Creating Immersive Virtual Landscapes

A User-Centered Approach to Enhance Depth Perception in Head-Mounted Displays

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This paper investigates the effects of color, luminance, and transparency as depth distortion cues in Virtual Reality (VR) Head-mounted Displays (HMD). The aim is to tackle more in-depth immersion: focusing on interaction accuracy with transparent objects in HMDs. Due to the illumination and absence of texture, transparent objects are mainly displayed with colors. Recently, studies on transparent hands and objects have elucidated potential approaches regarding interaction with transparent elements. However, findings have not considered color and luminance as depth distortion cues for interacting in virtual landscapes. This paper used the forced-choice pairwise comparison experiment method and evaluated data based on the Kendall coefficient of agreement and consistency. Reverse effects of transparency on color and luminance are discovered. Cool colors are perceived nearer than warm colors in 90% transparency. Dark colors are sensed closer than bright colors in high transparency levels. These results reject the classical effects of color and luminance within VR HMDs. These findings help VR design tool developers who emphasize a particular use of depth cues. Designers can utilize the studied effects of color and luminance on transparent objects as an advantage in designing more interactive and immersive virtual landscapes.

Keywords: *Virtual Landscapes, Immersion, Human-Computer Interaction, VR Head Mounted Displays, Depth Perception.*

INTRODUCTION

Virtual reality has affected visual fields like architecture and landscape architecture more than other domains. Afshar et al. (2022) have depicted positive results for adapting virtual reality with architectural studies. Korkmaz and Kim (2022) have confirmed the role of better spatial cognition in users' sense of enclosure and perception accuracy in virtual reality environments. Interacting and manipulating object properties increasingly prevails in virtual reality headsets, ranging from simple *XYZ* axis movements to assembling 3D objects into existing architectural models in virtual reality using remote robots. However, Several studies have found that distance could be better perceived in VR systems (Creem-Regehr et al., 2005). Vienne et al. (2020) illustrated that human factors best explain most perceptual distortions in VR systems. Hence, this paper investigates the effects of color, luminance, and transparency on depth perception in VR HMDs. Transparent objects have been categorized as primary architectural elements; however, their nature produces several phenomena that make them challenging to interact with in virtual environments. Glass and similar architectural materials generally contain no easily detectable conventional Computer Vision features. Due to their lack of texture and visual elements, Semi-Transparent Objects (STO) are mostly presented with colors. Color and luminance are well-studied humancaused pictorial depth cues influencing which objects in a visual scene are perceived closer or farther away. Color temperature has a practical impact on depth perception; Several studies have found that warm colors, such as red, are perceived as being closer to the user, whereas cool colors, such as blue, are perceived as further away (Brewster, 1852). Luminance is a well-studied depth cue, and some evidence suggests it is more potent than color hue (Olguntürk, 2016). Luminance refers to a color's relative brightness and darkness. A pair comparison experiment was conducted to evaluate the effects of color, luminance, and transparency on depth perception in VR environments. Objects presented in experiments are opaque at the 0% transparency level and completely transparent at the 100% transparency level.

RELATED WORKS

Virtual reality has vastly affected architecture and landscape architecture designs. Verinlioglu et al. (2022) have published the positive effects of implementing VR and AR to create immersive digital cultural heritage studies. Estimating absolute depth in peripersonal space is critical for accurate and efficient reaching and grasping tasks in real and virtual environments using HMDs (Sakata et al., 1997). VR applications like Epic Games' Unreal Engine allow objects to be operated in 3D with synchronized joysticks or hand movement detective sensors. Human distance perception has been studied extensively for over 100 years (Cutting, 1997). Even when only elementary virtual environments are presented, participants underestimate virtual distances but can perceive distances in the correct metric order(Armbrüster et al., 2008). Transparent objects are omnipresent, but their nature causes a variety of phenomena that make them challenging to interact with, mainly in HMDs. It is intuitive to think that the perception of depth and transparency are linked and in interaction (Wallace & Mamassian, 2004). Comprehensive studies have depicted object manipulation with transparent hands in a virtual world using HMDs. They allowed the user to optimize her/her hand transparency level to interact tacitly within interpersonal space(Van Veldhuizen & Yang, 2021). However, studies have not discovered the relationship between color and luminance as two dominant pictorial depth cues with object transparency levels in semi-transparent objects.

METHODOLOGY

This research studied the effects of color (6 color conditions) and luminance (2 levels) on four different transparency levels (10%, 40%, 60%, and 90%) using a pair comparison experiment. The studied case was two 3D simple spheres with a 7.5 cm radius, including 2333 vertexes, 50 cm from the participant. Spheres created with Unreal Engine 4.27 editor. The Excel worksheet collected primary data from the survey and the results from paired comparison experiment methods.

Participants

Sixty participants (30 females, 30 males) among the university students with an average age of 23.68 years, ranging from 21 to 30, were selected.

Based on the research survey, 38 participants reported that they play digital games regularly. Eighteen of the participants use eyeglasses. All of the participants have noted that they have stated no issues regarding their eyesight.

Technical Instruments

The tools implemented in this experiment are Monster Abra A7 V11.1 as the base computer for executing the experiment and gathering data, along with Meta Oculus Quest 2 VR headset for virtual reality visualization. Objects that appeared in VR are symmetrical in front of the white (#FFFFFF) background, within a 50 cm distance from the objects.

Participants were asked to wear the headset and launch the Unreal Engine 4.27 VR scene. Participants are automatically centered toward the objects they see. Participants would press whether left or right triggers on the VR controller to choose the shape that appeared to be nearer. The results were then transferred to an Excel spreadsheet forming the preference matrix for each participant. Button functions are integrated into the objects through Unreal Engine 4.27 Blueprint Editor.

Pair comparison method

The paired comparison method displays two objects to a participant and requests them to pick the object most exhibiting the tested property. This process is recounted for all object pairs (Kendall & Smith, 1940). One research considers pair comparison methods precisely to calculate depth perception (Bailey et al., 2006). However, Do et al. (2020) are the most relevant practice to this study, which executed experiments on the effects of color, luminance, and shape fidelity on depth perception in AR applications. The forced-choice pairwise comparison method results in a minor measurement variance and produces the most accurate outcomes. This method is also the most time-efficient, assuming a moderate number of compared conditions (Mantiuk et al., 2012).

Experimental design

To evaluate the effects of transparency, color, and luminance on depth perception in VR HMDs, a 4x6x2 within-subject experiment is conducted. Subjects concluded four transparency levels (10%, 40%,60%,90%), six colors (red, magenta, yellow, green, blue, and cyan), and two luminance conditions (Dark and light).

Shape Transparency

Material assets are created in the Unreal Engine 4.27 editor, creating four different levels of transparency. In the material blueprint, the opacity tab to the material properties tab is connected, which controls the opacity level of the materials to change the transparency. This method efficiently alters transparency levels in different objects inside Unreal Engine 4.27.

Every participant completed four paired comparison tasks, one for each transparency level, shown in Figure 1, including color hue and luminance. A Latin square was designed to counteract the four models' presentation order throughout experiments to detour possible ordering effects such as learning or tiredness.

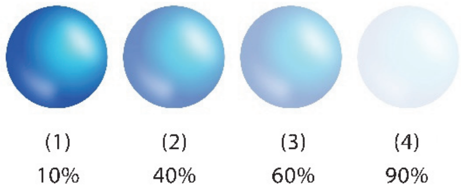


Figure 1
Four studied transparency levels in paired comparison method.

Color Hue and Luminance

Regarding do et al. (2020), six colors from the color wheel are selected. Three warm colors (Red, Magenta, and Yellow) and Three cold colors (Green, Blue, and Cyan). Two bright and dark versions of each color are included, creating 12 color conditions. figure 2

Figure 2
The color varieties that were used in the paired comparisons. Color is shown with its acronym and hex color code.

Presented spheres are created in Unreal Engine 4.27 and then illuminated with a white (#FFFFFF) directional light with an intensity 1. Throughout the experiment, a white (#FFFFFF) background was used for all experiments.

Task Evaluation

Paired comparison experiments rely on participants to select between two same objects (spheres) with different color hues based on a shared quality. Via a handheld VR interface (Oculus Quest 2), the experiment presented participants with two differently colored versions of the same object, as in Figure 3. Participants were asked to select the sphere that appeared close to them.

Figure 3
Sample of presented environment. Participants were asked to select the shape perceived nearer.

All the participants were instructed beforehand to evaluate all the possible comparison pairs from the set of color conditions. Assume that n is the number of colors that are compared with each other. Participants are presented with $(n(n-1))/2$ pairs for a 3D transparent model. Each participant compares 66 pairs of stimuli per model in the experiment, which has 12 color conditions. Every selection receives a user vote, as displayed in Table 1. After evaluating all pairs for a model, these results are aggregated into a single x preference matrix. If a matrix cell in row i and column j contains a 1, it indicates that the participant chose the color in row i to be closer than the color in column j. It can be inferred that the matrix cell in row j and column i would be filled with 0. The preference matrixes of all participants are then added together to determine overall color scores for each experimental condition, as in Table 1. The participant repeats this process for all four models, resulting in 264 comparisons.

	R	G	B	M	Y	C	DR	DG	DB	DM	DY	DC	SCORE
R	-	1	1	1	1	1	1	1	1	1	1	1	11
G	0	-	0	0	0	1	1	1	1	1	1	1	7
B	0	0	-	0	0	0	1	1	1	1	1	1	6
M	1	0	1	-	0	1	1	1	1	1	1	1	9
Y	0	0	1	0	-	1	1	1	1	1	1	1	8
C	0	0	0	0	0	-	1	1	0	0	0	1	3
DR	0	0	0	0	0	0	-	1	0	1	0	1	3
DG	0	0	0	0	0	0	0	-	0	0	0	1	1
DB	0	0	0	0	0	1	0	0	-	1	0	1	3
DM	0	0	0	0	0	0	0	0	1	-	0	1	3
DY	0	0	0	0	0	0	0	1	1	1	-	1	4
DC	0	0	0	0	0	0	-	1	0	0	0	-	0

Sample of a preference matrix collected from a participant

Table 1
One participant's preference matrix when shown 12 color conditions of a given transparency level. Each color in a row is compared to all other colors to determine a preference score.

Research Questions and Hypotheses

RQ1: How does the transparency of a simple 3D sphere interact with color and luminance as depth cues in virtual landscapes?

H1: A high Transparent sphere (90%) tends to be less affected by color and luminance.

The classical impacts of color and luminance as depth cues in all transparency levels are expected to be observed, which indicates that warm colors are perceived as closer than cold and bright colors are closer than cool colors. In a 90% transparency level, color hue and luminance effects are insignificant and barely perceived.

RQ2: How does the color of a 3D transparent sphere affect its perceived depth?

H2: Warm colors will appear closer than cool colors of the same luminance.

It is expected that warm, bright colors would be perceived nearer than cool bright colors, and warm dark colors would be sensed nearer than cool dark colors.

RQ3: How does the luminance of a 3D model affect its perceived depth?

H3: Brighter colors are perceived closer than darker colors regardless of transparency levels.

Due to their contrast with their background color, brighter colors are expected to be perceived nearer than darker ones.

Results Evaluation

All preference matrix results for each transparency level are evaluated using Kendall's coefficiency of agreement and consistency.

Kendall Coefficient of Agreement

All participants answering the same way would lead to complete agreement. On the contrary, this is rarely the case, and it is essential to determine whether or not there is actual concurrence among participants. Kendall's coefficient of agreement uses the number of agreements between pairs:

$$\Sigma = \sum_{i \neq j} \binom{p_{ij}}{2} \qquad (1)$$

Assume in Equation 1, p_{ij} is the number of times that color i is preferred to color j. Since a color is never compared to itself, $\sum$ denotes the sum of the number of agreements in pairs, extending over all pairs except the diagonal. $\sum$ can then be applied to compute the Kendall and Babington coefficient of agreement u among participants (Kendall & Smith, 1940):

$$u = \frac{2\Sigma}{\binom{s}{2}\binom{n}{2}} - 1 \qquad (2)$$

Assume n represents the number of colors and s represents the number of participants. If all participants made the same choices, then u would equal 1. As participants disagree, u decreases, tending to -1/ $(\mathrm{s}-1)$ when n is even and -1/s when n is odd. The coefficient of agreement u can suggest how much the participants agree. Using a large sample approximation to the sampling distribution, the significance of u can be tested to determine if participants coordinate with one another(Siegel, 1957):

$$\chi^2 = \frac{n(n-1)(1+u(s-1))}{2} \qquad (3)$$

χ^2 is asymptotically distributed and has $\mathrm{n}(\mathrm{n}-1)/2$ degrees of freedom. For χ^2, we can use a table of probability values. this statistic can be used to test the null hypothesis H_0, which states no agreement among participants, suggesting that all colors are perceptually equivalent.

Coefficient of Consistency

Paired comparison experiments frequently assess a participant's consistency or transitivity. For example, if a participant selects that color A is closer than color B and that color B is closer than color C, they should also select that color A is closer than color C. They would have created a circular triad if they had chosen otherwise. Inconsistency is expected when the items being compared are alike, and making conclusions is challenging. Kendall and Babington coefficient of consistency ζ can be calculated for even n, where c symbolizes the number of circular triads(Siegel, 1957):

$$\zeta = 1 - \frac{24c}{n^3 - 4n} \qquad (4)$$

The number of circular triads c can be calculated using the formula below (Clarke & David, 1989):

$$c = \frac{n}{24}(n^2-1) - \frac{1}{2}\sum(p_i - \frac{n-1}{2})^2 \qquad (5)$$

Where n is the number of colors and $\mathrm{p_i}$ is the score assigned to each color. Participants can have a high coefficient of agreement u and a low coefficient of consistency ζ. Individually, participants can make inconsistent decisions and yet have a high u if they all agree on these inconsistent decisions. $\zeta \in [0,1]$, where 1 indicates perfect consistency. As inconsistency increases, ζ tends to zero.

Table 2
Statistical analysis of the four transparency levels with 66 degrees of freedom.

Transparency	*Coeff Cons (ave)* ζ	*Coeff Agr* u	χ^2	*Significance p, 66 df*
10%	0.653	0.724	170.4	<0.001
40%	0.594	0.658	282.3	>4.0
60%	0.617	0.632	146.7	>5.0
90%	10%	0.516	241.8	<0.001

RESULTS

The preference matrixes of all participants were tabulated in one combined preference matrix for each transparency level. Figure 4 depicts the total scores of each color in each of the transparency levels.

The coefficient of consistency was sufficient to rank statistical data's accuracy for a 10% transparency level. For a 10% transparency level, the same traditional effects of color and luminance on depth perception were observed. Warm colors were perceived nearer than cool colors, and bright colors were perceived nearer than dark colors.
Although bright red is perceived closer than bright yellow at a 10% transparency level, the dark version of yellow is sensed closer than dark red. Bright red scored the highest among all the other colors in the 10% transparency level. While the score difference between the bright version of red and blue is arguably significant, in the dark version in the 10% transparency sphere, the amount of this difference could be disregarded. In the 40% transparency level, though the same traditional impacts took place among warm/cool and bright/dark color versions, small turbulences regarding the traditional effects of color and luminance could be observed. Bright magenta is seen to be nearer than the bright version of yellow. Dark yellow has obtained a higher compared to bright cyan. Dark yellow is perceived to have the highest score among all the dark colors. Despite being the last in the score list, Dark cyan increased in score compared with the 10% transparency level.

With a 60% transparency level, bright yellow has obtained the highest score among all the other colors. Bright versions of red, blue, and cyan were perceived to be in the same perceptional grouping. Dark yellow is perceived to have a higher rank than the bright versions of red, blue, and cyan. Dark red and dark blue are in the same perceptional grouping. Also, dark magenta and dark green have a similar perceptual effect on depth perception within HMDs.

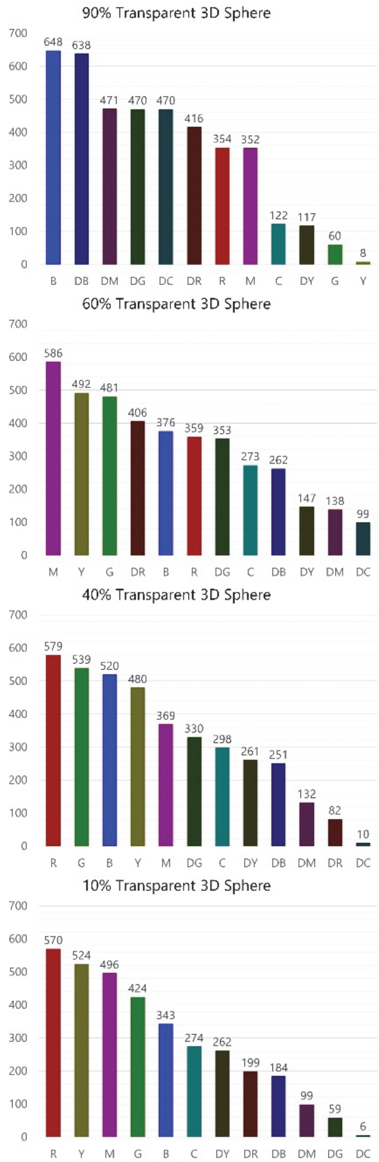
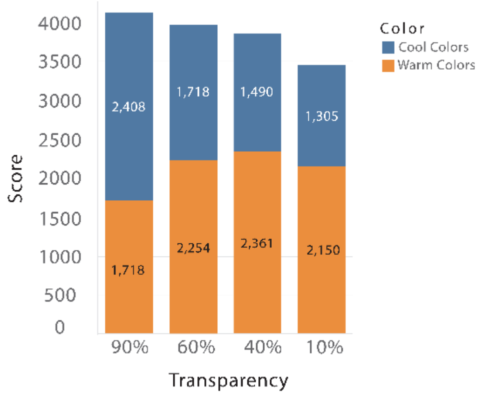
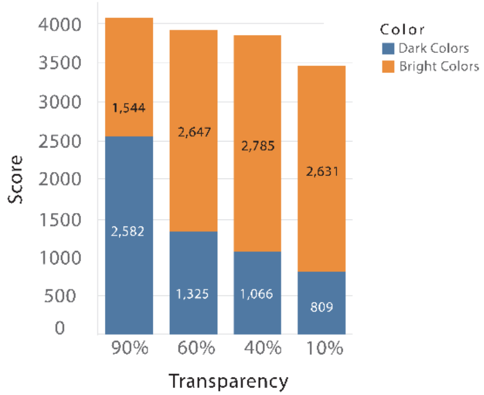


Figure 4
Bar Graphs of the total score of each color per each transparency level. Colors are ordered from the highest to the lowest score.

Figure 5
Overview of transparency effects on color and luminance as depth perception cues.



Interaction Between Cool Colors and Warm Colors With Four Transparency Levels



Interaction Between Dark Colors and Bright Colors With Four Transparency Levels

At a 90% transparency level, contrary effects with the formal studies on color and luminance can be observed. Cool colors are perceived nearer than warm colors. Furthermore, dark colors are perceived as nearer than bright colors. Blue scored highest among all the others. Blue and dark blue are observed to be perceptually equivalent. In addition, dark magenta, dark green, and dark cyan are in the same perceptual grouping. It can be inferred that bright cyan and dark yellow belong to another perceptual grouping and score relatively low. Bright yellow scored the lowest among all the other colors.

As represented in Table 2, the coefficient of consistency can be indicated as reasonably high to conclude that there is certain consistency among participants.

Using the overall circularity test proposed by Dunn-Rankin et al. to analyze the average number of circular triads, results rejected the null hypothesis that participants have the same circularity as picking at chance with α = 0.05 level and 66 degrees of freedom for all four transparency levels (Dunn-Rankin et al., 2014).

Based on the evaluation of results, a reasonably sufficient among of u was obtained. The null hypothesis H0 was rejected at α = 0.05 level for 11 degrees of freedom to conclude that there is a certain agreement among the participants.

H1 can be rejected: Since a high p-value for Kendall's coefficient of agreement for 90% transparency was obtained. Thus, specific perceptual differences among colors were observed. According to the analytical visualizations in Figures 4 and 5, this paper supports H2 in 10% and 40% transparency levels. However, in 60% and 90% levels, H2 was rejected due to the contrary results regarding the classical effects of cool and warm colors.

Referring to figures 4 and 5, in 40% and 60%transparency levels, Results can support H3. However, in 60% and 90% transparent spheres, H3 was rejected. Darker colors are perceived as nearer than bright colors in 60% and 90% of transparency.

DISCUSSION

This paper declared that the transparency levels of an object interact with its color and luminance as depth perception cues in VR landscapes. The study's findings on object transparency, color, luminance, and depth perception cues in virtual environments bear significant technical implications for VR tools, architecture, virtual landscape design, and machine learning. These insights enhance the authenticity and immersion of virtual experiences by manipulating transparency levels and leveraging color and luminance cues. Such advancements benefit architectural visualization and game development, improving design evaluation and fostering user engagement. Moreover, the findings contribute to the advancement of object recognition algorithms in machine learning. These algorithms achieve enhanced accuracy and performance by incorporating depth estimation techniques based on color and luminance cues, thereby advancing computer vision technology in real-world scenarios.

The implications extend to scene understanding and rendering algorithms in virtual reality, vital in creating visually captivating and realistic virtual environments. By incorporating the study's insights, scene rendering algorithms can accurately simulate the interplay of transparency, color, and luminance, resulting in more visually compelling virtual landscapes. Additionally, these findings inform user experience design by guiding the manipulation of transparency levels and color choices, leading to intuitive interactions within virtual environments and optimizing usability and engagement.

Furthermore, the outcomes have practical significance in machine learning through training data augmentation. Leveraging the knowledge gained from this study, machine learning models are better equipped to interpret visual cues, enhancing their performance and accuracy in real-world scenarios.

LIMITATIONS

The number of colors examined was relatively low, which decreased the number of comparisons. The research narrowed its analysis and observation to only four different transparency levels.

Although the results have achieved a general relation regarding transparency, color, and luminance, the nature of the results reflects that different transparency levels may have various impacts on color and luminance. This study used a white (#FFFFFF) background for pared comparison experiment. Different background colors would yield different results.

CONCLUSION

This article compared the effects of four transparency levels on color and luminance as two pictorial depth cues. To estimate these impacts, we applied a paired comparison experiment. Results suggest that 10% and 40% of transparency, color, and luminance depict the classical effects on depth perception. However, in 60% and 90% transparency, results have discovered the reversed effects of transparency on color and luminance.

In 60% and especially in 90% transparent 3D objects, cool colors are perceived nearer than warm colors, and dark colors are sensed nearer than bright colors.

Future research can focus on employing machine learning to anticipate the effects of color tones and transparency levels in virtual environments. This includes supervised learning with labeled datasets and generative adversarial networks for synthetic environments, enhancing anticipation capabilities through analyzing varied color and luminance alternatives.

Current results will help understand the spatial cognition in virtual landscapes, besides helping digital design tool developers improve interaction accuracy to enhance immersion in virtual landscapes.

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