

A virtual reality study on the influence of indoor visual quality on thermal comfort perception

Marco Bernagozzi ^{a,*}, Raffaella Siagkri ^a, Marco Picco ^b

^a School of Architecture, Technology and Engineering, University of Brighton, UK

^b School of Engineering & Computing, University of Lancashire, UK

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ABSTRACT

Improving thermal comfort while reducing building energy demand represents a key challenge in the transition towards more sustainable and occupant-centred buildings. Although previous research demonstrated that individual visual stimuli influence thermal perception, the effect of the overall visual quality of an indoor environment remains poorly understood. This study investigates the influence of indoor visual quality on thermal comfort perception using an immersive Virtual Reality experimental approach. Thirty participants were exposed to three distinct representations of the same office environment (named Base, Cozy, Industrial) while seated inside a controlled environmental chamber maintained at 17 °C and 50 % relative humidity. Subjective thermal responses, environmental conditions and physiological parameters were recorded throughout the experiments. Results showed that participants exposed to the Cozy scenario reported significantly higher Global Comfort Vote ($p = 0.022$) and warmer Thermal Sensation Vote ($p = 0.026$) compared to Base and Industrial environments, despite identical physical conditions and no significant differences in skin temperature or heart rate. Thermal sensation progressively increased throughout the exposure period only in the Cozy scenario, suggesting that visual indoor quality influence may strengthen over time. Qualitative analysis further revealed that warm colours, natural materials, domestic features, and perceptions of inhabitation were frequently associated with enhanced comfort. These findings provide experimental evidence that, in the tested indoor environment, indoor visual quality can influence thermal comfort perception independently of the physical thermal conditions, supporting a broader understanding of thermal comfort as a multisensory phenomenon and highlighting the potential for integrating architectural and interior design strategies to support energy reduction in buildings.

Nomenclature

Symbol / Abbreviation	Description	Unit
CBE	Center for the Built Environment	-
I_{cl}	Clothing insulation	clo
GCV	Global Comfort Vote	-
HR	Heart rate	bpm
HVAC	Heating, Ventilation and Air Conditioning	-
IEA	International Energy Agency	-
M	Metabolic rate	met
PECS	Personalised Environmental Control Systems	-
PMV	Predicted Mean Vote	-
PPD	Predicted Percentage of Dissatisfied	%
RH	Relative humidity	%
TA	Thematic Analysis	-
T_a	Air temperature	°C

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Symbol / Abbreviation	Description	Unit
T_{neck}	Neck skin temperature	°C
T_r	Mean Radiant Temperature	°C
TPV	Thermal Preference Vote	-
TSV	Thermal Sensation Vote	-
V_a	Air velocity	m·s ⁻¹
VP	Visual Preference	-
VR	Virtual Reality	-
χ^2	Chi-square statistic (Friedman test)	-
p	Probability value (statistical significance)	-
r	Effect size	-
F	F-statistic	-
t	t-statistic	-

* Corresponding author.

E-mail address: m.bernagozzi3@brighton.ac.uk (M. Bernagozzi).

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1. Introduction

The efficient use of energy in buildings is fundamental to achieving global decarbonisation targets and mitigating climate change [1]. According to the International Energy Agency (IEA), building operations account for approximately 30 % of global final energy consumption and 26 % of energy-related CO₂ emissions, highlighting the substantial potential for improvements in building performance [2]. At the same time, maintaining acceptable thermal comfort remains essential for occupants' health, wellbeing and productivity. Balancing these two objectives, reducing energy consumption while ensuring satisfactory indoor environmental quality, represents therefore one of the principal challenges facing contemporary building design and operation [3], sparking a growing interest in developing innovative HVAC strategies. This challenge is compounded by the prevalence of thermal discomfort and avoidable energy waste in current HVAC systems and building operations [4]. There is a pressing need for the HVAC and construction industries to advance beyond conventional practices by investigating, evaluating and, where appropriate, implementing innovative strategies to achieve environmental savings whilst maintaining occupant's thermal comfort.

Numerous strategies have been proposed to improve building energy performance while maintaining occupant comfort. These can broadly be categorised into two complementary approaches. The first seeks to reduce building energy demand through improvements to the building fabric and environmental control systems, including passive design measures [5,6], high-performance envelopes [7–11], advanced HVAC control and optimisation strategies [12–14]. The second focuses on the occupants by improving thermal acceptability through behavioural adaptation [15–17] and occupant-centred conditioning technologies, such as Personal Environmental Comfort Systems (PECS) [18–20], enabling acceptable comfort conditions to be maintained over a wider range of indoor temperatures.

Both approaches have demonstrated considerable potential for reducing HVAC energy demand. Improvements to building design and environmental control systems, including passive design measures and high performance building envelopes, have consistently been shown to reduce heating and cooling loads across a wide range of climates and building typologies [21,22]. Similarly, previous studies have shown that relatively small adjustments to heating and cooling setpoints can produce substantial energy savings, reducing heating and cooling demand by up to approximately 34 %, depending on the climate, building type and operational strategy [23–26], while occupant-centred conditioning strategies can further increase acceptable temperature ranges and energy savings without compromising perceived thermal comfort [27,28]. However, these approaches primarily operate by modifying either the physical indoor environment or the physiological thermal experience of occupants.

Beyond modifying the physical environment or the physiological thermal experience of occupants, increasing attention has recently been directed towards the role of perceptual and psychological factors in shaping thermal comfort. Growing evidence suggests that occupants do not respond exclusively to measurable environmental parameters, but also to how indoor environments are experienced and interpreted. For example, the presence of windows has been associated with improvements in perceived thermal comfort and positive emotional responses [29], while psychological factors such as stress have been shown to influence thermal acceptability and comfort perception [30]. Together, these findings support the growing recognition that thermal comfort is a multisensory experience and depending on the context rather than a purely physiological response. In fact, recent studies have increasingly recognised that occupants experience indoor environments through the simultaneous integration of multiple sensory inputs [31]. Visual, acoustic, olfactory and tactile cues all contribute to the overall perception of indoor environmental quality and may interact to influence thermal appraisal [32,33]. This multimodal perspective challenges the

traditional view of thermal comfort as a predominantly physiological response, instead suggesting that occupants continuously integrate physical sensations with contextual and psychological information when evaluating their thermal environment [34,35].

The conceptual basis for these interactions has been discussed for more than two decades within the broader literature on multisensory environmental perception. Early work by Candas and Dufour [36] highlighted the potential for thermal comfort to be influenced by concurrent stimulation of non-thermal sensory modalities, including visual, auditory and olfactory cues. Subsequent research has increasingly examined indoor environmental quality from a multi-domain perspective, recognising that occupants experience indoor environments as integrated combinations of thermal, visual, acoustic and air quality conditions rather than as isolated stimuli. Reviews by Schweiker et al. [31] and experimental investigations by Berger and Mahdavi [32] further demonstrate that evaluations of individual environmental domains can be influenced by concurrent conditions in other domains, supporting the interpretation of thermal comfort as a cross-modal and context-dependent phenomenon.

Building upon this understanding, a growing number of studies have investigated the influence of individual visual attributes on thermal perception, including outdoor views [37], window geometry [38], colour [39,40] and lighting characteristics [41]. These studies consistently indicate that non-thermal visual stimuli can modify occupants' thermal sensation despite unchanged environmental conditions. However, they have primarily examined individual design variables in isolation. Comparatively little attention has been paid to the overall indoor visual quality resulting from the combined influence of materials, colours, textures, furnishings, and spatial character. Since occupants experience indoor environments holistically rather than as a collection of independent visual elements [42], understanding how indoor visual quality influences thermal comfort perception represents an important and largely unexplored research question.

From this literature review we can see that no previous study has investigated whether the overall indoor visual quality of a realistic office environment can independently influence thermal comfort under controlled thermal conditions. However, to investigate this experimentally by physically modifying the visual characteristics whilst maintaining the same physical thermal conditions is rather challenging. For this reason, we adopted immersive Virtual Reality (VR), as it allows to overcome this limitation by enabling the visual environment to be systematically manipulated while keeping environmental variables under strict control. This allows the influence of indoor visual quality on thermal comfort perception to be investigated independently of changes in temperature, humidity, air movement or radiant conditions.

The suitability of VR for thermal comfort research has been demonstrated in a growing number of studies. Previous work has shown good agreement between thermal perceptions experienced in immersive virtual and equivalent physical environments [43], supporting the validity of VR as an experimental platform. In parallel, VR has been successfully applied to investigate the influence of non-thermal visual factors on thermal perception [37–40], broader aspects of occupant experience including productivity [44], stress [45], and engagement [46], and as a tool for communicating and visualising building thermal performance [47] as a design and assessment support tool. Together, these studies demonstrate that VR provides a reliable and well-established methodology for investigating perceptual aspects of thermal comfort while maintaining rigorous experimental control.

Building upon the identified research gap, the present study investigates the influence of indoor visual quality on thermal comfort perception by exposing participants to three visually distinct representations of the same office environment within an immersive VR setting while maintaining identical physical environmental conditions inside a controlled climate chamber. In doing so, the study aims to (i) quantify the influence of indoor visual quality on thermal comfort perception, (ii) isolate visual effects from physical thermal conditions, and (iii) explore

the temporal evolution of these perceptual responses. The study therefore contributes to the growing understanding of thermal comfort as a multisensory phenomenon and highlights new opportunities for occupant-centred and energy efficient building design.

2. Experimental methodology

The aim of this work is to evaluate the perceived thermal comfort conditions in less-conditioned environment whilst subjected to different levels of indoor visual quality. For this purpose, a less-conditioned space is defined as a conditioned environment where the main HVAC system aims to achieve a target set-point temperature that is further away from thermal neutrality, or in general outside of the thermal comfort zone as defined by ISO Standard 7730 [48]. Thirty participants were enrolled in the experiment and subjected to three different scenarios of the same room representing different visual environments through the use of a VR visor (Meta Quest 3), while sitting inside an environmental chamber kept at 17 °C and 50 % relative humidity. The 17 °C chamber setpoint was therefore deliberately selected to represent a cool, less-conditioned environment rather than a conventionally heated office operating within standard thermal comfort conditions. This allowed the study to investigate whether indoor visual quality could influence thermal perception when conventional space conditioning is reduced.

2.1. Experimental setup

We performed the experiments in a controlled laboratory environment representative of realistic conditions. To achieve this, we recreated a test setup mimicking an office room inside an Environmental Chamber set to maintain a temperature of 17 °C and 50 % relative humidity, representative of a less-conditioned environment. The selected environmental chamber, available at the University of Brighton is visible in Fig. 1, with approximate internal size of 5 × 4 × 3.5 m, capable of maintaining temperatures from −40 °C to 60 °C. For the purpose of this study, the environmental chamber was sectioned into a smaller space of 2 × 4 × 3.5 m, more representative of a single office setup. The chamber, in its smaller configuration, is large enough to stand for a typical office room and fit all equipment required for the tests, in addition to the participants, while maintaining stable environmental conditions.

We positioned an office chair in the chamber, to match the space designed in VR and ensure the participants would not feel discomfort during the tests. Additionally, a second chair was positioned within the room to allow for a member of the research team to sit alongside the participants, collecting data and ensuring the correct running of the



Fig. 1. Exterior view of the environmental chamber at the University of Brighton, UK.

experiment.

2.2. Design and technical implementation of the virtual environments

2.2.1. Design rationale

Three virtual environments were developed to examine the effects of interior design on participants' thermal comfort perception, while controlling for confounding spatial variables. The first, baseline environment (Fig. 2a) served as a spatially familiar reference condition, replicating the physical chamber's dimensions, layout, materials, colours and furnishings as closely as possible. Presentation order of the three environments (Base, Cozy and Industrial) was randomised across participants to mitigate order and carry-over effects. Therefore, the baseline condition did not consistently precede the modified conditions. As all three environments shared identical room dimensions and spatial layout, participants encountered a consistent spatial configuration each time the headset was removed and reapplied between conditions, which may have eased reorientation between trials, although this effect was not separately measured or tested in the present study.

Two further virtual environments were then derived from the baseline, retaining identical dimensions, layout, and lighting conditions while varying only surface materials, textures, colour palette and furnishings. The Cozy condition (Fig. 2b) incorporated wood materials, warm toned wall colours, textiles, curtains, frames artwork, plants and books. While the Industrial environment (Fig. 2c) featured exposed ceiling, concrete surfaces, rough-unfinished textures, darker colour palette, magazines and metal furnishings and venetian blind. These material choices were selected to represent contrasting interior design styles commonly described in design practice as "warm" and "cool" respectively [49]. Prior thermal perception studies have isolated single variables rather than combining multiple design elements into a coherent stylistic ensemble. Fenko et al. tested single colour-material pairings on individual objects [50]. Wastiels et al. examined single wall materials, isolating colour from non-colour material effects, in architectural context [51]. In immersive VR specifically, Chinazzo et al. showed that a coloured filter tinting the entire visual scene shifts thermal perception [40], and Kocur et al. demonstrated that non-naturalistic themed VR environments (fire and ice worlds) affect thermal sensation and skin temperature [52]. To our knowledge, no prior study has tested a full multi-element interior design ensemble, combining material, colour, texture and furnishings into a naturalistic stylistic space. Any expectation of a directional effect on participants' perception should therefore be treated as a hypothesis to be tested in this study rather than an established finding.

The lighting conditions were maintained identical across all three virtual environments, which were designed to provide an illuminance of approximately 500 lx at the working plane, in accordance with recommendations for office workplaces provided in EN 12,464-1 and within the broader indoor environmental framework defined by EN 16,798-1 [53,54]. We made this decision to isolate the effect of material and colour association from the independently documented effect of light colour temperature on thermal perception [41], since varying both simultaneously would have confounded the specific contribution of interior materiality to perceived comfort.

2.2.2. Software and technical methodology

The digital environments were built in Autodesk 3Ds Max 2025, a three-dimensional modelling, and rendering software widely used in architecture, and V-Ray plug-in for applying materials and textures for rendering and visualisation. All three environments were modelled with identical room dimensions and spatial layout, following the existing chamber, differing only in the surface materials, furnishings, and decorative spatial elements described above.

We transferred the modelled environments from 3Ds Max into Unreal Engine 5.4 via the Datasmith plug-in, an interoperability tool that preserves scene hierarchy, material assignments, and lighting data during

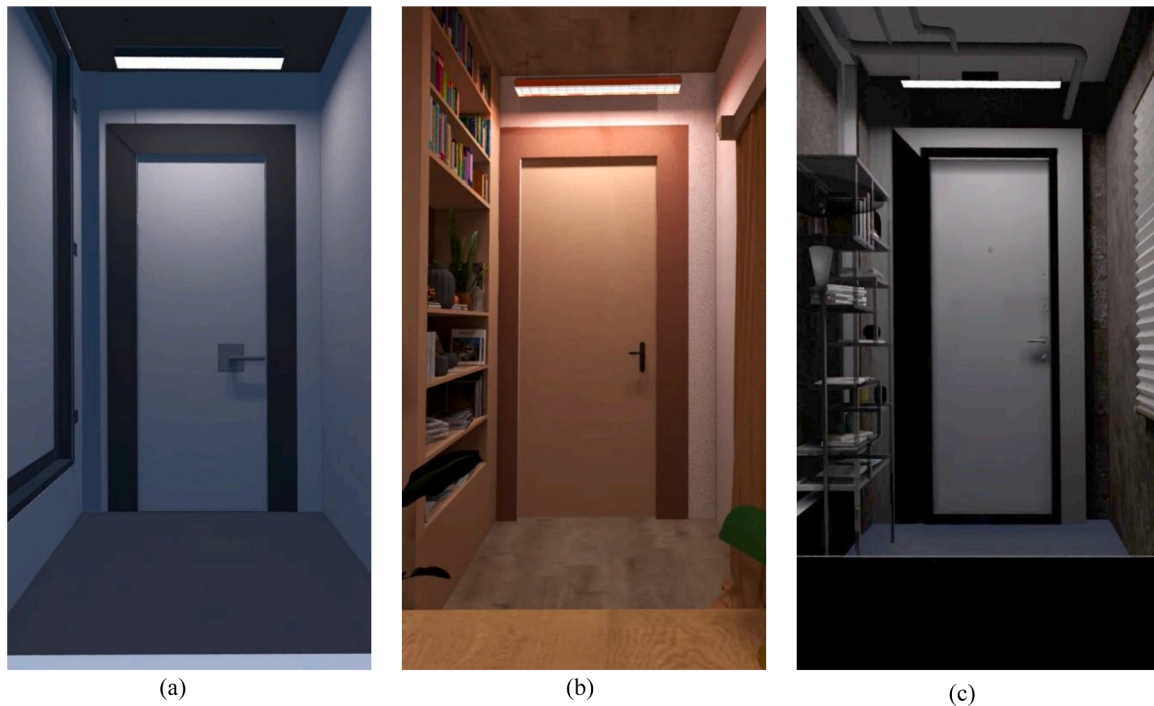


Fig. 2. Virtual Reality scenarios: a) Base; b) Cozy; c) Industrial scenarios.

the transfer of assets from third-party design software to Unreal Engine, without requiring manual re-modelling within the engine environment. This workflow is an established procedure in architectural and design visualisation practice. Its application to the modelling of the experimental scenarios is consistent with standard industry use [47].

The completed environments were compiled and packaged as standalone application builds and deployed directly to the Meta Quest 3 head-mounted display, rather than rendered in real time via a tethered connection to a desktop workstation, as in Kocur et al. [52] or via headsets requiring a wired PC connection [47]. This deployment choice was made to avoid introducing a laptop or PC as an additional heat-generating device within the chamber, which could otherwise have constituted a confound for a study concerned with participants' thermal perception. Therefore, the standalone deployment on the Meta Quest 3 allowed the VR experience to be delivered without altering the chamber's thermal conditions through heat generated by equipment.

2.3. Experimental procedure

The test procedure comprised setting the air temperature and relative humidity of the chamber at 17 °C and 50 % respectively, once the chamber reached stable conditions, and all monitoring equipment stabilized, the experiment can commence.

A total of 30 volunteers participated in this study, all of legal age in the UK and in good health conditions. Each participant lived in the south of England, in the Sussex area at the time of the experiments. We asked participants to attend the session without prior alcohol, hot beverage or caffeine intake, and without physical activity and fasting for at least 2 h. All participants were asked to dress as they would normally for a casual workday. We collected clothing data through a questionnaire. Before entering the environmental chamber, participants remained in an adjacent neutral space maintained at an average air temperature of 22 ± 1 °C and relative humidity of 50 ± 10 %. Participants remained in this space for 15 min while completing the consent procedure and receiving instructions, allowing them to reach a thermally neutral condition before exposure to the experimental environment. The participants are then led inside the thermal chamber and asked to sit on an

office chair where a member of the research team would help them wear the VR headset and stay with them for the duration of the test, to ensure the correct progression of the scenarios and collect the experimental data. Each participant experienced each of the three scenarios in direct succession, however the order in which they were experienced was randomized for each participant, to avoid the risk of bias in responses due to a predetermined sequence. Each scenario was maintained for 15 min, for a total test duration of 45 min, and questionnaire data was collected at 5 min intervals. During this time, participants engaged in light conversation with the research team member present, aimed at keeping the participants engaged in the test and collecting further qualitative data and feedback. After completion of all three scenarios, the participants were asked to leave the environmental chamber and debriefed, meanwhile the room was reset, ready for the next subjects. Fig. 3 below shows a visual representation of the experimental procedure for added clarity.

To minimize demand characteristics and response bias, we employed a single-blind design with incomplete disclosure: participants were told the study concerned thermal comfort in office environments, without revealing that (i) the three scenarios were visual variations of the same room (as per Fig. 2) and (ii) the chamber's physical conditions were held constant throughout a 45-minute session. Full debriefing occurred after data collection, in line with UK best practice guidance for ethically justified deception and debriefing [55].

2.4. Data collection

We collected three types of data during the experiment: subjective data from participants, empirical probe measurements of environmental conditions and physiological data. Environmental conditions measurements were obtained using a Deltaohm HD32.3 data logger, equipped with a thermo-hygrometer, a globe thermometer, and an omnidirectional hot wire anemometer. The following objective parameters and variables have been measured throughout the experiments: Air Temperature T_a [°C]; Air velocity V_a [m/s]; Relative humidity RH [%]; Mean radiant temperature T_r [°C]. Microclimatic parameters have been measured at head height of 1.1 m, assuming a seated position. Detailed

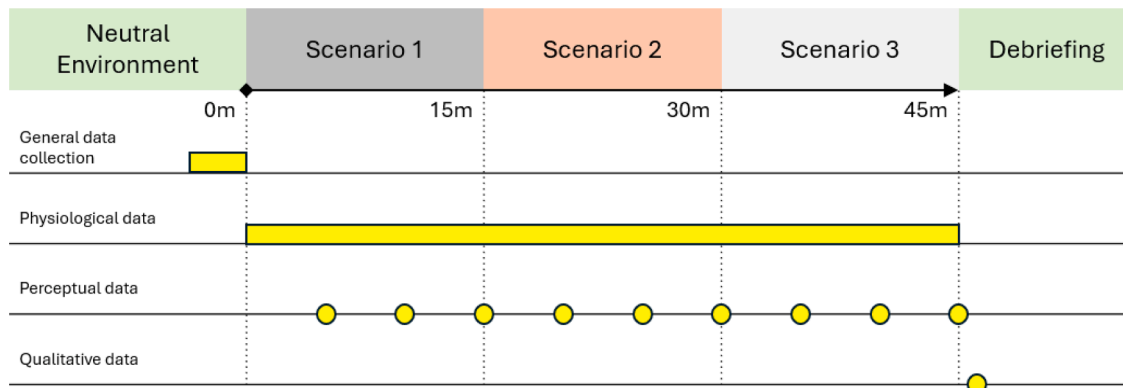


Fig. 3. Experimental procedure.

probes characteristic accuracies are shown in Table 1 in line with international standards [56,57]. During the experimental campaign involving human participants, the probes were placed in proximity to the subjects but out of reach and, due to the VR setup, away from their field of vision, to ensure any bias was avoided. The data was used primarily to monitor environmental conditions during the test as control measure. Indoor air quality was monitored throughout the experimental sessions through measurement of CO₂ concentration, with a target of maintaining concentrations below 1000 ppm. This threshold was maintained throughout the experiments without requiring additional intervention, facilitated by the volume of the environmental chamber and the low occupant density. As all three scenarios were experienced within the same chamber during a continuous experimental session, indoor air quality was therefore considered a controlled rather than independent experimental variable.

Data from this experimental run was used to calculate thermal comfort by means of validated models such as Fanger's thermal model (the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD)) in line with ISO 7730 [48] to compare with direct participant testing. Air temperature, mean radiant temperature, relative humidity and air velocity registered during the experimental run were combined with clothing values obtained from the human participant tests. As metabolic rate was not directly measured, PMV was calculated considering two metabolic rate assumptions. A value of 1.2 met was adopted as representative of standard sedentary office activity, while 1.5 met was considered as a conservative upper-bound assumption representing light activity. The latter was not intended to characterise VR use, but to assess whether the predicted thermal conditions remained cool even under a higher metabolic rate assumption potentially caused by interacting, completing questionnaires and wearing the VR equipment. Where applicable, both air velocity and total clothing insulation was corrected in accordance with ISO 7730 [48] and ISO 9920 [58] to determine the relative air velocity and the resultant total clothing insulation, accounting for the effects associated with body movement. The correction was applicable to both the 1.2 met and the 1.5 met assumption. These corrections were incorporated into the PMV calculation using participant-specific clothing insulation values. This approach also addressed the importance of appropriately accounting for

clothing and body-movement effects when applying thermal comfort indices, as highlighted in recent methodological reviews [59].

For the purpose of those calculations, the CBE Thermal Comfort tool was used [60] to ensure reliable calculations in compliance with international standards [61]. Due to their nature, the probes must be allowed to stabilize, reaching a condition of thermo-hygrometric equilibrium with the environment, for a time of no less than 20 min or in any case according to what is stated by the probe manufacturer (25 min for the globe-thermometer probe). Measurements are taken at 30 s intervals. The data was used primarily to monitor environmental conditions during the test as control measure, and to establish a comparison point with established thermal comfort metrics such as PMV and PPD.

For the second subset of data collected, subjective data from participants related to the perceived comfort, both visual and thermal, is collected through the administration of a written survey in the form of a questionnaire. We developed the questionnaire used to collect data from the participants following the principles established by international ISO standards [62] and in line with previous publications from the authors [41,63], in order to ensure comparability. The questionnaire is comprised of three parts: i) personal information, ii) overall thermal comfort evaluation and iii) open ended questions. The answers to the latter have been used to perform a Thematic Analysis presented herein.

In part one, general information such as time and date of the experiment, gender, height, weight, colour blindness, age group are recorded and a detailed clothing assessment associated is conducted to each body part, used to estimate the I_{cl} values for each participant. This part is meant to be completed prior to the start of the experiment.

Participants ranged in height from 1.45 m to 1.88 m, with an average of $1.69 \text{ m} \pm 0.11$, similarly weight ranged from 42 kg to 100 kg, with an average of $67 \text{ kg} \pm 0.14$. Clothing values for all participants averaged at $0.81 \text{ clo} \pm 0.13$, in line with expectations given the instructions given and the period of the year in which the tests were performed, between November and December.

Participant anthropometric characteristics and clothing insulation levels are summarised in Table 2. Mean clothing insulation for the overall sample was $0.80 \pm 0.13 \text{ clo}$, with female participants exhibiting slightly higher average clothing insulation ($0.84 \pm 0.15 \text{ clo}$) than male participants ($0.77 \pm 0.10 \text{ clo}$). These values were subsequently used in

Table 1

Deltaohm's data logger probes details. Each probe was already factory calibrated.

Probes	Variables	Resolution	Accuracy
Pt100 - RH	T and RH	$\pm 0.1 \text{ }^\circ\text{C} / \pm 0.1 \%$	1/3 DIN (T); $\pm 1.5 \%$ (RH)
Globe thermometer	Radiant T	$\pm 0.1 \text{ }^\circ\text{C}$	1/3 DIN
hot wire anemometer	Air speed	$\pm 0.01 \text{ m/s}$	$\pm(0.05+0.05 \text{ v}) \text{ m/s}$

Table 2

Participant characteristics and clothing insulation. Values reported as mean $\pm$ standard deviation.

Variable	Overall (n = 30)	Female (n = 16)	Male (n = 14)
Age group*	3.77 ± 0.82	3.75 ± 0.86	3.79 ± 0.80
Height (cm)	170.1 ± 11.2	162.1 ± 7.6	179.2 ± 6.8
Weight (kg)	68.8 ± 14.6	59.8 ± 8.8	79.1 ± 13.1
BMI (kg/m ²)	23.5 ± 2.9	22.7 ± 2.5	24.5 ± 3.2
Clothing insulation (clo)	0.80 ± 0.13	0.84 ± 0.15	0.77 ± 0.10

the PMV calculations described below.

The second part is repeated three times for the different scenarios and administered at fixed 5-minute intervals across the three scenarios. Each part comprises questions targeting four domains: global (whole body) thermal comfort, thermal sensation, thermal preference, and visual preference. To ensure consistency, the complete response scales (Table 3) appear in every scenario, even when only a restricted range of responses is anticipated. Scoring is as follows: Global Comfort Vote (GCV), 4-point scale; Thermal Sensation Vote (TSV), 7-point scale (to facilitate comparison with prior literature); Thermal Preference Vote (TPV), 3-point scale; Visual Preference (VP), 0–10 scale, where 0 indicates “unacceptable” and 10 “completely acceptable.”

Finally, the third part (shown in Table 4) captures participants’ overall reflections on the environment and is completed at the end of the 45-minute session. It includes open ended questions on the main reasons for comfort/discomfort and on specific features that positively or negatively influenced perceived comfort. Responses informed the thematic analysis reported below.

Lastly, physiological measurements are collected through the use of monitoring devices. Skin temperature was recorded at 2 locations using I-buttons DS1922L temperature dataloggers (-10 to $+65$ °C @ 0.5 °C accuracy): the left forearm at wrist level, and the posterior cervical area or nape, as established literature practice [64]. These measurements were not intended to provide an estimate of mean skin temperature in accordance with ISO 9886 [65], which requires higher measurement accuracy and established multi-site measurement configurations. Instead, wrist and neck temperatures were monitored as local physiological indicators to assess whether substantial changes in participants’ peripheral skin temperature occurred between the three visual scenarios. Heart rate (HR) was monitored using armbands (Garmin Vivosmart 5). Due to the limited nature of physiological measurements available, the aim of such measurements is not to establish a complete physiological model of the participants, but rather to prove the starting assumption that, since environmental and metabolic conditions do not change throughout the experiment, there is no significant change in physiological responses, and eventual perceptual changes between scenarios can be fully attributed to the different visual environments.

2.5. Data analysis

The data collected from the subjective survey responses were treated as ordinal because they consisted of ordered categorical ratings rather than scale measurements. Given the ordinal and non-normal nature of the data, we employed non-parametric statistical methods in IBM SPSS Statistics v30.0. Differences between scenarios and exposure times were evaluated using Friedman’s test for repeated measures, followed where appropriate by Bonferroni-adjusted pairwise post-hoc comparisons and effect size calculations. Associations between clothing insulation and subjective responses were explored using Spearman’s rank correlation. Additional analyses were conducted to examine the influence of demographic factors (age and sex), clothing insulation, and physiological variables on thermal responses. Linear mixed effects models and

multiple linear regression analyses were used to assess the contribution of clothing insulation and physiological measurements to subjective comfort outcomes. Open ended questionnaire responses were analysed separately using reflexive thematic analysis, supported by NVivo 14. Bar charts and boxplots were generated to support interpretation of the quantitative results.

3. Results

A total of 30 participants were involved in the test of the different scenarios. Only 1 participant identified as colour blind during the test, and as per test procedure, their results have been discarded, and therefore they are not accounted for in the aforementioned figure of 30 participants. Across all participants, 16 identified as female, and 14 identified as male. No participant identified as non-binary. Age was recorded per age group, as seen in Fig. 4, compatibly with the requirements established by the experimental procedure for both ethical, and health and health and safety reasons, no minor or elderly above 75 years old was allowed to take part in the test, resulting in a distribution dominated by the 18–30 years group, partly representative of the academic environment in which the tests were run.

During the entirety of the tests, the Deltaohm environmental monitoring station was used to control the room conditions, in agreement with the experimental procedure and the environmental chamber setting, the air temperature was maintained at an average temperature of 17.0 °C $\pm$ 0.20 , similarly due to the level of insulation present, the mean radiant temperature also kept stable values of 16.9 °C $\pm$ 0.17 . Additionally, relative humidity was kept in an acceptable range of 50 % $\pm$ 5 . Although the primary aim of environmental monitoring is to ensure temperatures and humidity are within acceptable ranges during the experiment, this also allows us to estimate the expected PMV for the room for comparison [58]. Based on the measured environmental conditions and participant-specific clothing insulation values, the resulting mean PMV was -1.62 ± 0.35 at 1.2 met and -1.08 ± 0.29 at 1.5 met. At 1.5 met, application of the correction for resultant total clothing insulation reduced the average clothing insulation from approximately 0.81 to 0.76 clo, resulting in a mean PMV of -1.08 ± 0.29 , compared with -0.97 ± 0.29 without the correction. The 1.2 met assumption shows similar albeit less pronounced changes, with resulting total clothing insulation reducing from 0.81 to 0.79 clo, and the corrected mean PMV value of -1.62 ± 0.35 against the uncorrected value of -1.59 ± 0.35 . According to the classification framework provided in ISO 7730, both scenarios fall outside the lower boundary of Category IV ($-1.0 \leq \text{PMV} \leq +1.0$), albeit to different degrees. These results therefore indicate predicted thermal conditions at or below the lower limit of the conventional comfort classification. As the physical environmental conditions and individual clothing insulation remained unchanged across the three VR scenarios, the calculated PMV for each participant was likewise unchanged between scenarios.

Table 5, below, summarises the overall subjective results from the experimental campaign, further details on each are given in the following sections through detailed statistical analysis.

Additionally, results from physiological monitoring show both skin temperatures and heart rate remaining constant throughout the experiment, independently from the scenario being experienced, with average values of 30.6 °C $\pm$ 1.7 and 34.0 °C $\pm$ 1.5 for wrist and neck skin temperatures respectively, and 75 bpm $\pm$ 8.5 for heart rate. While standard deviation for those measurements may appear high, it is important to note this is representative of a wide range of metabolic rates and personal conditions among the 30 participants. The average standard deviation when accounting for each participant in isolation results at ± 0.4 °C for temperatures, highlighting stable physiological measurements despite the presence of different scenarios. This validates the initial hypothesis that the differences experienced in perceptual comfort are not correlated to the physiological response and instead motivated by the change in visual environment.

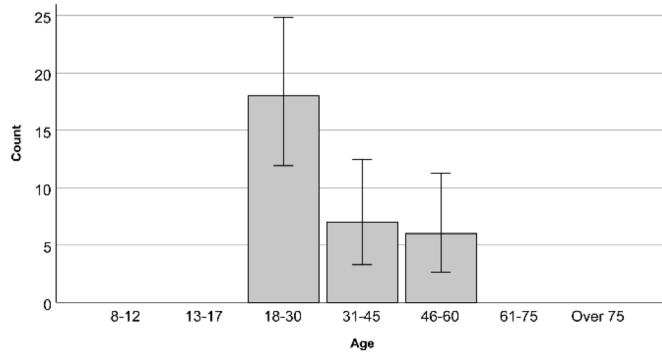
Table 3
Thermal evaluation scales.

Scale	Global Thermal Comfort	Thermal Sensation (global/local)	Thermal Preference
3	-	Hot	-
2	Completely Acceptable	Warm	-
1	Acceptable	Slightly warm	Cooler
0	-	Neutral	No Change
-1	Unacceptable	Slightly cool	Warmer
-2	Completely Unacceptable	Cool	-
-3	-	Cold	-

Table 4

Part 3 of questionnaire: open-ended questions.

What were the main reasons for your comfort/discomfort in the above answers during the experiments?
 Was there any particular visual item that improved your perceived comfort?
 Was there any particular visual item that reduced your perceived comfort?
 Do you have any further comments you would like to make known to the researchers?

**Fig. 4.** Age distribution of the participants.**Table 5**

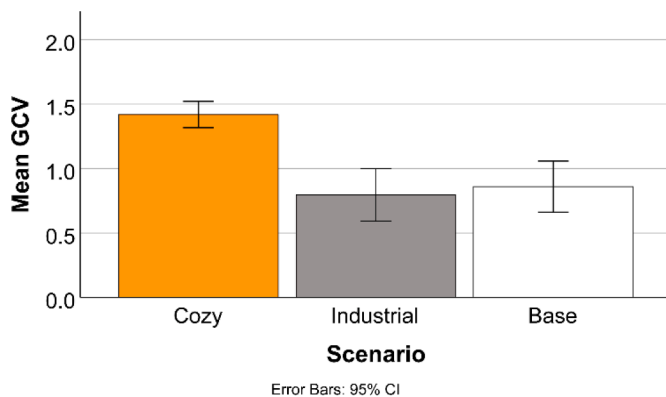
Overall perceived comfort results.

	GCV	TSV	TPV	VP
Cozy	1.42	-0.31	-0.53	8.13
Industrial	0.80	-0.78	-0.69	4.63
Base	0.86	-0.65	-0.54	4.59

In the following sections, each perceptual comfort parameter is analysed in detail through the use of statistical analysis to highlight the presence (or absence) of significant correlation between each parameter and the different visual scenarios tested.

3.1. Effect of scenario on GCV

Results show that participants felt a higher GCV (almost double) for the Cozy scenario ($GCV = 1.42 \pm 0.50$), over Industrial ($GCV = 0.80 \pm 0.99$) and Base ($GCV = 0.86 \pm 0.96$). The results of a Friedman's nonparametric test reveal that there is a significant difference in the GCV between the three different scenarios, $\chi^2(2) = 10.165$, $p = 0.006$. Post-hoc pairwise comparison shows that, despite the difference in average value showed in Fig. 5, there are no significant differences between Industrial and Base scenarios, but there are instead significant differences between Cozy and Base ($p = 0.022$, effect size

**Fig. 5.** Global Comfort Vote (GCV) reported over the three scenarios by the 30 participants. Data shown is mean $\pm$ 95 % confidence interval.

$r = 0.41$) and between Cozy and Industrial ($p = 0.022$, effect size $r = 0.41$), indicating a moderate effect size.

3.2. Effect of scenario on TSV

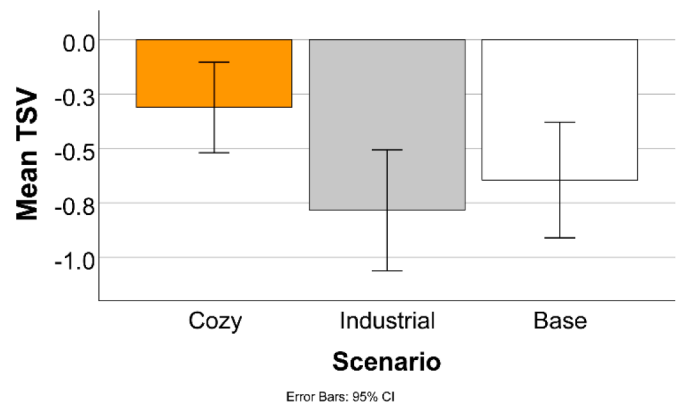
The TSV exhibits differences between Cozy ($TSV = -0.31 \pm 1.01$), Industrial ($TSV = -0.79 \pm 1.35$) and Base ($TSV = -0.66 \pm 1.29$), as shown in Fig. 6. Following a Friedman's non-parametric test, it shows that these differences are significant, $\chi^2(2) = 7.137$, $p = 0.028$. Pairwise comparison following the Bonferroni method, revealed that there was no significant difference in the scores for Base and Industrial scenarios, but there was a significant effect of Cozy over Base ($p = 0.026$, $r = 0.41$) and Cozy over Industrial ($p = 0.036$, $r = 0.39$), revealing a medium effect size.

This result is the main element proving the initial hypothesis that the visual indoor quality does indeed influence the thermal perception of comfort, whilst not acting on the temperature of the room and hence on the related energy consumption.

3.3. Effect of scenario on TPV

A related-samples Friedman test indicates no statistically significant differences: $\chi^2(2) = 1.877$, $p = 0.391$, so the null hypothesis (equal TPV distributions across scenarios) is retained. The grouped bar chart in Fig. 7 shows similar, slightly negative mean TPV values for all three scenarios with substantial overlap of the 95 % confidence intervals, visually reinforcing the non-significant test outcome.

While the room's visual character may shape occupants' thermal sensations, it does not translate into a systematic directional preference (i.e., a consistent tendency to want warmer or cooler conditions) for one scenario over another. In other words, variations provided by the different scenarios that emerge on a sensation scale are not strong enough or are too variable to appear on the preference scale. Our findings align with recent literature [66,67], which distinguish thermal sensation, acceptability, and preference. While thermal sensation is more directly linked to the physical thermal stimulus, thermal preference requires an evaluative judgment regarding a desired change (e.g., warmer, cooler, or no change). As a result, preference is more strongly influenced by contextual factors, expectations, and prior thermal history, introducing additional cognitive and attitudinal variability. This

**Fig. 6.** Thermal Sensation Vote (TSV) reported over the three scenarios by the 30 participants. Data shown is mean $\pm$ 95 % confidence interval.

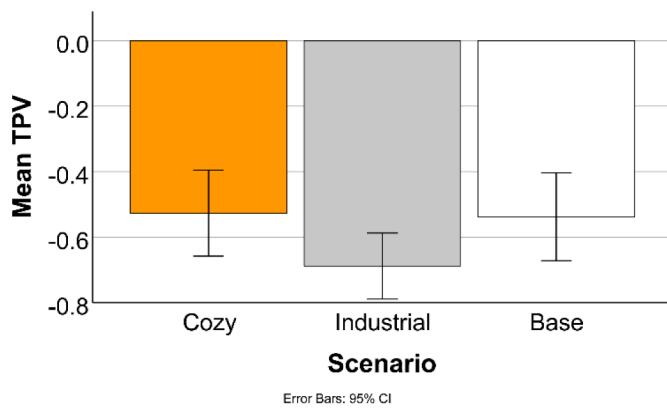


Fig. 7. Thermal Preference Vote (TPV) reported over the three scenarios by the 30 participants. Data shown is mean $\pm$ 95 % confidence interval.

added variance explains why TPV effects are often weaker or non-significant even when significant differences in TSV are observed. Consequently, thermal preference generally exhibits lower sensitivity and fewer significant contrasts than thermal sensation.

3.4. Effect of scenario on visual preference

Participants have a clear preference for the visuals of the Cozy room (VP = 8.13 ± 1.56) vs the score for Base (VP = 4.59 ± 2.28) and Industrial (VP = 4.63 ± 2.2), as shown in Fig. 8. Following a Friedman's test, we notice that this difference is significant ($\chi^2(2) = 38.623$, $p < 0.001$). Post-hoc pairwise comparison showed again no significant difference for industrial and base scenarios, whereas Cozy prevailed over the Base ($p < 0.001$, $r = 0.94$) and Industrial ($p < 0.001$, $r = 0.98$), reflecting very large effect sizes.

3.5. Effect on time on GCV different scenarios

It is common practice that every time an individual enters a new environment, there is an acclimating phase. That is the reason why identical questions were asked every 5 min interval, to explore whether the response changed over time.

Firstly, non-parametric Friedman's test was performed on the effect of time on the GCV, which resulted in non-significant differences ($p = 0.122$ for the Cozy scenario, $p = 0.838$ for the Industrial scenario, and $p = 0.92$ for the Base scenario). This tells us that the comfort perceived by the participants in the room is not influenced by the time spent in the room at each scenario.

We investigated the effect of exposure time on thermal sensation by

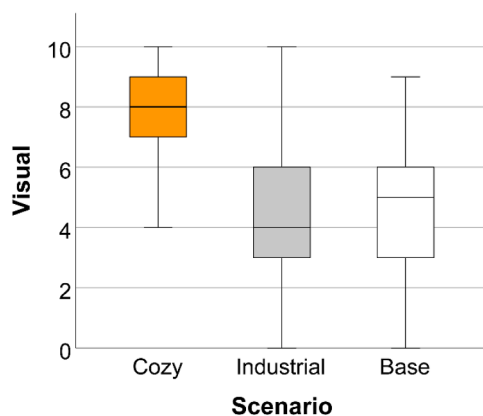


Fig. 8. Boxplot of Visual Preference (VP) reported over the three scenarios by the 30 participants.

conducting a related-samples Friedman's Two-Way ANOVA. The analysis revealed a significant effect of time on TSV, $\chi^2(2) = 15.151$, $p < 0.001$. Post-hoc pairwise comparisons with Bonferroni correction showed no significant differences between the 5 and 10 min measurements or between the 10 and 15 min measurements. However, a significant difference was observed between the 5 and 15 min measurements ($Z = -2.985$, $p = .003$, $r = .54$), indicating a moderate-to-large effect. Across all scenarios, mean TSV increased from -0.61 ± 0.88 after 5 min to 0.07 ± 0.99 after 15 min, suggesting a shift toward warmer and more comfortable thermal sensations over time. As shown in Fig. 9, this trend was primarily driven by the Cozy scenario, for which the mean TSV became positive after 15 min. In contrast, TSV remained negative throughout the Industrial and Base scenarios. These findings suggest that prolonged exposure to the Cozy environment was associated with a progressively more favourable thermal perception, despite no changes in the physical thermal conditions.

Similar statistical tests performed on the effect of time on TSV for the Industrial and Base scenario showed no significant difference ($p = 0.426$ for the Industrial scenario and $p = 0.321$ for the Base scenario).

Analogue results were obtained for the influence of time on TPV, which is non-significant ($p = 0.895$ for Cozy, $p = 0.513$ for Industrial, $p = 0.558$ for Base). These findings align with the previously cited literature as preference is always too subjective. Equally, the visual preference did not significantly change with time ($p = 0.417$ for Cozy, $p = 0.974$ for Industrial, $p = 0.095$ for Base).

We also examined the effects of age and sex on the GCV. TSV, TPV, and VP, and no significant effects were found. This finding suggests that the results are applicable across a wide range of population and that the difference in thermal sensation reported by the participants can be attributed primarily to the influence of the visual indoor quality rather than to demographic variation.

3.6. Thematic analysis

This qualitative section presents the main themes and subthemes following a Thematic Analysis (TA) that was conducted using reflexive TA, with an inductive approach. This method involves the active role of the researcher in the qualitative analysis process, with data-driven emerged themes. The TA identified key themes that addressed participants' perceived comfort experiences across the three visual scenarios using both semantic and latent coding [68]. Semantic coding was prominent in the initial stages, using descriptive phrases to capture the content of participants' answers regarding their comfort and discomfort

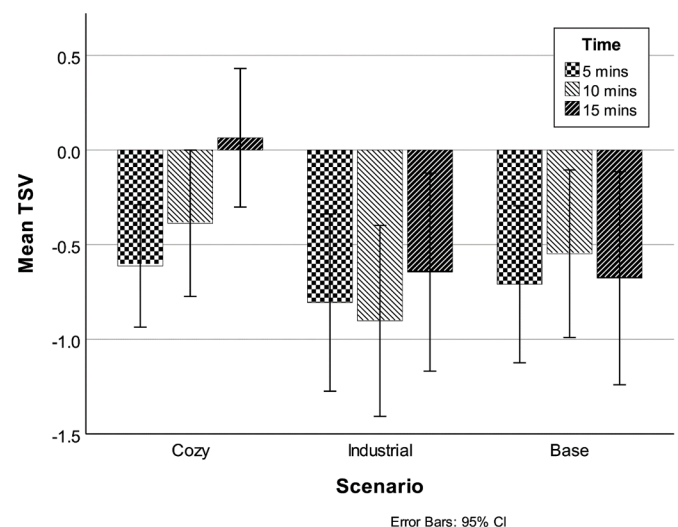


Fig. 9. Effect of time on the TSV for the different scenarios. Data shown is mean $\pm$ 95 % confidence interval.

experiences and shape the first round of themes. Latent coding was then used to interpret and analyse their answers on a deeper level, focusing on the underlying meanings behind participants' comfort perceptions and the potential links between visual environmental cues and thermal comfort perception. The analysis was grounded in the data, rather than being led by predetermined theoretical perspectives. Participants' answers were critically examined in relation to the hypothesis that differences in perceptual comfort were not correlated to the physiological response but instead driven by the change in visual environment. We used NVivo 14 was used for coding and categorising the collected data.

Through systematic coding of insights and patterns, data was shaped into five main themes and their subthemes. The first theme explores how visual warmth cues, including colour, lighting, materials, and textures, served as a pathway to thermal comfort. The second theme examines how domesticity and the sense of inhabitation through familiar objects and lived-in spatial qualities, functioned as a source of perceived comfort. The third theme addresses the limits of visual influence on thermal comfort, where persistent bodily sensation of cold overrode the visual environment. Lastly, theme four explores how social presence, i.e. the researcher's role and participants' desire for human's presence within the VR environments, contributed to comfort perception. A visual representation of the themes and subthemes can be found in Fig. 10.

Theme 1: Visual Warmth as a Pathway to Thermal Comfort.

More than 80 % of the participants reported that visual elements associated with warmth influenced their perceived comfort despite the chamber temperature remaining constant at 17 °C. This pattern was evident across all four questions reported in Table 4, with participants identifying visual cues associated with warmth as both sources of comfort and, in their absence, sources of discomfort. Through the analysis of their answers, four main subthemes were identified as the key visual factors contributing to this effect.

Subtheme 1.1: Colour as Thermal Cue

When asked about the main reasons for their comfort or discomfort during the experiments, the most frequently cited visual factor was colour. Participants consistently associated warm colour palettes with improved comfort and darker tones with discomfort. For example, P9 and P12, referring to the Cozy VR scenario, stated:

"Room colours in the last room made me feel more comfortable" — P9

"The colours in the last environment. As well as then plants and textures (certain textures felt warm and cosy)" — P12

P12's response is notable as it not only identifies colour as a comfort

factor, but explicitly connects the visual experience to a feeling of warmth and cosiness, suggesting that colour was being experienced as a thermal quality. Conversely, when asked whether any particular visual item reduced their perceived comfort, participants reported that the absence of colour or the presence of cool tones diminished their comfort.

"The cool tones of the walls and the décor felt aggressive" — P15

From the above, it becomes apparent that colour was not simply an aesthetic preference, but functioned as a thermal cue, with warm colours being perceptually linked to comfort and cool tones reinforcing the sensation of cold in the sub-neutral environment.

Subtheme 1.2: Lighting Quality and Thermal Perception

Alongside colour, lighting quality emerged as a significant factor in participants' comfort judgements. When asked about the main reasons for their comfort/discomfort, warm and bright lighting was consistently associated with improved comfort, while dim, cool, or fluorescent lighting reduced it.

"Warmer /brighter light improved comfort" — P21

As mentioned in the methodology section, it is worth noting that the actual lighting conditions in the VR environment remained constant across all three scenarios. The perceived differences in lighting quality reported by participants were therefore likely influenced by the colour palettes and materials texture of each VR environment rather than intended changes in illumination, adding an additional variable in the experiment set up.

"I enjoyed being in the better lit, brighter environment where the light was stable and where there were nicer clear spaces around me. I also felt warmer there. Perhaps because it was less distracting, more calming?" — P18.

P18's perception of being in a "better lit, brighter environment" despite constant lighting conditions is notable. Their report of feeling physically warmer in this perceived brighter environment suggests that the visual impression of lighting quality may directly influence thermal perception. In contrast, when asked about visual items that reduces their comfort there were participants who associated perceived poor lighting with discomfort:

"The cooler lightning made me feel discomfort. The gloominess of the first [Industrial scenario] and emptiness of the third were discomforting [Base scenario]." — P3

"The concrete wall. Fluorescent lighting." — P23

Subtheme 1.3: Texture and Materiality as Thermal Cues

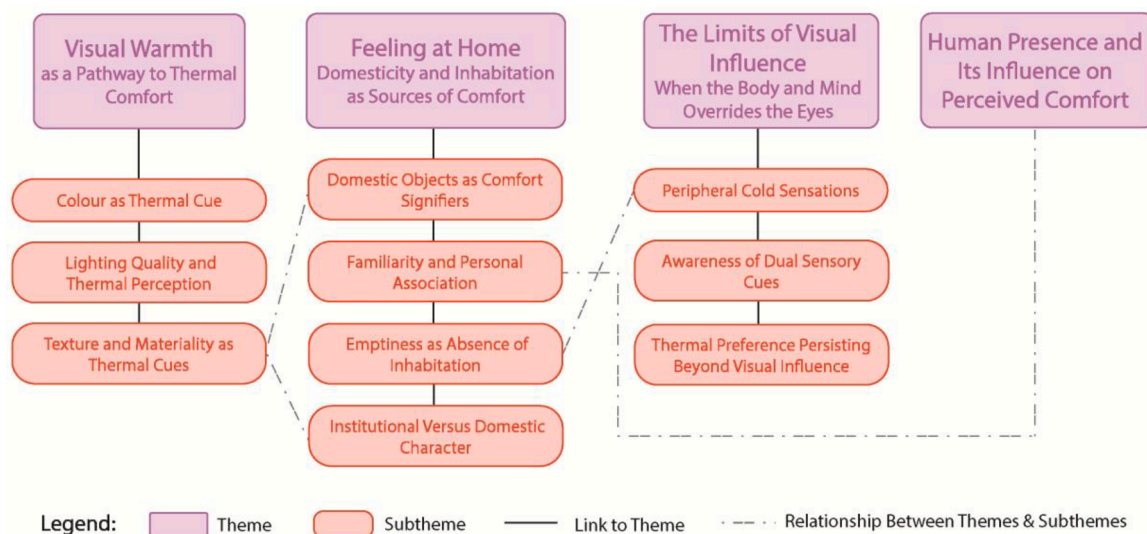


Fig. 10. Thematic analysis map of the qualitative data from the participants' survey.

Participants frequently identified material textures as influencing their perceived comfort. Responding to what reduced their comfort P23 articulated a direct relationship between material texture and thermal comfort.

“The visual helped to make me feel cosier for example when they were colourful, warmer in regards to texture, I felt more relaxed. When the material used were harsher, i.e. concrete, I felt less comfortable and more exposed.” — P23

On the other hand, soft, natural, and wooden textures were consistently associated with improved comfort:

“The plants and textures (certain textures felt warm and cosy)” — P12

“The soft furnishing helped.” — P13

“Plants and wooden textures” — P19

P23's response is particularly significant as it articulates how harsh materials produced a feeling of exposure that extends beyond simple temperature perception, while P12's description of textures as feeling “warm and cosy” reinforces the crossover between visual and thermal experience.

The combined influence of these visual factors (colour, lighting, materiality and textures) did not merely influence participants' aesthetic preferences but appeared to collectively shape their thermal perception. A notable finding is that some participants reported feeling physically warmer despite the temperature remaining constant at 17 °C throughout the experiment. P12, and P20 stated:

“The third environment [Cozy scenario] differently felt the best. I think if I was wearing gloves, I would have rated the felt temperature to be higher.” — P12 “The various ambients altered my perception of comfort” — P20

P18 also offered particularly significant reflections on this process:

“I think I was basing my judgement on my skin temperature, but I think the environment influenced this. The colours, the lighting, the cleanness of space (no clutter)” — P18

P18 demonstrates a meta-awareness of this process, acknowledging that the visual environment was influencing their thermal judgement while simultaneously recognising that their assessment was based on skin temperature. These findings suggest that the interplay between colour, lighting perception, and material texture contributed to participants' thermal comfort appraisal in less-conditioned environments, though the extent of this influence requires further investigation.

Theme 2: Feeling at Home: Domesticity and Inhabitation as Sources of Comfort

Distinct from visual warmth cues, a 70 % of participants identified the presence of domestic objects and the sense of inhabitation as contributing to their comfort. This theme addresses a broader psychological appraisal of the environment, whether it was perceived as a place of dwelling rather than an institutional or impersonal space. This pattern was most distinct in responses to the questions about specific visual items that improved or reduced comfort.

Subtheme 2.1: Domestic Objects as Comfort Signifiers

Among the visual items that participants identified as improving their perceived comfort, plants were the most frequently cited item, mentioned by eight participants. Bookshelves, curtains, lamps, painting, books and general furnishings were also consistently associated with improved comfort.

“The plant, the bookshelf.” — P11

“Flowerpot, nice warm paintings, thick curtains.” — P25

“Bookshelves made environment hospitable.” — P28

These items did not function in isolation, but collectively signalled a

furnished, liveable space. [28's use of the word “hospitable” is noteworthy, suggesting that the presence of domestic objects transformed the environment from a neutral or clinical space into one perceived as welcoming and inviting.

Subtheme 2.2: Familiarity and Personal Association

Several participants explicitly connected their comfort to the environment resembling their own home or personal living space. When asked about the main reasons for their comfort or discomfort, P15 and P16 stated:

“The décor was a big reason; I felt more comfortable in a setting I was used to (it felt like my room at home).” — P15

“The ambience of the space wall textures for some reasons played a big part. First room [Industrial scenario] felt similar to the other cold rooms I have experienced, second room [Cozy scenario] reminded me of home.” — P16

“Second room [Cozy scenario] was similar to my room, so I felt comfortable.” — P30

From the above, it is apparent that comfort was mediated not only by the objective visual qualities of the environment but by participants' personal associations and memories. P16's extract is particularly revealing as it demonstrates both sides of this process; the first room (Industrial scenario) triggered memories of cold, uncomfortable spaces while the second (Cozy scenario) evoked the familiarity of home. This suggests that prior spatial experiences shape how new environments are thermally perceived. When asked about visual items that improved their comfort, P26 further supported this pattern:

“Plant/bookcase in room 2 felt [Cozy scenario] homely.” — P26

Subtheme 2.3: Emptiness as Absence of Inhabitation

Conversely, participants consistently reported discomfort in environments that appeared empty, bare, or uninhabited. P8 stated that “*Absence of any visual stimuli was uncomfortable*”. Further participants described emptiness as a source of discomfort:

“Too much white, lack of inhabitation.” — P29

“Empty room felt cold and dull.” — P30

P29's explicit use of the phrase “lack of inhabitation” directly supports this subtheme's central concept that comfort is partly determined by whether a space communicates human presence and use. P30's association of emptiness with coldness is also notable, as it suggests that visual bareness may amplify the perception of thermal discomfort in a sub-neutral environment.

Subtheme 2.4: Institutional Versus Domestic Character

Participants distinguished between environments that conveyed domestic character and those that appeared industrial or institutional. Visual items that reported to reduce their comfort were exposed infrastructure, unfinished surfaces, and utilitarian fixtures.

“The pipes on the ceilings.” — P2

“The exposed ducts in the second environment as well as exposed non-finished walls.” — P12

“Metal pipework, tall dark bookcase, cheap blind.” — P25

These elements most likely signalled an environment that was not designed for dwelling, evoking associations with institutional, industrial or neglected spaces. P2 reinforced this pattern by reporting that the visual cues that improved their comfort were the colour and the type of curtains, “*The orange one feels like a home office, but the black room was like a room in a company*” and they continue saying “*The temperature, the room colour, the room size was the source of discomfort*”. This contrast between “home office” and “room in a company” captures the distinction that underlies this subtheme; comfort was enhanced when the environment conveyed domestic purpose and diminished when it

conveyed institutional function.

Theme 3: The Interaction Between Visual and Physical Thermal Cues

While Themes 1 and 2 demonstrate how visual indoor quality enhanced participants' thermal comfort, Theme 3 reveals that these perceptual benefits often coexisted with continued awareness of the cool physical environment. About a third of the participants reported feeling more comfortable in the Cozy scenario while simultaneously recognising localised sensations of cold, particularly in the hands. Rather than contradicting the quantitative findings, these observations suggest that visual indoor quality can substantially modify thermal appraisal without entirely removing physiological awareness of temperature.

Subtheme 3.1: Peripheral Cold Sensations

Based on participants' responses, the most commonly reported physical intrusion was cold hands. Several participants noted that while their overall comfort improved in visually warm environments, their extremities remained cold.

"Room colours in the last room [Cozy scenario] made me feel more comfortable. Discomfort may have been due to coldness – hands felt cold." — P9

"The third environment [Cozy scenario] definitely felt better/warmer in some ways. The reasons I kept feeling slightly cool is because my hands felt cold, but the rest of my body felt fine." — P12

P12's response highlights the localised nature of persistent thermal discomfort. These responses are notable because they often occurred alongside positive evaluations of comfort and warmth. Participants therefore distinguished between localised physical discomfort and their overall appraisal of the environment. This suggests that visual quality influenced higher-level thermal evaluations even when some physiological sensations remained unchanged. This further opens the conversation to hybridise the approach by including PECS to deal with specific body parts that cannot be compensated by visual cues.

Subtheme 3.2: Awareness of Dual Sensory Cues

Two participants (P1 and P18) demonstrated conscious awareness of the relationship between their visual experiences and their thermal judgements. Reflecting on what shaped their comfort ratings, P1 and P18 described actively weighing bodily sensation against the visual environment:

"I tried to concentrate on the temperature and visual experience." — P1

"I think I was basing my judgement on my skin temperature, but I think the environment influenced this." — P18

P18's extract is significant revealing an active process of self-monitoring; the participant recognised that their judgements were rooted in bodily sensation while simultaneously acknowledging that the visual environment had some influence over it. P1's comment similarly reflects a deliberate effort to attend to both sensory channels at once, rather than relying on one. Together, these accounts suggest that for some participants, visual and bodily cues were not simply competing in the background of perception, but were consciously weighed against one another in forming a judgement about comfort.

Although this subtheme is based on limited numbers of statements, participants demonstrated awareness that both bodily sensations and environmental appearance contributed to their comfort judgements. Rather than relying exclusively on either source of information, they appeared to integrate physical and visual cues when evaluating thermal comfort. These reflections provide direct qualitative support for the interpretation of thermal comfort as a multisensory process.

Subtheme 3.3: Thermal Preference Persisting Beyond Visual Influence

Some participants who reported improved visual comfort nonetheless expressed desire for the room to be warmer, revealing a gap between perceived comfort and thermal preference. When asked about the main

reasons for their comfort or discomfort, P20 stated:

"Just generally the room was cooler than my comfort zone." — P20

P12 offered a counterfactual reflection:

"I think if I was wearing gloves, I would have rated the felt temperature to be higher." — P12

Their statements highlights that they believed that eliminating the cold sensation in their hands through gloves would have changes their temperature ratings, suggesting that localised physical discomfort may disproportionately influence overall thermal assessments even when visual comfort is achieved.

The persistence of a preference for warmer conditions, despite improved thermal sensations in the Cozy environment, highlights the distinction between thermal sensation and thermal preference. Participants reported feeling more comfortable and warmer in the Cozy scenario while simultaneously recognising that the chamber temperature remained below their ideal comfort range. This finding is consistent with the quantitative analyses, which showed significant scenario effects for TSV but not TPV.

Theme 4: Human Presence and Its Influence on Perceived Comfort

Although social presence was not a variable under investigation, several participants spontaneously identified it as a factor contributing to their comfort during the experiment. This theme draws on fewer participants (10 %) than the preceding themes. However, it is included because the finding emerged unprompted and was not directly elicited by the research questions, suggesting that social presence was important to participants' comfort experience to merit reporting. When invited to answer the open-ended questions at the end of the experiment, P14 identified conversation as a comfort factor:

"Conversation between questions added to comfort." — P14

Other participants went further by attributing their comfort specifically to the researcher's presence and personal familiarity:

"If [anonymised] researcher was not in the room with me, my perceived comfort in room 3 [Base scenario] would be lower." — P16

P16 and P30 statements are particularly direct, they explicitly attribute part of their comfort to the researcher's presence and offer a counterfactual suggesting their discomfort would have been greater alone. This indicated that social presence may have partially mediated the relationship between visual environment and perceived comfort, a factor that should be considered when interpreting the quantitative results.

3.7. Effect of physiological data on comfort perception

We fitted linear mixed-effects models with scenario and clothing insulation as fixed effects and participant as a random intercept for each thermal outcome. Clothing did not significantly affect GCV (I_{CI} : $F(1, 70.12) = 0.86$, $p = .357$) and the Scenario $\times$ I_{CI} interaction was also nonsignificant ($F(2, 56.54) = 0.46$, $p = .636$). Consistent patterns were observed for TSV and TPV, where no clothing terms reached significance ($p > .05$). Thus, observed differences across scenarios can be interpreted independently of clothing insulation.

Furthermore, to summarize the influence of physiological measurements on participant feedback, we conducted multiple linear regression analyses for each dependent variables. In all models, wrist temperature (Twrist) and neck temperature (Tneck) were entered as predictors. The results of these analyses are as follows:

- Neither wrist temperature ($\beta = .099$, $t = 1.651$, $p = .100$) nor neck temperature ($\beta = -.040$, $t = -0.660$, $p = .510$) significantly predicted GCV.

- Regression analysis indicated that wrist temperature ($\beta = .065$, $t = 1.086$, $p = .279$) and neck temperature ($\beta = .035$, $t = .576$, $p = .56$) were not statistically significant predictors of TSV.
- Neither wrist temperature ($\beta = .091$, $t = 1.526$, $p = .128$) nor neck temperature ($\beta = .057$, $t = .954$, $p = .341$) significantly predicted TPV.
- Results demonstrated that visual preference was not significantly influenced by wrist temperature ($\beta = -.038$, $t = -.638$, $p = .524$) or neck temperature ($\beta = .007$, $t = .122$, $p = .903$).

Collectively, these findings demonstrate that physiological skin temperatures at the wrist and neck did not serve as significant predictors for the subjective comfort, sensation, preference, or visual votes reported by participants in this study. This suggests that participants' subjective evaluations were likely driven primarily by the quality of the indoor scenarios.

4. Discussion

The present study demonstrates that indoor visual quality can significantly influence thermal comfort perception under identical physical conditions. Participants exposed to the Cozy virtual scenario reported significantly higher GCV and warmer TSV than when exposed to the Base and Industrial scenarios, despite all experiments being conducted under the same controlled environmental conditions. In contrast, no significant differences were observed between the Base and Industrial environments, suggesting that the introduction of positive visual characteristics may enhance perceived thermal comfort more effectively than the presence of visually neutral or less appealing surroundings. This pattern aligns with Theme 2 of the TA, in which both the Base and Industrial scenarios were described by participants as impersonal or uninhabited.

The pattern of statistical results provides a coherent interpretation of the mechanisms underlying the observed differences in thermal perception. Significant improvements in both GCV and TSV were identified for the Cozy scenario, whereas no significant differences were observed between the Base and Industrial environments. This is consistent with Theme 1 of the TA, in which participants repeatedly linked the colour palette, lighting quality and material warmth of the Cozy scenario to an improved sense of thermal comfort. Furthermore, TPV remained statistically unchanged across the three scenarios, indicating that while participants perceived the Cozy environment as thermally more comfortable, this did not necessarily translate into a greater desire for warmer or cooler conditions. This distinction is consistent with the established understanding that thermal sensation and thermal preference represent related but independent dimensions of thermal comfort, with the latter being influenced by additional behavioural and cognitive factors. Additionally, to further corroborate this point, prior work shows that when occupants are offered granular thermal options, they tend to interact frequently with controls rather than settle on a single optimal setting. From a Human-Computer Interaction perspective, feature-rich interfaces and ambiguous feedback often amplify this behaviour [69]. Conceptually, thermal alliesthesia (the hedonic value of change [70]) and perceived control help explain why giving options elicits action, even when conditions are already acceptable.

No significant effects were observed for physiological measures, clothing insulation, age or sex. Together with the stability of the environmental conditions, these findings suggest that differences in thermal perception were primarily associated with indoor visual quality rather than physiological or demographic variation.

The present findings build upon a growing body of research demonstrating that thermal comfort is a multi-sensory phenomenon, influenced by multiple factors including visual and psychological in addition to the physical thermal environment. Previous studies have shown that visual exposure to windows, natural environments, colour schemes and other non-thermal stimuli can significantly affect

occupants' thermal perception [31,32], while recent applications of VR have confirmed its suitability as a reliable platform for investigating these cross-modal interactions [37,44,52]. The current study extends this body of evidence by demonstrating that the overall indoor visual quality, rather than an isolated visual attribute, can significantly influence thermal sensation and global comfort under controlled environmental conditions.

Unlike previous investigations that have primarily focused on individual design elements, such as light colour temperature, window characteristics or outdoor scenery [8,29,41], the virtual scenarios employed in this study combined multiple aspects of interior design, including colour palette, materiality, lighting characteristics and furnishing, creating environments that more closely resemble the holistic way in which occupants experience indoor spaces. The significant improvements observed in both GCV and TSV suggest that thermal perception may emerge from the integrated cognitive appraisal of the surrounding environment rather than from the influence of a single visual stimulus. In fact, while conventional thermal comfort models remain fundamentally based on heat balance principles, the present results suggest that perceptual characteristics of the built environment may contribute to broadening occupants' acceptance of less-conditioned spaces, providing an additional dimension through which comfort can be enhanced without modifying the physical indoor climate.

An additional and particularly noteworthy finding of the present study is the temporal evolution of perceived thermal sensation. While GCV remained stable throughout the exposure period and no significant temporal effects were observed for the Base or Industrial scenarios, TSV in the Cozy environment increased progressively over time, reaching positive values after 15 min of exposure. This suggests that the influence of a positive visual environment is not limited to an immediate perceptual response but may strengthen as occupants become increasingly immersed in the surrounding space.

The absence of similar temporal trends in the Base and Industrial scenarios indicates that this effect is unlikely to be attributable to simple acclimatisation to the experimental conditions or to increasing familiarity with the virtual reality environment. Instead, the progressive shift towards thermal neutrality observed only in the Cozy scenario suggests that visual indoor quality may gradually influence occupants' cognitive appraisal of the indoor environment, reinforcing perceptions of warmth and comfort despite unchanged physical conditions. Such findings are consistent with the concept of multisensory integration, whereby subjective thermal experience emerges from the continuous interaction between physiological information and contextual environmental cues.

The observed temporal behaviour also raises important questions regarding the persistence of this perceptual effect. Although participants experienced progressively warmer thermal sensations over the 15-minute exposure period, it remains unclear whether this trend would stabilise, continue to increase, or gradually diminish during longer periods of occupancy as physiological sensations become more dominant. Addressing this question is particularly relevant for practical applications, as the effectiveness of visual interventions may depend on the typical occupancy duration of the space. Environments characterised by relatively short stays, such as waiting areas, hotel lobbies or reception spaces, may benefit primarily from the immediate perceptual enhancement provided by high-quality interior design, whereas longer-term occupied spaces such as offices or classrooms may exhibit different adaptation dynamics. Future studies extending the exposure duration are therefore needed to establish the temporal limits of this effect and to determine how visual indoor quality can most effectively contribute to long-term thermal comfort.

Participants consistently associated the Cozy environment with descriptors such as warm, welcoming, lived-in and comfortable, frequently highlighting the presence of warm colours, natural materials, soft lighting and domestic features as elements contributing to an increased sense of comfort. Conversely, the Industrial and Base scenarios were commonly described as cold, sterile, impersonal or unwelcoming. These

qualitative observations align closely with the significant differences observed in GCV and TSV, suggesting that occupants integrate multiple visual cues into a holistic appraisal of the indoor environment that subsequently influences their subjective thermal perception. Overall, the qualitative evidence supports the interpretation that visual indoor quality acts primarily through cognitive and emotional pathways, helping to explain the statistically significant improvements in perceived comfort observed in the present study.

Within the controlled conditions investigated in this study, the results suggest that the perceived quality of the visual environment may represent an additional, non-physical dimension capable of influencing occupants' thermal experience despite unchanged physical thermal conditions. This supports further investigation of thermal comfort as a multisensory phenomenon in which sensory and cognitive factors may interact with the physical thermal environment.

From an architectural perspective, these findings reinforce the role of interior design as an active contributor to occupant comfort. Elements such as materiality, colour palette, lighting characteristics and perceived inhabitation may contribute to creating environments that are experienced as more thermally comfortable without requiring modifications to the physical indoor climate. Although such interventions cannot substitute for appropriate environmental control, they may complement conventional HVAC strategies by improving occupants' acceptance of environments operating under less stringent thermal conditions. In practical terms, if indoor visual quality increases occupants' acceptance of cooler indoor environments, it may support operation at lower heating setpoints while maintaining acceptable comfort conditions. Previous research has demonstrated that reducing indoor heating setpoints can yield meaningful reductions in building energy demand and therefore generate substantial HVAC energy savings [23,24]. Thus, the approach proposed in this work contributes to reducing heating demand without requiring additional building services interventions, offering a potentially low energy pathway for improving occupant comfort.

The qualitative responses collected at the end of the experimental sessions provide context for the quantitative findings by illustrating how participants interpreted the different visual environments and how these interpretations shaped their thermal experience. As outlined above, Theme 1 and Theme 2 help explain the significant improvements observed in GCV and TSV for the Cozy scenario, while Theme 3 offers a plausible explanation for the absence of a corresponding shift in TPV. Social presence also emerges as a comfort factor: several participants attributed comfort to the researcher's presence or conversation, and two suggested incorporating human or dynamic elements into future VR designs, complementing Theme 4.

Taken together, the quantitative and qualitative findings suggest a potential mechanism through which indoor visual quality influences thermal comfort perception. As illustrated in the conceptual framework of Fig. 11, participants appeared to respond to visual cues such as colour, materiality and furnishings by forming broader cognitive appraisals related to warmth, domesticity and inhabitation. These appraisals subsequently influenced thermal perception, contributing to higher GCV and TSV. Although the present study was not designed to directly test this causal pathway, the proposed framework provides an interpretation that is consistent with both the statistical outcomes and the themes identified through the qualitative analysis.

5. Limitations and future work

The experimental campaign was conducted under controlled laboratory conditions using immersive virtual reality and a single deliberately cool indoor condition. This condition was selected to investigate whether indoor visual quality could influence thermal perception in a less-conditioned environment and was not intended to represent a conventionally heated office operating within standard thermal comfort categories. Consequently, the findings cannot be directly generalised to neutral or warm thermal environments, different seasons, or the broader

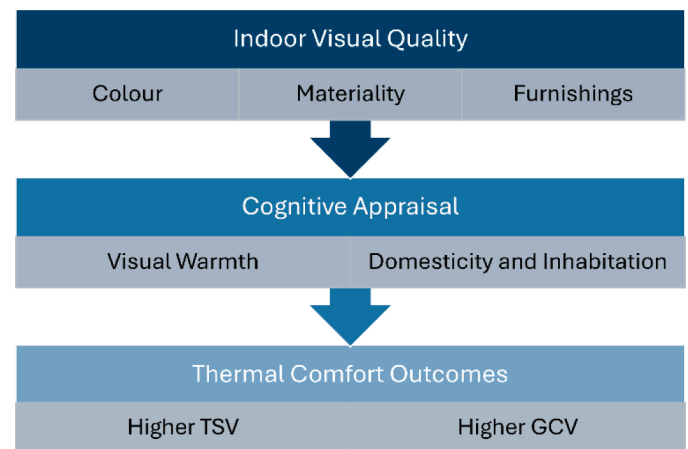


Fig. 11. Conceptual framework illustrating the proposed pathway linking indoor visual quality, cognitive appraisal, and subjective thermal comfort outcomes based on the quantitative and qualitative findings of the present study.

range of conditions encountered in occupied buildings. Additionally, although participants remained in a pre-experimental environment maintained at approximately 22 °C and 50 % relative humidity, individual thermal neutrality was not directly assessed prior to entering the environmental chamber, but was assumed based on the expected neutral conditions predicted by Fanger's PMV model and supported by the available literature. While this approach enabled the visual component of the indoor environment to be isolated and investigated independently from physical thermal conditions, it inevitably simplifies the complexity of real occupied buildings. Furthermore, each scenario was experienced for 15 min, limiting the assessment of longer-term perceptual adaptation, and physiological monitoring was restricted to local skin temperature measurements at the wrist and neck and heart rate, providing only a partial representation of occupants' physiological responses. The skin-temperature measurements were not designed to estimate mean skin temperature according to ISO 9886, and the instrumentation accuracy and measurement locations therefore limit their interpretation to relative changes in local skin temperature across experimental conditions. Although these methodological choices were appropriate for the objectives of the study, they should be considered when extrapolating the findings to real-world applications. In addition, the thematic analysis indicates that the researcher's presence in the room (Theme 4) may have acted as an uncontrolled social variable, future studies should consider controlling or systematically varying social presence to isolate this effect, perhaps by using interactive elements within the VR realm.

Although this study was not designed to investigate the cognitive mechanisms underlying the observed temporal changes, the results suggest that occupants may progressively incorporate visual information into their thermal evaluations, leading to a reinterpretation of otherwise unchanged conditions. This reflects a form of psychological adaptation in which environmental perception increasingly influences thermal comfort over time. While the present findings cannot confirm this hypothesis, they highlight a promising avenue for future research, particularly through longer-duration studies capable of distinguishing short-term perceptual effects from more persistent cognitive adaptation.

Future work should examine a wider range of thermal conditions, including both heating and cooling scenarios, and extend exposure durations to determine whether the improvements observed in the Cozy environment will vary over time. Combining physiological measurements with more realistic virtual environments and diverse visual stimuli could also help clarify the mechanisms underpinning perceptual thermal comfort. In addition, investigating how visual indoor quality interacts with occupant-centred conditioning strategies, such as PECS, may reveal new opportunities to improve comfort while reducing energy consumption of conventional HVAC systems.

6. Conclusions

This study investigated the influence of indoor visual quality on thermal comfort by exposing participants to three virtual representations of the same office environment while maintaining identical physical environmental conditions within a controlled climate chamber at 17 °C and 50 % relative humidity. The results demonstrated that participants experienced significantly higher Global Comfort Vote ($p = 0.022$) and warmer Thermal Sensation Vote ($p = 0.026$) in the Cozy scenario compared with the Base and Industrial environments, despite no measurable differences in environmental parameters or physiological responses. These findings provide quantitative evidence that the indoor visual quality can influence subjective thermal comfort independently of changes in the physical thermal conditions.

Beyond confirming the influence of visual indoor quality on thermal perception, the results suggest that this effect may evolve over time. While thermal sensation remained stable in the Base and Industrial scenarios, participants exposed to the Cozy environment progressively reported warmer sensations throughout the experimental period, with TSV going from -0.61 at 5 min to $+0.065$ at 15 min ($p < 0.001$), highlighting the potential importance of temporal dynamics in perceptual thermal comfort. Although the underlying mechanisms require further investigation, this observation suggests that cognitive appraisal of the surrounding environment may increasingly contribute to occupants' thermal experience during prolonged exposure.

The findings contribute to the growing recognition of thermal comfort as a multisensory phenomenon and demonstrate that indoor visual quality can influence thermal comfort perception independently of physical thermal conditions. While visual interventions cannot replace appropriate environmental conditioning, they may complement conventional thermal control approaches by enhancing occupants' acceptance of less-conditioned spaces. This may enable greater flexibility in heating and cooling operation, potentially supporting wider temperature setpoints and lower building energy demand while maintaining acceptable comfort conditions.

These results support a broader understanding of thermal comfort as a cognitively mediated and multisensory process, highlighting the importance of integrating architectural design and thermal comfort research in the pursuit of more comfortable, resilient and energy efficient buildings.

CRedit authorship contribution statement

Marco Bernagozzi: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rafaella Siagkri:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Picco:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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