Quantitative analysis of colour harmony in living environments using VR simulations

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This study investigates the quantitative assessment of colour harmony in living environments using Virtual Reality (VR) simulations. The primary objective is to develop a comprehensive model of colour harmony in three-dimensional interior spaces. Twenty participants were recruited to evaluate 36 different colour combinations of walls and furniture using VR technology. The experiment assessed colour harmony by varying lightness, saturation, and hue within spatial combinations. Key findings indicate significant negative correlations between both saturation and value differences and perceived harmony. The derived regression formulas for these relationships are $CH=-1.27-7.02\Delta S+2.46\Delta S^2$ ($0 \le \Delta S \le 100$, $R^2=0.865$) for saturation difference and $CH=3.11-0.02\Delta V$ ($0 \le \Delta V \le 100$, $R^2=0.705$) for value difference. The results suggest that the spatial colour harmony model has some characteristic that are different with human perceived. This study bridges the gap between two-dimensional and three-dimensional colour harmony frameworks and provides practical guidelines for designing harmonious living spaces. Future applications may include automated systems such as painting robots and spatial colour design AI.

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Introduction

Colour harmony is a critical concept in colour theory; yet despite extensive study, a precise definition of colour harmony remains elusive. Although many studies have explained what colour harmony is over the past few decades, there is still not a universally accepted definition. Most studies tend to state the characteristics of colour harmony. O'Connor defines colour harmony as a colour combination that elicits a positive aesthetic response, which depends on the characteristics of the observer's age, gender, cultural experience, personality, emotional state, the human perception of surroundings, and the influence of time factors [1]. Colour wheels and theories, from Newton's geometric colour wheel to later models by Ostwald, Munsell, and Itten, have attempted to explain colour harmony through systematic arrangements and relationships between colours in various colour spaces. These models emphasise the importance of hue, chroma, and brightness interactions. However, contemporary teaching in this field often places too much focus on hue (and sometimes completely ignores the other attributes of colour).

Traditionally, research in the field of colour harmony has focused on colour harmony in two-dimensional images; such studies are relatively easy to carry out but may not fully capture the complexity of colour interactions in the three-dimensional spaces in which we live. This study explores the role of colour harmony in three-dimensional environments using Virtual Reality (VR) simulations.

Albers highlighted that the aesthetics of colour combinations are context-dependent and influenced by perceptual effects, making colour harmony a subjective experience [2]. This subjectivity is further complicated by individual differences in age, gender, cultural background, and emotional state, which may affect aesthetic responses to colour. Burchett suggested that colour harmony should be defined by the emotional response it elicits, though this lacks universal consensus [3].

Preferences for spatial colours vary by context and function, as shown by studies indicating that people prefer cooler colours for hospitals and warmer colours for restaurants [4]. These preferences highlight the need to consider the specific functions and user profiles of spaces when designing for colour harmony. Additionally, elements such as walls, temperature, and user preferences play significant roles in perception. Studies have demonstrated that brighter spatial colours are often perceived more positively, contributing to a sense of well-being [5-6]. This study aims to extend these findings by developing a model of colour harmony for three-dimensional spaces, focusing on variations in hue, saturation, and lightness.

Although some models of colour harmony may be descriptive or based on geometric relationships there is a need for more quantitative models that are based on data. Scholars such as Itten, Munsell, Ostwald and Nemcsics defined and developed colour order systems and rules governing colour harmonic sets. Nemcsics stated a three-tiered process of colour harmony experience, employing psychometric scales to record experimental data—a theoretical foundation for constructing his Coloroid colour system. The three-tiered model of Nemcsics consists of perception, the effect of perceived colours on the human psyche and physique, and the interrelation between colour, human and environment. This model covered the complexity between people and the process by colour harmony experiences are created. The Coloroid colour system is suitable to explain the harmonic colours relationship and fostering improved colour combinations, thus enhancing the arithmetic of colour harmony experience [7]. Large-scale experiments by Ou and Szabó have quantified colour harmony using psychometric scales and detailed models, though primarily in two-dimensional settings [8-9]. In contrast to Nemcsics's experiments that involve many elements, Ou *et al.* concentrated specifically on the principles of colour harmony within two-colour combinations and concluded that there are three main factors that contribute to colour harmony (CH) - the chromatic effect (HC), the lightness effect (HI), and hue effect (H_H).

$$CH = H_C + H_I + H_H \tag{1}$$

Building on Ou's experiment, Szabó carried out experiments in which all colour stimuli were defined in terms of the CIECAM02 colour appearance model. They developed functions that were later verified by additional experiments and established that the sum and differences of perceptual colour attributes (the greyness of CIECAM02 – J, chroma – C and hue – h) can predict colour harmony. The formulas could be descriptor by lightness difference, chroma difference, hue difference, hue, and the average lightness of the composition [9]. Szabó's model were categorised into monochromatic and differing hue combinations.

$$\begin{aligned} CHF_{3M} = 2.523 * (&-0.0325 CHF_{3M,Jdiff} + 2.2659 CHF_{3M,Jsum} + 3.4194 CHF_{3M,Cdiff} \\ &- 1.355 CHF_{3M,Csum} + 0.721 CHF_{3M,HP}) + 1.318 \end{aligned} \tag{2}$$

$$CHF_{3T} = 2.187 * \left(0.967CHF_{3T,Jdiff} + 1.9397CHF_{3T,Jsum} + 0.4399CHF_{3T,Cdiff} - 0.1153CHF_{3T,Chrdiff} + 0.11CHF_{3T,HP}\right) + 0.134 \quad (3)$$

Ou's experiments used colour combinations based on the CIELAB model. Although CIELAB offers greater accuracy in colour management and reflecting perceptual differences in human vision better, the HSV parameters are more intuitive and easier to control [10]. Additionally, the HSV colour system provides more visually uniform compared to CIELAB (see Figure 1). However, it is challenging to achieve uniform colour calibration across different devices using the HSV system, especially for VR. Without precise colour measurement, it is difficult to create a reliable model that correlates the RGB values of colours displayed on an HMD with CIE XYZ values, and accurately reproducing colours on the HMD for colour and imaging research is also problematic. Although colour measurement instruments specifically designed for HMDs are available, this approach remains insufficient. To address these issues, some researchers proposed a method to characterise HMDs based on visual colour assessment, but this method is still experimental.

Figure 1: The top row colours have constant L and C* from CIELAB and the bottom row colours have constant V and S from HSV; note the top row blue is much stronger than the other colours in the row.*

This study aims to bridge the gap between 2-D and 3-D colour harmony studies. Virtual Reality simulations provide a realistic platform for assessing colour combinations in interior spaces. Although colour calibration using HSV on VR equipment is still under investigation, this study considers that CIECAM02 is less intuitive in its operability compared to HSV. Additionally, the characterisation of VR displays is more complex than monitor calibration, and traditional instrument-based measurements are not entirely precision [11]. Research in this area requires an analysis of VR display characteristics, as well as an examination of gamma correction and colour matrix conversion. This is a promising research topic but is not directly relevant to the objectives of the current study. Therefore, this study adopts a new approach to determine colour combination parameters to achieve its research goals. These findings will inform future applications of automated systems and artificial intelligence driven design tools, enhancing our understanding of colour interactions in complex environments. This research aims to contribute to the field by improving theoretical and practical knowledge of colour harmony, particularly in the context of 3-D living spaces.

Method

This study aims to develop a model for evaluating colour harmony in living environments based on experiments in simulated 3-D environments. An empirical research methodology is adopted, aligned with positivist paradigm, emphasising objective assessment through systematic observation and measurement. The research involves multiple phases of experimentation, with the initial phase focusing on testing the spatial colour harmony model under normal emotional conditions. The methodological framework is based on previously published work by Ou and Szabó who carried out experiments about colour harmony of two-dimensional colour combinations based on variations in hue, saturation, and value [8-9]. In this study a VR system will be used to allow different colours in a 3-D environment to be experienced (whereas both Ou and Szabó used simple 2-D displays). Moreover, in this experiment differences in lightness, saturation, and hue for spatial colour combinations (namely walls and furniture) are considered, with further exploration into the effects of luminance variation and its interaction with natural and artificial lighting conditions in subsequent experiments. The collected data were analysed using SPSS and R to conduct descriptive statistics and regression analysis. The analytical objectives include identifying bedroom colour schemes that elicit harmonious psychological responses under normal emotional conditions and evaluating colour harmony relative to hue, saturation, and luminance differences for comparative analyses with two-dimensional colour harmony models. Furthermore, the examination of the relationship between spatial colour harmony and colour preference will be expanded upon. Noted that this study focuses on the bedroom environment.

Twenty participants from the University of Leeds were recruited for the experiment. The final participant cohort comprised 6 males and 14 females, primarily aged 20-40 years. To diversify the sample and account for potential cultural influences on colour preferences, invitations were halted upon reaching 10 participants of the same nationality. Consequently, the participant pool included individuals from various cultural backgrounds, including 10 Chinese, 5 British, 2 Indonesia, and participants from South Korea, Spain, and Mexico.

Before the experiment, participants were introduced to the VR operation were informed that colour harmony is concerned with combinations of colours. Participants then completed a survey to gauge their understanding of colour harmony and its psychological impacts. The main purpose of this survey is to understand participants' cognition of "colour harmony", focusing on whether colour harmony elicits a "pleasant" psychological response, or a "peaceful" psychological response, or both; whether the definition of colour harmony is the same in general contexts as in artistic works; and what participants' definitions of colour harmony are. This survey is not intended to draw definitive conclusions about colour harmony but to provide participants with a basic understanding of the factors related to colour harmony and to supplement the explanation of their criteria for scoring colour harmony. If any anomalies appear in the subsequent experimental data, this questionnaire can serve as a reference for analysing the causes.

For this study, the environmental context for the work was a bedroom. To avoid introducing extra variables, the experiment was set up with a colour-constant white ceiling and a medium yellow wooden floor to maintain consistency with the real bedroom. The colours of the walls and furniture were chosen from the HSV (Hue, Saturation, Value) colour system, supported by Unity software which is commonly used for virtual reality scene construction (see Figure 2).

For a more realistic representation, the wall colour selection was based on the Dulux 2023 – selecting a low saturation and high value [12]. The hues selected were pure red (0/360 degrees), green (120 degrees), yellow (60 degrees) and azure (210 degrees)[1], all saturated at 10 with a value of 90. However, yellow is somewhat of a special colour; it tends to acquire a greenish hue when darkened. The value or lightness of yellow was adjusted to 100 to ensure a consistent perceptual effect with the other hues.

[1] Note that in the HSV system, a hue angle of 210 degrees is azure, while pure blue is at 240 degrees. However, given that 210 azure is more commonly found in the interior blue walls compared to 240 pure blue, this report uses 210 azure to represent blue walls. Additionally, in the CIE system, 210 azure is in the range of 230 degrees to 260 degrees.

Considering that the calculation of hue difference (ΔH) in the HSV system is based on the hue angle and given that wall colours occupy a large area in the scene, which may significantly impact overall perception. Additionally, the subsequent test groups will focus on single-variable saturation and value differences. Using other hue angles values in the ΔH group might introduce extra saturation and value variations. Therefore, this report used the hue angles of red, green, yellow, and blue from the walls to alternate the ΔH measurement. Combining these conditions, the calculation of ΔH between walls and furniture will use the wall hue angle as the starting angle from which to measure the furniture hue angle. ΔH may be positive or negative. Due to the periodicity and normalisation of the circumference (i.e., 0 degrees to 360 degrees is one cycle, with 0 degrees coinciding with 360 degrees) and the central symmetry (centred at 180 degrees), the angle difference can be normalised to between -180 degrees and 180 degrees to make the representation of angle differences more intuitive. If ΔH > 180, then ΔH = ΔH – 360; if ΔH < -180, then ΔH = ΔH + 360.

$$\Delta \mathrm{H} = H_{wall} - H_{furniture} \ (-180° < \Delta \mathrm{H} < 180°) \tag{4}$$

In discussing differences in saturation (ΔS) and value (ΔV) between walls and furniture, it was found that, when hue remained consistent, these differences had a lesser impact on colour perception compared to hue difference (ΔH), regardless of the spatial range of colours. For ease of subsequent analysis, this experiment only considered the absolute values of saturation and value differences. Saturation and value differences were measured as follows:

$$\Delta \mathrm{S} = \left|S_{wall} - S_{furniture}\right| = \left|10 - S_{furniture}\right| \tag{5}$$

$$\Delta \mathrm{V} = \left|V_{wall} - V_{furniture}\right| = \left|90 - V_{furniture}\right| \tag{6}$$

When H=60,

$$\Delta \mathrm{V} = \left|V_{wall} - V_{furniture}\right| = \left|100 - V_{furniture}\right| \tag{7}$$

However, when hue remained consistent, these differences had a lesser impact on colour perception compared to hue difference (ΔH), regardless of the spatial range of colours. For ease of subsequent analysis, ΔS and ΔV are analysed using absolute values. To observe the relationship of ΔS / ΔV and colour harmony score for the equations optimising, it is important to ensure that ΔS / ΔV have sufficient values for robustness and reliability in the final data analysis; specifically, the values of ΔS and ΔV need to be expressed as an arithmetic sequence with a maximum common difference. As shown in Figure 2 the ΔS and ΔV groups in this experiment can accommodate up to 12 independent variables. In summary, it could be concluded that the optimum common difference of ΔS is 9, and the optimum common difference of ΔV is 8. Namely, the $\Delta S_{(1,2,3,\ldots,12)}$ and $\Delta V_{(1,2,3,\ldots,12)}$ incrementally increase by values of 9 or 8 starting from 0.

In addition, the range of saturation (S) and value (V) in the HSV system is from 0 to 100, but when S < 5 and V < 10, the hues are too colourless and dark to distinguish between them. Therefore, the values of $S_{furniture}$ and $V_{furniture}$ in this experiment are in the range of $5 \leq S_{furniture} \leq 100$, and $10 \leq V_{furniture} \leq 100$. Taking these conditions into account, assigning $S_{(furniture1,2,3,\ldots,12)}$ and $V_{(furniture1,2,3,\ldots,12)}$ to each of red wall, green wall, yellow wall and blue wall groups in order, the final 36 colour combinations are obtained as shown in Table 1. The final 36 colour combinations used to test ΔH, ΔS and ΔV were carefully designed to ensure full coverage of potential variations (see Figure 2).

Participants evaluated the 36 colour combinations (4 wall colours × 9 furniture colours) in a simulated modern-style room using a HTC Vive Pro VR headset. Each combination was rated on an 11-point Likert-scale from -5 to 5 (-5 represents least harmonious and 5 represents most harmonious). The experiment included predetermined and randomly ordered assessments to minimise bias.

The first experiment was carried out with 20 participants and the data from this experiment were used to develop models – where appropriate – to predict colour harmony from hue, value and saturation and their differences (between walls and furniture). A second experiment was then carried out with a further 10 participants to evaluate the models that were derived from the first experiment.

<table>
<tr><th colspan="2" rowspan="2">Wall colour</th><th colspan="4" rowspan="2">Furniture colour</th><th colspan="3">Colour Combination Difference</th></tr>
<tr><th>ΔH</th><th>|ΔS|</th><th>|ΔV|</th></tr>
<tr><td rowspan="9">Red</td><td rowspan="3">H=0</td><td>1</td><td>H=60</td><td>S=10</td><td>V=90</td><td>-60</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>H=120</td><td>S=10</td><td>V=90</td><td>-120</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>H=210</td><td>S=10</td><td>V=90</td><td>-210</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">S=10</td><td>4</td><td>H=0</td><td>S=6</td><td>V=90</td><td>-</td><td>4</td><td>-</td></tr>
<tr><td>5</td><td>H=0</td><td>S=30</td><td>V=90</td><td>-</td><td>20</td><td>-</td></tr>
<tr><td>6</td><td>H=0</td><td>S=66</td><td>V=90</td><td>-</td><td>56</td><td>-</td></tr>
<tr><td rowspan="3">V=90</td><td>7</td><td>H=0</td><td>S=10</td><td>V=10</td><td>-</td><td>-</td><td>80</td></tr>
<tr><td>8</td><td>H=0</td><td>S=10</td><td>V=38</td><td>-</td><td>-</td><td>52</td></tr>
<tr><td>9</td><td>H=0</td><td>S=10</td><td>V=70</td><td>-</td><td>-</td><td>20</td></tr>
<tr><td rowspan="9">Green</td><td rowspan="3">H=120</td><td>1</td><td>H=0</td><td>S=10</td><td>V=90</td><td>120</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>H=60</td><td>S=10</td><td>V=90</td><td>60</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>H=210</td><td>S=10</td><td>V=90</td><td>-90</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">S=10</td><td>4</td><td>H=120</td><td>S=12</td><td>V=90</td><td>-</td><td>2</td><td>-</td></tr>
<tr><td>5</td><td>H=120</td><td>S=39</td><td>V=90</td><td>-</td><td>29</td><td>-</td></tr>
<tr><td>6</td><td>H=120</td><td>S=75</td><td>V=90</td><td>-</td><td>65</td><td>-</td></tr>
<tr><td rowspan="3">V=90</td><td>7</td><td>H=120</td><td>S=10</td><td>V=16</td><td>-</td><td>-</td><td>74</td></tr>
<tr><td>8</td><td>H=120</td><td>S=10</td><td>V=46</td><td>-</td><td>-</td><td>44</td></tr>
<tr><td>9</td><td>H=120</td><td>S=10</td><td>V=78</td><td>-</td><td>-</td><td>12</td></tr>
<tr><td rowspan="9">Yellow</td><td rowspan="3">H=60</td><td>1</td><td>H=0</td><td>S=10</td><td>V=100</td><td>60</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>H=120</td><td>S=10</td><td>V=100</td><td>-60</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>H=210</td><td>S=10</td><td>V=100</td><td>-150</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">S=10</td><td>4</td><td>H=60</td><td>S=15</td><td>V=100</td><td>-</td><td>5</td><td>-</td></tr>
<tr><td>5</td><td>H=60</td><td>S=48</td><td>V=100</td><td>-</td><td>38</td><td>-</td></tr>
<tr><td>6</td><td>H=60</td><td>S=84</td><td>V=100</td><td>-</td><td>74</td><td>-</td></tr>
<tr><td rowspan="3">V=100</td><td>7</td><td>H=60</td><td>S=10</td><td>V=22</td><td>-</td><td>-</td><td>78</td></tr>
<tr><td>8</td><td>H=60</td><td>S=10</td><td>V=64</td><td>-</td><td>-</td><td>36</td></tr>
<tr><td>9</td><td>H=60</td><td>S=10</td><td>V=84</td><td>-</td><td>-</td><td>16</td></tr>
<tr><td rowspan="9">Blue</td><td rowspan="3">H=210</td><td>1</td><td>H=0</td><td>S=10</td><td>V=90</td><td>210</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>H=60</td><td>S=10</td><td>V=90</td><td>150</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>H=120</td><td>S=10</td><td>V=90</td><td>90</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">S=10</td><td>4</td><td>H=210</td><td>S=21</td><td>V=90</td><td>-</td><td>11</td><td>-</td></tr>
<tr><td>5</td><td>H=210</td><td>S=57</td><td>V=90</td><td>-</td><td>47</td><td>-</td></tr>
<tr><td>6</td><td>H=210</td><td>S=93</td><td>V=90</td><td>-</td><td>83</td><td>-</td></tr>
<tr><td rowspan="3">V=90</td><td>7</td><td>H=210</td><td>S=10</td><td>V=30</td><td>-</td><td>-</td><td>60</td></tr>
<tr><td>8</td><td>H=210</td><td>S=10</td><td>V=62</td><td>-</td><td>-</td><td>28</td></tr>
<tr><td>9</td><td>H=210</td><td>S=10</td><td>V=94</td><td>-</td><td>-</td><td>4</td></tr>
</table>

Table 1: Experimental colour data defined by HSV.

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Figure 2: Within each wall colour group (each column), hue (ΔH), saturation (ΔS), and value (ΔV) vary to assess their effects. In each control group, one attribute changes while the others remain constant, creating contrast in hue or gradual shifts in saturation and lightness relative to the wall colour.

Results

According to the survey results, 70% of participants tended to understand colour harmony as something that can elicit both pleasant and peaceful psychological responses. Additionally, 99% of participants believe that the definition of colour harmony in general contexts is the same as in artistic works—colour harmony is seen as orderly, creating a pleasing effect, and a combination of colours that evoke tranquillity; Colour harmony is also influenced by many factors, such as colour preference, culture, age, and gender. The results from the survey are illustrated in Figure 3.

Participants rated the colour harmony of simulated 3-D bedroom scenes on a scale from -5 to 5, ranging from disharmony to harmony. A score of 0 represents neither disharmonious nor harmonious responses. Positive scores reflect colour combinations that elicit positive psychological responses, while negative scores indicate combinations that evoke negative psychological responses. To ensure the reliability of the experimental data, inter-observer reliability analysis was conducted using Cronbach's Alpha across different groups of colour combinations and participants (Table 2). Descriptive data for the 36 colour combinations show a wide range of concordant perceptions ranging from highly negative (lowest mean: 3.25) to highly positive (highest mean: -4.30), which suggests that there are differences in perceptions across colour combinations. Standard deviations ranged from 1.302 to 3.895, indicating that the degree of agreement among participants' scores for the different colour combinations was generally more consistent, albeit different. Additionally, the skewness values were close to zero, indicating that the distribution of scores for most colour combinations was symmetrical and showed normal peaks. The variability, as well as the overall normal distribution of scores, demonstrates the robustness of the experimental design and the reliability of the data collected.

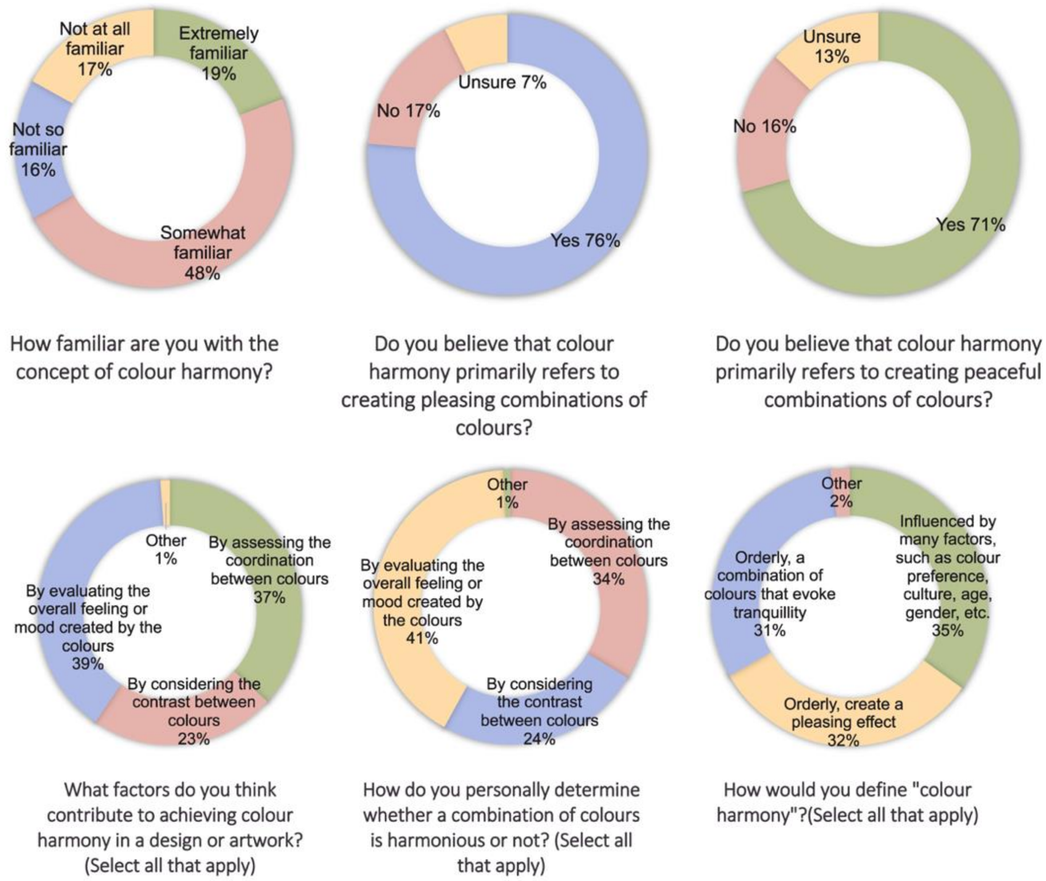


Figure 3: Results of colour harmony definition survey.

<table>
<tr><td colspan="2">Inter-observer</td><td colspan="2">Reliability (Cronbach's Alpha)</td></tr>
<tr><td rowspan="3">36 colour combinations (20 participants)</td><td>Hue Difference group</td><td>0.902</td><td rowspan="3">0.848</td></tr>
<tr><td>Saturation Difference group</td><td>0.82</td></tr>
<tr><td>Value Difference group</td><td>0.777</td></tr>
<tr><td rowspan="2">Participants</td><td>20 participants for formal experiments</td><td>0.957</td><td rowspan="2">0.972</td></tr>
<tr><td>10 participants for verification experiment</td><td>0.934</td></tr>
</table>

Table 2: Inter-observer matrix[2].

[2] The experiment is hold in two stages, and these two stages are the same. The first stage is formal experiment with 20 participants. All the finding of the report are based on it. The second stage is to verify the accuracy of the regression equation, and the participants are 10.

The data collected from the experiment indicates that blue walls received the highest mean scores (1.11), while green walls received the lowest (0.18). This suggests that walls with blue hues are more likely to result in harmonious colour combinations, whereas walls with green hues pose a greater challenge when used in bedrooms. The means for red and yellow walls fall in between, at 0.83 and 0.33 respectively. Additionally, the variability in scores is quite evident. The interquartile ranges for blue and red walls are larger, reflecting more diverse perceptions among participants. Interestingly, the low average score for green walls is paired with a narrower interquartile range (IQR: −0.47 to 0.67), indicating consistent negative perceptions among participants. Yellow walls exhibited significant variability (IQR: −0.56 to 1.28), suggesting their potential as a versatile but risky choice. These results highlight the impact of wall colour on perceived harmony, with blue and red walls receiving higher harmony ratings than green and yellow walls. The variability and presence of outliers emphasise the subjective nature of colour harmony perception.

There was no significant relationship between hue difference (ΔH) and colour harmony (Pearson correlation coefficient = -0.03, p-value = 0.925) as illustrated by Figure 4. In the ΔH experimental group, the hues used are derived from the hue angle values of the four walls. This results in six combinations of the same hues, with each hue serving as both the wall colour in one group and the furniture colour in another group. The combinations involving blue and yellow hues(| ΔH | =150), regardless of whether they are used for walls or furniture, received the highest harmony scores. In contrast, combinations with red and green hues(| ΔH | =120) scored the lowest. Combinations of red and blue, red, and yellow, yellow and green, and green and blue hues scored intermediately. However, it is important to note that no significant relationship between hue difference and harmony can be established from these data. Therefore, the high/low harmony scores observed at |ΔH| = 150/|ΔH| = 120 do not indicate that all colour combinations with these conditions will yield the same results. Additional experimental combinations could be tested in future research to verify this finding.

As shown in Figure 5, a strong negative correlation was found between saturation difference (ΔS) and colour harmony, with a Pearson correlation coefficient of -0.862 (p < 0.01). The regression equation indicated that increasing saturation differences significantly decreased perceived harmony. The following model was developed to predict colour harmony from ΔS values.

$$CH = -1.37 - 6.88\Delta S + 2.53\Delta S^2 \tag{8}$$

Furthermore, a classification analysis based on the wall-hues for all saturation difference combinations shows that the negative correlation is robust across all wall's groups. Although the degree of impact varies slightly; green walls exhibit the most pronounced decrease in harmony as saturation difference increases. However, the general pattern indicates that an increase in saturation difference is consistently accompanied by a decrease in harmony scores, with high reliability. This pattern emphasises the importance of minimising saturation differences, highlighting the strong negative correlation between saturation difference and colour harmony, and underscoring the critical role of saturation consistency in perceived colour harmony.

Colour Harmony and Value Difference (ΔV)

A correlation was observed between value difference (ΔV) and colour harmony, with a Pearson correlation coefficient of -0.558 (p = 0.060). indicating a medium negative correlation between value difference and colour harmony. Although the correlation is not statistically significant at the 0.05 level, the significance level of 0.06 is very close to the standard of 0.05, suggesting a slight negative correlation between value difference (ΔV) and colour harmony. The data points of Figure 6 show a slight decrease in harmony as the value difference increases, especially beyond a value difference of 60, where the trend line exhibits a general downward slope, knowing a subtle negative impact on harmony with larger value differences.

Evaluation of Models

To validate the reliability of the saturation harmony model and the possibility of ΔV with colour harmony, a follow-up experiment was carried out. The aim was to ensure that the model accurately reflects colour harmony. Ten new participants were randomly invited from the University to join in the same experiment as before. Their scores of the saturation difference and value difference combinations were then compared with the previously collected data.

Comparing colour harmony scores for saturation differences from 10 new participants and all 30 combined. The significance value remains below 0.01, and Pearson correlation is -0.877, indicating consistent trends. Increased saturation differences consistently lead to decreased harmony scores. Using R Studio, the sample was resampled 2000 times, and Curve C was generated. Curve C is the precise form of Curve B with the standard error near zero. From Curve A to Curve C, the changes shown curve C demonstrates the highest accuracy and reliability of the model (Table 3). Additionally, the slight changes in the constant, linear, and quadratic terms indicate that the fundamental relationship between saturation difference and colour harmony remains stable. Despite these slight changes, the core trend remains consistent, emphasising the model's robustness. Furthermore, the continuous increase in the R-squared value from Curve A to Curve C indicates that the model's ability to explain the variance in colour harmony scores improves with the application of statistical sampling that includes more data. Curve C, with the highest R-squared value, provides the best fit for the data. Considering the colour limitations in the experimental conditions (in the HSV system of the Unity software), the range of x values in the regression equation is $0 \leq \Delta S \leq 100$. Therefore, Regardless of the sample size, the conclusion that increased saturation difference results in decreased harmony unchanged, indicating the robustness of this finding.

To verify the value difference model, ten additional participants scored value difference combinations following the same procedure as the initial experiment. When the sample size increased to 30, the p-value for the correlation between value difference and harmony score dropped from 0.06 to less than 0.01, with a Pearson correlation of -0.838, indicating a strong negative relationship. Figure 7 can be seen that the difference between N=20 and N=30 is that, at value differences (ΔV) in 30-60, several combinations' means significantly closer to the regression line. The range of 30 to 60 is Medium value difference interval. This indicates that increasing the sample size alters the means in the medium range, thereby creating a more pronounced buffer zone where harmony scores grow more gradually with value differences, to revealing the relationship more clearly. Line B represents the form of Line A with near-zero standard error. The constant term and linear term of both equations are the same, but the R-squared value slightly increases. The small linear term of 0.02 and the range of x is $0 \leq \Delta V \leq 100$, which indicates that the change in harmony scores is narrow. It could be the reasons that the relationship coefficient between value difference and harmony score becomes significant with an increased sample size, and it might explain the regression coefficients are not easily changed.

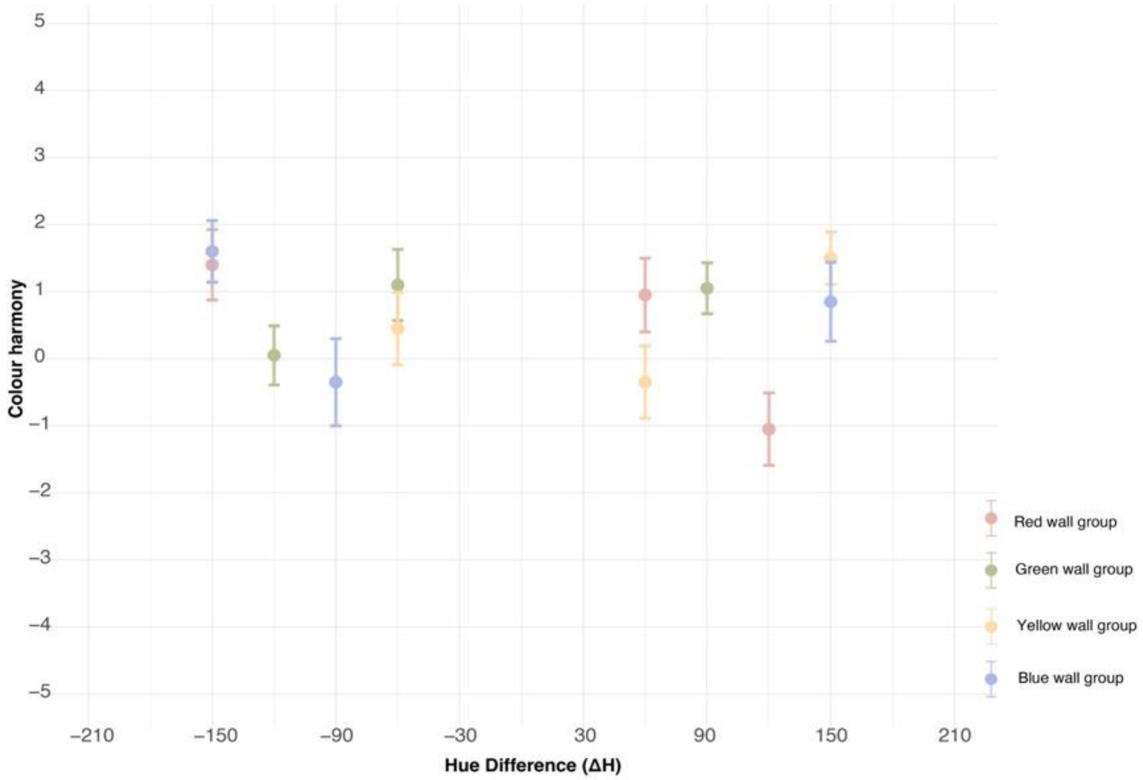


Figure 4: Colour harmony ratings for different hue difference (ΔH) between wall and furniture.

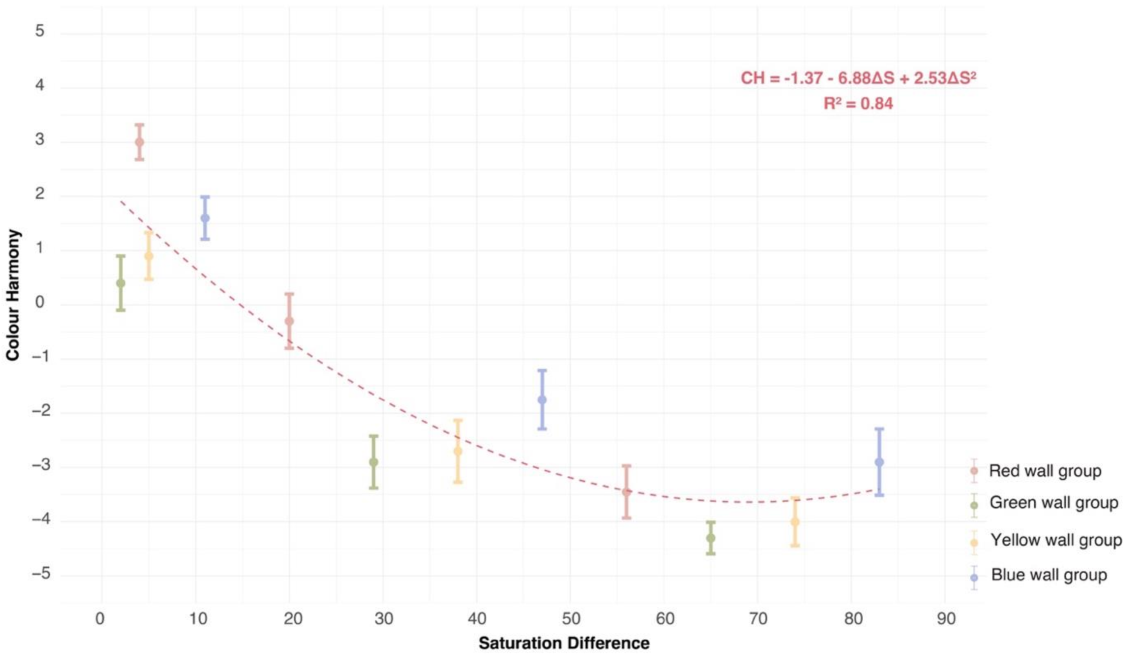


Figure 5: The scatter with error plot of saturation difference (ΔS).

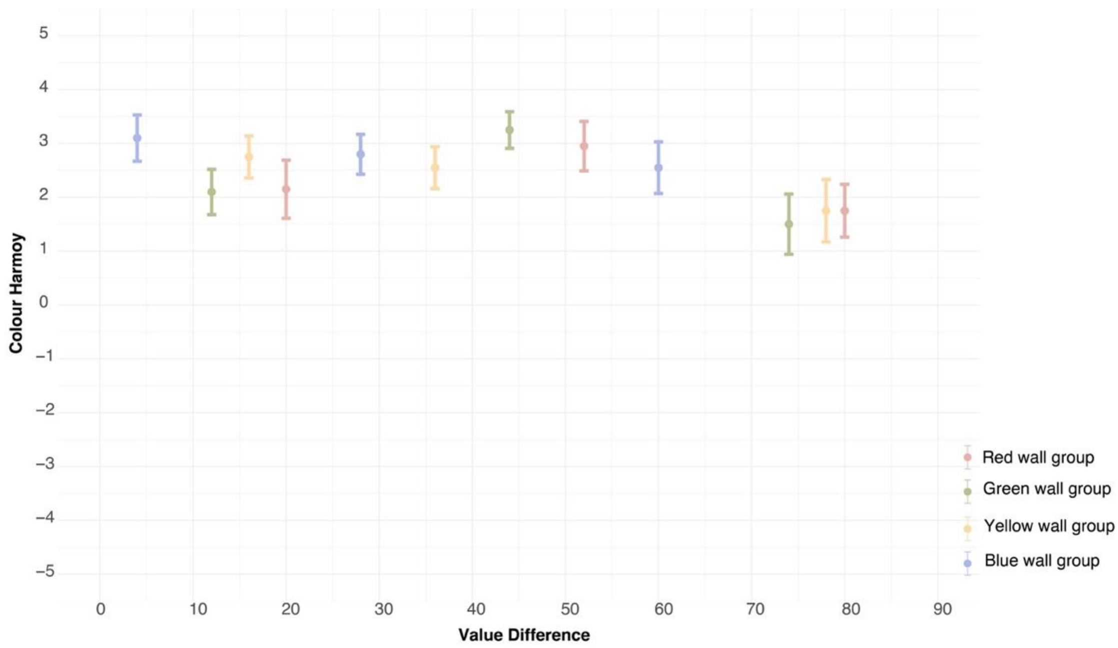
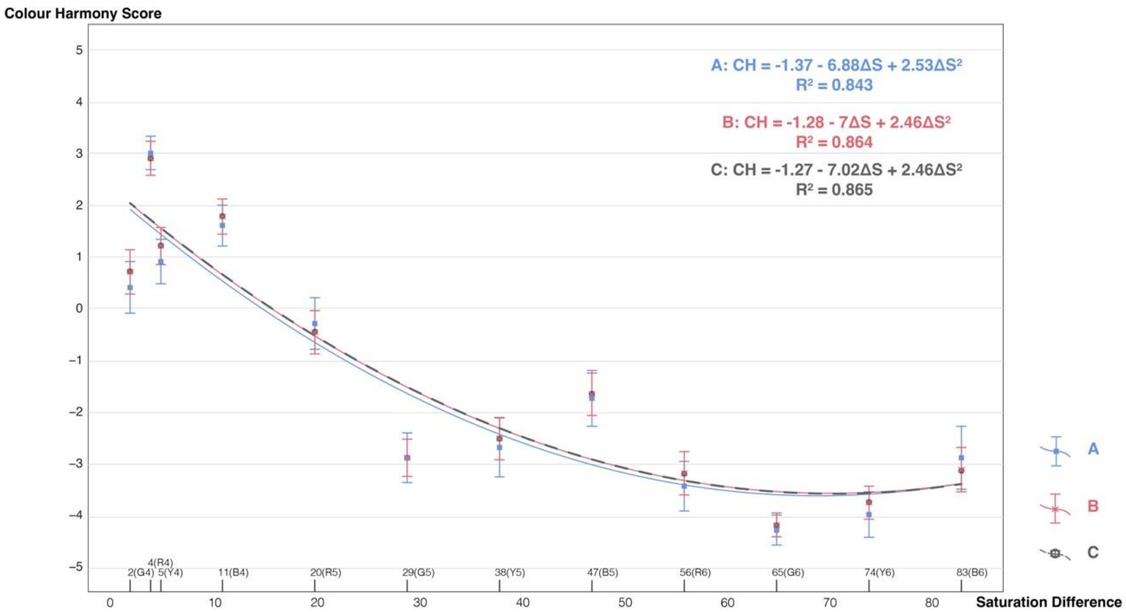
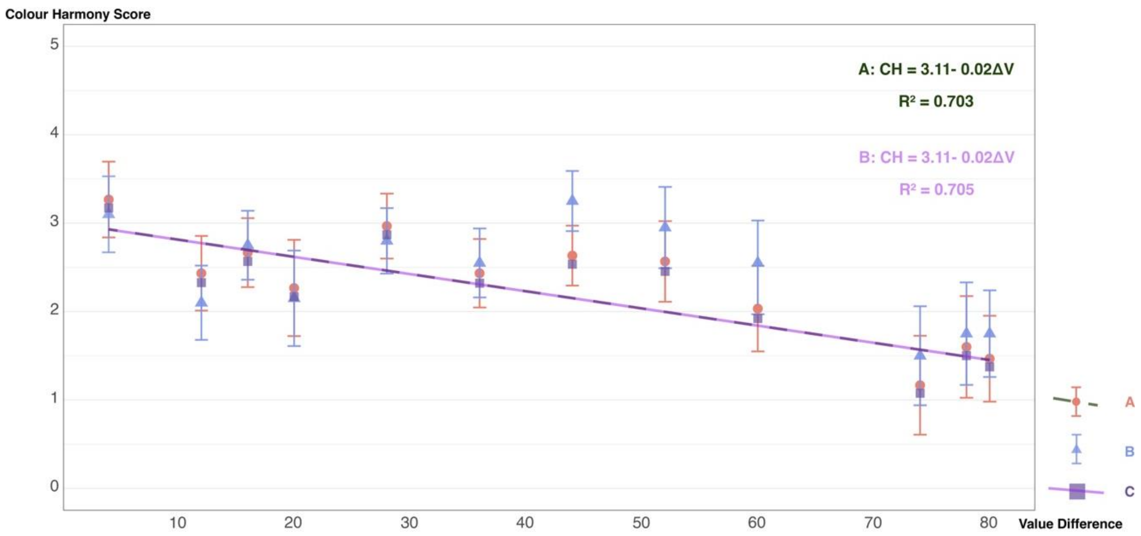


Figure 6: The scatter with error plot of value difference (ΔV).



A: Harmony scores of colour combinations with different saturation differences by 20 participants; **B:**After the test experiment, a total of 30 participants scored the harmony of colour combinations with saturation differences; **C**:The same operation for 12 groups of colour combinations with various saturation differences - each group including 30 samples, 24 randomly sampled and repeated 2000 times. Result in 12 grand mean and standard error distributions

Figure 7: The best fitting model of Saturation harmony model.



A: Colour harmony score of difference value difference combination from 30 participants; B:Colour harmony score of difference value difference combination from 20 participants; C:The same operation for 12 groups of colour combinations with various value differences - each group including 30 samples, 24 randomly sampled and repeated 2000 times. Result in 12 grand mean and standard error distributions

Figure 8: The best fitting model of Value harmony model.

Main findings

1. Blue walls are more conducive to a higher spatial harmony experience.
2. Spatial colour harmony is not significantly related to the hues difference between walls and furniture. However, the combination of yellow and blue results in a higher harmony experience, while the combination of red and green does not easily create a harmonious experience.
3. Spatial colour harmony decreases as the saturation difference between walls and furniture increases. The regression curve for this trend is:

$$CH = -1.27 - 7.02\Delta S + 2.46\Delta S^2 \ (0 \leq \Delta S \leq 100, R^2 = 0.865) \quad (9)$$

4. The spatial colour harmony decreases as the value difference between walls and furniture increases. The precise regression equation for this trend is a monotonic linear descending line.

$$CH = 3.11 - 0.02\Delta V \ (0 \leq \Delta V \leq 100, R^2 = 0.705) \quad (10)$$

Discussion

This paper developed a preliminary model of spatial colour harmony through VR simulations, exploring the relationship between colour harmony and differences in hue (ΔH), saturation (ΔS), and value (ΔV) between walls and furniture. Comparing these findings with two-dimensional studies by Ou and Szabó, the report found that blue walls achieve higher colour harmony, consistent with Ou and Luo [8-9]. However, while Ou and Luo noted low harmony for red walls, this study found green walls had the lowest harmony [8]. Contrary to Szabó, who suggested similar hues result in higher harmony [9], this study found no significant relationship between hue difference and colour harmony. Only when the hue differences were large (e.g. ±150 degrees) did the harmony scores slightly increase. This discrepancy may be due to the different perceptual effects between 2D and 3D, or the different specific colour combinations used in the two experiments, or the differing colour perceptions of the participants. It can be explored in future experiments to discover the impact of hue in 2D versus 3D.

Both this study and Szabó observed a significant influence of saturation on colour harmony [9]. However, while Ou and Szabó found low value differences reduce harmony, this study identified a negative correlation between colour harmony and value difference when the sample size was large [8-9]. Generally, 3D spaces are more affected by sunlight/lighting and other light sources. The complexity of 3D spaces might introduce more interference, affecting colour perception. This reflects the uniqueness of 3D spaces, and exploring the reasons may lead to the importance of establishing a colour harmony model based on 3D spaces. Nonetheless, changing the value difference seems to be a viable method in any dimension.

In conclusion, while this study identifies commonalities and differences in colour harmony across dimensions, further research is needed to unify experimental variables in the same CIELAB system and explore more functional rooms. This study utilised VR simulations to summarise a preliminary colour harmony model for living environments. Future work should involve larger participant groups and diverse colour system conversions to better capture real-world complexities. This report enhances understanding of colour harmony in 3D spaces and provides practical guidelines for living environments, with future research aimed at developing automated systems for spatial colour management.

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