Article

Integrating Virtual Reality to Enhance Thermal Comfort in Educational Spaces: A Pilot Study Towards Sustainable Learning Environments

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Abstract: This pilot study explores the use of Virtual Reality (VR) to enhance perceived thermal comfort (TC) within educational settings, where physical modifications to classrooms are often limited. As sustainability becomes a priority in building design, VR and Immersive Virtual Environments (IVE) offer an innovative approach to optimizing user comfort without altering physical conditions. This study investigates how VR influences comfort perception through qualitative data collected from semi-structured interviews with four architecture students who attended academic presentations in a VR setting. Thematic analysis identified key factors affecting user experience, including visual satisfaction, physical discomfort, engagement, and perceived shifts in comfort parameters. Results indicate that VR environments featuring natural and calming visual elements can enhance perceived TC by reducing stress and increasing focus. However, challenges such as device discomfort, visual limitations, and distractions from non-task-related virtual elements were also noted. Findings highlight the importance of aligning visual elements with task requirements, optimizing brightness for engagement, and ensuring better connectivity between VR settings and real-world surroundings. As a pilot study, these findings provide preliminary insights into VR's potential to support user comfort and engagement in student-centered learning environments, particularly in automated climate-controlled spaces with limited user control, laying the groundwork for future research.

Keywords: pilot study; virtual reality; user comfort; thermal perception; visual comfort; learning environment

1. Introduction

Virtual Reality (VR) is increasingly used to explore user comfort in built environments, providing a controlled setting to test visual–thermal interactions without physical modifications. VR and Immersive Virtual Environments (IVE) provide an effective means to explore virtual–thermal interactions under controlled conditions, allowing researchers to test various scenarios without physical modifications [1,2]. For instance, studies by ref. [3] have demonstrated that VR can simulate thermal environments effectively, allowing users to experience varying thermal conditions without physical changes to the environment. Additionally, ref. [4] found that visual cues such as color and lighting in VR can significantly influence perceived thermal comfort (TC), supporting the idea that VR can be used to manipulate thermal perception. These findings highlight the potential of VR to create immersive environments that enhance comfort through visual–thermal interactions.

When users experience a high sense of presence in the digital environment, they can shift from a physical to an Immersive Virtual Environment (IVE) [5,6], thus allowing them to "live" a "digital" life [7] that represents the physical environment through virtual elements [5,7–9]. This requires surrounding the user, who is wearing Head-Mounted Displays (HMD) with images and sound, similar to the physical world [8,10]. Consequently, VR affects physiological responses [1,11] and vital functions, such as heart rate, environmental perception, blood pressure, temperature [1], and productivity [1,12]. In design, refs. [13,14] used VR to explore user behavior in different architectural settings, demonstrating its potential for simulating real-world environments.

While sustainable buildings prioritize energy efficiency, they do not always guarantee optimal indoor conditions for all occupants. Research highlights that user satisfaction is strongly linked to individual control over TC variables [15]. Given these limitations, VR-based studies provide a promising alternative for assessing and enhancing user comfort in built environments. It is argued that sustainable buildings can offer higher user comfort with the Indoor Environmental Quality (IEQ) [16–20]. Comfort can be defined by either the physical or the subjective state [21]. It is a subjective evaluation that can be triggered by physical, physiological, and psychological factors derived from a combination of environmental and personal parameters [21]. Comfort in IEQ can be identified through four main categories: thermal comfort (TC), indoor air quality (IAQ), visual comfort (VC), and acoustical comfort (AC) [22–25]. Recent research, however, examined some qualifying conditions that explain users' comfort in sustainable buildings, revealing that these buildings do not consistently deliver comfortable indoor conditions for all occupants. For instance, ref. [15] conducted Post-Occupancy Evaluations (POE) through occupant surveys and environmental assessments in four Swiss green buildings certified with the Minergie label, to evaluate user satisfaction. The study concluded that to enhance user satisfaction, environmentally sustainable buildings need to be more user-engaging and allow for a level of control of factors in the interior environment. While some scholars argue TC to be the most significant among comfort variables in affecting user satisfaction and work productivity [1], Pastore and Andersen [15] found that most complaints from users in certified sustainable buildings were not only concerned with TC, but also with IAQ and VC. Suggested solutions acknowledged limitations in the use of non-openable windows, central air systems, and automated shading devices, emphasizing the need for careful design and operation to balance environmental control with occupant comfort. Those results have echoed previous studies, such as refs. [17,18,20].

However, while these suggestions comply with the energy efficiency requirements, they impose further limitations on users' individual control of the surrounding environment, which leads back to a decrease in the level of user satisfaction within the space [17,18,20]. Ref. [26] argued that thermal quality is found most crucial when ambient thermal condition is set based on the user's preference. Consequently, further research is needed to better meet user comfort requirements without affecting sustainability and energy efficiency. This study investigates how visual–thermal interactions influence user comfort and engagement in VR-based educational environments, bridging this gap and exploring potential solutions for balancing comfort and sustainability. Nonetheless, while comfort is a complex construct, its experience can be affected by many intricate factors. Perceived TC is argued to be influenced by thermal expectations, adaptations [27,28], and past experiences, as well as emotions and stress [28].

Research shows the possibility of altering perceived body temperature using visual images such as fire and ice that generate certain expectations [4,29]. Furthermore, scholars suggest the existence of visual–thermal interaction. The hue-heat hypothesis (HHH) assumes a relationship between color and light and perceived TC. Thus, colors and lights

closer to the red end of the spectrum can be associated with "warm" perceptions, as opposed to those closer to the blue end, which are perceived as "cool" [30,31]. Additionally, window sizes and wall colors were found as influencing factors of thermal perception [28]. Connection to natural elements such as natural light, water, plants, etc. [28], and wood [31,32] also contribute to reduced levels of stress and higher TC [28,31–33].

Further expanding on visual–thermal interactions, recent research has explored the cross-modal associations between hue, saturation, brightness, and temperature perception. A study from ref. [34] used the Implicit Association Test (IAT) combined with event-related potentials (ERPs) to investigate how individuals unconsciously associate colors with thermal sensations. The results confirmed that hue and saturation significantly influence perceived temperature, with warm colors and highly saturated hues linked to warmth and cool colors and low saturation associated with coolness. However, brightness did not exhibit a clear relationship with temperature perception. These findings suggest that cognitive biases toward color–temperature associations are deeply embedded, reinforcing the importance of considering visual cues when assessing TC, particularly in immersive environments. This placement ensures a logical flow by introducing the cognitive basis of color–temperature associations right after explaining the HHH while maintaining coherence with the next paragraph on wall color studies.

Recent studies have explored the role of wall colors in shaping occupants' comfort and productivity, particularly in controlled environments and Immersive Virtual Environments (IVE) settings. Research from ref. [35] examined participants' responses to different wall colors—red, blue, and white—under two indoor temperature conditions. Participants performed productivity tasks and reported their thermal and visual perceptions in both a physical office setting and an IVE that replicated the real-world conditions. Results showed that while individuals expressed subjective preferences for certain colors, neither temperature perception nor work productivity was significantly affected. These findings suggest that while color can shape psychological responses, its measurable impact on TC and efficiency remains inconclusive, reinforcing the need for further research into visual–environmental interactions, particularly within IVE and VR-based studies.

Recent findings by ref. [36] further support this hypothesis, demonstrating that color influences temperature perception through cross-modal interactions. Using a virtual environment combined with real temperature stimuli, their study examined how participants perceived temperature when touching a warm or cold object while seeing a corresponding red or blue visual cue. Results indicated that cold stimuli felt warmer when paired with red and hot stimuli felt cooler when paired with blue, reinforcing the effect of color on thermal perception. These findings provide empirical evidence that visual elements in virtual settings can alter perceived comfort, suggesting that careful selection of color schemes in VR environments may enhance user experience.

Building on this, studies have examined how colored lighting influences both perceptual and physiological responses in controlled thermal environments. Research has shown that exposure to red, blue, and white lighting can affect perceived TC, with blue light often associated with cooler sensations, particularly in thermally neutral conditions. However, the effect of red lighting appears to be less pronounced. While these visual cues can alter subjective perceptions of comfort, physiological measurements, such as skin temperature, indicate that ambient conditions remain the dominant factor in thermoregulation. These findings suggest that while color may play a role in shaping thermal perception, its impact is likely limited to psychological rather than physiological responses [37].

However, the reliability of this effect remains debated. In their study, ref. [38] investigated whether red and blue lighting influenced participants' thermal sensitivity in controlled climate chambers. Their findings suggest that while some individuals exhibited

behavior aligning with the hue-heat hypothesis, others showed the opposite trend, leading to inconclusive results. Furthermore, the study found that the presence of colored lighting did not enhance thermal perception and instead appeared to increase cognitive load, which may have interfered with accurate temperature discrimination. These results highlight the need for further exploration of color–temperature associations, particularly in immersive environments where visual stimuli play a key role in user experience.

Research has shown that stress levels can significantly alter thermal perception, with higher stress leading to increased sensitivity to thermal discomfort [39]. In VR environments, studies have demonstrated that immersive experiences can reduce stress and improve comfort [11], suggesting that VR has the potential to enhance TC by creating calming and engaging environments. Additionally, physiological responses such as heart rate variability and skin temperature have been shown to correlate with perceived comfort in VR settings, as highlighted by ref. [1]. These findings underscore the importance of considering psychological and physiological factors when designing VR environments for educational purposes. Furthermore, it is argued that TC can be influenced by VC and illumination intensity [40,41]. For instance, refs. [40,42,43] found that low-light environments contribute to feelings of lower temperatures.

In addressing *perceived* thermal situations and visual stimuli, ref. [44] explored the effects of avatars and IVE on user perception, skin temperature, and VR experience. In their study, participants were assigned a first-person shooting game task, while being represented by avatars with fire or ice hands placed in fire or ice environments. Results show that thermal perception was influenced by the environment, with participants reporting higher comfort in the ice world due to its cooling visual cues and consistent associations with lower thermal sensations. Participants also experienced distinct thermal perceptions depending on the visual alignment between the environment and the avatar (e.g., ice hands in the ice world). These findings align with the hue-heat hypothesis (HHH), which suggests that colors closer to the red end of the spectrum are associated with "warm" perceptions, while those closer to the blue end are perceived as "cool" [30,31].

Some scholars suggest that aligning the physical thermal environment with the one implied in VR can influence users' thermal perception, potentially enhancing comfort by synchronizing physical and virtual cues [1,45]. In another study, ref. [31] used VR to investigate the effect of wood as a natural material on perceived TC. Participants were exposed to different environments with four levels of integration of wood into a small residential space. Results showed that the application of wood in indoor environments significantly affected participants' thermal sensation, by increasing the perceived temperature.

A study by ref. [28] examined the influence of outdoor visual scenery on thermal perception using VR. They assessed participants in three scenarios: indoor VR, outdoor VR, and a physical room to measure thermal and VC. Results indicated that outdoor VR scenarios led to the highest TC, followed by indoor VR, with physical environments rated the lowest. Ref. [3] aimed to investigate the cross-modal effects of daylight color on thermal perception, as well as the effects of temperature on the visual perception of daylight. In their experiment, researchers placed participants in a virtual office environment under varying daylight colors (blue, orange, and neutral) and two temperatures (24 °C and 29 °C). Participants were asked to explore their surroundings and report on their thermal perception. The study found that daylight color significantly influenced thermal perception, with orange daylight leading to warmer thermal perceptions. However, no significant effects of temperature on visual perception were observed. Furthermore, the acceptability of the workspace was influenced by both color and temperature. These findings suggest that the perceived temperature can be affected by the color of daylight.

However, there are limitations to using VR. In addition to their heavy weight, which enhances feelings of discomfort [46], users can suffer from dizziness [8,47–49], eye fatigue [8,47], nausea [48,49], headaches, motion sickness, as well as the illusion of "self-motion" and discomfort [48], due to inconsistency between head movement and corresponding scene changes [8,49]. Those symptoms are linked to technical factors related to the HMDs used. Ref. [49] argues that those are related to field of view and duration of use. Ref. [48] explains that a lower refresh rate means longer lasting time per frame, causing images to be unstable, thus increasing the potential for motion sickness to occur. Furthermore, to reduce dizziness, ref. [48] recommends using devices with refresh rates of 90 Hz or higher, while [49] recommends using devices that offer a frame rate of 90 FPS.

Although visual–thermal interaction has been thoroughly studied in various contexts, addressing it in educational settings requires further investigation. Previous research has shown that VR can enhance engagement and learning outcomes in educational environments [50], but few studies have explored its impact on TC. For example, ref. [51] found that students in VR-based learning environments reported higher levels of engagement but also noted discomfort due to prolonged use of VR headsets. This highlights the need for further research into how VR can optimize comfort in educational settings.

This is crucial, as TC significantly influences work performance [22,52,53] and stress levels [39], which in turn affect students' academic performance. Assessing this interaction is particularly important when users engage in demanding cognitive tasks, such as those that occur in classrooms, often without special attention to their state of comfort. This research aims to fill the gap in the literature by evaluating the use of VR and IVE to enhance user comfort in educational settings while users focus on classroom tasks. As a pilot study within a broader research project, this investigation explores how VR can enhance user comfort in educational settings, with potential implications for improving learning outcomes. The goal is to explore methods to utilize VR and IVE to optimize comfort in educational spaces. It is hypothesized that the integration of IVE and VR in educational classrooms will simulate enhanced visuals to improve students' perceived TC compared to traditional physical settings, even when the actual physical environment remains unchanged.

To understand the relationship between VR and user comfort in educational settings, this study adopts a conceptual framework that examines how various factors interact to influence comfort and learning outcomes. As shown in Figure 1, the framework highlights three primary components: the context/environment, personal traits, and activities, which collectively shape the user comfort. VR is introduced as a tool to modify environmental and contextual elements, such as visual conditions, while also addressing individual factors like stress levels and sensory needs. These elements ultimately influence comfort and engagement, which are critical for achieving optimal learning efficiency in educational spaces. The diagram provides a comprehensive overview of these interconnections, forming the basis for the study's exploration of VR's potential in enhancing comfort during class-related tasks.

The remainder of this paper is structured as follows: Section 2 presents the materials and methods used in this pilot study, including details of the experimental setup, participants, and VR environment. Section 3 discusses the results, highlighting key themes identified from participant feedback. Section 4 provides an in-depth discussion of the findings, linking them to existing literature and identifying potential areas for improvement. Finally, Section 5 concludes this study by summarizing key insights, summarizing key limitations discussed in Section 4, and proposing directions for future research.
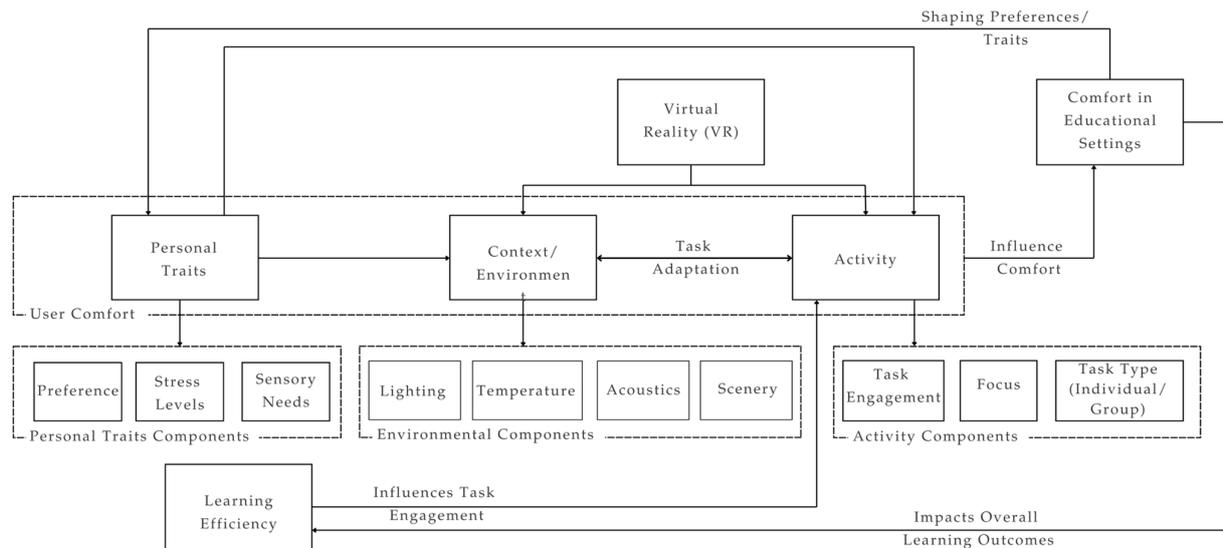
Figure 1. Conceptual framework illustrating the interplay between Virtual Reality (VR), environmental context, personal traits, and activities in shaping comfort and learning outcomes in educational settings.

2. Materials and Methods

This pilot study, part of a larger research project investigating the use of VR to enhance user comfort in educational spaces, employed an exploratory experimental design. This study compared user experiences with and without VR presentations through semi-structured interviews and researcher observations. Participants were not informed beforehand about the specific questions to minimize bias and ensure a more authentic exploration of their comfort experiences. This approach aimed to identify various characteristics influencing the students' comfort and engagement in the VR environment while conducting classroom-related tasks. This study tested the feasibility and limitations of VR equipment in educational settings, assessing its potential for future research.

Semi-structured interviews were a central part of this exploratory study, conducted in pairs immediately following the VR experience. This approach ensured that participants' impressions were fresh and uninfluenced by extended delays. Conducting interviews in pairs allowed for the potential cross-verification of experiences between participants, while ensuring that those who had not yet completed the VR tasks remained unaffected by prior discussions. The interviews followed a semi-structured format with six guiding questions designed to explore participants' general impressions of the VR environment, specific features that enhanced or detracted from their comfort, and distinctive characteristics of their experiences. The questions included the following:

1. How was your overall experience? Can you describe it?
2. How would you compare your experience in the virtual space compared to physical environment?
3. Which environment felt more comfortable to listen to the presentation in?
4. What made you feel more comfortable in the environment you chose?
5. What are the positive aspects you encountered in the virtual environment?
6. If you could make one change to improve comfort in the virtual environment, what would it be? and why?

The qualitative data were analyzed using an inductive thematic analysis approach, following ref. [54] methodology. Transcripts were manually coded by a single researcher due to the limited dataset. The analysis process involved a detailed reading of the transcriptions to identify recurring patterns, from which initial codes were developed. These

codes were then iteratively reviewed, refined, and grouped into broader themes based on conceptual similarities. Given the exploratory nature of this pilot study, no predefined coding framework was applied. The final themes emerged through an organic process of identifying patterns across participant responses, ensuring that they reflected key experiential aspects of VR-based comfort perception. Themes were finalized through iterative comparison of coded data, ensuring that each theme represented a distinct and meaningful aspect of participants' experiences. A summary of the themes and associated codes is presented in Table 1.

Table 1. Summary of themes and codes identified through thematic analysis.

Theme	Code
Theme 1. Visual Experience	Lack of Visual Connection, Familiarity with Scene, VC—Peripheral Vision, VC—Image Quality, VC—Lighting, VC—Scene
Theme 2. Physical Discomfort	Motion Sickness, General Physical Discomfort, Dizziness, Pain, Weight
Theme 3: Engagement and Distractions	Curiosity, Distractions, Engagement, Presence, Practicality, Adaptation Time, Individual Control, Concentration, Isolation
Theme 4: Perceived Changes in Comfort Parameters	Physical Sensation, No Perceived Change in TC, AC, or IAQ, Perceived Difference in TC, Perceived Difference in VC—Lighting, Lack of Physical Heat Sources, Influence of VC on TC, VC—Preference for Physical Lighting
Theme 5: General VR Experience	Enjoyable Experience, Dissonance, Playfulness, Positive Evaluation

2.1. Classroom and Participants

This study took place at KU Leuven, in Ghent Campus, in Belgium. The research was reviewed and approved by KU Leuven's Privacy and Ethics platform (PRET) and by the Social and Societal Ethics Committee (SMEC) of KU Leuven. Consent forms were distributed, signed, and returned to researchers prior to initiating the experiments. To avoid symptoms associated with motion sickness, all participants were informed that they could remove the HMD at any point. Participants received no compensation for their participation in the experiments.

In total, this study recruited 4 participants: 3 males and 1 female, all aged between 20 and 30 years. Participants were enrolled in a master-level course at KU Leuven, attending a regular class where they were expected to present the last stages of their designed project to their peers and instructor. All participants had limited VR experience. The demographic distribution of the participants is illustrated in Figure 2. To avoid overemphasis on comfort status, the exact purpose of the research was kept confidential. However, participants were informed that researchers were interested in obtaining their reflections and perceptions after they attended a part of the class in a VR environment.

The experiment took place on 4th June 2024, in the afternoon, between 14:00 pm and 17:00 pm. The room temperature was approximately 20 °C. As seen in Figure 3, the room had a rectangular shape, with warm colors on the walls and naturally brown with some white-colored furniture. The room was not air conditioned. On the wall facing the entrance, a large window overlooking a tree allowed natural light and visual connection to natural scenes. However, both the door and window remained closed throughout the experiment. A Zoom link was created and shared with all attendees, where a shared screen showing the presentation slides replaced the projector. However, all microphones and speakers were muted, and participants could hear the presentation content directly from the presenter. As each student presented their work, only one participant was asked to view the slides in a VR environment. With each new presentation, the following participant entered the VR

environment, and a new experiment started. All presentations had a combination of text and images, while a few had physical models that were not documented in the slides.
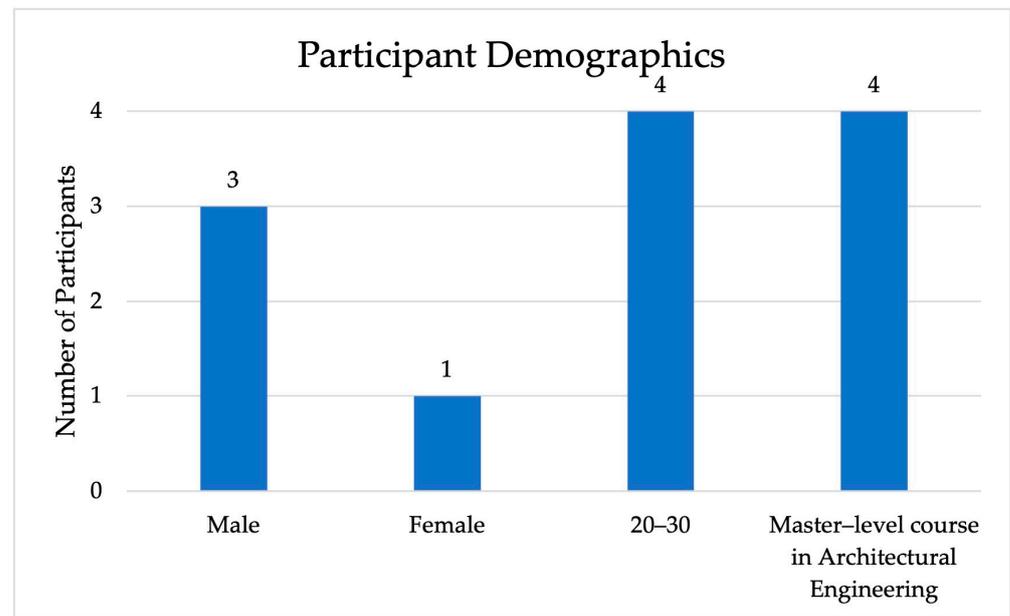

Figure 2. Demographic distribution of study participants, including gender, age, and academic background.

Figure 3. The room in which the experiment took place.

2.2. VR Tools

During the experiment, HTC VIVE system was used (Figure 4). The HMDs had a refresh rate of 90 Frames per Second (FPS) and 108° Field of View (FOV) and a resolution of 2160 × 1200 (1080 × 1200 per eye). In addition to the HMD device, the system required two base stations installed at opposite angles of the room, that captured the room scale and allowed for tracking locations of the hand controllers. Furthermore, two hand controllers were placed in the participants' hands, which allowed them to control movement and adjust the virtual screen location and size.

Figure 4. HTC VIVE system used to conduct the experiment.

2.3. VR Environment

The VR environment was selected from a list of pre-made environments offered on VIVE Sync software v2.18.12 (Figure 5). The choice was made based on maximizing the contrast between the physical and virtual environments, thus allowing for connection with more natural elements and lights, which was expected to reduce stress. Furthermore, the environment offered more openness and a strong sun to maximize hypothesized effects on users' thermal experience. The subtle occasional movement of a few tree leaves and waves mimicked a gentle breeze, enhancing the realism of the environment. The shared presentation of the Zoom meeting was projected on a large virtual screen in the VR environment. (Figure 6). Participants could change the size, orientation, and their distance from this virtual screen.

Each experiment started with a 5–10-min-long VR training. Participants were introduced to VR controllers and navigation around the VR space. Each presentation lasted for approximately 45 min. Each participant had the HMDs on the during entire time. Some verbal discussions took place between attendees during some presentations. The experimental procedure followed a structured sequence, ensuring that participants experienced VR systematically. As illustrated in Figure 7, each stage of the process was linked to themes identified in participant interviews, reflecting their evolving perceptions of comfort and engagement throughout the session.

Figure 5. The virtual environment in which participants viewed the presentation.

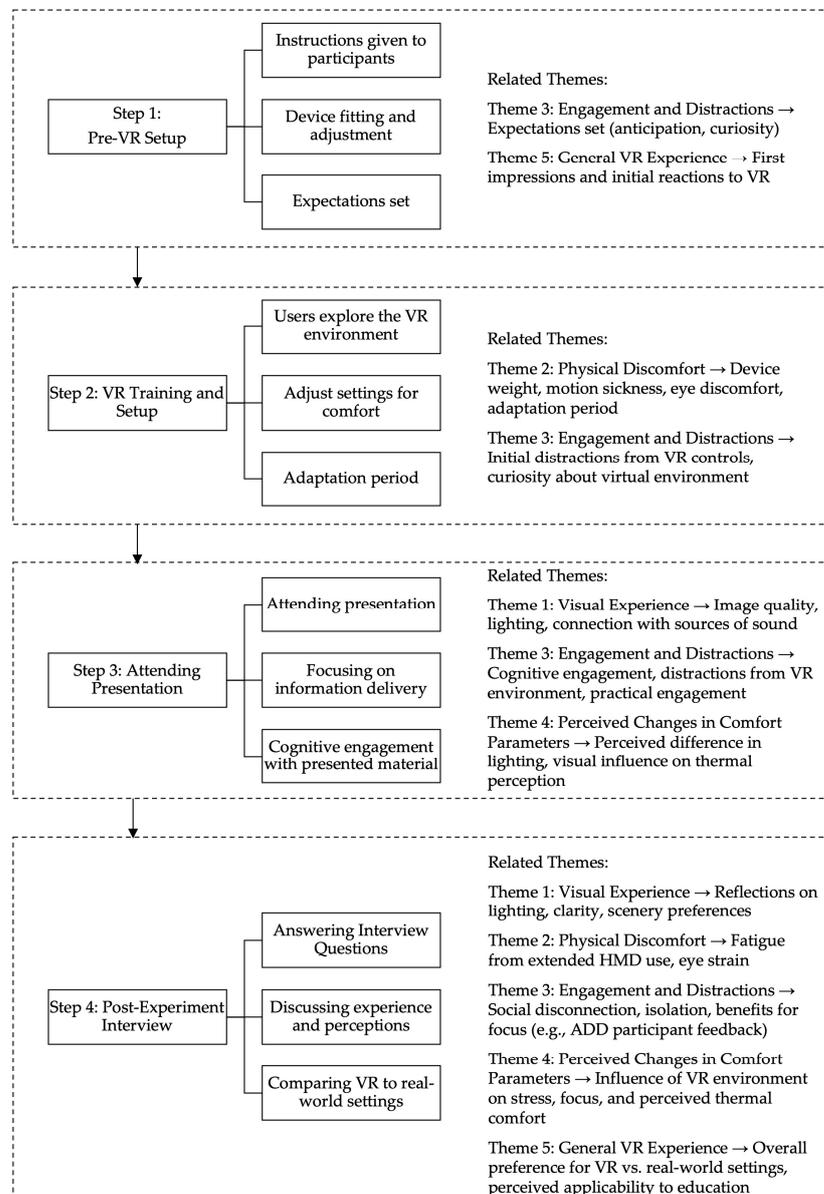**Figure 6.** The screen in the VR environment.

Figure 7. Flowchart depicting the steps participants went through while experiencing VR and how each stage relates to key themes identified in interviews.

3. Results

This study investigates the use of VR and IVE in enhancing user comfort in educational spaces, without affecting the physical condition. As a pilot study, which is part of a larger investigation, its results are preliminary and are intended to provide some initial insights into the extent to which VR environments can be used to enhance user comfort in educational settings. Results indicated five important themes: (1) Visual Experience, (2) Physical Discomfort, (3) Engagement and Distractions, (4) Perceived Changes in Comfort Parameters, and (5) General VR Experience. Each theme will be discussed in detail in the following subsections.

To understand how participants' experiences varied across different groups, the frequency of mentions in each theme was analyzed. As shown in Figure 8, 'Engagement and Distractions' was the most frequently reported theme across all participants (57 mentions), followed by 'Visual Experience' (16 mentions) and 'Perceived Changes in Comfort Parameters' (10 mentions). Meanwhile, themes such as 'Physical Discomfort' (5 mentions) and 'VR Experience' (6 mentions) were mentioned less frequently.
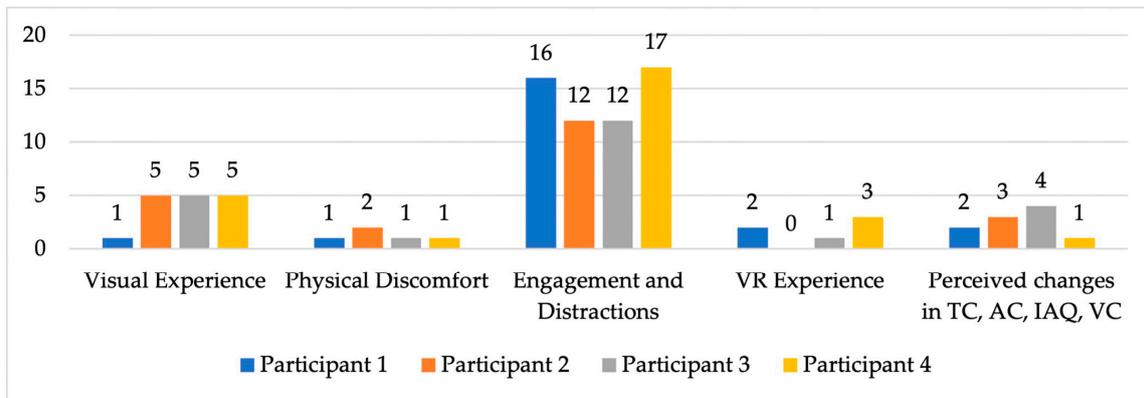

Figure 8. Distribution of participant experiences in relation to key themes.

Expanding on these findings, Figure 9 examines how demographic factors, such as gender, influenced participant experiences across key themes. Male participants, on average, reported 13.7 mentions of distractions compared to the female participant's 16 mentions, suggesting a possible trend but requiring caution due to the unequal sample sizes. Males also noted more instances of physical discomfort, whereas the female participant expressed slightly higher sensitivity to visual experience. However, the data do not strongly support the claim that the female participant was more sensitive to image quality and lighting conditions, as males reported slightly more mentions in the 'Visual Experience' category. Additionally, while all participants had limited VR exposure, individual differences in adaptability may have influenced their comfort levels, though further analysis would be required to confirm this effect.

To better understand the prominence of each theme in participant responses, the frequency of mentions was analyzed. As shown in Figure 10, 'Engagement and Distractions' remained the most frequently discussed theme (57 mentions), followed by 'Visual Experience' (16 mentions) and 'Perceived Changes in Comfort Parameters' (10 mentions). 'Physical Discomfort' (5 mentions) and 'VR Experience' (6 mentions) were mentioned the least, though they still played a role in shaping participant perceptions of comfort in the VR environment.
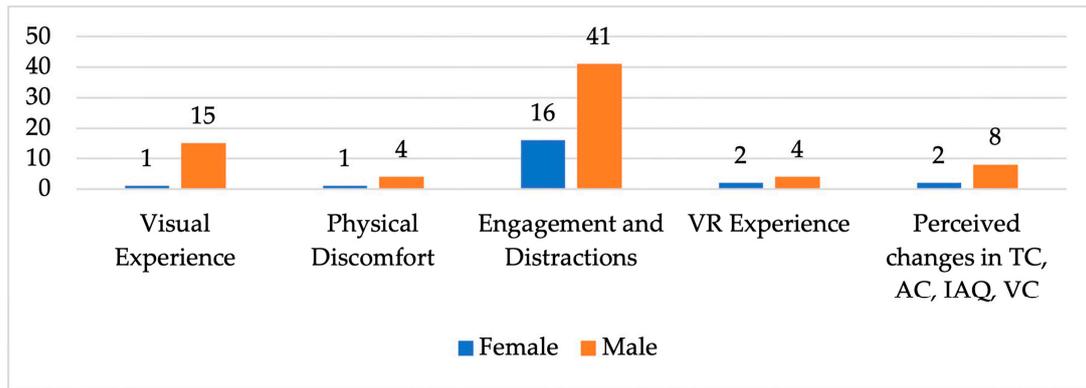
Figure 9. Comparison of participant experiences across demographics and background factors in relation to key themes.
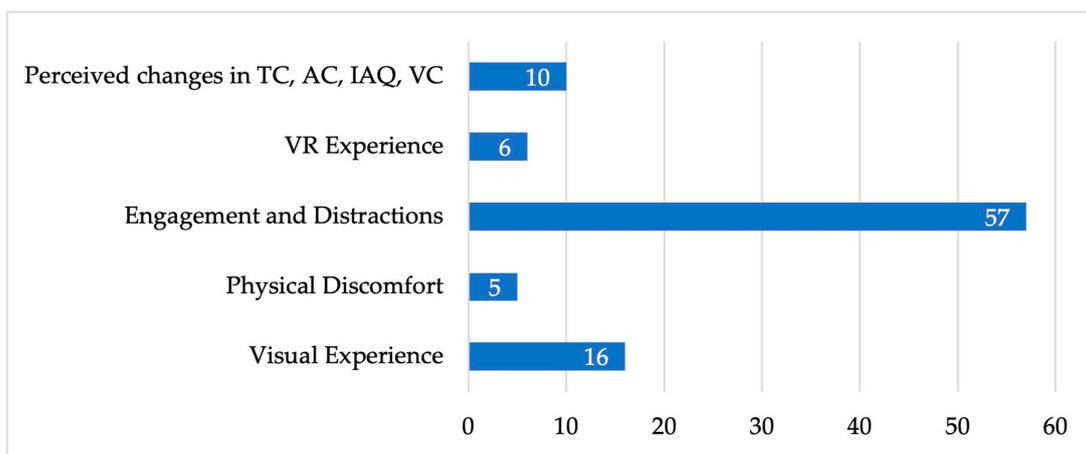

Figure 10. Frequency distribution of main themes derived from participant interviews.

3.1. Theme 1: Visual Experience

The visual experience is a crucial part that affected user experience in the VR environment in an educational setting. Three main subthemes emerged: (1) visual connection with sources of sound, (2) image quality, and (3) lighting and chosen scenery. To understand the prominence of these subthemes, Figure 11 illustrates the frequency of mentions across participant responses. Lighting conditions were the most frequently mentioned aspect, followed by image quality and visual connection with sound sources. These factors influenced participants' comfort and ability to engage with the virtual environment.

First, challenges in connecting sounds to their sources were frequently mentioned by participants. Participants 1 and 2, respectively, noted the following: "you hear people, but you don't see people", and "you don't see the people talking". This issue was further emphasized when physical models were involved, as participants struggled to follow discussions. One participant explained, "They were showing things in models, and I couldn't see it". Despite this limitation, others expressed interest in VR presentations if this issue were addressed. "If the physical model issue is resolved, I would rather attend the presentation in the VR Environment", noted another participant. Additionally, some participants reported feeling socially isolated, stating that the inability to visually locate speakers reduced their willingness to engage in verbal discussions. However, this experience varied, as some participants still actively contributed despite the audio-visual disconnection.
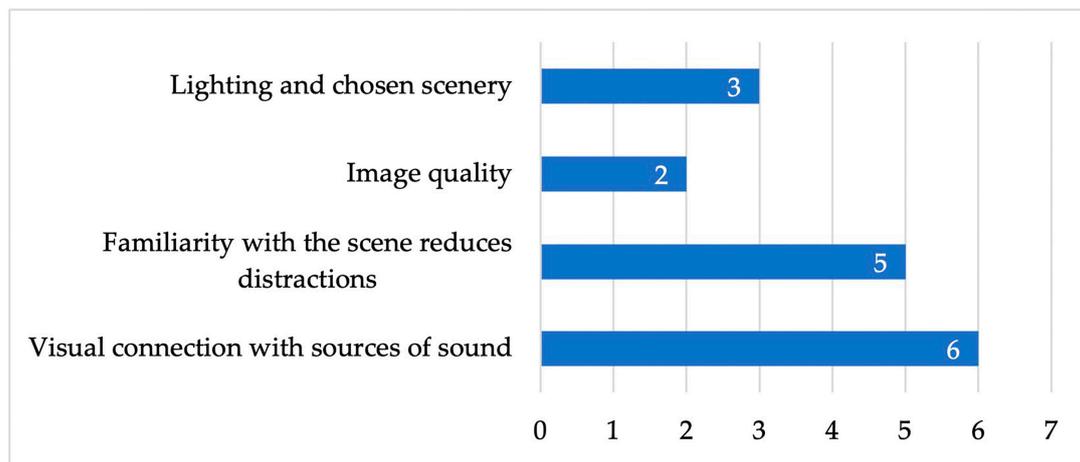
Figure 11. Breakdown of visual experience subthemes mentioned in participant interviews.

Second, image quality was also perceived as a limitation. Five participants found it difficult to read text on presentation slides, particularly when the content was too small. "I had a little trouble with reading text", one participant noted, while another added, "the sharpness of the screen; I couldn't read everything when I was in the VR world. Only the big words I read if I focused". Additionally, some reported that the narrowed field of view in the headset required excessive head movements to see content clearly. One participant described it as, "If you want to look at something, you have to move your head so the sharpest is right in front of you and everything around is a bit blurrier". Others mentioned the distracting presence of a black frame around their vision, which was not present in the physical setting. "Now, we see almost 180 degrees vision, and with device on, it's more limited to narrower view", explained one participant. Another added, "you can see the black frame, it's a little distracting".

Finally, the lighting conditions and the scenery in the VR environment were key factors influencing participants' comfort. While all participants noticed differences in lighting conditions, comfort levels varied. One preferred the physical environment, stating, "Only the light [was different] but I prefer the physical environment's light". In contrast, others appreciated the brighter, more natural VR lighting, reporting that it made them feel more alert and engaged. One participant noted, "I did feel a difference in lighting because in this room it's pretty dark, but back there in VR, it was a clear day. The sun was shining, so I did feel more awake than in here". Furthermore, one participant valued the perceived natural light, stating, "The light was good, because I was outside". However, the chosen VR scenery was widely seen as a distraction. All participants agreed that the beach setting made it difficult to focus. "You're like on vacation that was also a bit distracting", one participant said, while another added, "it was very difficult to concentrate on the presentation because of everything you see—the trees, the sand".

When asked about preferred environments, participants expressed highly varied preferences, highlighting the potential of VR to enable personalized settings. Some preferred a classroom setting, while others favored a cozy home-like environment with warm colors. Another participant preferred a green space with vegetation, explaining that nature helped them feel relaxed and focused. These diverse preferences highlight the potential of VR to offer customizable environments tailored to visual comfort and user preferences. Just as some participants may prefer absolute silence for work, others might benefit from background sounds, illustrating how VR can enhance engagement by allowing for personalized settings. Below are the participants' exact descriptions of their preferred environments:

- "Maybe create a normal environment, I mean, in a room or something, maybe better than this [physical] room, with better lighting".—participant 1.
- "A classroom would be more perfect to concentrate"—participant 2.
- "I would choose an environment that is more comfortable, for example, at home, or a farm, so natural aspects that would calm me down and make me feel more relaxed […] I would choose agriculture and greenery. It feels more like home. The lighting has an important factor. A clear day is a clear mind. […] I would have it at 10:00 AM. It's a beautiful time. I would also add a second screen in the VR environment for notetaking".—participant 3.
- "It depends on the situation […] if it's not so serious presentation, I'm ok with the more nature background. Nothing too busy. Not serious, not too many movements, because that distracts a lot […] If it would be more serious presentation, where everybody has to really pay attention I think […] just a blank white box that you're in would be good. It's boring, but I think that would maybe keep your attention to the screen that's there. I would change the scenery, but the lighting was good. It was midday. It keeps you awake and clears your mind"—participant 4.

3.2. Theme 2: Physical Discomfort

As expected, most participants experienced physical discomfort related to wearing VR HMDs. The most frequently reported issue was of a general physical nature, rather than any single symptom. Reports included (1) the weight of the device on the participant's head and (2) isolated symptoms such as dizziness and an unpleasant sensation around the eyes. Nonetheless, all participants chose to tolerate these discomforts and continued attending the presentation in VR mode.

Only one participant explicitly mentioned the headset's weight as an issue, stating, "It was also heavy for me to wear for a long time". Reports of other discomforts were limited. One participant described experiencing dizziness and forehead pain, stating, "I also got a little bit dizzy […] Also, the pain goes here [points on the forehead area]". Another noted a mild discomfort around the eyes, explaining, "I had no problems with dizziness or whatsoever. I did feel unpleasant feeling in my eyes". Finally, one participant, who usually experiences motion sickness, reported no issues in the VR environment, stating, "It was fun. It was alright. Usually, I have motion sickness in the car, but I didn't feel anything".

Figure 12 illustrates the distribution of specific physical discomforts mentioned by participants. The most frequently reported category was general physical discomfort, while other symptoms—including dizziness, pain, and the weight of the headset—were reported less frequently.
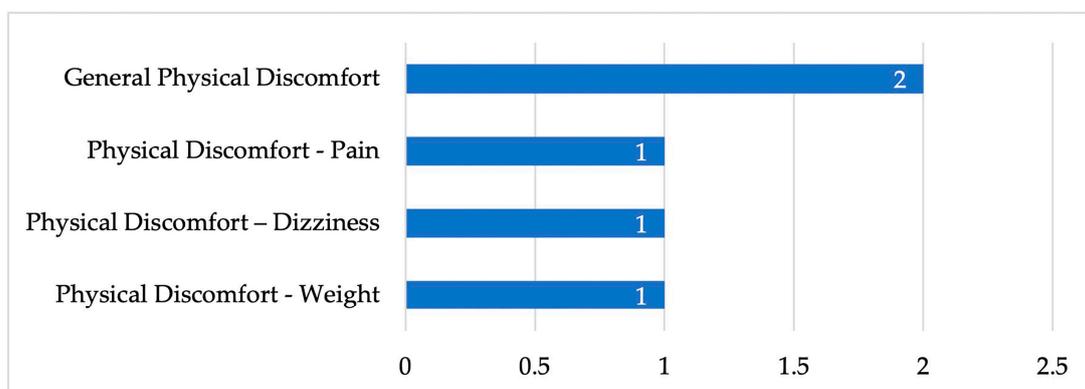
Figure 12. Breakdown of physical discomfort subthemes mentioned in participant interviews.

3.3. Theme 3: Engagement and Distractions

Engagement and distraction are crucial aspects of conducting tasks in educational settings, particularly in VR environments. Understanding how students engage with academic material in VR helps evaluate its effectiveness as a learning tool. Subthemes included (1) distractions, (2) feelings of social disconnection, and (3) isolation from physical distractions. Although some of these aspects overlap with other themes, their prominence in participant responses justifies their inclusion as a separate theme.

Multiple forms of distractions were mentioned during the interviews. Many of these stemmed from adapting to the VR environment and its interactive features. The VR scenery itself contributed to a 'vacation mode' feeling, distracting students from the content presented. Additionally, participants' curiosity to explore VR features—such as adjusting controls—initially acted as a temporary distraction. One participant noted, "I do think having the controls yourself is a bit distracting because you can keep playing with the screen size and the exact position of everything. For me that's a bit distracting because it's a bit playful". However, However, the same participant also noted that this was a temporary issue, stating, "After a while, if you have seen everything it doesn't distract anymore".

As shown in Figure 13, the most frequently discussed subtheme was practicality (14 mentions), highlighting concerns about the ease or difficulty of interacting with the VR setting. Participants discussed whether VR environments were intuitive and whether they allowed for smooth engagement with learning material. Some noted that VR improved their focus, while others found it challenging to adjust to the lack of physical materials, such as notebooks or physical models.
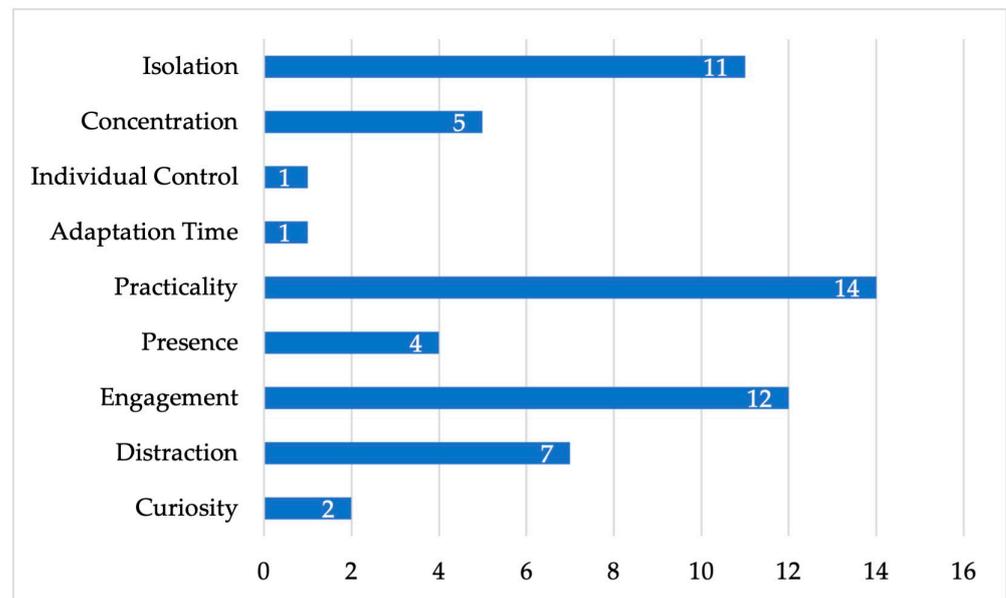
Figure 13. Breakdown of engagement and distractions subthemes mentioned in participant interviews.

Engagement (12 mentions) and isolation (11 mentions) were also widely discussed. While some participants struggled with feelings of social disconnection, others appreciated the separation from external distractions. For some, the VR environment reduced engagement because they could not make eye contact or visually locate speakers, which impacted participation in discussions. However, many overcame this barrier and were still able to engage in conversations, suggesting that adaptation plays a key role in how users experience social isolation in VR.

Another significant aspect was concentration (5 mentions). Some participants felt that VR enhanced their focus by eliminating external disturbances. However, others found it harder to concentrate due to the novelty of the VR setting and its initial distractions.

A unique case involved a participant with a confirmed ADD diagnosis, who found the VR environment beneficial. They explained that VR helped them avoid external distractions, such as checking their phone or browsing the internet during class. Additionally, some participants noted that VR reduced stress related to being constantly observed by others. This lower stress level influenced their TC, which will be discussed further in the following subsection.

3.4. Theme 4: Perceived Changes and Their Impact on Comfort

This theme explores perceived changes in comfort parameters, including VC, AC, IAQ, and TC. Subthemes include (1) perceived differences in acoustic and air quality conditions, (2) perceived differences in VC, (3) perceived differences in TC, and (4) the influence of visual elements on perceived temperature.

No participants noticed any difference in acoustical quality or indoor air conditions between the VR and physical settings. In contrast, visual differences were the most frequently mentioned change, particularly regarding lighting and environmental realism. As previously discussed, most participants preferred the VR lighting, as it simulated natural light and reduced eye strain. However, one participant preferred the physical lighting conditions due to the ability to see real-world objects.

Perceived differences in TC were less frequently reported (2 mentions). Most participants did not notice any significant temperature change between the VR and physical environments. However, one participant stated that the VR setting felt cooler due to being farther from their laptop heat source and experiencing less stress from being visually observed.

A single participant (participant 3) linked their thermal perception to visual elements. They explained how the IVE contributed to relaxation, which, in turn, influenced their perception of temperature:

> "I think the scenery is most important to me, but if everything is right, it can also trick your brain to think it's cool (temperature wise [...] This has to do with the fact that you feel more relaxed like I said earlier, you don't feel the eyes of the professor on you, and VR helps you ignore those things, which is for me more relaxed and less stressed, and so cooler temperature."
>
> —participant 3.

Furthermore, participant 4 identified TC as the most important factor when choosing an environment. They suggested that alternative VR scenes might more effectively impact comfort through perceived temperature changes. Their response to the question 'Which environment felt more comfortable to listen to the presentation in?' emphasized their thermal preferences when choosing between VR and physical settings:

> "The thermal element would be the most important element for me to choose my environment. Because all the other aspects can be controlled in the physical world, but the thermal one I think is the most difficult to generate it if you're in a VR. [...] I didn't feel any changes in the tropical climate, maybe if it was a colder climate, I don't know If it would change for me."
>
> —participant 4.

Figure 14 illustrates the breakdown of perceived changes in comfort parameters. Participants most frequently noticed changes in VC, particularly in relation to lighting

and realism. Fewer participants reported differences in TC, and no participants noted differences in acoustics or IAQ.
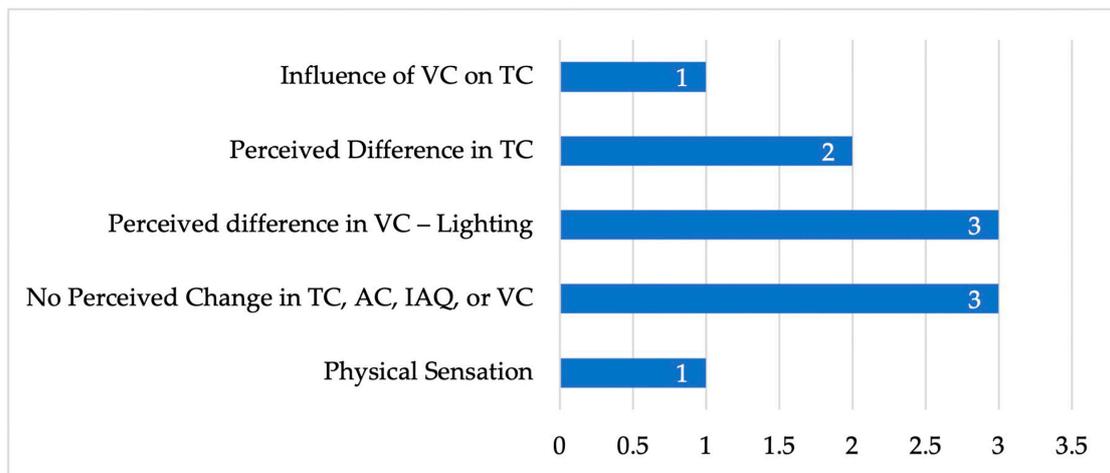

Figure 14. Breakdown of perceived changes in comfort parameters subthemes mentioned in participant interviews.

3.5. Theme 5: General VR Experience

Participants shared a variety of reflections on their overall VR experience, highlighting three key aspects: playfulness, dissonance, and general enjoyment.

(1) Some participants found VR to be a fun and engaging tool, particularly for non-academic activities. While they saw potential in VR for education, they primarily associated it with entertainment. Participant 1 stated, "For a Zoom meeting or a presentation, I would rather see it in real life, but for games or something, it can be a nice experience". Similarly, participant 2 stated, "I prefer real life. VR is for pleasure".

(2) Other participants recognized VR's educational potential but identified key limitations. They suggested that VR could be improved by enhancing image quality, modifying scene choices, and adapting tasks to exclude physical models. Participant 3 commented, "If the physical model issue is resolved, I would rather attend the presentation in the VR environment".

(3) Despite these positive aspects, some participants experienced a sense of dissonance when engaging with VR for academic tasks. They found that the technology did not seamlessly align with real-world learning needs. Participant 4 explained, "I would choose real life—first of all the sharpness of the screen [. . .] We still have physical models. I think VR would be good if you have a 3D model on your computer [. . .] In the VR you can walk into the model. Through the camera you can't show everything in the physical model [. . .] So I think, I prefer more in the real world".

As shown in Figure 15, participants equally highlighted playfulness, enjoyment, and dissonance in their reflections. While some saw VR primarily as a tool for entertainment, others reflected on their experience, recognizing both its enjoyable aspects and the challenges it presented for practical applications. The findings suggest that VR's effectiveness in academic settings depends on how well it integrates with practical learning needs while maintaining engagement and usability.
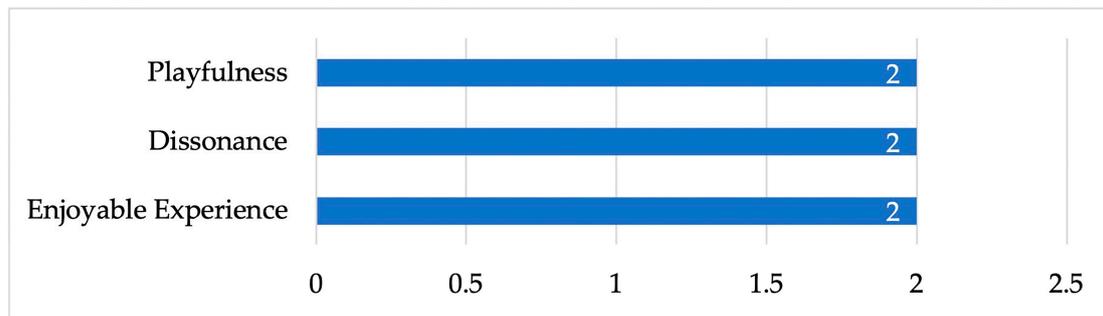
Figure 15. Breakdown of VR experience subthemes mentioned in participant interviews.

4. Discussion

The results of this pilot study provide initial insights into the use of VR for assessing TC in educational buildings, with potential applications for improving user experience, sustainable building management, and energy efficiency. However, the findings suggest that participants did not consistently notice differences in perceived temperature or TC. While some participants perceived a cooling effect in the VR environment, others did not register any thermal changes at all. One participant reported feeling cooler in the VR environment due to reduced stress, but this was not a universal experience. Additionally, one participant explicitly linked their comfort level to the scenery, suggesting that alternative environments might enhance perceived TC more effectively. These variations highlight the complexity of perceived TC in VR environments and the influence of individual factors such as stress levels and task-related dissonance. This aligns with findings from ref. [28], who emphasized that TC in VR is highly subjective and influenced by psychological and environmental factors.

This exploratory research aimed to investigate the possible impact of VR on students' comfort during studio education and to analyze the experiment setup for possible improvements and limitations. While the primary objective was to examine differences in thermal perception and comfort, the findings revealed additional influential factors. Visual elements, stress levels, and task-related interactions played a crucial role in shaping students' overall comfort in VR learning environments. This is consistent with ref. [33], who found visual environmental factors, such as natural views and daylight, influence thermal perception and stress reduction. These findings align with broader research on multisensory integration, suggesting that visual cues can modulate comfort perception—an effect that may extend to VR environments where simulated natural elements could be used to enhance user experience.

Further investigations into the role of wall colors in VR environments reveal the intricate relationship between visual stimuli, thermal perception, and productivity. A study from ref. [35] tested this interaction in both real and virtual office environments, using controlled temperature conditions and performance tasks to assess the influence of color. While subjective responses indicated clear preferences, objective measures of productivity and comfort showed no statistically significant differences. This suggests that while color may psychologically affect perceptions of warmth or coolness, these effects do not always translate into physiological or performance-based changes. In the context of VR applications, these findings indicate that modifying wall colors alone may not be sufficient to enhance user comfort, emphasizing the need for a more integrated approach when designing immersive environments.

Further evidence from ref. [37]'s study suggests that the relationship between visual stimuli and thermal perception is complex and context-dependent. While blue light consistently contributes to a cooler sensation, the influence of red light varies, indicating that

factors such as thermal neutrality may moderate the hue-heat effect. Additionally, studies highlight the distinction between perception and physiological response, reinforcing that while color can influence comfort, thermoregulatory changes are primarily driven by ambient temperature. This distinction is particularly relevant for VR environments, where visual elements are used to enhance comfort. Given these findings, relying solely on color manipulation may not be sufficient to produce meaningful thermoregulatory effects, underscoring the need for a more holistic approach to optimizing TC in immersive settings

One of the aspects that require improvement is the VR environment, which can be limiting in various ways. In this case, the scene of the background was pre-selected for the users, but allowing them to choose their own environment could have a greater impact on their comfort. As the results indicated, participants expressed diverse scenery preferences, ranging from classroom settings to natural environments, highlighting the potential for personalized VR customization. By allowing user customization of virtual environments, educational institutions could foster more adaptable and energy-efficient solutions, reducing the need for physical alterations to classroom environments. This approach is supported by ref. [15], who demonstrated that user-controlled VR environments enhance engagement and comfort [15], leading to better work performance [22,52,53], thus influencing learning outcomes.

However, despite exposure to the same natural elements, not all participants perceived a difference. Some explicitly stated that they noticed no significant changes in air quality or acoustics between the two environments. This inconsistency with previous studies suggests the need for further investigation into factors influencing thermal perception in VR environments. First, TC could have been compromised by the VR headset's heavy weight and potential visual discomfort due to reduced image quality. The results showed that physical discomfort, including dizziness, eye strain, and device weight, were frequently mentioned concerns that may have influenced participants' perceptions of comfort. Another justification could involve thermal expectation being a determining factor to perceived TC [4,28,29]. As many users expressed confusion due to the dissonance between perceived and felt sensations, this could explain the limited effect VR had on perceived TC. As noted by ref. [28], VR's effectiveness in influencing thermal perception is contingent on specific thermal ranges. Since this study did not explicitly control for temperature variations, this factor may explain the lack of perceived thermal changes in the VR environment.

On the other hand, lighting was found to be a significant aspect enhanced by VR. While many participants found the chosen scene distracting, all participants noted that attending a presentation under simulated natural light, during midday, and under a clear sky created superior lighting conditions for task performance and concentration. This is also consistent with findings of previous scholars, including refs. [28,30,33]. However, participants identified the beach-like scenery as distracting, reinforcing the need for selecting VR environments that align with the intended task. Additionally, the lack of visual connections to physical surroundings led to mixed reactions, with some experiencing isolation and others finding it beneficial for focus. This can also be explained by the sources of stress significantly affecting TC [28,33]. Depending on the subjective sources of stress, VR can either enhance or reduce stress levels, thus affecting perceived TC differently from one person to another.

It is important to note that as a pilot study, the results above are inconclusive, and require further investigation. Future research should expand the participant pool to enhance the generalizability of findings. Additionally, incorporating more advanced VR devices with higher image resolution and wider fields of view could mitigate visual discomfort, thereby improving user experience and measurement accuracy in future studies. This recommendation is supported by refs. [48,49], who demonstrated that higher-resolution VR

devices significantly reduce visual discomfort and improve user engagement. Furthermore, as the study indicated, VR may offer benefits for students with ADD/ADHD by reducing external distractions, providing a potential avenue for further exploration into inclusive learning applications. While this study did not specifically target this population, this observation highlights the potential for VR to create more inclusive learning environments that accommodate diverse cognitive needs. Future research should further explore the role of VR in supporting individuals with ADD and other learning disabilities, particularly in educational settings, to determine whether VR-based interventions can enhance engagement, reduce stress, or improve learning outcomes.

Beyond its impact on user comfort, VR presents an opportunity for sustainable building strategies. By enabling virtual modifications to classroom environments, VR can provide adaptable solutions that reduce the need for energy-intensive HVAC systems, optimizing energy consumption while maintaining or even enhancing student comfort. This aligns with broader sustainability goals, as VR-based interventions offer a low-energy complement to traditional climate control methods. Similarly, ref. [33] demonstrated that incorporating natural views and daylighting strategies in physical environments can lead to significant energy savings. These findings suggest that virtual simulations of such strategies in VR could provide an alternative pathway to improving comfort while reducing energy demand.

As this study was a pilot investigation, the participant pool was intentionally kept small to allow for an in-depth qualitative exploration of user experiences in VR environments. While the findings provide valuable initial insights, the limited sample size restricts the generalizability of the results. However, this study serves as the foundation for a follow-up investigation, where a larger and more diverse participant pool will be considered. The follow-up study will refine the methodology and expand data collection to strengthen the reliability of findings and further explore the impact of VR on perceived comfort in educational settings. Apart from sample size limitations, other factors may have introduced biases into the results. First, participant expectations and prior experiences with VR could have affected their perception of comfort, introducing a subjective bias. Since this study relied on self-reported qualitative data, there is also a potential for recall bias, where participants' descriptions of their experiences may not fully capture their real-time responses. To mitigate these limitations, future research should implement randomization techniques, include a more diverse participant pool, and incorporate objective physiological measurements alongside self-reported comfort levels.

To further strengthen methodological rigor, future research should integrate quantitative TC measures alongside qualitative insights. This mixed-methods approach will include objective data collection methods such as ambient temperature sensors, skin temperature monitoring, and physiological responses (e.g., heart rate variability). Incorporating these empirical metrics will provide a more comprehensive and scientifically robust understanding of how VR environments influence perceived TC, helping to validate qualitative findings with measurable data.

Future studies should adopt a longitudinal approach to assess how prolonged exposure to VR environments affects user comfort, adaptation, and cognitive performance over time. Tracking participants across multiple VR sessions could reveal adaptation effects, changes in thermal perception, and potential long-term benefits or drawbacks of using VR for educational purposes. Additionally, while this study focused on studio education, future investigations could assess the applicability of VR-based comfort interventions in other settings, such as corporate workspaces, healthcare environments, and residential applications. By testing VR's impact across diverse contexts, researchers can further vali-

date its effectiveness and identify setting-specific design considerations that optimize user experience and well-being.

To better understand the implications of the findings, Table 2 provides a detailed breakdown of the key themes identified in this study and their potential applications in VR-based learning environments. Furthermore, the themes identified in this study not only influence user comfort in VR environments but also have direct implications for learning outcomes in educational settings. As shown in Figure 16, these themes align with various educational benefits, including enhanced engagement, reduced cognitive load, and improved focus. By examining how students experience and interact with VR-based learning spaces, educators and designers can refine virtual environments to better support learning effectiveness and student well-being. This is consistent with ref. [50], who found that well-designed VR environments can significantly enhance learning outcomes.

Table 2. Main themes resulting from interviews that reflected participant reflections on experiencing VR in educational settings.

Theme	Subtheme	Patterns and Insights	Implications
Theme 1. Visual Experience	Visual connection with sources of sound	Students struggled to follow with some parts of the presentations due to the presence of physical models.	VR environments can only be used when physical models are not necessary. Alternatively, presenting digital models in a VR environment.
	Image quality	Participants struggled with the angle of vision.	The use of more advanced devices with wider angles of vision would help enhance comfort.
	Lighting and chosen scenery	Most found lighting comfortable. Some had problems with the choice of the scene, contradicting the nature of the task.	Maintaining similar lighting conditions, but considering different settings would help students concentrate more on the task itself.
Theme 2. Physical Discomfort	Device weight	Feelings of discomfort due to the weight of the device.	Using more recent light-weight devices.
	Motion sickness symptoms, discomfort in the eyes and headaches	Discomfort experienced by most participants.	Using more advanced devices that reduce symptoms.
Theme 3: Engagement and Distractions	Distractions	Participant curiosity, scene imposed a holiday mood.	Allowing time for users to explore the IVE prior to initiating the presentation.
	Feelings of isolation	Isolation prevented some users from taking part in the discussion.	Allowing a metaverse experience, with multiple avatars of participants at the same time.
	Isolation from physical distraction	Isolation from surrounding distractions was reported by participants with ADD.	Further investigation of enhancing learning experience with different cases of learning difficulties.

Table 2. *Cont.*

Theme	Subtheme	Patterns and Insights	Implications
Theme 4: Perceived Changes in Comfort Parameters	No perceived difference in AC, nor IAQ	Participants felt no difference in AC, nor IAQ.	Explore other physical and virtual settings.
	Perceived difference in lighting	Participants noticed a difference in lighting conditions, most preferred the virtual situation, a few preferred the physical situation.	Explore different settings while maintaining the same lighting situation.
	Perceived difference in TC	A few noticed a slight difference in the thermal environment due to being away from the computer's heat, and from stress associated with being watched by others.	Consider the use of VR in enhancing educational spaces for people with learning difficulties.
	Influence of VC on perceived temperature	Some participants expressed the influence of VC on TC.	Explore other virtual settings.
Theme 5: General VR Experience	VR for entertainment purposes only	Participants felt distracted due to their ability to move around the virtual space.	Allow more time prior to the experiment for exploration and training.
	VR for educational purposes	Some enjoyed VR for educational purposes but preferred a different scene.	Consider environments that comply with the required mode for the task.
	Dissonance	Participants experienced contradicting situations—feeling cold under the sun, and seeing movement, but not hearing it.	Consider other environments, including cold, wind, etc.

Additionally, to further optimize user experience, future studies should consider VR environments that minimize social isolation by facilitating more interactive or collaborative virtual spaces. The task design should also exclude elements that require physical models or real-world visual references, ensuring that participants can fully engage in the VR setting without disruptions. Finally, considering VR environments that suggest a more relaxed, yet comfortable environment with moods consistent with that of the tasks would help better assess that effect. The findings of this study open several potential avenues for further research. As illustrated in Figure 17, each theme identified in this study presents opportunities for deeper investigation into user comfort, engagement, and the optimization of VR learning environments. Future research could explore personalized VR experiences, the long-term effects of VR on cognitive performance, and the integration of adaptive technologies for enhancing virtual educational spaces. This aligns with ref. [51], who emphasized the potential of adaptive VR environments to enhance user comfort over time.
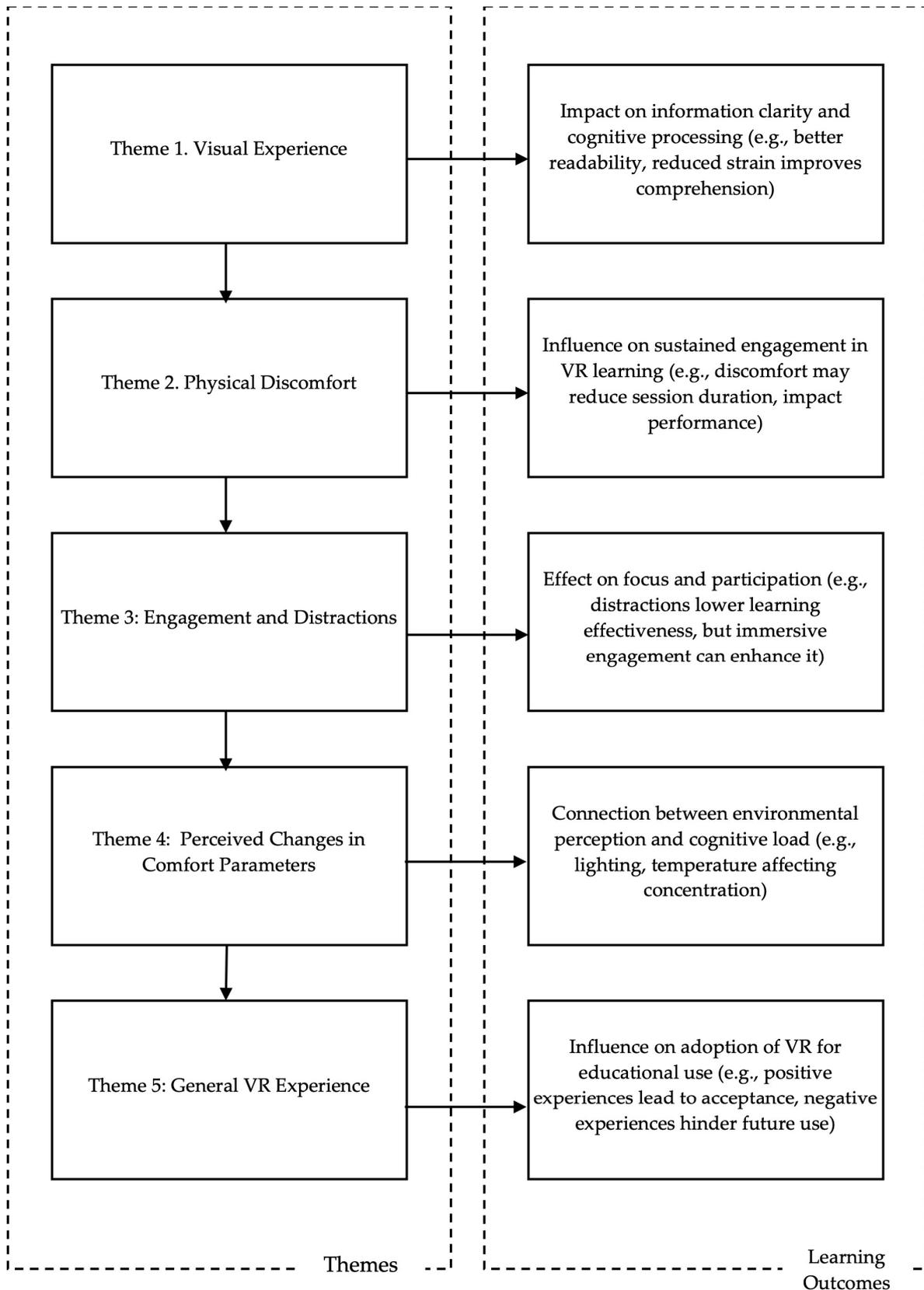
| Theme 1. Visual Experience | → | Impact on information clarity and cognitive processing (e.g., better readability, reduced strain improves comprehension) |

| Theme 2. Physical Discomfort | → | Influence on sustained engagement in VR learning (e.g., discomfort may reduce session duration, impact performance) |

| Theme 3: Engagement and Distractions | → | Effect on focus and participation (e.g., distractions lower learning effectiveness, but immersive engagement can enhance it) |

| Theme 4: Perceived Changes in Comfort Parameters | → | Connection between environmental perception and cognitive load (e.g., lighting, temperature affecting concentration) |

| Theme 5: General VR Experience | → | Influence on adoption of VR for educational use (e.g., positive experiences lead to acceptance, negative experiences hinder future use) |

Themes   Learning Outcomes

Figure 16. Diagram linking identified themes to potential learning outcomes and educational benefits in VR-based environments.
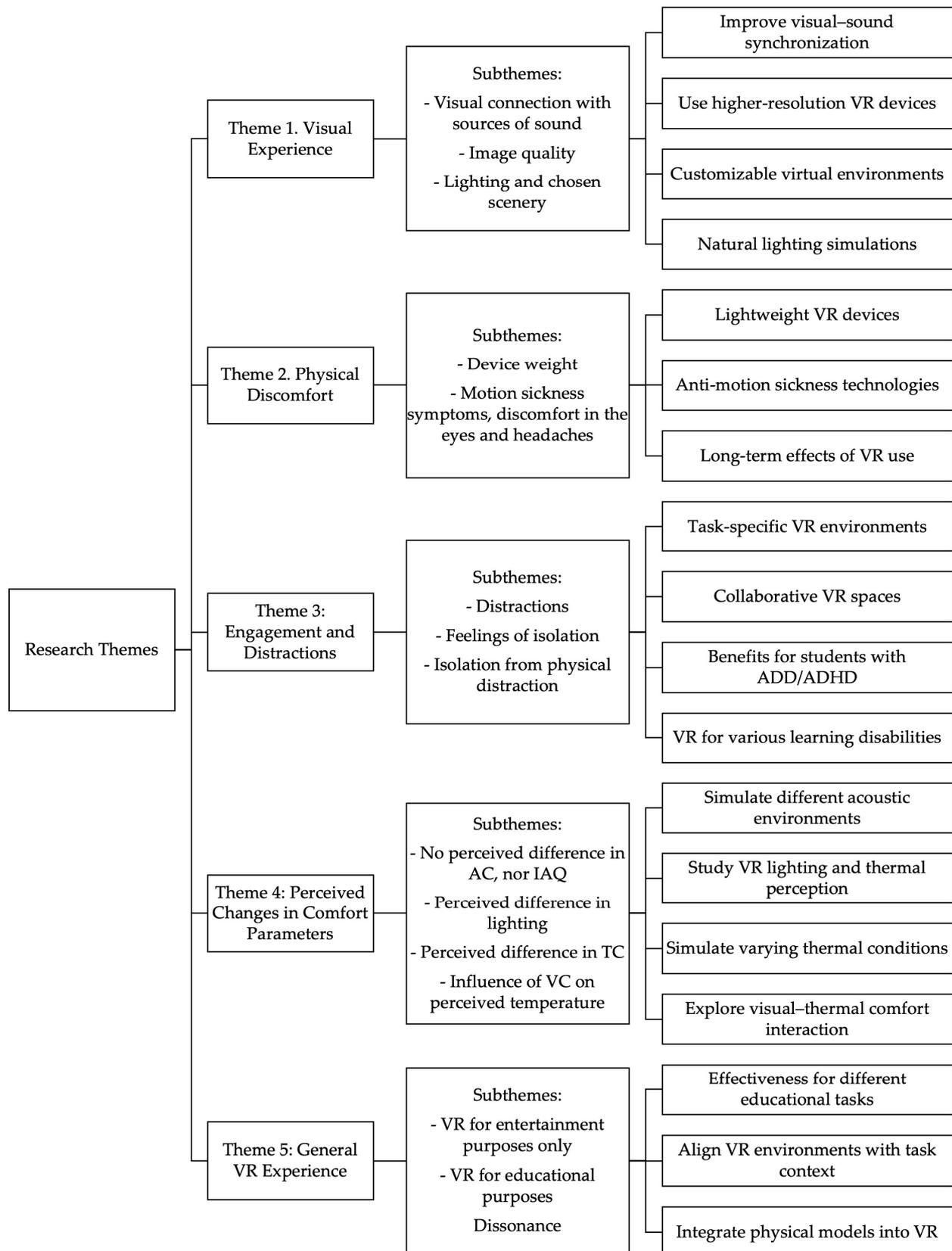
Figure 17. Potential research avenues based on identified themes, outlining directions for future investigations in VR-based user comfort and learning environments.

5. Conclusions

This pilot study explored the use of Virtual Reality (VR) to enhance user comfort in educational settings. The findings suggest when participants were not consciously aware of their comfort state, VR environments had a limited effect on enhancing perceived TC. However, when appropriate visual scenes were selected, the results indicated that stress-reducing visuals could enhance users' thermal perception, subsequently improving performance. Beyond TC, this study highlighted the significance of VC, physical comfort, and engagement in shaping participants' experiences in VR environments. Factors such as lighting, scene selection, and task-related dissonance played a critical role in determining user satisfaction. These insights underscore VR's potential as a tool for sustainable architectural and educational design, offering adaptable solutions for enhancing comfort without excessive reliance on energy-intensive mechanical systems.

VR offers an immersive and adaptable alternative to physical modifications, potentially supporting sustainability goals by minimizing the need for costly retrofits, reducing HVAC reliance, and lowering overall energy consumption. These findings align with previous literature, where refs. [33,51] suggest that connection to natural elements—including natural light and water—may contribute to reduced stress levels and improved TC [28,33]. By simulating these natural elements, VR has the potential to help designers create energy-efficient environments that enhance comfort without relying on energy-intensive mechanical systems. For example, ref. [51] found that VR-based simulations of natural ventilation and daylighting strategies could lead to energy savings, while ref. [12] highlighted VR's potential for pre-assessing comfort interventions, thereby reducing the need for physical prototypes and costly retrofits. While further research is needed to confirm these effects, these findings suggest that VR may offer dual benefits in promoting both sustainability and occupant well-being.

Table 2 summarizes students' reflections on their VR experience, serving as a foundation for the next stage of this doctoral research. While the initial focus was on TC, the results underscore the multifaceted nature of comfort in VR, including psychological and sensory dimensions that extend to learning outcomes, task performance, energy efficiency, and sustainable building practices. Moreover, this study opens avenues for using VR as a sustainable, cost-effective alternative for pre-assessing comfort interventions, potentially reducing the need for extensive retrofitting and lowering the environmental footprint of educational institutions.

This study provides valuable insights for educational institutions seeking to improve indoor comfort through VR-based pre-assessment models. Moreover, assessing participant preferences prior to implementing retrofit strategies enhances well-being while aligning with sustainable building practices in educational settings.

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