valuable data on how various factors influence perceptual color differences. The fifteen color-normal observers evaluated the color differences between pairs of 3D objects under controlled D65 lighting conditions. The grey scale method was used to quantify these differences.

The data indicated that the shape of the object, surface glossiness, and lighting direction had significant effects on color perception. Specifically, objects with a glossy surface exhibited smaller perceptual color differences compared to those with a matte surface. Additionally, the lighting direction played a crucial role; diffuse lighting combined with spot lighting reduced the visibility of color differences more effectively than diffuse lighting alone. The results are summarized in Table 2.

Table 2. Summary of real-world object results

Factor	Observed effect
Shape of the object	Minimal impact on color perception
Glossiness of the surface	Glossy surfaces showed smaller color differences
Lighting direction	Combination of diffuse and spot lighting reduced color differences

The results from the real-world object experiments highlight the complexity of perceptual color differences influenced by various factors. The controlled environment with D65 lighting provided consistent

conditions, allowing for reliable data collection. The findings show that surface glossiness and lighting direction significantly impact perceived color differences. Glossy surfaces exhibited smaller perceptual differences compared to matte surfaces, likely due to the specular reflection that reduces the apparent variation in color.

Moreover, the combination of diffuse lighting and spot lighting effectively minimized perceived color differences. This suggests that lighting direction and intensity are crucial in color evaluation, as they can enhance or obscure color variations. These insights are valuable for applications in civil engineering where accurate color reproduction is essential, such as in material selection and safety markings.

3.2 Virtual Objects

The virtual object experiments were conducted to compare the perceptual color differences under simulated real-world conditions. The 3D models created in Autodesk 3dsMAX were displayed on a 42" HDR monitor, with images scaled to 200 cd/m² to simulate LDR conditions. The grey scale method was used again, and twelve color-normal observers participated in these experiments.

The data from the virtual object experiments showed a high correlation between the results from HDR and LDR displays ($r = 0.703$), indicating that HDR displays are more effective in simulating real-world color perception compared to LDR displays. However, the correlation between real-world and HDR virtual objects ($r = 0.461$) was higher than that between real-world and LDR virtual objects ($r = 0.301$), suggesting that HDR displays provide a more accurate representation of real-world color differences. The findings are detailed in Table 3.

Table 3. Summary of virtual object results

Display Type	Correlation with Real-world Data
LDR Display	$r = 0.301$
HDR Display	$r = 0.461$

When comparing the real-world and virtual object experiments, it was evident that virtual environments, particularly those using HDR displays, can closely replicate real-world color differences. However, some discrepancies still exist. These differences are likely due to the limitations of virtual rendering techniques and the inherent challenges in perfectly simulating real-world lighting and material properties.

The optimal weighting factors for the CIEDE2000 color difference formula were higher for real-world objects than for virtual objects, suggesting that lightness differences are less noticeable in 3D objects viewed in real-world conditions. This finding supports the hypothesis that human vision discounts lightness differences due to highlight and shadow effects in 3D objects.

The virtual object experiments provided a comparative analysis of LDR and HDR displays in simulating real-world color perception. The high correlation between HDR and LDR results indicates that both display types can produce consistent color differences. However, the closer correlation of HDR displays to real-world data compared to LDR displays underscores the superiority of HDR technology in mimicking real-world lighting conditions and material properties.

HDR displays' ability to better represent real-world color differences can be attributed to their higher dynamic range and color accuracy, which allow for more nuanced and realistic visualizations. This finding supports the use of

HDR displays in virtual simulations for civil engineering applications, where precise color representation is critical for design accuracy and effective communication.

3.3 Comparison and Implications

The comparison between real-world and virtual object experiments reveals that while virtual environments, especially those using HDR displays, can closely replicate real-world color differences, there are still noticeable discrepancies. These differences may stem from the limitations of virtual rendering techniques and the inherent challenges in simulating complex lighting and material interactions in real-world settings.

The optimal weighting factors for the CIEDE2000 color difference formula being higher for real-world objects suggest that human vision is more sensitive to color differences in physical objects than in virtual representations. This over-discounting of lightness differences in virtual environments might be due to the way human vision processes highlights and shadows in 3D objects, making lightness differences less noticeable.

The findings from the real-world and virtual object experiments highlight the significant influence of surface glossiness, object shape, and lighting direction on perceived color differences. Glossy surfaces and the combination of diffuse and spot lighting were found to reduce perceptual color differences, underscoring the importance of these factors in accurate color reproduction for civil engineering applications, such as material selection and safety markings. In virtual environments, HDR displays demonstrated a closer correlation with real-world color perception compared to LDR displays, validating the effectiveness of HDR technology in simulating complex lighting conditions and material properties. However, the results also

revealed discrepancies between real-world and virtual environments, suggesting that virtual simulations, while advanced, still have limitations in perfectly replicating real-world conditions.

Several limitations of this study should be addressed in future research. First, the experiments were conducted in controlled laboratory settings, which may not fully represent the variability found in real-world environments. Future studies should explore more diverse lighting conditions, including natural light, and consider a broader range of ambient settings. Additionally, the relatively small sample size and the focus on color-normal observers limit the generalizability of the findings. Expanding the participant pool to include those with varying levels of color vision could provide a more comprehensive understanding. Further research could also investigate the effects of different rendering algorithms, display technologies, and calibration methods to standardize virtual simulations across platforms and enhance their accuracy and reliability.

4. CONCLUSION

This study aimed to investigate the perceptual color differences of 3D objects in both real and virtual environments, with a focus on understanding the factors that influence these differences and the effectiveness of different display technologies. The experiments conducted with real-world objects under controlled lighting conditions provided valuable insights into how surface glossiness and lighting direction significantly impact color perception. Glossy surfaces and the combination of diffuse and spot lighting were found to reduce perceptual color differences, highlighting the importance of these factors in accurate color reproduction.

In virtual environments, the use of HDR displays demonstrated a higher fidelity in simulating real-world color differences compared to LDR displays. The closer correlation of HDR display results with real-world data suggests that HDR technology is more effective in replicating complex lighting and material properties. However, some discrepancies between real and virtual environments remain, underscoring the need for continued improvements in virtual rendering techniques.

The findings from this study have important implications for the use of 3D models in civil engineering. Accurate color reproduction in virtual simulations can enhance design accuracy, improve material selection processes, and ensure effective communication of design intent and safety features. Future research should focus on further refining virtual rendering methods and exploring additional factors that influence color perception to develop more comprehensive guidelines for accurate color representation.

This research uniquely integrates the evaluation of color perception differences with practical civil engineering applications, such as improving the accuracy of 3D modeling, material selection, and safety visualization. By demonstrating how HDR displays can better simulate real-world lighting conditions and material properties, the study introduces new possibilities for leveraging advanced display technologies in architectural and engineering simulations. The proposed framework for assessing perceptual color differences can be adopted by practitioners to optimize virtual environments for more realistic and reliable representations. This innovative approach not only enhances the visual fidelity of digital models but also provides a foundation for developing standardized guidelines for color

reproduction in civil engineering, ultimately leading to more effective design and decision-making processes.

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