Review Article

Exploring Virtual Reality for Enhancing Perceived Indoor Environmental Comfort in Educational Buildings: A Scoping Review

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Abstract

This scoping review systematically explores the role of Virtual Reality (VR) in assessing and enhancing perceived indoor environmental comfort within educational buildings. The main objective was to map existing literature addressing VR applications across thermal, visual, acoustic, spatial, general environmental comfort, and indoor air quality dimensions. Given the inconsistent user satisfaction with indoor environmental quality (IEQ) in educational spaces, this study highlights VR's potential as a cost-effective tool for assessing and optimizing occupant comfort post-construction. Employing the Joanna Briggs Institute (JBI) methodology, structured searches were conducted in the Scopus database, resulting in 1,125 unique records. After rigorous screening based on predefined criteria, 17 peer-reviewed journal articles published between 2014 and 2024 were included. Findings demonstrate VR's diverse effectiveness in comfort assessments, educational interventions, and informed design decision-making processes. Visual comfort was the most frequently studied dimension, with VR reliably simulating optimal lighting conditions but showing limitations in dim or high-contrast scenarios. Thermal comfort simulations effectively enhanced students' understanding of complex concepts. Acoustic comfort evaluations highlighted beneficial impacts on cognitive performance, while biophilic VR environments improved general comfort, reducing stress indicators. Notable limitations include small participant samples, technological realism constraints, limited multisensory integration, and reliance on a single database. This review uniquely contributes to architectural practices by providing insights for informed design, educational enhancement, and policy-making, ultimately promoting occupant well-being, sustainable design, and improved educational environment

Keywords: Virtual Reality; User Comfort; Indoor Environmental Quality; Educational Spaces; Immersive Environments; Occupant Satisfaction; Scoping Review; PRISMA

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Highlights

- VR effectively assesses and enhances visual and thermal comfort in educational settings.
- Limited research (n=17) highlights need for more studies on VR and IEQ comfort.
- VR shows promise for occupant-centred, sustainable architectural design practices

1 Introduction

Optimizing indoor environmental comfort in educational buildings has become critical. Traditional post-occupancy evaluations assess indoor parameters like temperature, air quality, lighting, and acoustics (Clausen & Wyon, 2008; Lai, Mui, Wong, & Law, 2009), user satisfaction with these indoor parameters remains inconsistent—even in buildings explicitly designed for sustainability (Feige, Wallbaum, Janser, & Windlinger, 2013; Pastore & Andersen, 2019). This inconsistency highlights a critical gap in understanding how indoor environmental quality (IEQ) conditions translate into perceived comfort.

Virtual Reality (VR) provides precise, flexible simulations of indoor environments —covering multiple sensory dimensions including visual, acoustic, thermal, and spatial aspects— without costly physical modifications, significantly influencing user comfort and well-being (Heydarian et al., 2015; Yeom, Choi, & Kang, 2019). It is worth noting that VR may influence perceived comfort either by altering perceptions of existing physical conditions or by introducing entirely virtual stimuli. However, as this review aims broadly at mapping existing literature on VR and indoor environmental comfort, it does not explicitly distinguish between these two mechanisms. While recent studies noted VR's ability to simulate visual and thermal comfort (Chinazzo, Chamilothori, Wienold, & Andersen, 2021; Günther, Skogseide, Buhlmann, & Mühlhäuser, 2024), the literature remains fragmented, highlighting the need for a systematic synthesis of VR's role in perceived indoor comfort in educational spaces.

This scoping review maps literature on VR applications for assessing or enhancing perceived indoor environmental comfort in educational buildings. The review seeks to answer three central research questions: (1) What roles has Virtual Reality (VR) played in assessing or improving user comfort within educational settings? (2) Which indoor environmental comfort dimensions—thermal, visual, acoustic, spatial, and general—are most frequently addressed in VR studies? (3) How has research interest in different comfort dimensions evolved over the last decade (2014–2024)? It is important to clarify that this review broadly considers both VR applications aimed at predicting comfort perceptions of future occupants of educational buildings and those directly studying the immediate comfort responses of VR users themselves.

This review identifies trends, highlights gaps, and proposes directions for future research, underscoring VR's potential as a practical, cost-effective approach to enhancing comfort in educational buildings.

2 Methodology

This study uses Joanna Briggs Institute (JBI) guidelines to systematically map literature on VR applications for enhancing perceived IEQ comfort in educational environments. The JBI methodology includes clearly defining research questions, structured literature searches (Peters et al., 2024).

2.1 Review Framework and Approach

A scoping review was selected to systematically explore available evidence, clarify conceptual boundaries, and identify knowledge gaps regarding VR-based IEQ comfort studies. Ethical approval was not required, as this research involves secondary analysis of publicly available literature; nevertheless, ethical standards for accuracy and transparency were strictly followed.

2.2 Data Collection Methods

Literature searches used the Scopus database, targeting empirical studies, reviews, and pilot studies (2014–2024) published in English-language peer-reviewed journals and conference proceedings. The initial search round utilized a targeted keyword combination: "Virtual Reality" AND ("comfort" OR "thermal comfort" OR "visual comfort" OR "acoustic comfort") AND ("education" OR "learning environment" OR "classroom"). This yielded a relatively small number of relevant records (n=147), of which only 13 appeared potentially relevant after an initial abstract screening. Given this limited outcome, an expanded second round of searches was warranted.

The second search broadened the keywords to include additional synonyms and related terms: ("Virtual Reality" OR "immersive environment" OR "virtual simulation") AND ("indoor environmental quality" OR "occupant comfort" OR "environmental satisfaction" OR "spatial comfort" OR "indoor comfort" OR "perceived comfort") AND ("schools" OR "universities" OR "higher education" OR "educational facilities" OR "learning spaces" OR "study spaces" OR "lecture hall" OR "training facility"). Despite broadening the criteria, this second round returned only two additional records, indicating a persisting gap in the retrieved literature.

To address this issue comprehensively, a third and significantly broader search was conducted focusing exclusively on educational spaces, independent of VR-related terms: "schools" OR "universities" OR "higher education" OR "educational facilities" OR "learning spaces" OR "study spaces" OR "lecture hall" OR "training facility". This search resulted in 998 additional records, which significantly increased the initial dataset.

Collectively, the three search rounds resulted in a combined total of 1,147 records. After removing duplicates (n=22), 1,125 unique records remained for detailed title and abstract screening. The screening and data management process was facilitated using Rayyan.ai, which supported the structured categorization of references based on predefined eligibility criteria into "Include," "Exclude," or "Maybe" categories.

2.3 PRISMA Flow Diagram

Title and abstract screening were systematically managed using Rayyan.ai software (Ouzzani, Hammady, Fedorowicz, & Elmagarmid, 2016), allowing structured categorization into "Include," "Exclude," or "Maybe" categories based on predefined criteria. Following title and abstract screening, 55 records were selected for full-text retrieval, of which 12 could not be retrieved due to limited institutional database access, document availability restrictions, or unsuccessful attempts to obtain texts from authors. The remaining 43 full texts were assessed in detail, resulting in 17 studies included in this review. Figure 1 provides the PRISMA diagram illustrating this systematic process.

2.4 Data Extraction and Analysis

Selected studies underwent systematic data extraction and descriptive analysis using a structured table format designed explicitly for this review. Key dimensions extracted included VR technology used, comfort dimensions assessed (visual, thermal, acoustic, spatial, general), methodologies applied, key findings, and reported limitations. This approach facilitated clear thematic mapping and consistent interpretation of the reviewed literature.

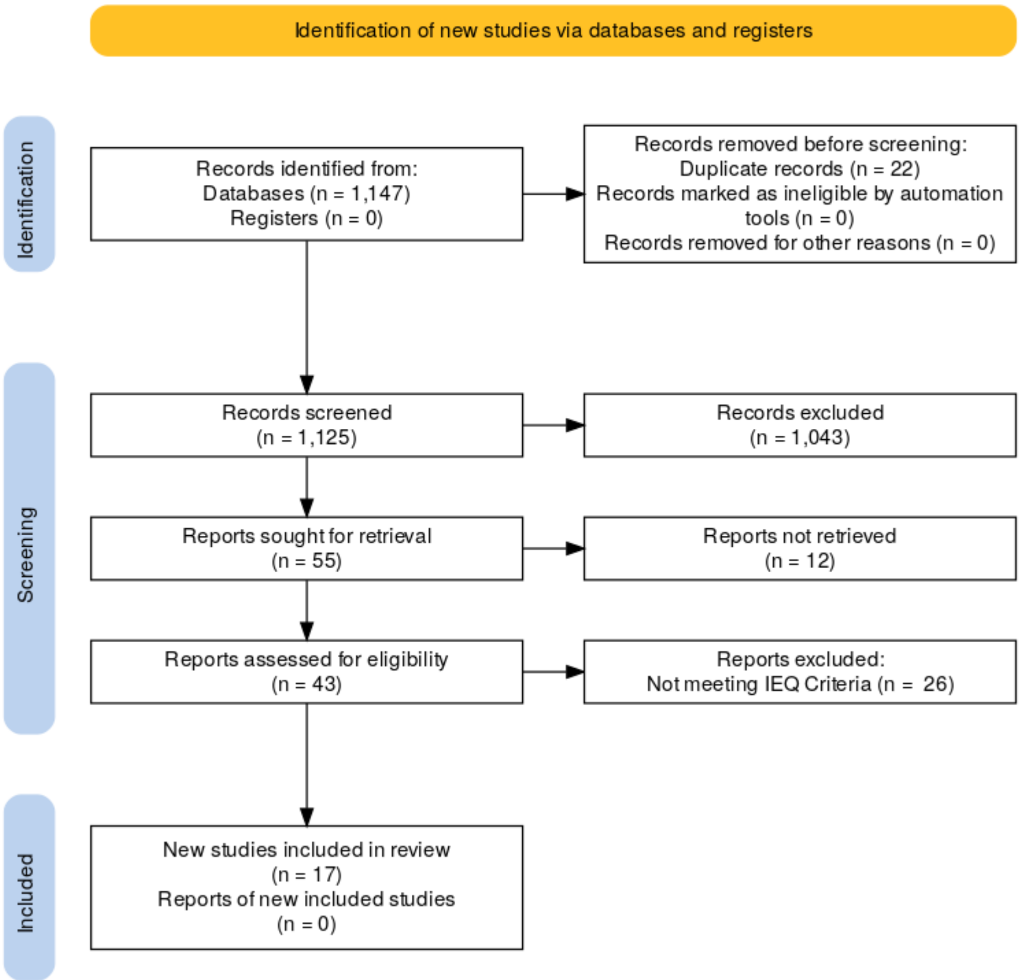

Figure 1. PRISMA flow diagram illustrating the systematic search, screening, and selection process for studies included in the scoping review.

3 Results- Key Findings

The scoping review identified diverse applications of VR in assessing and enhancing comfort perceptions within educational environments. Reviewed studies (n=17) predominantly highlighted VR's role in evaluating indoor comfort, supporting educational understanding, and design decisions. VR effectively visual comfort within the VR-generated visual environment, though limitations emerged in dimly-lit or high-contrast scenarios, impacting the accuracy of perceived brightness and contrast assessments (Rockcastle et al., 2021). Educationally, VR proved beneficial in helping students grasp complex concepts such as thermal comfort through interactive simulations (Hou, 2023). Additionally, VR was valuable for visualizing environmental design impacts, notably demonstrating shading effects on thermal and visual comfort, through interactive solar irradiation visualizations, thus supporting subjective design decision-making regarding indoor comfort perceptions (Bartosh & Krietemeyer, 2017). However, it should be noted that these visualizations influenced thermal comfort through visual cues rather than direct manipulation of actual thermal states.

Across the reviewed literature, visual and thermal comfort dimensions were most frequently addressed. Table 1 summarizes the frequency and types of VR technologies utilized in assessing each comfort dimension across the reviewed studies.

Table1. Summary of VR Technologies and Comfort Dimensions Assessed in Reviewed Studies

Comfort Dimension	Number of Studies	VR Technology Used	References (Authors, Year)
Visual	13	HTC VIVE, HTC VIVE PRO, Oculus Rift, Oculus Quest 2, Computer Automatic Virtual Environment (CAVE)-like VR system, unspecified Head-Mounted Display (HMD)	(Anuar, Sulaiman, Din, & Razak, 2024; Bartosh & Krietemeyer, 2017; Castilla, Luis Higuera-Trujillo, & Llinares, 2023; Gómez-Sirvent et al., 2024; Hasa & Husein, 2023; Jafarifiroozabadi, MacNaughton, & Osnaga, 2022; Jing, Liu, Li, Gao, & Fukuda, 2024; Lyu, De Dear, Brambilla, & Globa, 2022; Mahrous, Dewidar, Refaat, & Nessim, 2024; Mirdamadi, Zomorodian, & Tahsildoost, 2023; Rockcastle et al., 2021; Shin, Browning, & Dzhambov, 2022; You, Wen, Liu, Yin, & Ji, 2023)
Thermal	6	Oculus Rift, HTC VIVE, Oculus Quest 2, unspecified HMD	(Anuar et al., 2024; Bartosh & Krietemeyer, 2017; Hou, 2023; Jafarifiroozabadi et al., 2022; Lyu et al., 2022; Mahrous et al., 2024)
Acoustic	6	Oculus Rift, Oculus Quest 2, Oculus Quest, CAVE-like VR system, unspecified HMD	(Anuar et al., 2024; Castro, Verstappen, & Platt, 2019; Hasa & Husein, 2023; Mahrous et al., 2024; Piroozfar, Farooqi, Boseley, Judd, & Farr, 2022; Shin et al., 2022)
Indoor Air Quality	1	Oculus Quest 2	(Hasa & Husein, 2023)
Spatial	5	Oculus Quest 2, Oculus Rift, HTC VIVE, HTC VIVE PRO	(Anuar et al., 2024; Bartosh & Krietemeyer, 2017; Doggett, Sander, Birt, Ottley, & Baumann, 2021; Gómez-Sirvent et al., 2024; Hasa & Husein, 2023)
General	7	Oculus Quest 2, Oculus Rift, HTC VIVE, HTC VIVE PRO, CAVE, unspecified HMD	(Anuar et al., 2024; Gómez-Sirvent et al., 2024; Jing et al., 2024; Lyu et al., 2022; Mahrous et al., 2024; Shin et al., 2022; You et al., 2023)

Visual comfort studies primarily utilized technologies such as HTC VIVE, HTC VIVE PRO, Oculus Rift, Oculus Quest 2, and Computer Automatic Virtual Environment (CAVE)-like systems, focusing on aspects like simulated lighting quality and daylight views. Castilla et al. (2023) highlighted significant correlations between VR-simulated lighting conditions and students' cognitive performance and satisfaction. Thermal comfort, examined using Oculus Rift, HTC VIVE, Oculus Quest 2, and unspecified HMDs, consistently enhanced thermal comfort through VR visualizations and facilitated educational comprehension (Bartosh & Krietemeyer, 2017; Hou, 2023). Acoustic comfort, though less frequently explored, employed technologies like Oculus Quest 2, Oculus Quest, Oculus Rift, CAVE-like systems, and unspecified HMDs, underscoring VR's effectiveness in in evaluating how simulated acoustic interventions (e.g., reverberation control) influence participants' cognitive responses within virtual acoustic environments (Doggett et al., 2021).

Spatial comfort investigations utilized Oculus Quest 2, Oculus Rift, HTC VIVE, and HTC VIVE PRO, emphasizing positive perceptions linked to visually simulated spatial openness and large windows in VR environments, reducing anxiety and enhancing spatial experience independently from actual physical spatial conditions (Gómez-Sirvent et al., 2024). General environmental comfort studies utilized Oculus Quest 2, Oculus Rift, HTC VIVE, HTC VIVE PRO, CAVE, and unspecified HMDs, highlighting biophilic and restorative design principles, consistently demonstrating VR's potential to improve physiological stress responses and overall restorative experiences (Mahrous et al., 2024).

Notably, one study addressed indoor air quality explicitly using Oculus Quest 2, visually simulating biophilic attributes that implied improved air quality, natural lighting, spatial experience, and indirect acoustic comfort. This study demonstrated that biophilic design significantly improved physiological indicators of stress, suggesting better indoor environmental comfort (Hasa & Husein, 2023).

To further understand research trends over the past decade, the temporal distribution of studies addressing each indoor environmental comfort dimension was analyzed. Table 2 illustrates these trends, showing the progression of interest and technological application in the use of Virtual Reality (VR) for different comfort aspects between 2014 and 2024. This temporal analysis highlights shifts in research focus, indicating emerging or declining attention towards specific comfort dimensions within educational environments.

Table 2. Annual Distribution of Publications by Comfort Dimensions (2017–2024)

Year	Visual Comfort	Thermal Comfort	Acoustic Comfort	Indoor Air Quality	Spatial Comfort	General Comfort	Total number of publications
2017	1	1	0	0	1	0	1
2020	0	0	1	0	0	0	1
2021	1	0	0	0	1	0	2
2022	3	2	2	0	0	2	4
2023	4	1	1	1	1	1	5
2024	4	2	2	0	2	4	4
Total	13	6	6	1	5	7	17

[1] Some studies addressed multiple comfort dimensions; therefore, individual studies may be counted multiple times across different comfort dimension columns. Thus, column totals do not sum to the total number of unique studies reviewed (n=17).

The temporal distribution of research on Virtual Reality (VR) applications addressing different dimensions of indoor environmental comfort within educational environments indicates evolving trends over the reviewed period (2017–2024). The earliest reviewed publication, from 2017, simultaneously addressed visual, thermal, and spatial comfort. However, between 2020 and 2024, a notable increase in the number of publications occurred, reaching a peak in 2023 with five publications, suggesting a growing interest and diversification in this research area.

Visual comfort has consistently remained the most frequently explored dimension across the years, with an evident increase in studies addressing this aspect from 2022 onwards. General environmental comfort also gained attention, particularly noticeable in 2022 and 2024, reflecting a shift towards holistic approaches incorporating multiple environmental quality dimensions within biophilic and restorative design frameworks.

Thermal and acoustic comfort dimensions have seen relatively moderate but stable attention, particularly from 2022, highlighting an increasing acknowledgment of their importance in educational environments. Spatial comfort, though less consistently explored, showed a resurgence of interest in recent years, while indoor air quality remained largely underrepresented throughout the review period, with only one study in 2023 explicitly addressing it.

Overall, this temporal analysis highlights a clear trajectory towards more comprehensive and integrative studies on indoor comfort, with recent research showing increased complexity and interdisciplinary approaches. This suggests a promising shift towards multifaceted assessments of VR's potential in enhancing environmental comfort within educational buildings.

4 Discussion

This review provides insights into VR's evolving role in enhancing perceived IEQ comfort in educational environments. Addressing the initial research objectives, this review identified that VR technologies effectively simulate various environmental comfort dimensions, predominantly visual and thermal comfort. However, VR demonstrated certain limitations under extreme lighting contrasts, highlighting areas needing technological refinement.

In alignment with previous literature, our findings confirm that immersive VR environments significantly facilitate educational activities, specifically in the context visually illustrating and interactively teaching complex theoretical thermal comfort concepts. Hou (2023) underscores VR's efficacy in interactive learning scenarios. This educational use of VR could similarly support teaching other complex theoretical concepts. The review extends the current academic discourse by highlighting how interactive VR platforms can support adaptive comfort approaches, enabling occupants to intuitively manage their comfort preferences through simulated environmental adjustments, thus bridging theory and practical applications effectively.

The limited yet insightful explorations of acoustic and spatial comfort dimensions suggest promising avenues for further research. Similarly, spatial comfort investigations, such as those by Gómez-Sirvent et al. (2024), emphasize the psychological benefits derived from architectural features like larger windows, which contribute positively to perceived openness and reduced anxiety levels. Furthermore, indoor air quality, though minimally addressed, indicates additional unexplored potential in VR-based IEQ studies. These findings collectively indicate VR's potential in guiding architectural designs toward enhancing mental well-being, spatial satisfaction, and overall environmental comfort.

This review's outcomes offer critical practical implications for professional practice in architecture and urban planning. VR allows architects to evaluate comfort solutions before physical implementation. Policymakers could utilize these insights to advocate for the integration of VR-based evaluations in standard design practices, potentially shaping building regulations to prioritize occupant comfort proactively.

Theoretically, this review demonstrates VR's alignment with Attention Restoration and Stress Reduction theories. This integration provides a nuanced understanding of how virtual environments influence human-environment interactions, potentially redefining comfort assessments and user-centered design practices in educational buildings.

Nevertheless, several methodological limitations must be acknowledged. First, the relatively small number of studies (n=17) identified over a ten-year span underscores a significant gap in existing research literature, highlighting an urgent need for broader, more comprehensive investigations. Additionally, twelve potentially relevant full-text articles were inaccessible, possibly limiting comprehensiveness. Focusing exclusively on peer-reviewed journal articles and conference proceedings might have also omitted critical insights available in broader or unpublished literature. Furthermore, relying solely on the Scopus database may have restricted the scope of retrieved literature; expanding searches to additional databases such as ScienceDirect, Web of Science, and others could potentially reveal more relevant studies, thereby enriching the review outcomes. Future studies should thus expand the scope by incorporating multiple databases and grey literature, improving technological realism in VR simulations, and employing more extensive, diverse participant samples to strengthen generalizability and practical relevance.

This review was intentionally limited to educational buildings to specifically map literature directly relevant to this context, aligning closely with our research objectives. However, this context-specific approach inherently restricted the number of included studies and thus the generalizability of findings. Future research is encouraged to broaden the scope by including studies from other indoor environments (e.g., offices, residential spaces, healthcare facilities), potentially yielding more comprehensive insights into VR's impacts on perceived indoor comfort.

In conclusion, this review highlights VR's potential to redefine methodologies for assessing IEQ comfort in educational settings. By highlighting critical trends, opportunities, and gaps in current research, this review provides valuable directions for future inquiry and practice.

5 Conclusions

This scoping review systematically mapped existing research exploring VR's role in assessing or enhancing indoor environmental comfort—covering visual, thermal, acoustic, spatial, general comfort, and indoor air quality—in educational buildings. The findings confirm that VR effectively simulates environmental conditions, significantly influencing user perceptions across various comfort dimensions. Visual comfort was the most studied dimension, with VR accurately simulating well-lit conditions but having limitations under dim or high-contrast scenarios. General environmental comfort studies emphasized physiological and psychological well-being, while thermal and acoustic comfort demonstrated VR's effectiveness in communicating concepts and enhancing cognitive performance. Spatial comfort studies highlighted VR's potential to reduce anxiety through spatial openness, whereas indoor air quality was minimally explored.

This review was intentionally limited to educational buildings to specifically map literature directly relevant to this context, aligning closely with our research objectives. However, this context-specific approach inherently restricted the number of included studies and thus the generalizability of findings. Future research is encouraged to broaden the scope by including studies from other indoor environments (e.g., offices, residential spaces, healthcare facilities), potentially yielding more comprehensive insights into VR's impacts on perceived indoor comfort.

This review contributes practically by emphasizing VR's utility in informed design decisions, educational interventions, and participatory design, promoting occupant-focused solutions before physical implementation. Theoretically, the findings reinforce VR's relevance within environmental psychology, particularly in sensory perception, cognitive function, and stress recovery. Methodological limitations included a small number of studies (n=17), technological realism constraints, limited multisensory integration, short exposure durations, and reliance on a single database (Scopus). Future research should address these gaps by expanding database searches, enhancing technological realism, and exploring additional comfort dimensions.

Overall, this review highlights VR's significant promise in transforming methods for assessing and enhancing indoor environmental comfort, encouraging innovative, occupant-centered solutions in architectural design and urban planning.

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Data Availability Statement

The data supporting the findings of this scoping review, including the list of included studies and data extraction details, are available upon reasonable request from the authors.

Conflicts of Interest

The authors declare no conflict of interest. The research did not receive external funding; thus, no funders had any role in the research design, data collection, analysis, manuscript writing, or publication decisions.

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