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APPLICATION OF VIRTUAL REALITY TO ASSESS THERMAL, VISUAL PERCEPTION, AND USERS' ADAPTIVE BEHAVIORS FOR SEDENTARY ACTIVITIES

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SUMMARY: *VR technology has shown to effectively explore the psychological and physiological effects of the built environment on users. This study investigates multisensory integration using VR technology, focusing on same-modal and cross-modal effects during sedentary activities. A survey-based approach was employed to collect data from participants within a controlled climate setting. A virtual replica of Monash Makerspace was developed to assess its thermal, visual impact, and behavioral responses. The results revealed significant differences in the same modal effects, however, no significant differences in cross-modal effects were observed regarding the influence of visual stimuli on thermal sensations, preferences, and comfort. Conversely, cross-modal effects of thermal conditions on visual perceptions demonstrated significant differences in visual sensation and comfort, except for visual preferences. Furthermore, there was no significant difference in physiological responses between IVEs and among thermal conditions. The findings indicate that warm yellow lights are only suitable and comfortable for users during cool temperatures. In contrast, cool white light was most preferred and comfortable across conditions for users. A small number of participants preferred the lighting in between the two visual scenarios evaluated. The insight can inform the design of new buildings and retrofitting of existing ones to accommodate user comfort, particularly given that Australian buildings maintain indoor thermal conditions between 18ºC to 30ºC across seasons. Nevertheless, the study has some limitations, including that participants were exposed to these visual scenarios and thermal conditions for a short duration, which does not represent the long-term adaptation effects. Also, the study was conducted using students within the age bracket of 18-40 years, limiting the generalizability of the findings to younger or older groups.*

KEYWORDS: *Buildings, Thermal comfort, User adaptive behavior, virtual reality, virtual environment.*

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1. INTRODUCTION

In recent years, technological innovation has moved rapidly at an unprecedented pace, bringing revolution to the ways we perceive, interact, and experience our surroundings. Among these technological advancements is Virtual reality (VR), which enables users to fully immerse themselves in a computer-generated 3D environment (Kim et al., 2013). Through Virtual reality, users can hear, see, and interact with simulations that closely mimic real environments. The high level of immersion makes VR makes it not just a tool for visualization but also for interactions and learning

The potential of cutting-edge technology (VR) cuts across different industries such as entertainment, gaming, education, training, healthcare, architecture, engineering, and construction (AEC) (Davila Delgado et al., 2020). This gained widespread popularity in entertainment and gaming, but today it is now incorporated in education, health for immersive learning experience, training, safe and practice environment. In the AEC sector, it has brought revolution to the visualization of design, innovation, coordination, and collaboration among stakeholders

This technology has emerged as a low-cost, effective, and flexible tool for conducting repeatable experiments across a wide range of variables, which aid in understanding complex phenomena (Latini et al., 2023a). An immersive virtual environment provides an alternative means of manipulating factors such as lighting, acoustics, and spatial elements. The ability of VR technology to simulate different conditions helps experts to properly evaluate the strengths and weaknesses of design options, which facilitates better informed decision-making for stakeholders (Du et al., 2018, Lin et al., 2018). Importantly, these groundbreaking technologies are not only restricted to the design and construction. VR also plays a crucial role in assessing existing buildings, which allows for studying thermal comfort, visual comfort, and behavioral actions in the virtual world. VR holds immense potential as it continues to expand the boundaries of human perception, interaction, and experience in virtual environments (Zhang et al., 2020). With rapid advancements in technology, VR has growing applications in exploring human comfort perception and behavior in the built environment.

There is a growing interest in studying mutual interactions within the indoor environment as individuals experience the environment holistically with multiple sensory stimuli simultaneously influencing their perception, behavior, and overall comfort. Immersive Virtual Environments (IVEs) have predominantly focused on a single domain, particularly visual conditions, to investigate the effects of different building design elements in buildings on users' comfort and behaviors (Saeidi et al., 2015, Saeidi et al., 2018, Chamilothori et al., 2019, Carneiro et al., 2021, Abd-Alhamid et al., 2020, Latini et al., 2023a). These studies advanced our understanding of the impact of lighting, views, and spatial elements on users' experience. Recently, researchers have begun to expand their focus to multi-domain by leveraging VR technology to test variables. Some notable research in this space that investigated visual conditions, i.e, daylight levels and the Hue-Heat Hypothesis, with thermal conditions (Ozcelik et al., 2019, Chinazzo et al., 2020). Despite these advancements in research, there remains a significant gap concerning the application of VR in studying multi-domain interactions involving artificial lighting.

By addressing this research gap, this study aims to explore the effect of multisensory integration on thermal, visual perception, behavioral intentions, and physiological responses during sedentary activity. This study will investigate users' perceptual experiences within IVEs, considering the same modal (visual-visual, thermal-thermal) and cross-modal (visual-thermal, thermal-visual) effects; explore the impact of users' physiological responses in IVEs, and examine user adaptive behavioral strategies for varying conditions in IVEs. The multi-domain aspects that will be examined include two visual scenarios (Cool white and Warm Yellow light simulation) across three controlled thermal environments (18ºC, 24ºC, and 30ºC). This seeks to comprehend perceptions, behaviors, and physiological responses (Wang et al., 2018, Te Kulve et al.).

The rest of the paper is as follows: Section 2 reviews existing literature on applications of VR in the study of thermal comfort, visual comfort, and occupant behaviors within the built environments by highlighting key findings and identifying gaps. Section 3 discusses the methodological framework adopted for the experimental study, including experimental design, setup, measurement tools and procedures, while Section 4 presents the results obtained, in-depth discussion, its relation to existing theories and previous research, and their implications. Section 5 describes the conclusion by summarizing key insights, limitations encountered, the generability of findings, and proposes an area of future research

2. LITERATURE REVIEW

2.1 Trends of VR application for thermal, visual perception, and Adaptive behavioral Strategies

VR has emerged as a powerful immersive and visualization tool that has been widely adopted across built environment research. This application spans single domains (visual or thermal), validation of simulated environments against real environments, and multi-domains (visual and thermal; thermal and acoustic; visual and acoustic; air quality and visual) for built environments. In the context of a single domain, VR was adopted to comprehend users' responses to isolated indoor environmental factors. For example, (Heydarian et al., 2014) used VR to investigate reading/task performance under two visual conditions. Similarly, VR has been applied to explore users' visual preferences (Heydarian et al., 2017), and satisfaction under various visual/lighting scenarios (Mahmoudzadeh et al., 2021). Beyond this, researchers have utilised VR to examine users' thermal perceptions, which allows participants to experience different thermal environments (Yeom et al., 2019, Salamone et al., 2020, Latini et al., 2023a). VR has also served as an effective validation tool to compare virtual simulations with real environmental conditions (Rockcastle et al., 2021, Latini et al., 2023b).

Conversely, VR has been instrumental in examining behavioral actions in response to environmental stimuli. Studies have been conducted to investigate thermal adaptive behaviors, including clothing & thermostat adjustment, fan use, and so on (Latini et al., 2023b, Latini et al., 2023a, Saeidi, 2016, Saeidi et al., 2018). Lighting-related behaviors research was conducted, which included users manipulating shading and lighting controls (Heydarian et al., 2016, Mahmoudzadeh et al., 2021). The above studies have utilized either a between-subjects or a within-subjects design for their experiments. In between-subjects designs, participant numbers varied widely, ranging from 1 to 160 individuals, whereas within-subjects designs have engaged sample sizes between 17 and 25 participants.

Regarding multi-domain studies, a small number of works have explored multi-sensory factors. Chinazzo et al. (2020) employed VR to study the impact of visual conditions (color glazing) on thermal, visual perception, and physiological responses. Also, Ozcelik et al. (2019) investigated the combined effects of thermal and visual discomfort stimuli in virtual office environments. Based on previous extant studies, few studies have examined the multi-domain aspect using VR (Alamirah et al., 2022) conducted a systematic review, which highlighted that a limited number of studies have been conducted in multi-domain research, which indicates a significant need for further exploration. However, despite these efforts, there remains a notable gap in the literature regards multidomain applications of VR

To address this gap, the study seeks to deepen the understanding of multisensory interactions by examining the combined effects of various visual and thermal conditions on visual and thermal perceptions, behavioral intentions, and physiological responses during sedentary activities. The study adopts a within-subjects experimental design in a detailed and controlled comparison across various environmental conditions, aiming to provide insights into users' experience within immersive virtual environments.

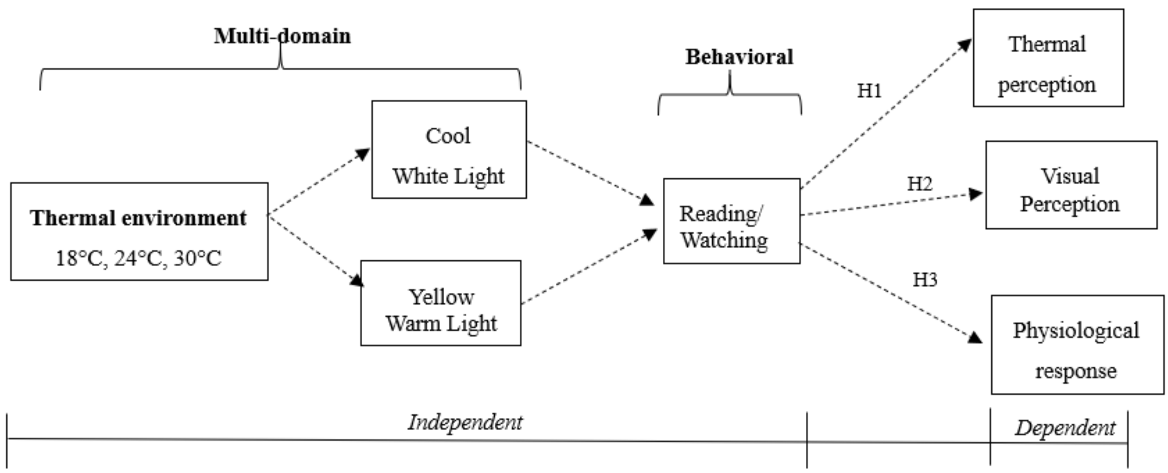


Figure 1: Conceptual model for IVE hypothesis testing.

2.2 Research hypotheses

From the identified objectives, the following were hypothesized

Ho1: There is no significant difference between the physiological responses in the IVEs (warm yellow light and cool white light) for sedentary activity

Ho2: There is no significant difference between thermal perception in the IVEs (warm yellow light and cool white light) for sedentary activity

Ho3: There is no significant difference between the visual perception of IVEs (warm yellow light and cool white light) under different thermal conditions for sedentary activity

3. MEHODS

3.1 VR Model and Climate Chamber

The existing BIM of Makerspace was utilized to create a realistic 3D virtual environment. The model was imported into 3D Max to incorporate missing objects and refine the scene. The refined model was exported to Unity for VR development, HP Reverb G2 VR Headset was deployed due to its high resolution level (Bellazzi et al., 2022, Mukhopadhyay et al., 2022). Lighting conditions were simulated within the virtual environment to represent two correlated color temperatures, i.e., 3000K (Warm Yellow Light, WYL) and 6000K (Cool White Light, CWL). These CCTs were translated into RGB values for proper visualization in Unity. WYL was represented by RGB values of 255, 124, and 38, while CWL was represented by RGB values of 255, 252, and 224.

C# scripts were developed in Unity to enable user interaction, which includes functions like rotating virtual fans, teleportation, avatar movement, spawning human characters, and toggling a virtual heater (Arowoiya et al., 2025a). To engage users, reading materials were displayed on a virtual computer screen while audiovisual content was attached to separate game objects to simulate realistic listening and viewing tasks within the environment.

The experiments were carried out in a climate-controlled chamber, where ambient temperatures were adjusted to 18ºC, 24ºC, and 30ºC for the testing room, while a constant 22 ºC was maintained in the waiting room (Dawe et al., 2020). Each lighting scenario (WYL and CWL) was tested across the three thermal conditions to examine users' thermal and visual perception, as detailed in Table 3. Behavioral intentions of users were recorded at each thermal condition to explore adaptive responses. Environmental variables were monitored to ensure this is similar to real-world indoor conditions. Relative humidity was tracked using a WBGT SD card data logger and maintained between 30%-60%, and air velocity was controlled at 0.1 m/s. NEMo sensor was used to collect environmental parameters such as C02 in the climate chamber.

3.2 Procedure for IVE Testing, Data Collection, and Analysis

This study employed a repeated-measure experimental design to examine users' physiological and perceptual responses within IVE settings. The required sample size was calculated using the G*Power software, assuming a medium effect size of 0.5. Based on this calculation, twenty-four (24) participants were recruited through direct mail and one-on-one approaches. Approval was obtained from Monash Human Ethics before the experiments (Project ID = 36957). All participants were invited into the climate chambers for the experiment conducted under controlled thermal and visual conditions. To ensure consistency in the observations, a uniform clothing insulation was implemented; participants were asked to wear long-sleeved shirts and trousers (0.61 clo).

Subjective data were collected based on participants' reported perceptions during VR experiments. Within the virtual environment, textual cues were displayed relating to various thermal and visual perceptions, including but not limited to Hot, Warm, Cooler, Comfortable, Uncomfortable, and very warm (Arowoiya et al., 2025b). The participants' responses were recorded using the questionnaire on visual, thermal states, and behavioral intentions in response to environmental perception. Some behavioral options were interactable in the virtual space (such as a virtual fan and virtual heater to select), while others were either selected or implemented in the real world, like thermostat adjustment. Physiological responses, i.e., heart rate, were recorded every one-minute intervals using a Fitbit Versa 3 smart watch throughout each experimental session. The data were exported in a JSON file and organized for each participant's heart rate analysis.

Thermal Sensation Votes (TSV), Thermal Comfort Votes (TCV), Thermal Preferences votes (TPV), Visual Sensation Votes (VSV), Visual Preference Votes (VPV), and Visual Comfort Votes (VCV) were visualized using a 100% stacked column bar chart to show the distribution of subjective responses. Following the Shapiro-Wilk test ($p<0.05$), the data were revealed to be non-normally distributed; hence, non-parametric tests were used for inferential analysis.

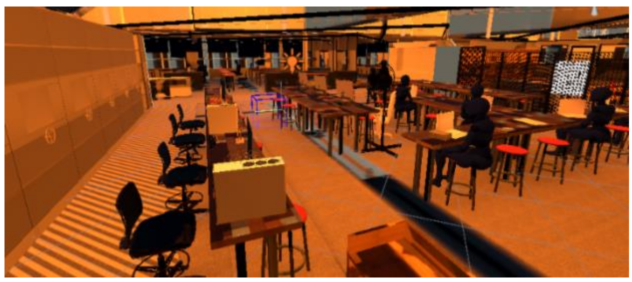
Specifically, the Mann-Whitney U test was applied to compare two groups (e.g., WYL and CWL) for differences in thermal perception and physiological responses during sedentary activities. Also, the Kruskal-Wallis test was used to analyse differences across multiple thermal conditions. A 5% significance level ($p < 0.05$) was used as a threshold to determine whether to accept or reject the null hypothesis in the statistical analysis. Finally, behavioral intentions of users, simulation sickness, and user experience were analyzed through a bar chart.

Table 2: Instruments for measuring environmental parameters in the Chamber.

Environmental Parameters	**Name of the instrument (Detection/Sensor)**	**Range**	**Accuracy**	**Placement of the sensor**	**ASHRAE 55 Standard/ISO 7726**
1. Carbon dioxide	NEMo (NDIR)	0 to 5000 ppm	± 50 ppm (± 3 % of reading value)	Center of the testing room at 1.2 m high	<1000ppm
2. Relative Humidity	NEMo (Capacitive)	0 to 95 %	± 3 % between 11% and 89%	Center of the room at 1.2 m high	30% -60%
3. Mean radiant temperature	WBGT SD card data logger	32F-176F (0ºC to 80 ºC)	±0.6 ºC	Center of the room at 1.2 m high	Prevent asymmetric radiation
4. Air temperature	NEMo (CMOS)	-55°C to +125°C	± 2°C between -25°C and 100°C	Center of the room at 1.2 m high	18 ºC, 24 ºC and 30 ºC

(a)

(b)

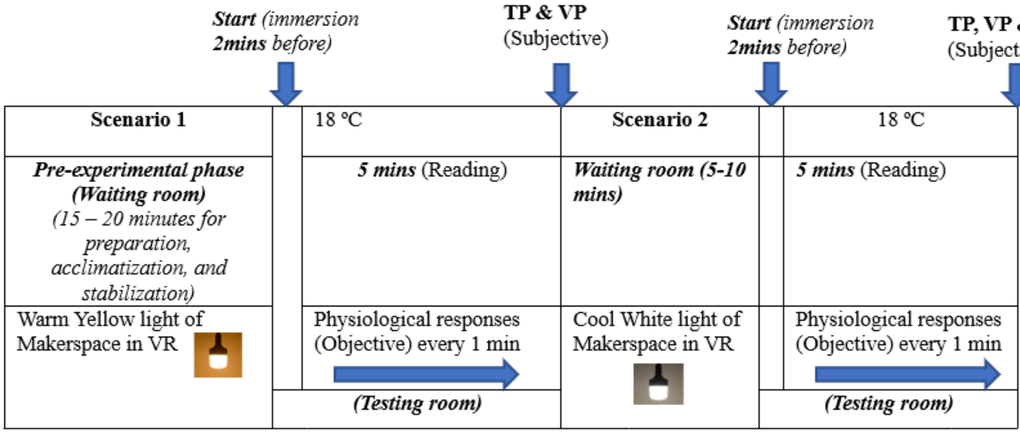


(c)

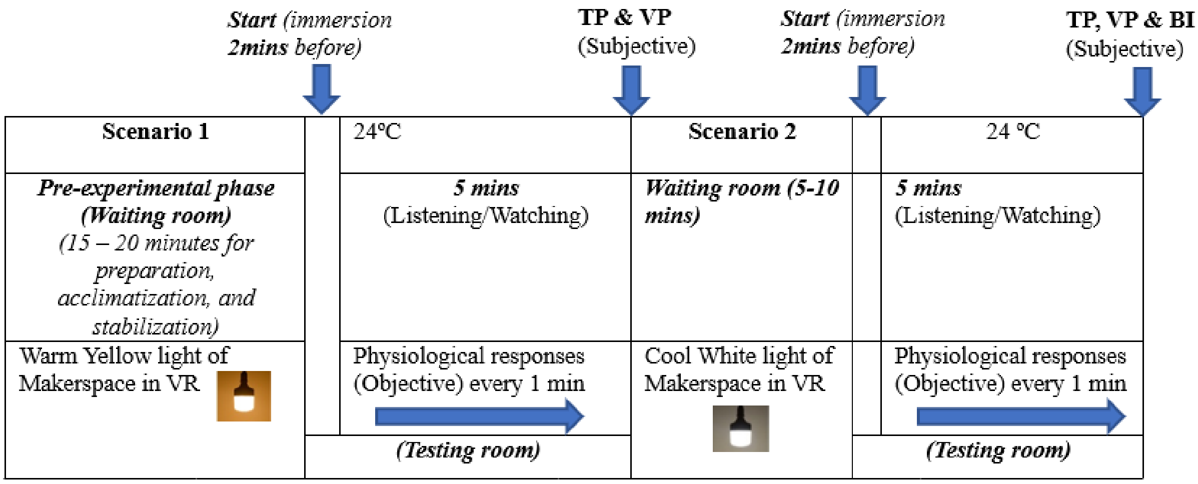
Figure 2: Participants carrying out reading/watching activity (a), and the VR environment with simulated cool white light (b), warm yellow light (c).

Table 3: VR Experimental design for sedentary activities.

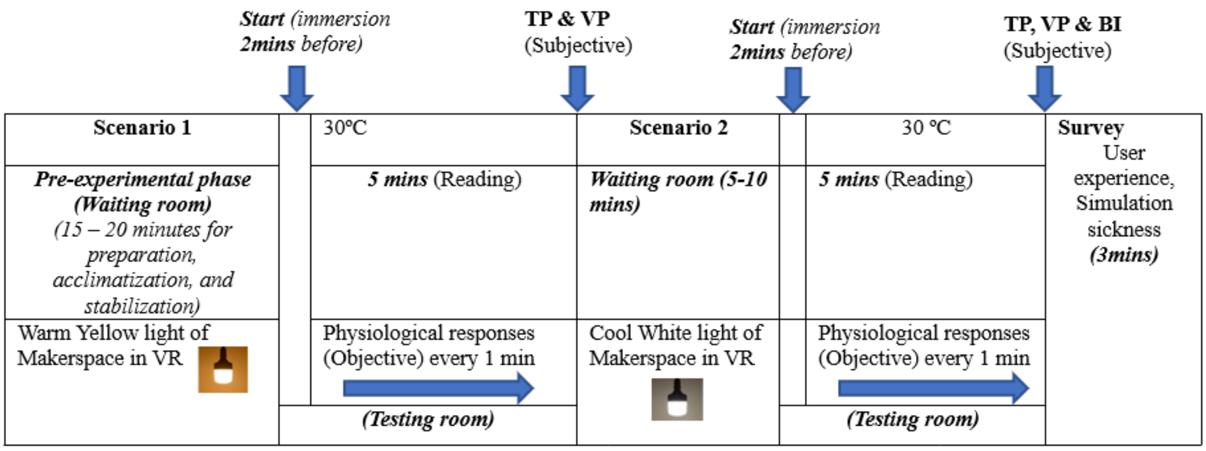
Experiment A



Experiment B



Experiment C



Legend: TP – Thermal Perception **VP –** Visual Perception **BI –** Behavioral Intentions

4. FINDINGS AND DISCUSSION

4.1 Demographic Information

The demographic characteristics of participants are shown in Figure 3a- 3d. The total of 62.5% identified as male, while 37.5% identified as female, as shown in Figure 3a. In terms of academic level, the majority of participants were postgraduate students with 70.84%, whereas undergraduates comprised 29.16% of the population, as indicated in Figure 3b. Ethnic group distribution revealed that the sample was predominantly Asian, which accounts for 70.83% of the population. Other ethnic groups include 8.13% of Africans, 8.13% of Arabs/Middle Eastern, Caucasians are 8.33%, and Pacific Islanders are 4.17%, as revealed in Figure 3c. This distribution reflects diversity in cultures in perceptions. The age distribution indicates a concentration in the 26 to 30-year group, which represents 45.83%. Participants aged between 31-35 years accounted for 25%, while individuals between 18 and 20 years were 12.5%, those between 21 and 25 years were 8.33%, and 36-40 years were 8.33%, as shown in Figure 3d. Concerning the physical characteristics, participants' height ranged from 1.48m to 1.82m, and body weight varied from 48kg -98.5kg, respectively

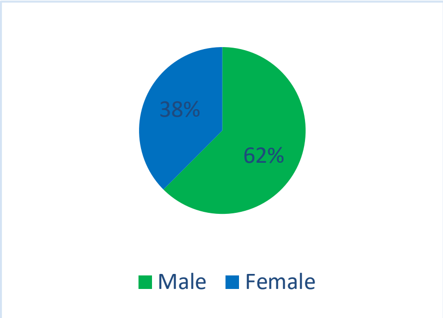


Figure 3a: Gender.

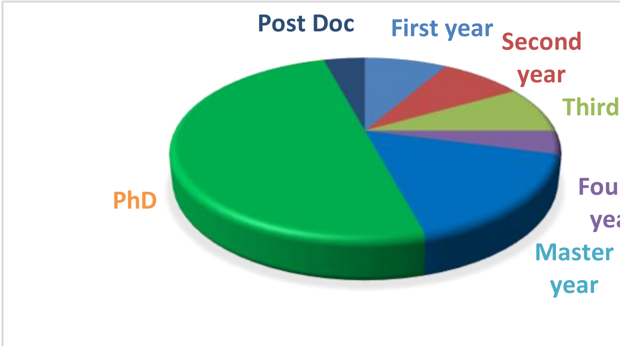


Figure 3b: Academic qualification.

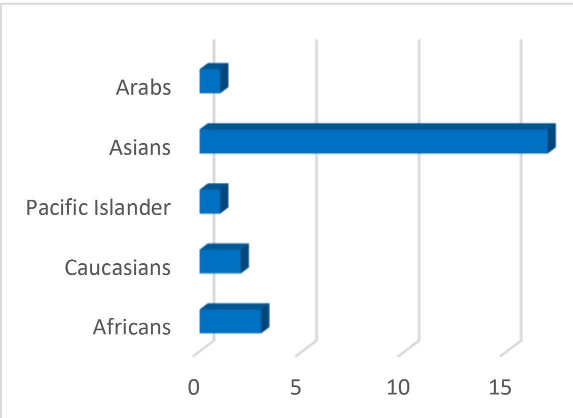


Figure 3c: Ethnicity.

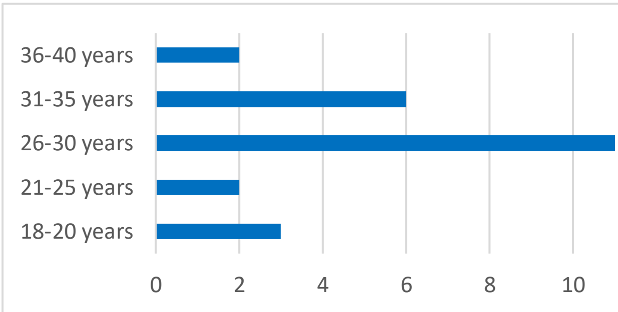


Figure 3d: Age.

4.2 Subjective perception evaluation and Inferential analysis

Figures 4a, 4b, 4c, 5a, 5b, and 5c present a detailed summary of subjective responses across six categories, which include Thermal Sensation Votes (TSV), Thermal Comfort Vote (TCV), Thermal Preferences Votes (TPV), Visual Sensation Votes (VSV), Visual Comfort Votes (VCV), and Visual Preference Votes (VPV). The figures show how participants perceived thermal and visual conditions under different thermal conditions (18 °C, 24°C, and 30 °C) for cool white light and warm yellow light simulations.

The mean thermal sensation votes (TSVs) showed a consistent upward movement across the three thermal scenarios (18°C, 24°C, and 30°C) under the yellow warm light simulation. Specifically, the TSVs increased from -1.38 at 18°C to 0.79 at 24°C, reaching a high of +2.54 at 30°C. In contrast, the TSVs under cool white light followed a similar but more subdued upward trajectory: from -1.58 at 18°C to 0.29 at 24°C, and then to +2.29 at

30°C. However, the mean thermal comfort (TC) scores, both lighting conditions yielded -0.33 at 18°C, signifying thermal acceptability of a larger percentage of users. At 24°C, the mean comfort score declined from 0.21 under yellow warm light to 0.08 under cool white light, suggesting a marginal reduction in perceived comfort under cooler lighting. At 30°C, this trend persisted, with a slight drop in comfort ratings from 0.92 (yellow warm) to 0.79 (cool white).

Regarding thermal preference (TP), the responses under yellow warm light revealed a shift toward a cooler preference, with votes decreasing from 0.54 at 18°C to -0.5 at 24°C, and reaching -0.92 at 30°C. In comparison, thermal preference scores under cool white light were a bit similar, starting at 0.58 at 18°C, then dropping to -0.375 at 24°C, and finally to -0.96 at 30°C. In terms of mean visual sensation votes (VSVs), showed a consistent upward movement across the three thermal scenarios (18°C, 24°C, and 30°C) under the yellow warm light simulation. Specifically, the VSVs were stable at 18°C with a mean of 1.58 and increased at 30°C with a mean of +2.25. In contrast, the VSVs under cool white light increased but more subdued upward trajectory: from -0.92 at 18°C to -0.67 at 24°C, and then to -0.08 at 30°C.

For mean visual comfort (VC) scores, warm lighting conditions yielded 1.75 at 18°C while cool lighting conditions yielded 2.21, signifying general visual comfort. However, the slight decline began to emerge at higher temperatures. At 24°C, the mean comfort score under yellow warm light was 1.42, while under cool white light it was 2.17. At 30°C, this trend persisted, with a slight drop in comfort ratings from 1.21 (yellow warm) to 1.92(cool white) compared to comfort at 18°C. Regarding visual preference (VP), the responses under yellow warm light revealed a gradual shift toward a cooler preference, with votes decreasing from -0.67 at 18°C to -0.71 at 24°C, and reaching -0.83 at 30°C. In comparison, visual preference scores under cool white light, starting at 0.125 at 18°C, then dropping to -0.04 at 24°C, and finally -0.04 at 30°C.

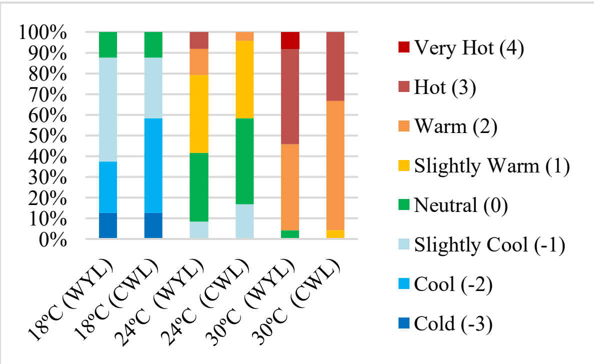


Figure 4a: Thermal sensation Votes (TSV)

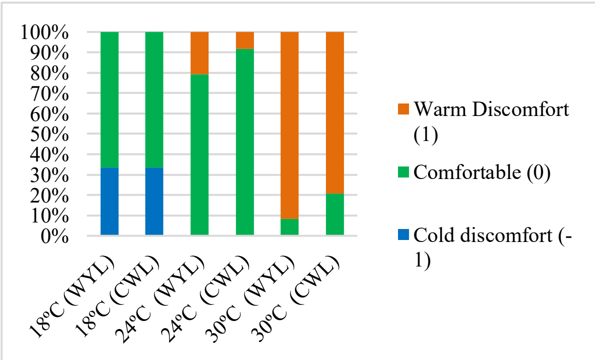


Figure 4b: Thermal Comfort Votes (TCV)

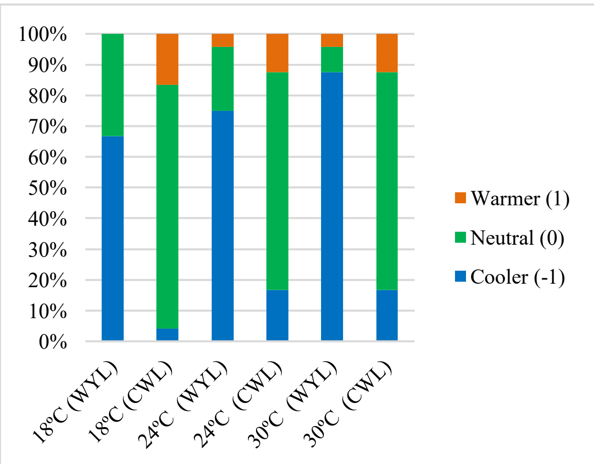


Figure 4c: Thermal preference Votes (TPV)

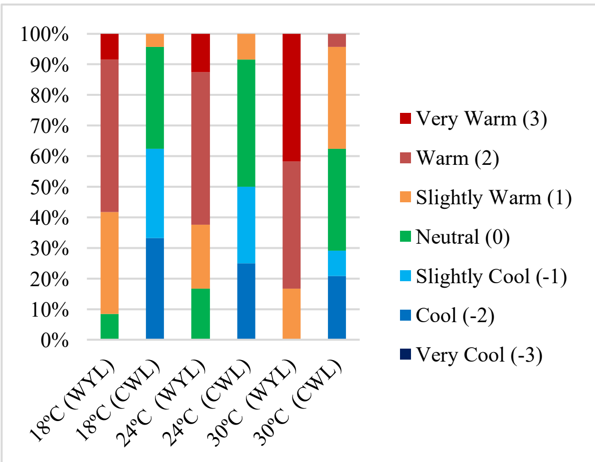
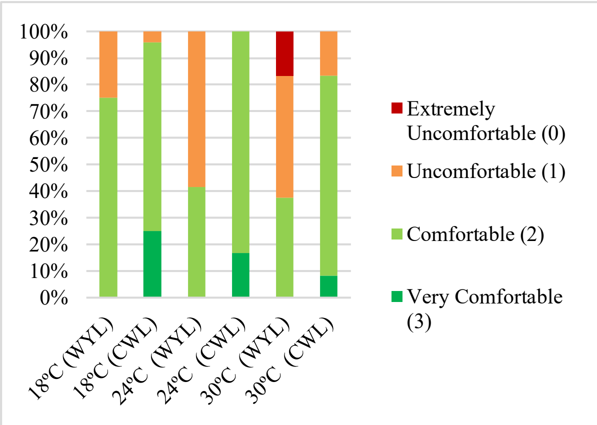


Figure 5a: Visual Sensation Votes (VSV)



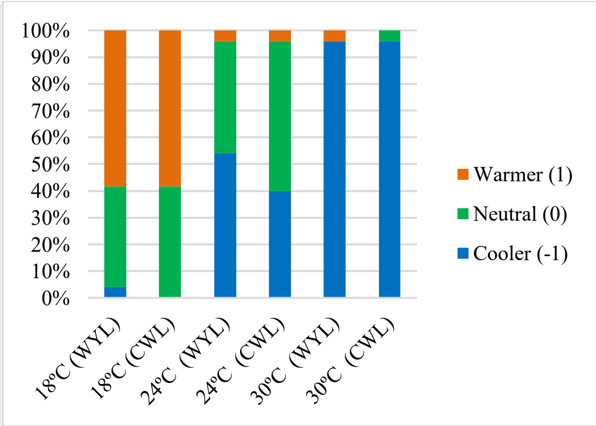


Figure 5b: Visual Comfort Votes (VCV) *Figure 5c: Visual Preferences Votes (VPV)*

A statistical test was conducted to understand the significant difference between the two simulated environments on thermal and visual perception, as shown in Table 4. The result indicates no statistically significant differences in cross-modal effects except in same-modal effects. In addition, Table 5 shows the result of a statistical test examining the differences in thermal conditions on thermal and visual perception. The findings showed significant differences in the same modal effects and cross-modal effects, except in visual preferences.

Table 4: Mann-Whitney U test between CWL and WYL on thermal and visual perception.

	Parameters	Sum of Ranks WYL	Sum of Ranks CWL	U-value	Z-score	p-value
TP	TSV	5477.50	4962.50	2334.50	-1.042	0.297
	TCV	5412.00	5028.00	2400.00	-0.863	0.388
	TPV	5214.50	5225.50	2586.50	-0.028	0.978
VP	VSV	7534.50	2905.50	277.50	-9.425	<0.001*
	VCV	6532.00	3908.00	1280.00	-6.165	<0.001*
	VPV	6898.00	3541.00	914.00	-7.466	<0.001*

Note: TP = Thermal perception, VP = Visual perception, Significant at p-value < 0.05.

Table 5: Kruskal-Wallis test among thermal conditions on thermal and visual perception.

Test statistics[a b]

	Thermal sensations	Thermal Preferences	Thermal comfort	Visual sensation	Visual Comfort	Visual Preferences
Kruskal-Wallis H	112.987	56.434	89.499	6.733	9.240	2.113
Df	2	2	2	2	2	2
Asymp. Sig	<0.001*	<0.001*	<0.001*	0.035*	0.010*	0.348

a. Kruskal Wallis test b. Grouping variable: Thermal conditions, *Significant at p-value < 0.05.*

4.3 Objective physiological parameters

A statistical test was conducted to understand the significant difference in physiological responses in both simulated environments, as reported in Table 6. The result indicates no statistically significant differences in physiological responses between the CWL and WYL environments. In addition, Table 7 shows the result of a statistical test examining the differences in physiological responses across three thermal conditions under each lighting condition. The findings showed no significant differences in color-induced physiological responses.

Table 6: Mann-Whitney U test on physiological response.

Physiological Responses	Group	Sum of ranks	Mann-Whitney U test value	Z-score	P-value
Heart rate	WYL	5296.50	2515.50	-0.306	0.760
	CWL	5143.50			

Significant at p-value < 0.05.

Table 7: Kruskal Wallis test on physiological response.

Test statistics a b	
	Physiological response
Kruskal Wallis H	4.580
df	2
Asymp. Sig	0.101

4.4 Behavioral intentions

Behavioral adaptation was analysed across three thermal conditions. At 18ºC, the most common adaptive behaviors were wearing a jacket/cloth, increasing the thermostat setting, and using a heater. At 24ºC, the majority of the users stated no action or intention, although some reported opening a window or using a fan. Finally, at 30ºC, the most common adaptive behaviors are lowering the thermostat, followed by opening the window, next by removal of jacket, and fans, as indicated in Figure 6.

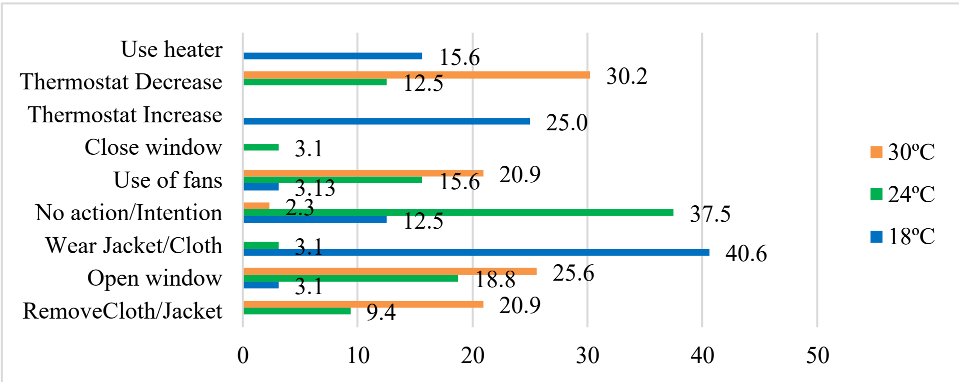


Figure 6: Intention of interactions percentage of votes for different thermal conditions.

4.5 User experience and simulation sickness

At the end of the experiment, a user experience and simulation sickness questionnaire was administered to participants to evaluate the impact of VR on users and their experiences. The questionnaire was assessed using a 5-point Likert scale (1 – Very low, 2 – Low, 3 – Average, 4 – High, 5 – Very High). Also, participants reported high levels of experience with the virtual environment. Regarding perceived realism, 54.2% of the respondents rated it “High,” indicating high authenticity. Similarly, 54.2% of respondents reported concentration in the virtual world, with a “Very High” scale indicating high cognitive engagement. Regarding event control, i.e ability to navigate and manipulate virtual elements, users rated this “High”, which accounts for 50% of the responses. For engagement level, 50% of the responses rated it as “High”. The visual quality level of the environment was rated “High”, depicting 52.2% of responses, while VR movement and manipulation were rated “High”. Also, interaction within the virtual environment, 41.7% of the responses selected “High”, and adaptability with the environment was rated “High” with 54.2% responses. The presence felt in the VR was rated “High”, accounting for 41.7% as indicated in Figure 7.

For the simulation sickness aspect, this was ranked using a 4-point Likert Scale (0 = Not at all, 1 – Mild, 2 = Moderate, 3 = Severe) adapted from (Kennedy et al., 1993). The majority of participants reported mild to no discomfort. 50% of the users did not feel physical discomfort, and 70.8% of responses reported that they did not feel fatigue while using VR. Additionally, 62.5% of participants did not feel a headache, 45.8% did not experience eye strain, and 54.2% reported no difficulty in focusing. 87% of participants did not experience increased salivation. A majority also reported no sweating (79.2%), nausea (83.3%), dizziness (79.2%), blurred vision

(58.3%), or difficulty concentrating (62.5%) during the experiment, as shown in Figures 8a and 8b. This suggests that the VR setup was generally fine for participants and did not induce substantial simulation sickness that would affect the result.

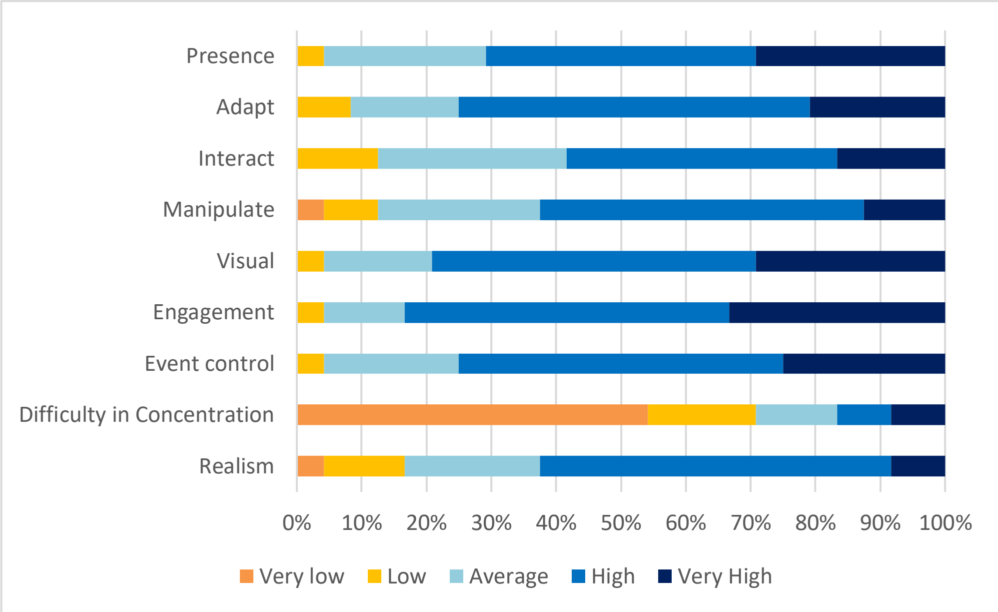


Figure 7: User experience.

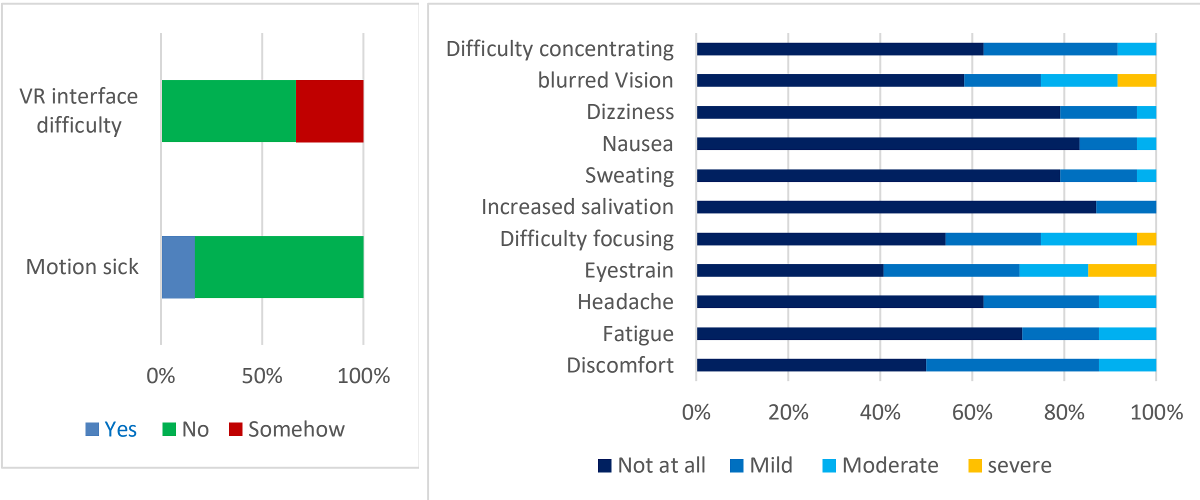


Figure 8 a&b: VR interface and simulation sickness.

4.6 Discussions

4.6.1 Same Modal and Cross-Modal Effects of Correlated Color Temperature on Thermal Perception

The same modal effects of correlated color temperature (CCT) demonstrate significant differences in visual perception of users, which indicate CCT influences how users perceive the visual environment. However, correlated color temperature does not significantly influence users' thermal perception regarding thermal sensation, comfort, and preferences. This revealed that no color-induced thermal perception exists, which aligns with the findings of (Chinazzo et al., 2020) who reported no significant differences in thermal sensation and preferences. Though there was no statistical significance, there were higher thermal sensations recorded under warm yellow conditions across all thermal conditions, with 0.21, 0.50, and 0.25 mean differences compared to the cool white conditions at 18°C, 24°C, and 30°C, respectively. These outcomes do not support the hue-heat hypothesis (i.e., red leads to warmer feelings and blue to colder ones). This does not corroborate with previous literature findings of colored stimuli affecting thermal comfort (Chinazzo et al., 2017, Chinazzo et al., 2020). However, the study was a bit different from previous studies because it focused on the visual glare of different daylight (blue, orange, and neutral) with two thermal conditions (24°C and 29°C).

Concerning thermal comfort, responses tended towards warm discomfort under warm yellow light simulations compared to the cool white light conditions, especially at 24°C and 30°C, where the mean difference was 0.13. In addition, the thermal preference responses during warm yellow simulation move in the direction of cooler conditions compared to cool white light simulations. The mean difference for preference responses was -0.04 at 18°C and -0.12 at 24°C, compared to CWL. These observations are consistent with the findings of (Wang et al., 2018, Brambilla et al., 2020) who revealed that exposure to warm colors increases thermal sensation and cool colored light decreases perceived warmth.

4.6.2 Same modal and Cross-Modal effects of temperature on visual perception

The same modal effects of thermal conditions showed statistically significant differences in thermal perception, which resonates with (Yeom et al., 2019). This confirms that temperature has a direct influence on how users perceive the thermal environment, including sensations, comfort, and preferences. For cross-modal effects, thermal conditions significantly influence visual sensation and comfort, except preferences. This non-significant effect of temperature on visual preferences is consistent with the findings of (Latini et al., 2023a), which suggest that while temperature may alter visual sensation and comfort, it may not influence users' preferred visual environment. However, visual sensation and comfort do not align with past studies, which reported no or minimal cross-modal interactions between thermal and visual domains. Previous studies also emphasized the interaction between color and temperature levels where blue stimuli are evaluated more positively in warm environments and orange in cold ones (Wang et al., 2018, Chinazzo et al., 2020). This applies to the study where, at cool temperatures, warm yellow is suitable, comfortable, and visually pleasant to users compared to warm (24°C) and hot conditions (30°C). This supports that certain visual stimuli, such as warm colors, are more effective when combined with cooler ambient temperatures, which create a balanced and comfortable indoor environment.

4.6.3 Cross-Modal effects of correlated color and temperature on physiological responses

This study investigated the cross-modal effects of different artificial lighting colors and temperatures on physiological responses. Two main relationships were examined: (1) the effect of correlated color temperature on thermal physiological responses (i.e., heart rate), and (2) the effect of temperature on color-induced physiological responses. The results showed that users' thermal physiological response was higher with an average of 2.12 bpm under warm yellow compared to cool white light simulation. Additionally, an average heart rate difference of 8.40 bpm was observed across the thermal conditions (18°C, 24°C, and 30°C).

Despite this variation, there were no significant effects of correlated color temperature on thermal physiological responses, i.e., heart rate, in both IVEs. This is in line with the result of (Lu et al., 2015) where the cross-modal effect of CCT was carried out on physiological responses in the real environment. This implies that color temperature on thermal perception has some psychological effect, while the physiological responses did not change. Similarly, the lack of significant difference in the physiological effects in this virtual environment aligns with (Chamilothori et al., 2019), who found there were no significant differences in physiological responses for both real and virtual. This means VR could replicate perceptual experience but has limited influence on physiological responses. Furthermore, this study also corroborates with (Chinazzo et al., 2020) who stated that there were no significant differences between the temperature and color-induced physiological responses, including Heart rate, Electrodermal activity (EDA), skin temperature, and Skin conductance level (SCL).

5. CONCLUSION

The study contributes to the growing body of knowledge on the same and cross-modal effects of interaction using VR, specifically focusing on artificial lighting, i.e., color-correlated temperature. By leveraging this VR technology, it aids in examining the effect of independent variables (temperature and lighting) on users' thermal, visual perception, behavior, and physiological responses. VR technology provides a controlled, immersive, and multi-sensory 3D environment that can simulate natural or artificial lighting, combined with activity-like real environment settings to explore users' responses.

The findings of the study revealed that the visual conditions had a moderate influence on thermal perception (i.e., sensation, comfort, and preferences) but had no significant differences. In contrast, there were significant differences in thermal conditions on visual perception, particularly in visual sensation and comfort, except for visual preferences. There was a significant difference in the same modal effects within thermal and visual perception. However, the study revealed no significant difference between the physiological responses under the two visual scenarios during sedentary activities. In addition, there was no significant difference in the effect of thermal conditions on color-induced physiological responses.

The behavioral intentions of users varied across the three thermal conditions. The most commonly selected behavior intentions chosen by participants during 18°C were wearing jackets. At 24°C, no intentions were majorly selected, while at 30°C, the most predominant behavior was decreasing the thermostat. Overall, the result implies that thermal conditions have a significant impact on the visual perception of users. This suggests the need to adopt a multi-dimensional perspective for thermal comfort perception for future building design. Creating more pleasant visual conditions and thermally balanced indoor environments will increase well-being and productivity, giving users a positive attitude towards energy-efficient behaviors. Nevertheless, the study has several limitations which are; (1) the exposure of participants to various visual scenarios under different thermal conditions is for a short term which do not represent the long-term effects or experiences of users in VR; (2) this study was limited to university students within the age bracket of 18-40 years. Future research should explore responses across broader age groups, including adult and children groups, to enhance the generalizability of the findings.

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