Effects of coloured lighting in the real world environment and virtual reality

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Many studies have shown that colour can affect emotional and physiological responses in real environments but do the same effects occur in virtual environments? This study investigated human subjective and objective responses to different coloured lighting environments, first in a physical laboratory (PE) and then in an approximately identical virtual reality (VR) environment, using three experimental techniques. Data from a smiley-face self-reporting exercise and from electroencephalography (EEG) revealed differential effects of coloured lighting in both the PE and VR environments. However, although data from the Positive and Negative Affect Schedule (PANAS) revealed an effect of coloured lighting in the RE, the same effects were not statistically significant in the VR. We suggest that this might be because of a limited sample size. The results of this study demonstrate the potential of colour for positive emotional effect in an immersive 'real-world' environment for participants in a natural state, i.e. not engaged in any specific cognitive activity. Importantly, the results also indicate that in a VR replica of the same environment, participants also experienced an increase in positive emotions.

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Introduction

This study evaluates the emotional responses to coloured lighting in real and virtual environments. Colour and coloured light have been shown to be capable to generate a positive emotional effect in real environment [1-3] but have been little explored in virtual environments. Yet the 'immersive' capabilities of virtual reality (VR) applications are already recognised as an important aspect of user engagement be this gaming based, learning platforms or therapy-based aversion treatments [4-6]. The evaluation of design principles generally for VR is relatively new and could add to the study of human behaviour, offering new insights into intuitive response, imagination, and focused concentration. These traits are important in applied gaming design, media research, and therapies (e.g. anxiety disorders, social phobia, and driving phobia) [7-9]. VR technology is also being effectively adopted in a number of industries (e.g. tourism marketing, lighting planning, and decision-making tools in product design) [10-12]. Collectively, part of the success of immersive VR environments is that they can be designed to consistently trigger human emotions and behaviours. The foremost technical emphasis regarding immersive VR technology is likely to be the visual fidelity of the stimuli, resulting in a high level of immersion [13-15]. These insights into the significance of immersion and visual stimuli emphasise the necessity of better understanding how vision experience could be effectively designed to enhance positive human emotions and behaviours in VR environments [16-19].

Colour and coloured light are integral to vision experience but also connected to human emotions, behaviours, decision making and health [20-24]. Arousal refers to the physiological and psychological state of being awake and relates to the psychological experience of attention, alertness, information processing (decision-making or judgments), emotions, memory, and consciousness [25-27], it ranges from deactivation (i.e., calm, mind-wandering effects, and meditation states) to activation (i.e., stress or happiness) [28]. Some studies have suggested that arousal increases at the red end of the spectrum while it reduces under bluer wavelengths [2,29]. For instance, Jacobs and Suess [2] explored the effects of four object colours (red, yellow, green, and blue) on emotion and revealed that red and yellow colours increase participants' anxiety levels compared to blue and green colours. Later, Spielberger *et al.* [30] found that higher-state anxiety has a stronger correlation with perceptions of yellow and red than with green. In addition, Adams and Osgood [31] found that blue and green are generally perceived positively by participants: but yellow as powerless and bad; red as powerful and full of action; black as simply bad, dominant and non-active; grey as unpleasant, tiresome, and inactive; and white as good, though ineffective. Elliot *et al.* [32] found that people's performance is influenced by the colour red, and such effects seem to take place outside of people's self-consciousness. More recently, Volpe [33] demonstrated that applying a combination of two light orange colours in a non-clinical consulting room enhanced participants' sense of emotional well-being compared with off-white colours. Generally, reddish colours have been shown be associated with emotional arousal (and concepts such as warm, warning, angry, and anxiety) whereas blue and green have been shown to be associated with reduced arousal (i.e., openness, peace, and calmness). With regard to colour and immersion, important contributions have been made by Geslin *et al.* [34] and Roohi and Forouzandeh [35] in a number of experiments that demonstrate the design potential of colour and light in video game environments to effectively prompt people's psychological feelings, thereby leading to a high-level immersion as well as presence. In line with these observations, the arguments highlight immersion and presence as the key features of the VR experience, but there are questions as to how well this experience is fully understood or whether there is further potential to improve the design.

Researchers have also found that people's psychological and physiological reactions to colour stimuli in real-world environments vary depending on the context in which the colour is presented [36-39]. For instance, the use of Baker-Miller Pink in a painted room significantly lowers state anxiety [40]. However, there is no lasting influence on state anxiety when in pained prison cells [41]. One possible explanation for this fact is that human's photoreceptors' (cones and rods) distribution is nonuniform across the human retina, colour vision in the peripheral retina is therefore changed from colour vision in the fovea [39]. In that case, people's emotional responses to a colour stimulus can differ depending on the context, which means that discoveries from experiments in the real-world environment cannot necessarily be generalised to explain how people experience colour in immersive VR environments.

In the context of VR, existing colour and light research has been mainly concerned with better understanding human visual experience [42-44]. For example, Chamilothori, Wienold and Andersen [42] compared user experiences between the real and virtual environments. They cited a range of existing research that identifies 'user interaction', 'visual perception', and 'immersion' as the key important elements when replicating real-world environments within VR [45-48]. Their experiment simultaneously evaluated five aspects of subjective perception of daylit spaces: the perceived pleasantness, interest, excitement, complexity, and satisfaction with the amount of view in the space. In line with our work, Chamilothori's study focuses on exploring the impact of the immersive qualities of VR and how this experience compares to the real-world context with colour and light as triggers for emotional response. Both studies help support and better understand the potential of VR based research as a means to better understand human behaviours. VR also offers critical benefits in terms of experimental design. Some researchers have studied temperature–colour interaction in both the real-world laboratory setting and the identical VR environment with the use of daylight as triggers. Participants' subjective (i.e., thermal, visual, and overall perception) and physiological (i.e., heart rate, electrodermal activity, and skin temperature) responses were simultaneously evaluated and daylight colour significantly affected thermal perception in the VR setting [43]. On the other hand, it has been argued that participants' reactions to daylight colour in the real-world and VR settings were different. There has been also research to explore alternative media (VR, photo, and video) to present physical light environments [44]. They designed experiments to compare human subjective feeling towards the physical lighting environment and three identical lighting environments delivered via VR, photo and video, and suggest that human subjects are most satisfied with VR reproductions. Although many experiments have used VR technology to study colour and lighting, there has been limited research exploring the question of how human emotional responses to immersive colour stimulations in the context of VR compared with the real-world settings.

Previous colour research has demonstrated the vital visual design elements of colour and light, as fundamental components of visual attributes that affect people's arousal and can influence their emotions [1-2,32]. However, it is not clear whether people's responses to colour stimulations can be better triggered in VR systems. Our first hypothesis is that emotional responses can be affected by different coloured lighting conditions, in line with previous findings [1-2,29,49]. Our second hypothesis is that in a VR replica of the same environment, participants' would have similar, but not the same, emotional responses to those evoked by colour stimulations produced by real environment. Here, we report experiments to investigate if the VR technology can trigger similar human emotional responses to immersive colour environments compared to the real world. An immersive real-world environment utilising LED lighting is used and compared with a replica VR.

Experimental

Participants and ethics

A total of ten participants (23–42 years old, median = 24), five females and five males, were invited to participate in the experiment. All were university students and none had any colour science training before the experiment was conducted. No participants reported any medical or visual disabilities and all were required to report their daily consumption of nicotine, caffeine and alcohol. The study was approved by the University of Leeds Ethics Committee (ethics reference: LTDESN-097). After a careful study of the experiment description, all participants provided written informed consent prior to the experiment. All participants had the right to withdraw at any time without any reason. Participants' data and personal identities have been kept anonymous.

Experimental design

A controlled colour environment (approximately 3.50 m, 3.43 m and 2.65 m) was illuminated using a Thouslite LED system. The lighting system equipped the laboratory with an immersive lighting environment allowed the control of the spectral properties of the illumination. Three coloured-lighting conditions were used across each experiment: white, red, and blue (see Figure 1). This study used red and blue because these two colours represent extreme ends of the visible spectrum and previous studies have shown that red and blue can differentially affect participants' alertness [49.50]. Luminosity across all conditions was set to be around 24 Lumi (7.6 lv), measured by the iPro X-rite (see Table 1). Other environmental conditions including air temperature, and humidity, furniture and layout settings, remained consistent, and all experiments were conducted in silence.

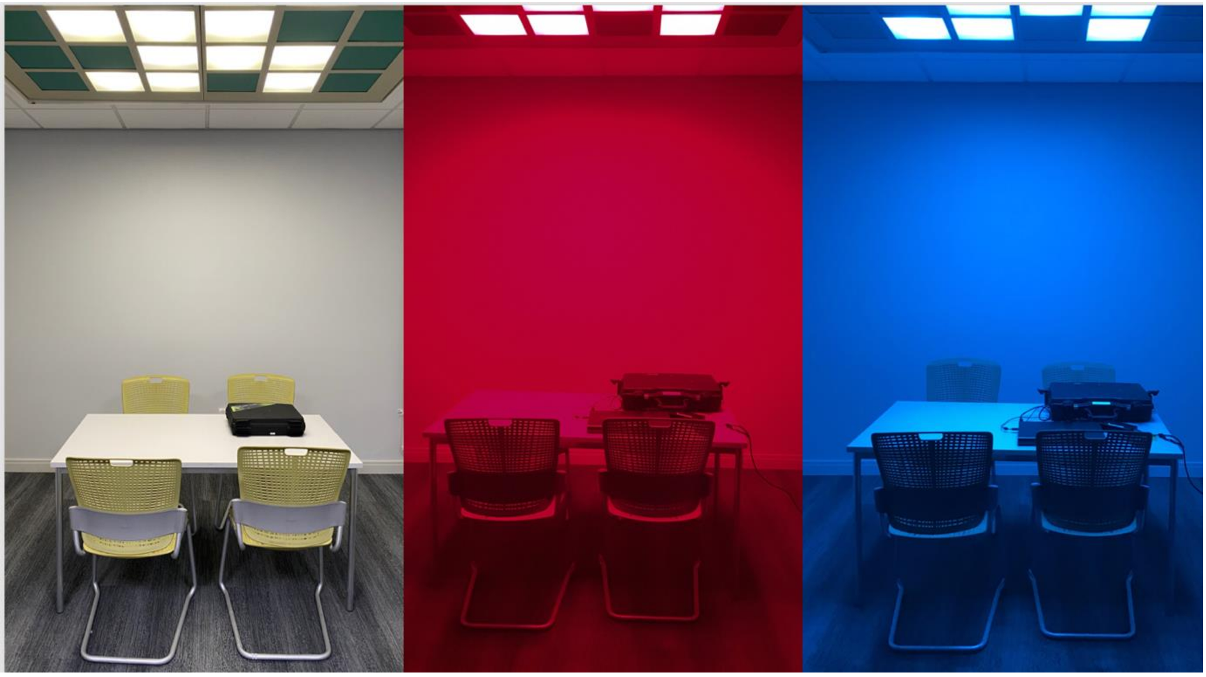

Figure 1: Three coloured-lighting conditions created with a Thouslite LED system. Note that the computer was not in the environments during either the physical or VR experiments.

	White		Red		Blue	
	PE	VR	PE	VR	PE	VR
CIE	X=0.3391 Y= 0.3554	X=0.3240 Y=0.3554	X=0.7140 Y=0.2821	X=0.7127 Y=0.2860	X=0.1515 Y=0.0281	X=0.1568 Y=0.0252
CCT	5240	5240	1000	1000	40000	40000
Lumi (CD/m^2)	24 (7.6)	25 (7.6)	24 (7.6)	24 (7.5)	24 (7.6)	24 (7.6)

Table 1: Colorimeter readings of the white, red and blue lighting conditions based on the wall colour in both the physical (PE) and virtual (VR) environments

An identical virtual colour environment was created using 3DS Max software (see Figure 2) and rendered as a high-dynamic-range (HDR) image and delivered through a head-mounted display (HMD) Oculus Go VR headset. The CIE chromaticities of the physical coloured-lighting conditions based on the wall colours were measured and exported by using the X-rite i1 Pro (Table 1), and the colour conditions of HDR images were adjusted by using Adobe Photoshop software (see Figure 3 for a comparison). However, participants' colour perceptions are subjective and can therefore be inconsistent. Therefore, a pre-experiment was conducted with extra five participants to confirm the colour and luminance consistency between the physical colour environment and the virtual colour environment, based on their visual perceptions.

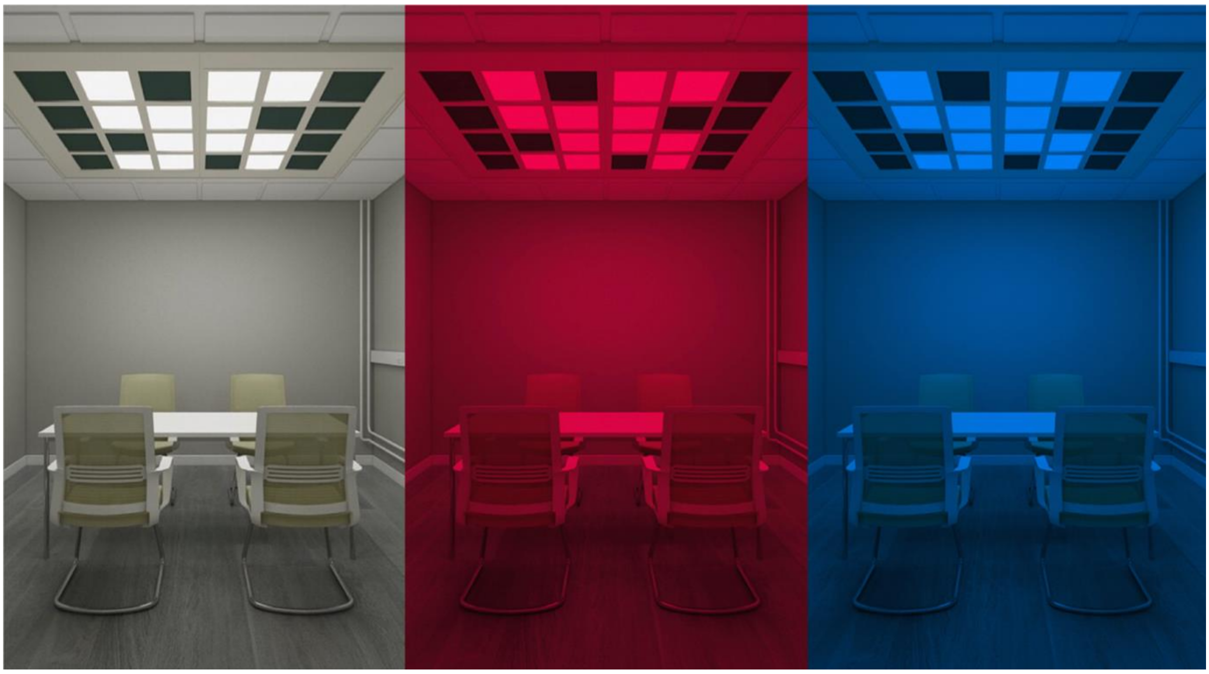

Figure 2: Virtual laboratory of lighting created with 3Ds Max software.

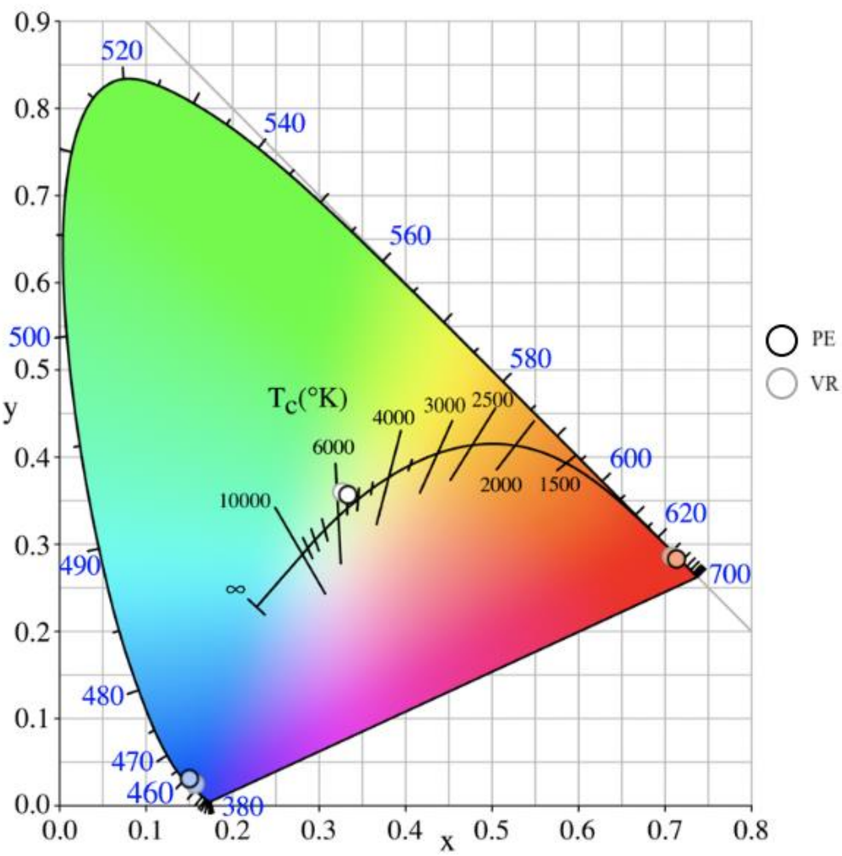

Figure 3: CIE1931 chromaticity diagram showing chromaticities for the white, red and blue lighting conditions in both the physical (PE) and virtual (VR) environments based on the wall colour.

Measures

Despite various methods to measure the colour influence on emotional responses, previous insights can be generally classified into two types: psychological (i.e., verbal scales, PANAS) and psychophysiological methods (i.e., GSR, EEG, heart rate) [16,52-54]. This study exploited three experimental techniques, namely 'Smiley face assessment scale', 'The PANAS Questionnaire', and Electroencephalography (EEG)'.

Smiley face assessment scale

The smiley face assessment scale used in this study was developed from the Meet me at MoMA project [54]. The survey used five faces with emotional expressions accompanied by descriptive text ranging from excited to depressed (Figure. 4). Previous studies have demonstrated the use of smiley faces can make the survey more enjoyable [54-55]. Moreover, since the PANAS assessment is more like a rigorous assessment on participants' perspective emotion feelings, requiring the participant to carefully read the question and think thoroughly before giving an answer, a "smiley face assessment" was employed to investigate a more "direct" and "intuitive" subjective response of the participants toward their emotions.

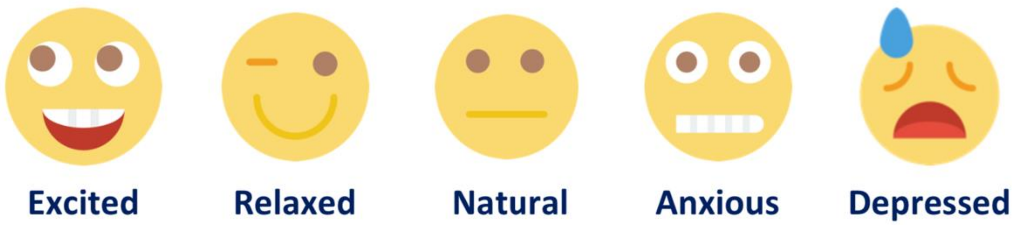

Figure 4: Smiley face assessment scale.

The PANAS Questionnaire

The Positive and Negative Affect Schedule (PANAS) is a self-rating scale designed to measure positive and negative emotions [56]. It has been widely applied in human well-being, psychological distress, mental disorders, stress and social activities [57]. PANAS consists of two scales: one for assessing the positive affect (PA) and the other for negative affect (NA). Each scale comprises ten items scored on a five-point Likert scale (from 'not at all' to 'very much'). NA reflects dispositional dimensions, with high NA epitomised by subjective distress and pleasurable engagement and low NA by the absence of such feelings [58]. In contrast, PA represents the extent to which an individual experiences pleasurable engagement in an environment [59]. Thus, emotions such as enthusiasm and alertness are indicative of high PA, while lethargy and sadness characterise low PA [60]. Moreover, both state and trait affects can be measured by the PANAS scale.

Electroencephalogram (EEG)

Since the accuracy and stability of data obtained via self-report methods from the participants are substantially low. A more objective method is thus employed to strength the measurement of emotional reactions to colour stimuli of this study. EEG is one of the most commonly used techniques to measure human physiological responses to object stimuli, such as music, light and film clips [61-62]. Efforts have been made to explore numerous biological signals for emotion recognition and classification. Furthermore, analyses of the single electrode have demonstrated the asymmetric activity at the frontal site of the brain, especially in the alpha band (8–12 Hz), which is associated with emotion [63-64]. For example, Ekman and Davidson [65] found that voluntary facial expressions of smiles of enjoyment are associated with higher left frontal activation, while Coan and Allen [66] found declined left frontal activity during the voluntary facial expressions of fear. Additionally, Davidson *et al.* [67] indicated that disgust causes less alpha power in the right frontal region, while happiness causes increase alpha power in the left frontal region. Moreover, previous research has revealed that the midline theta band power is related to mind-wandering effects and meditation states [66,68-69]. Fischer *et al.* [70] mentioned that an increase in scalp-wide theta activation could be explained as a mind-wandering effect. Given all of the above, in this study, the alpha power at channel F3 and the theta at channel Fz of the EEG headset were chosen as the single electrodes in the left frontal region for analysis (Figure 5).

In this study, the B-Alert Live system with active electrodes was used for EEG recordings. Electrodes were placed on participants' scalps, according to the international nine system, at Fz, F3, F4, Cz, C3, C4, POz, P3 and P4. Two extra electrodes were attached to both earlobes to serve as reference electrodes for those attached to the scalp. EEG data collected from nine electrode sites were averaged to produce overall EEG power, and then grouped into the following frequency bins: theta (3–7 Hz), alpha (8–12 Hz), beta (13–19 Hz), sigma (30–40 Hz). As shown in Figure 5, the electrode sites F3 and Fz were in the left frontal and midline of the brain, respectively and were therefore chosen.

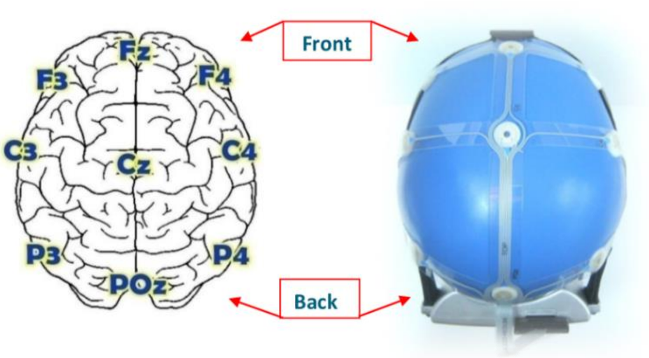

Figure 5: EEG headset.

Experimental protocol

Participants were invited to sit for 20 minutes under each of the three lighting conditions (sequenced as white, red and blue). Between the red and blue coloured-lighting session, there was a 15-minute break where the white lighting condition. The reason of the fixed order for colour stimuli was due to lack of evidence in previous studies that the extent of one's subjective feelings toward a certain type of emotion is independent of the previous emotion one poses and the extent of one's feelings toward it. A fixed order for colour stimulations in real world and the VR environment was designed to ensure the observations will not be affected if such dependences do exist. Moreover, the use of white first was to ensure that all participants had the same 'conditioning' under the white light at the start of the experiment. In the real-world experiment, participants were asked to complete the PANAS questionnaire via an iPad. One week later after the physical experiment, the same experiments were repeated in VR, and participants were asked to complete the PANAS questionnaire in the VR environment. A short mood and feelings test was applied before the PANAS questionnaire to measure participants' initial feelings to the white, red, and blue – coloured lighting conditions in both the PE and VR experiments. The EEG signals and HR of the participants were measured over the whole course of each experiment. During the data acquisition, all participants wore the wireless senor headset that acquired EEG from the bi-polar sensor sites F3–F4, C3–C4, Cz–POz, F3–Cz, Fz–C3, and Fz–POz.

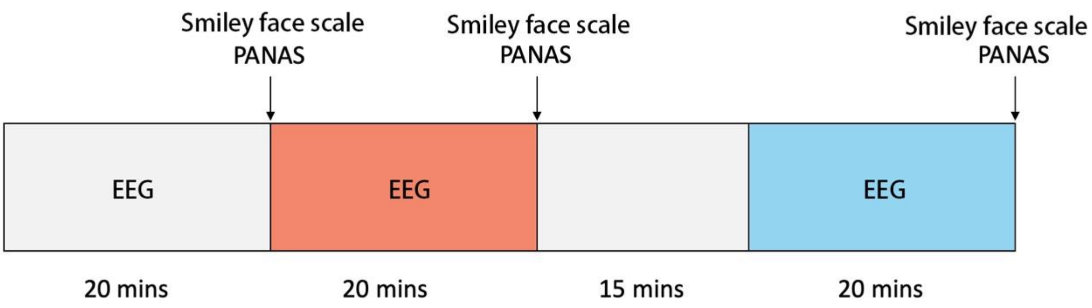

Figure 6: Experimental design.

Results

Statistical analysis was performed using Statistical Product and Service Solutions software. The t-test was conducted to show the statistical significance between the three coloured-lighting conditions and between the real world and the VR laboratory.

The smiley face assessment scale

Participants' mood responses to the white, red, and blue lighting conditions, in the PE and VR, are shown in Table 2. Specifically, almost all participants reported to have natural feelings under the white lighting condition, anxious feelings under the red lighting condition, and relaxed feelings under the blue lighting condition. This was true for both the PE and VR environments.

Image	Anxious	Depressed	Natural	Excited	Relaxed
PE					
White	-	-	8	1	1
Red	9	-	1	-	-
Blue	-	-	2	-	8
VR					
White	-	-	9	-	1
Red	9	-	1	-	-
Blue	-	-	1	-	9

Table 2: Numbers of participants' mood responses measured by the smiley face assessment scale to the white, red, and blue lighting conditions, in the PE and VR.

The PANAS

Figure 7 shows different trends between white, red and blue lighting conditions in both the PE and the VR environment with respect to the levels of positive and negative effects. The pairwise comparisons and effect size in addition to the statistical significance are listed in Table 3 and Table 5 (where * indicates statistical significance). In the real-world environment, participants under the red lighting condition showed a lower positive emotional response and a higher negative emotional responses compared with under the white lighting condition. People under the blue lighting condition reported a lower positive emotional response as well as lower negative emotional responses. Specifically, participants' positive emotions were shown to be lower under the blue-coloured lighting ($M = 18.50$, $SD = 9.43$) environment than under the white lighting ($M = 21.80$, $SD = 9.24$) environment ($t(9) = 3.03$, p

= 0.014, d = 0.35 > 0.2). Meanwhile, participants' negative emotions were higher in the red-coloured lighting (M = 19.30, SD = 8.35) environment than in the white (M = 13.30, SD = 2.75) (t(9) = -2.67, p = 0.026, d = 0.97 > 0.2) and the blue-coloured lighting (M = 13.30, SD = 2.75) environment (t(9) = 2.78, p = 0.021, d = 0.97 > 0.2). Interestingly, subjects' positive emotions were significantly lower in the white lighting environment in VR (M = 18.60, SD = 8.03) than the identical white lighting (M = 21.80, SD = 9.23) environment in PE (t(9) = 2.35, p = 0.044, d = 0.37 > 0.2).

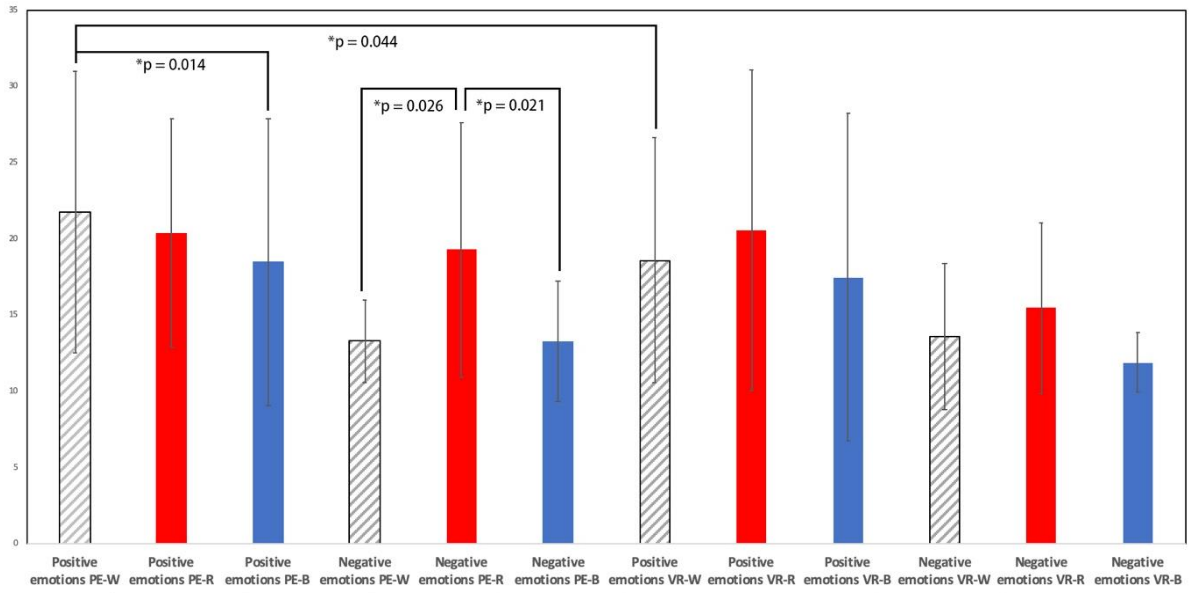

Figure 7: Participants' positive and negative emotions measured by PANAS under white (patterned bars), red (red bars), and blue (blue bars) lighting conditions in the PE and the VR. The bars represent mean changes, while the error bars are the standard error of the mean across individual participants.

Pairs	Significance*	Pairs	Significance*
P_PE_W & P_PE_R	0.438	N_VR_W & N_VR_R	0.387
P_PE_W & P_PE_B	0.014*	N_VR_W & N_VR_B	0.290
P_PE_R & P_PE_B	0.174	N_VR_R & N_VR_B	0.068
N_PE_W & N_PE_R	0.026*	P_PE_W & P_VR_W	0.044*
N_PE_W & N_PE_B	1.000	P_PE_R & P_VR_R	0.885
N_PE_R & N_PE_B	0.021*	P_PE_B & P_VR_B	0.273
P_VR_W & P_VR_R	0.161	N_PE_W & N_VR_W	0.815
P_VR_W & P_VR_B	0.633	N_PE_R & N_VR_R	0.263
P_VR_R & P_VR_B	0.152	N_PE_B & N_VR_B	0.268

*Statistically significant ($p \leq 0.05$)

Table 3: Responses in participants' positive (P) and negative (N) emotions measured by the PANAS under white (W), red (R), and blue (B) lighting conditions, in the PE and VR. The table presents pairwise comparisons for the PANAS scores.

EEG

The B-Alert Live system with active electrodes was used for EEG recordings. Electrodes were placed on participants' scalps according to the international 9 system at Fz, F3, F4, Cz, C3, C4, POz, P3 and P4. Two extra electrodes were attached to both earlobes to serve as reference electrodes for those attached to the scalps. EEG data were gathered using the B-Alert Live Software (BLS) as well as a wireless Advanced Brain Monitoring (ABM) EEG headset. The post-processed Z-score theta power at the channel Fz and alpha power at the channel F3 were analysed, respectively. Note that channel F3 of the B-Alert Live system headset was one of the electrodes at the frontal site, and Fz was one of the electrodes at the midline of the brain. To remove individual variability from various metrics, the Z-score was calculated on the mean and standard error of the mean for at least the first five seconds, with additional epochs (seconds) added. The t-test was performed to show the statistical significance of the differences between lighting conditions and environments (Table 4 & 5) (where * indicates statistical significance).

Different trends between white, red, and blue lighting conditions, in both the PE and the VR, are displayed in Figure 8. In the real-world environment, the normalised alpha range at the channel F3 was shown to be lower under the blue-coloured lighting ($M = 0.32$, $SD = 0.21$) environment than that under the white-coloured lighting ($M = 0.12$, $SD = 0.85$) environment ($t(9) = 3.15$, $p = 0.012$, $d = 0.32 > 0.2$). This implies that the alpha range at the channel F3 was significantly affected by the blue light. In VR, a very significant increase of theta power at the channel Fz was found between the white ($M = 0.12$, $SD = 0.23$) - and blue-coloured-lighting ($M = 0.23$, $SD = 0.78$) environments ($t(9) = -3.70$, $p = 0.005$, $d = 0.19 < 0.2$). However, the effect size ($d = 0.19 < 0.2$) showed no statistical difference in this range. Furthermore, participants' alpha range under the blue-coloured lighting environment was higher in the VR ($M = 0.26$, $SD = 0.20$) than in the PE ($M = 0.12$, $SD = 0.85$) ($t(9) = -2.26$, $p = 0.050$, $d = 0.23 > 0.2$). However, no statistical significances were detected in other coloured-lighting environments in either the PE or the VR.

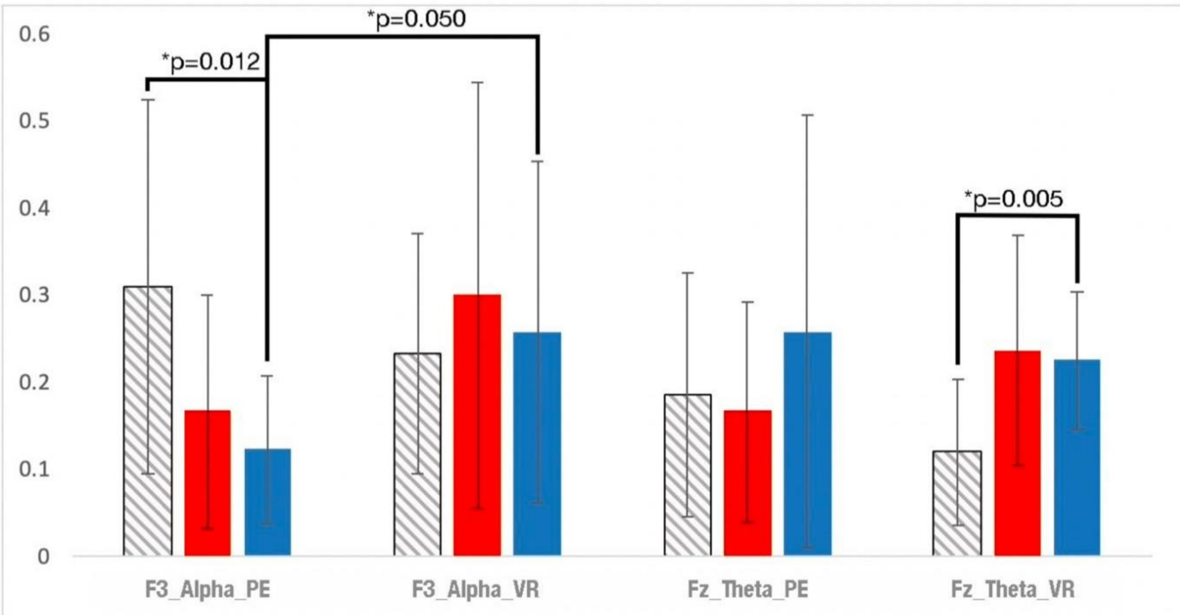

Figure 8: Ten participants' mean, ± standard error of the mean, normalised EEG power alpha (8–12 Hz) and theta (3–7 Hz) frequency ranges at the F3 and Fz channels, under white (patterned bars), red (red bars) and blue (blue bars) lighting conditions in both the PE and the VR during the last 15 minutes.

Pairs	Significance*	Pairs	Significance*
Alpha_PE_W & Alpha_PE_R	0.102	Theta_PE_W & Theta_PE_R	0.757
Alpha_PE_W & Alpha_PE_B	0.012*	Theta_PE_W & Theta_PE_B	0.411
Alpha_PE_R & Alpha_PE_B	0.059	Theta_PE_R & Theta_PE_B	0.376
Alpha_VR_W & Alpha_VR_R	0.511	Theta_VR_W & Theta_VR_R	0.104
Alpha_VR_W & Alpha_VR_B	0.686	Theta_VR_W & Theta_VR_B	0.005*
Alpha_VR_R & Alpha_VR_B	0.562	Theta_VR_R & Theta_VR_B	0.668
Alpha_PE_W & Alpha_VR_W	0.219	Theta_PE_W & Theta_VR_W	0.285
Alpha_PE_R & Alpha_VR_R	0.108	Theta_PE_R & Theta_VR_R	0.225
Alpha_PE_B & Alpha_VR_B	0.050*	Theta_PE_B & Theta_VR_B	0.712

*Statistically significant ($p \leq 0.05$)

Table 4: Ten participants' brain activities as measured by the EEG system under white (W), red (R), and blue (B) lighting conditions in the PE and VR. The table presents pairwise comparisons for the mean normalised EEG power alpha (8–12Hz) and theta (3–7Hz) frequency ranges in the channels F3 and Fz.

Pairs	Significance*	Effect size (Cogen's d)
P_PE_W & P_PE_B	0.014*	0.35*
N_PE_W & N_PE_R	0.026*	0.97*
N_PE_R & N_PE_B	0.021*	0.97*
P_PE_W & P_VR_W	0.044*	0.37*
Alpha_PE_W & Alpha_PE_B	0.012*	0.32*
Alpha_PE_B & Alpha_VR_B	0.050*	0.19
Theta_VR_W & Theta_VR_B	0.005*	0.23*

*Statistically significant ($p \leq 0.05$)

Table 5: The table presents statistical significance of pairwise comparisons and effect size for the PANAS scores and EEG. T-test conventional effect sizes was proposed by Cohen [71], where 0.2 (small effect), 0.5 (moderate effect) and 0.8 (large effect). white (W), red (R), and blue (B) lighting conditions; positive (P) and negative (N) emotions,; Physical environment (PE), Virtual reality (VR).

Discussion

This study investigated human subjective and objective responses to different coloured lighting environments, first in a physical laboratory and then in an identical VR environment, using three experimental techniques.

Analysis of the smiley face assessment scale indicated that participants' subjective emotional responses were shown to be affected by the coloured-lighting conditions in both real-world and virtual environments. For the smiley face assessment scale, for both the PE and VR, most participants' reported natural feelings under the white lighting condition, anxious feelings under the red lighting condition, and relaxed feelings under the blue lighting condition. Pairwise comparisons revealed significant differences in participants' emotions between white and red, white and blue, and red and blue lighting conditions for both PE and VR.

With regard to the PANAS, in the PE, we found that participants' positive emotions were significantly lower in the blue lighting environment than in the white lighting environment. We also found that participants' negative emotions were significantly higher in the red-coloured lighting environment than in the white and blue lighting environments. However, no statistically significant differences in emotions were found between the coloured lighting conditions for the VR. This contrasts with the data from the smiley-face scale where there was an effect of coloured lighting in the VR. We do note that the red environment gave higher positive and negative emotions in the VR (in agreement with the PE data) but that the differences were not statistically significant. We cannot rule out that the sample size was insufficient to reliably detect differences in the VR case. We only used ten participants and some further work might be needed to definitively conclude whether there are really differences between VR and PE. Certainly, the smiley-face data suggest no such differences. However, the smiley-face and PANAS data do not necessarily contradict each other because there are almost certainly measuring different types of emotional responses. Interestingly, a significant difference in response to the white-coloured lighting condition was detected between the PE and VR with a stronger positive emotional response in the PE than in the VR.

Our finding (based on PANAS) that the red environment is associated with people's negative feelings in the PE supports Jacobs and Suess [2], who reported that red colours are associated with negative feelings such as anxiety, anger, and annoyance. Our findings are also consistent with Lewinski [72] that red colours are associated with unpleasant feelings. Moreover, it has been agreed and observed in many studies that arousal difference effects could be observed that the red end of the spectrum increasing arousal [29,73-74]. We also found that participants' positive emotions were lower in the blue lighting environment than in the white lighting environments; many previous studies have indicated that blue is associated with relaxation and calmness [2,72,75]. The results to some extent could be explained in prior studies that demonstrated the blue reducing arousal [74,76]. Combined with the results of the smiley face assessment scale together, both results to some extend agreed that different effects of arousal could be observed that the red end of the spectrum increasing arousal and the blue reducing arousal [2,29,43].

In terms of EEG, the results between the VR and PE environments are not very similar (see Figure 8). However, we did find some statistically significant effects. In the PE, the normalised alpha range for channel F3 system was significantly lower under the blue lighting condition (compared with the white lighting condition) which could indicate reduced arousal in the blue environment. This reduced arousal under the blue environment is broadly consistent with the lower positive and negative emotional responses found in the PANAS under the blue PE environment. Both are consistent with previous research that blue reduces arousal [2,29,77-78]. It has previously been observed, negative feelings like disgust cause lower alpha power in the left frontal region [67].

In the identical VR environment, we found that participants' theta range at the channel Fz was shown to be higher in the blue lighting environment than in the white lighting environment. A recent study show has shown that an increase of theta power in the frontal midline is associated with pleasant music [79]. Fischer, Peres and Fiorani [70] showed that an increase to scalp-wide theta activation could be explained as a mind-wandering effect. Previous research has also revealed that the midline theta band power is related to mind-wandering effects and meditation states [64,68-69]. As such, our results suggest that participants feel relatively more calmed and relaxed under the blue lighting condition than under the white lighting condition in VR. This result concurs with the smiley face assessment scale and is somewhat consistent with the decreased arousal found in the PE.

Participants' paired t-test results also showed statistical significance in the normalised alpha range at the channel F3 under blue lighting conditions between the real-world and VR. Given that the participants' theta power at the Fz channel was shown to be higher in the blue lighting conditions than white in the VR. All these explanations could give the direction concerning the design potential of colour and light to enhance the level of immersion and presence, as well as influence people's emotion and cognition might be better delivered through VR systems than other mediums. However, the impacts of blue lighting conditions between the PE and VR are shown to have no statistical significance in the normalised theta ranges at channel Fz, which might be due to the limited sample size.

Conclusions

In summary we found an effect of coloured-lighting environment in both the PE and VR conditions. The smiley-face data agree strongly and there is some agreement between the PE and VR data for the EEG experiment. However, the PANAS data showed a statistically significant effect of colour in the PE but not in the VR. The discrepancy between the PANAS data and the other two experiments may be because there were only 10 participants. Further experiments will be performed in the future to expand our findings. Secondly, the order in which the participants experienced the PE and the VR was not randomised but interestingly there was no significant effect of order in the analysis. As suggested by previous VR studies [80-83], as a relatively new technology, VR may stimulate people's curiosity in exploring a new space, and further mobilise enthusiasm, which will improve the learning effect. A fixed order for participants to view the real-world environment first was therefore designed to ensure the observations will not be affected by new curiosity as it would already be a familiar environment. The learning effect is arguably important for more evaluative-based studies.

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