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Harmonizing Learning Spaces: A Comprehensive review of Environmental Factors in Italian Schools with a Focus on the Impact of Acoustics

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Article

Harmonizing Learning Spaces: A Comprehensive review of Environmental Factors in Italian Schools with a Focus on the Impact of Acoustics

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Abstract: Indoor comfort is a critical determinant of the holistic educational experience, significantly influencing the well-being, concentration, and performance of students within the confines of school environments. Despite the widespread implementation of heating, ventilation, and air conditioning (HVAC) systems in educational institutions, achieving satisfactory thermal conditions, acceptable acoustics, and optimal daylight levels for occupants continues to pose a considerable challenge. In this review, we specifically delves into the parameters characterizing Italian school environments, recognizing their direct impact on students'learning and concentration. The primary objectives of this review are conducting a thorough examination of the current acustic conditions in Italian schools. The initial phase of our search strategy involved retrieving data from key databases, namely, Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. Following the elimination of duplicate articles (n = 289), a total of 135 distinct papers remained for analysis. A critical review of the existing literature is presented based on these criteria, offering guidelines and recommendations for forthcoming studies. The critical review underscores various shortcomings in the current design, deployment, and documentation of multi-domain studies, signaling the need for enhanced quality in future research efforts.

Keywords: acoustic comfort; indoor air quality; thermal comfort; ventilation; visual comfort; heat storage; ISO standards

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0. Introduction

The Indoor Environmental Quality (IEQ) stands as a critical determinant of the holistic educational experience, significantly influencing the well-being, concentration, and performance of students within the confines of school environments.

In the context of Italian schools, the quest for optimal IEQ is underscored by the multifaceted challenges associated with maintaining comfortable thermal conditions, acceptable acoustics, and effective natural lighting. Despite the prevalent use of Heating, Ventilation, and Air Conditioning (HVAC) systems, achieving an ideal balance in these aspects remains an intricate task.

The refurbishment opportunities provided by climate policies require an adequate knowledge of the school building stock. Some studies emphasizing the critical need for comprehensive knowledge of the school building stock, which currently faces urgent maintenance requirements[1–4].

In[5] the research aims is to compare IAQ and thermal comfort standards (EN16798, BB101, ASHRAE 55, and 62.1) by analyzing data from northern Italian schools. Findings suggest the need to avoid inconsistencies within standards, endorse upper- and lower-bounded operative temperature scales for effective thermal comfort design, consider IAQ metrics preventing pollutant build-up, and advocate for a combined IAQ and thermal comfort analysis in standards to facilitate informed trade-off decisions encompassing IAQ, thermal comfort, and energy targets.

The goal of many studies is reducing children's exposure to air pollutants[6–10].

In[11] microclimatic conditions were recorded in an Italian school and Fanger's indexes PMV and PPD were calculated under different conditions.

Other studies addresses the challenge of ventilation in existing educational settings, focusing on indoor air quality (IAQ), comfort, and energy consumption. International standards advocate high air change rates, particularly in densely populated areas like school classrooms, to ensure an adequate supply of fresh air[12,13].

Italian schools often lack mechanical or controlled natural ventilation systems. Consequently, occupants must manually regulate air changes by opening or closing windows, leading to discomfort, poor air quality, and increased energy usage[11].

In[14] the aim is the analysis of indoor environmental quality (IEQ) conditions in a primary school in Bolzano, Italy, with a specific emphasis on thermo-hygrometric, visual, Indoor Air Quality (IAQ), and acoustic domains. The research involved a comprehensive survey within the school, incorporating measurements such as illuminance, luminance, material optical properties, air temperature, and CO2 concentration.

Poor IEQ conditions not only lead to occupant discomfort but can also result in reduced concentration and adverse health effects as demostrated in[15,16].

The emergence of the SARS-CoV-2 pandemic further underscored the complexity and vulnerability of decision-making processes regarding IEQ threats in educational settings[5,7,17].

Several studies have focused on analyzing the emissions of carbon dioxide (CO2) and volatile organic compounds (VOCs) within enclosed environments. This research area is particularly relevant as CO2 and VOC emissions directly impact indoor air quality, consequently influencing the health and comfort of occupants[18–20].

Schibuola et al.[21] involves experimenting with CO2-based ventilation control methods within the context of energy retrofitting. The focus is on assessing the feasibility and effectiveness of using carbon dioxide levels as a key parameter for regulating ventilation systems in existing structures undergoing energy-efficient upgrades. The experimental approach aims to provide insights into the potential energy savings and overall performance of such CO2-based ventilation strategies in retrofit applications

In recent years, most of the researchers have used a research approach that takes into account user preferences to assess energy saving opportunities.

In[22] the methodology consists of evaluating thermal comfort by combining the monitoring of physical environmental data through in situ measurements and subjective questionnaires to occupants. Finally, the research work presents and evaluates the results of this applied experimentation on a school building (the secondary school of Carrara) built in the 60s and located in Lucca (Italy).

Boeri et all.[23] aims to achieve a greater level of sustainability in the construction sector and has led to consider school buildings case studies perfect for testing sustainable technical solutions. The article proposes some of the most innovative case studies in Italy, highlighting criteria and strategies adopted in the design of spaces dedicated to children.

The goal is to promote sustainable design and construction strategies that combine high levels of energy efficiency, performance standards and indoor environmental quality, including innovative strategies to integrate the building and its related systems[24–26].

Frattari et all.[27] describes the process in the basic stages of the LEED certification and provides specific examples of working strategies that have been used on two different projects of schools and with activities targeted towards particular points on the LEED matrix. In particular the first case study is a project under the LEED New Construction v.2.2 rating system and the second is a building under the LEED for schools.

In[28] was proposes a feasibility study aimed at substantially improving the environmental quality of 14 school buildings in northern Italy, aspiring to meet the requirements for Leadership in Energy and Environmental Design (LEED) certification. The analysis encompasses both technical and economic aspects. The study demonstrates technical feasibility, with credits ranging between 42 and 54. Notably, the predominant cost—constituting 82.9% of the total—is associated with enhancing

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energy efficiency through retrofitting building envelopes and heating systems. The findings suggest that prioritizing sustainability is a viable strategy.

In[29] the study conducted an assessment of energy and carbon payback times, employing a life cycle analysis (LCA) approach. Additionally, the economic value of four proposed retrofits was determined using a probabilistic approach. The findings indicate that, from various perspectives, replacing windows emerges as the most cost-effective intervention among the proposed retrofits. The study underscores the importance of considering both economic and life cycle aspects in the evaluation of energy retrofits for schools.

Other aspects of the design related to thermal, acoustic, visual and air quality in different classrooms have been analysed in recent literature: in[30], the study involved the assessment of thermal comfort in 13 classrooms across four high schools in the Provincia di Torino and four medium-sized university classrooms at the Politecnico di Torino in Italy, specifically during the heating period. The research utilized both field measurements and subjective surveys conducted simultaneously during regular class sessions. The primary focus of the paper is on thermal comfort, a factor known to impact students' performance in terms of attention, comprehension, and learning levels.

In[31] was studied the indoor and outdoor concentrations of benzene, toluene, ethylbenzene, and xylene (BTEX) in eight Italian schools, particularly those situated in highly polluted areas. Conducted between 2014 and 2015 using passive samplers during both hot and cold seasons, the research sought to provide valuable insights into air quality within sensitive indoor and outdoor environments (schools). The objective was to offer information for understanding the current air quality status and to aid territorial administrations in developing strategies to improve environmental quality.

Various field studies have explored preferences for the indoor thermal environment in relation to conditions of thermal neutrality. Preferred temperatures do not necessarily align with thermal neutrality. In Buyak et al.[32] the dynamic modeling of the energy state of a typical preschool educational facility in Kyiv, Ukraine, was conducted, considering various levels of thermal comfort in each of the zones. This analysis took into account factors such as occupants' activity, metabolism, clothing, and other relevant parameters.

Recent field studies corroborate the same tendency outlined in [32] research and introduce additional findings[33–35].

Another fundamental aspect to consider is the acoustic quality of school classrooms. Several studies[24,36,37] in the literature address this issue, recognizing the importance of the acoustic environment in the educational context.

The acoustic quality of classrooms can significantly impact students' learning, concentration, and overall well-being. An environment that is too noisy or has acoustic issues can compromise the effective transmission of information, negatively affecting teaching activities[38,39].

Aspects considered in these studies include the architectural design of classrooms[40], acoustic insulation of walls[41], the type of flooring[42] and the appropriate placement of acoustic solutions, such as sound-absorbing panels.

Ensuring good acoustic quality in classrooms becomes essential to create an optimal learning environment, infact in the last year soundscape research in indoor environments is gaining attention for its potential to contribute to the design of supportive, healthier, and more comfortable spaces[43].

Visentin et all.[44] addressed the indoor soundscape of classrooms for primary school children aged 8 to 10 years old. Utilizing questionnaires based on pictorial scales, the study explores perceived loudness and affective dimensions such as pleasantness and arousal. Both the actual soundscape and the children's ideal soundscape are investigated. The study reveals that the most frequent sounds in classrooms come from the students themselves, including voices and movements, followed by traffic.

As a result, buildings and the technologies currently employed to regulate indoor environments are typically designed based on the assumption that indoor environmental stimuli have independent effects[41,45,46].

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By identifying motivations, theoretical foundations, key methods, findings, and gaps in the field of multi-domain approaches, in[47] the critical review underscores current shortcomings, emphasizing the need for improved quality in the design and reporting of multi-domain research, ultimately aiming to integrate this knowledge into regulatory guidelines dominated by single-domain information.

0.1. Structure of the paper

In Section 1, we delineate the systematic search strategy employed to identify and select articles, elucidating the criteria utilized for processing the obtained information. Section 2 delves into the review's findings, presenting a descriptive analysis of the identified papers. This analysis encompasses participant details, domains and tasks studied, as well as an examination of various effects. Additionally, in Section 3 we explore how each parameter type may influence environmental comfort and engages in a discussion of the impacts of noise and sound within the school environment, aligning the observations with regulatory standards. Finally, Section 4 draft the conslusion of the revision.

1. Materials and Methods

Presently, the impact of ambient noise in school classrooms is not thoroughly explored within the framework of indoor environmental quality (IEQ) parameters. Adhering to the PRISMA guidelines[48, 49], we conducted a systematic review comprising 55 studies published.

Encompassing students from primary school to university levels, the selected studies examined the effects of fan noise from HVAC systems and external sounds entering classrooms when windows are open (including traffic noise, aircraft noise, railway noise, human noise, sirens, construction noise, and natural sounds).

1.1. Literature review follows the PRISMA methods

Establishing eligibility criteria is crucial for evaluating the credibility, relevance, and thoroughness of a review[50]. In particular, the exclusion criteria were intentionally structured in an incremental fashion. In practical terms, if an article did not meet the requirements of the first exclusion criterion, it was automatically excluded from consideration, and subsequent exclusion criteria were not applied.

This systematic approach ensures a clear and efficient screening process, streamlining the review's focus on articles that align with the predefined standards from the outset, while minimizing unnecessary verification steps for articles that do not meet the initial criteria.

All the eligibility criteria divided into inclusion and exclusion criteria are summarized in Table 1.

The initial phase of our search strategy involved retrieving data from key databases, namely Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar[51]. These databases are widely acknowledged as reputable sources of high-quality publications in the fields of Physics and Engineering.

Our search began with a straightforward keyword combination representing the two primary aspects of our study, namely "Indoor Environmental Comfort" AND "HVAC Systems." However, to ensure a more exhaustive search, we expanded our query to include synonyms and related terms.

The search string was modified to be: "Indoor environmental quality" OR "IEQ" OR "Quality indoor" AND "Indoor Air Quality" OR "IAQ" AND "HVAC" OR "Heating Ventilation and Air Conditioning" AND "Acoustic comfort" AND "Combined Comfort" AND "Italian school" OR "Italian educational room" OR "Italian Classroom" AND "Language".

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Table 1. Eligibility criteria used in the selection process of the articles.

Inclusion criteria (IC)[1]	Exclusion Criteria (EC)[2]
Ia - Studies investigating the effect of indoor environmental comfort in school environment.	Ea - Studies involving only schools of each grade and number (children of all ages) and universities.
Ib - Studies investigating the effect of thermal, air, lighting and acoustic comfort on students.	Eb - Researches that not consider the combined effect of thermo-acoutic parameters and focuses only on the problems related to health impact.
Ic - Studies investigating only research article.	Ec - Proceedings, conference paper and book chapter were not consider for the study.
Id - Journal articles that regarded only italian schools and written in english language	Ed - The paper does not consider teaching/learning in other language and other country.

[1] These criteria are established by researchers or reviewers to define the parameters of the study and ensure that the selected subjects or articles align with the intended scope and objectives.

[2] These criteria are established by researchers or reviewers to define limitations and ensure that certain elements are excluded from the study based on predefined factors.

1.2. Study selection

The papers obtained through this search were imported into Mendeley using the BibTex format. This facilitated the removal of duplicate papers, adjustments as necessary, and subsequent export to a spreadsheet for further analysis.

502 records were initially identified across the aforementioned databases. Following the elimination of duplicate articles (n = 289), a total of 213 distinct papers remained for analysis. In the subsequent phase, 1114 records were excluded based on a thorough examination of titles, keywords, and abstracts, resulting in the identification of 135 papers deemed eligible for a comprehensive review. Subsequently, a detailed full-text analysis led to the exclusion of 93 records, ultimately leaving 42 full-text papers for in-depth examination. Additionally, a manual search was conducted across various search engines and citations manually identified within the selected articles, which were not part of the original query results.

Figure 1 presents a flow diagram with a report of the outcomes obtained in each phase.

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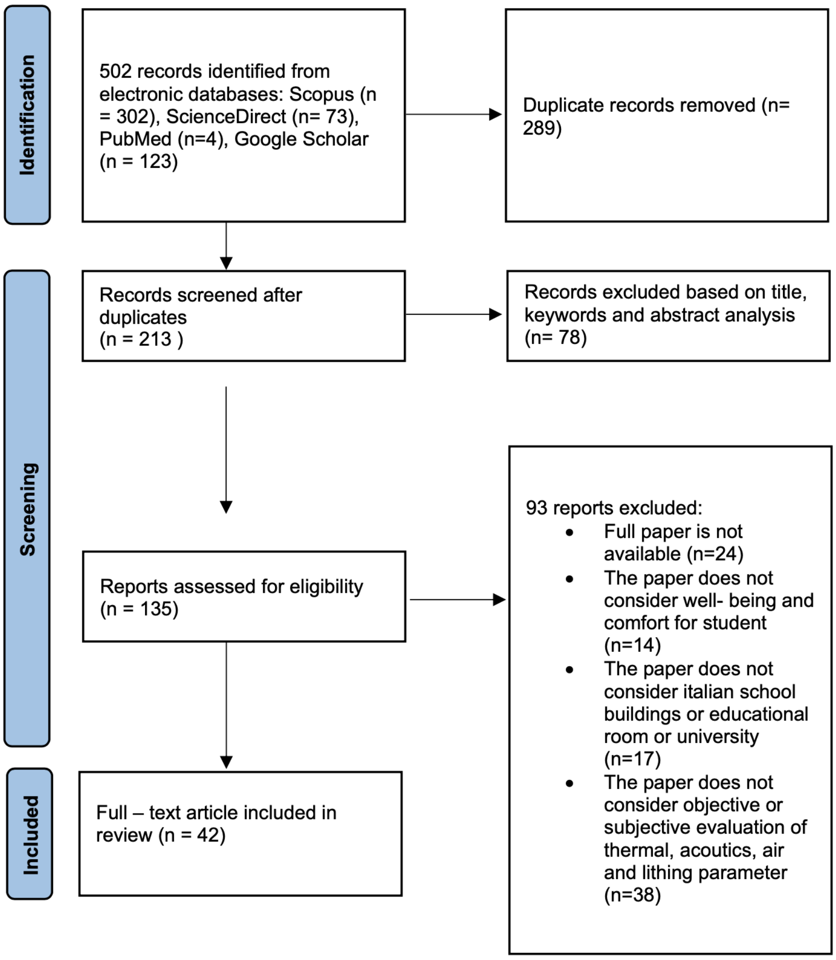

Figure 1. Flow diagram of the study selection.

2. Results

This section presents a comprehensive synthesis of the findings derived from the inclusion of 42 studies within our review. The synthesis is structured into two distinct subsections, each aligned with a specific thematic focus:

- Current State of Testing in Italy on Environmental Comfort Within Schools:

This subsection delves into the existing landscape of research and testing pertaining to environmental comfort within the scholastic context in Italy. It aims to provide a nuanced understanding of the ongoing efforts to assess and enhance conditions conducive to learning within educational institutions.

- School Typology, Key Influencing Factors on Comfort, and Their Combined Effects:

In this subsection, we explore the diverse landscape of school types in Italy and delve into the principal factors influencing environmental comfort. The intricate interplay of various factors, whether in isolation or in combination, is scrutinized to unravel their collective impact on the well-being, concentration, and academic performance of students. By elucidating the intricate web of influences, this section seeks to offer a nuanced perspective on the multifaceted nature of environmental comfort within the educational milieu. This deliberate organization aims to facilitate a nuanced exploration of the multifaceted dimensions encapsulated within the broader theme of environmental comfort in Italian schools.

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2.1. *Synthesis of Italian classroom environment quality*

Table 2 provides a comprehensive overview of the studies selected for the review. Each row in the table represents a specific study, while the columns contain relevant information such as the study title, authors, publication year, research method, and key findings or conclusions.

This table serves as a visual reference to quickly grasp the key characteristics of the studies included in the review, facilitating an overall understanding of the selected literature.

Table 2. The overview of the studies selected for the review where they are indicated: author, title, year of publication, source, keywords and database source.

Authors	Title	Year	Journal	Author Keywords	Source Database
Moschella A. et al.[52]	Lighting characterization of an Italian beginning twentieth-century school building	2023	Renewable Energy and Power Quality Journal	Classroom; Daylighting; Historic School Building; Simulation; Visual Comfort	Scopus
Ferrari S. et al.[53]	Air change rates and infection risk in school environments: Monitoring naturally ventilated classrooms in a northern Italian urban context	2023	Heliyon	Air change rates; Infection risk; Natural ventilation; School building; Transient mass-balance equation; Well-Riley equation	Scopus
Pittana I. et al.[54]	Within- and cross-domain effects of environmental factors on students' perception in educational buildings	2023	Science and Technology for the Built Environment	School building	Google Scholar
Visentin C. et al.[55]	Individual characteristics moderate listening effort in noisy classrooms	2023	Scientific Reports	School building; IAQ; speech	Scopus
Babich F. et al.[56]	Comparison of indoor air quality and thermal comfort standards and variations in exceedance for school buildings	2023	Journal of Building Engineering	Exceedance; Field measurements; IAQ; School buildings; Thermal comfort	Scopus
Lo Verso V.R.M. et al.[57]	Integrative Lighting in Classrooms: Preliminary Results from Simulations and Field Measurements	2023	Buildings	ALFA simulations; circadian measures; integrative lighting; lighting in classroom; non-visual effect of light	Scopus
Di Loreto S. et al.[58]	Comparison between Predictive and Measurement Methods of Speech Intelligibility for Educational Rooms of Different Sizes with and without HVAC Systems	2023	Energies	acoustic comfort; acoustic measurements; intelligibility; speech transmission index	Google Scholar
Torriani G. et al.[59]	Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools	2023	Journal of Building Engineering	Field survey; Indoor air quality; Perceived control; School buildings; Thermal comfort	Google Scholar
Di Loreto S. et al.[60]	Assessment of speech intelligibility in scholar classrooms by measurements and prediction methods	2023	Building Acoustics	classroom acoustics; objective intelligibility measurement; room acoustic simulation and modeling; Speech intelligibility prediction	Google Scholar
Visentin C. et al.[44]	Indoor soundscape in primary school classrooms)	2023	Journal of the Acoustical Society of America	Classroom acoustic; Classroom soundscape; Ventilation; Speech perception; Cognition; Indoor comfort	Scopus
Albertin R. et al.[61]	A Monte Carlo Assessment of the Effect of Different Ventilation Strategies to Mitigate the COVID-19 Contagion Risk in Educational Buildings	2023	Indoor Air	ventilation strategies; concentration	Scopus
Rubino C. et al.[62]	Sustainable Sound Absorbers to Improve Acoustical Comfort in Atria: A Methodological Approach	2023	Acoustics	acoustic comfort; acoustic simulation; atria; baffles; Lombard effect; open-air spaces; textile waste	Scopus
Visentin C. et al.[63]	Be Quiet! Effects of Competing Speakers and Individual Characteristics on Listening Comprehension for Primary School Students	2023	International Journal of Environmental Research and Public Health	attention; children; classroom acoustics; cognitive abilities; listening comprehension; noise; noise sensitivity; working memory	Scopus
Astolfi A.[64]	Premises for Effective Teaching and Learning: State of the Art, New Outcomes and Perspectives of Classroom Acoustics	2023	International Journal of Acoustics and Vibrations	attention; children; classroom acoustics;	Scopus

Table 2. *Cont.*

Authors	Title	Year	Journal	Author Keywords	Source Database
Croce P. et al.[65]	Proposal of a Simplified Tool for Early Acoustics Design Stage of Classrooms in Compliance with Speech Intelligibility Thresholds	2023	Energies	clarity index; classroom acoustics; prediction diagram; room acoustics; speech intelligibility; students learning	Scopus
Vettori G. et al.[66]	Primary school children's verbal working memory performances in classrooms with different acoustic conditions	2022	Cognitive Development	Auditory processing; Classroom acoustic quality; Primary school children; Reverberation time; Verbal working memory	Scopus
Astolfi A. et al.[67]	A basic protocol for the acoustic characterization of small and medium-sized classrooms	2022	Journal of the Acoustical Society of America	Speech communication; Vocalization; Acousticc; Sound level meters; Sound source perception; Speech intelligibility; Precision measurements; Signal processing; Signal-to-noise ratio; Descriptive statistics	PubMed
De Salvio D. et al.[68]	Effectiveness of acoustic treatments and PA redesign by means of student activity and speech levels	2022	Applied Acoustics	Classroom acoustics; Gaussian Mixture Model; K-means clustering; Line array; Machine learning; Public address; Student activity	Scopus
Lamberti G. et al.[69]	Advancement on thermal comfort in educational buildings: Current issues and way forward	2021	Sustainability (Switzerland)	Educational buildings; Energy consumptions; Indoor environmental quality; Local discomfort; Thermal comfort	Scopus
Zinzi M. et al.[70]	On the built-environment quality in nearly zero-energy renovated schools: Assessment and impact of passive strategies	2021	Energies	Building energy performance; Indoor Air Quality; Indoor environmental quality; Nearly Zero-Energy Buildings; School buildings; Thermal comfort	Scopus
Naddeo A. et al.[71]	Identifying factors that influenced wellbeing and learning effectiveness during the sudden transition into eLearning due to the COVID-19 lockdown	2021	Work	comfort; COVID-19; discomfort; human centred design; university lectures	Google Scholar
Lo Verso V.R.M. et al.[72]	Questionnaires and simulations to assess daylighting in Italian university classrooms for IEQ and energy issues	2021	Energy and Buildings	DAYKE project; DAYKE-Italy; Comfort in classrooms; Daylight metrics; Equivalent melanopic lux; Questionnaire survey; Statistical analyses	Scopus
Leccese F. et al.[73]	Towards a holistic approach to indoor environmental quality assessment: Weighting schemes to combine effects of multiple environmental factors	2021	Energy and Buildings	Environmental factors; Evaluation questionnaires; Indoor environmental quality; Occupant satisfaction; Subjective perception; Weighting schemes	Scopus
Avella F. et al.[74]	Low-Invasive CO2-based visual alerting systems to manage natural ventilation and improve IAQ in historic school buildings	2021	Heritage	Carbon dioxide (CO2); Historic buildings; Indoor air quality (IAQ); Monitoring strategies; Natural ventilation; Passive solution; Schools	Scopus
Leccese F. et al.[75]	A method to assess lighting quality in educational rooms using analytic hierarchy process	2020	Building and Environment	Analytic hierarchy process; Educational rooms; Experts subjective assessment; Lighting measurement campaign; Lighting quality assessment method; Users subjective questionnaire	Scopus
Laurìa A. et al.[76]	Acoustic comfort as a salutogenic resource in learning environments: a proposal for the design of a system to improve the acoustic quality of classrooms	2020	Sustainability (Switzerland)	Acoustic quality; Classroom; Healthy learning; Indoor environmental quality; Reverberation time; Salutogenesis; Wellbeing	Scopus

Table 2. *Cont.*

Authors	Title	Year	Journal	Author Keywords	Source Database
Balocco C. et al.[77]	Energy cost for effective ventilation and air quality for healthy buildings: Plant proposals for a historic building school reopening in the covid-19 era	2020	Sustainability (Switzerland)	Controlled ventilation; Energy sustainability; Healthy environment; Historical building school; Indoor air quality; Wellbeing	Scopus
Pistore L. et al.[78]	Analysis of subjective responses for the evaluation of the indoor environmental quality of an educational building	2020	Science and Technology for the Built Environment	School building	Scopus
Fabozzi M. et al.[79]	Field study on thermal comfort in naturally ventilated and air-conditioned university classrooms	2020	Indoor and Built Environment	Adaptive model; Fanger model; Field study; Gender; Natural ventilation; Thermal comfort	Scopus
Berardi U. et al.[80]	Acoustic treatments aiming to achieve the italian minimum environmental criteria (CAM) standards in large reverberant classrooms	2019	Canadian Acoustics	Clarity; Classrooms; Italian Minimum Environmental Criteria; Reverberation time; Speech intelligibility	Scopus
Leccese F. et al.[81]	Fast estimation of Speech Transmission Index using the Reverberation Time: Comparison between predictive equations for educational rooms of different sizes	2018	Applied Acoustics	Acoustic measurements; Educational rooms; Reverberation Time; Room acoustics; Speech Transmission Index	Scopus
Lassandro P. et al.[82]	A work-related learning project for energy efficiency evaluation and indoor comfort of school buildings	2018	Ingenierie des Systemes d'Information	Energy efficiency; ICT; Indoor comfort; SAPR; School building; Virtual tour	Google Scholar
Buratti C. et al.[83]	A new index combining thermal, acoustic, and visual comfort of moderate environments n temperate climates	2018	Building and Environment	Acoustic comfort; Classrooms; Combined comfort index; Questionnaire; Thermal comfort; Visual comfort	Scopus
Castilla N. et al.[84]	Affective evaluation of the luminous environment in university classrooms	2018	Journal of Environmental Psychology	Affective response; Classroom tasks; Kansei engineering; Luminous environment; Student perception; University classroom	Scopus
Balocco C. et al.[85]	Modelling of reversible plant system operations in a cultural heritage school building for indoor thermal comfort	2018	Sustainability (Switzerland)	CFD simulation; Cultural heritage; Energy refurbishment; Global and local comfort indexes; School building; Thermal comfort	Scopus
Ricciardi P. et al.[86]	Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions	2018	Building and Environment	Acoustic comfort; Classrooms; Questionnaire; Thermal comfort; Visual comfort	Scopus
Loreti L. et al.[87]	Overall indoor quality of a non-renewed secondary-school building	2016	Building Acoustics	Acoustic characterization; Building acoustics; Educational building; Overall indoor quality; Room acoustics	Scopus
De Giuli V. et al.[88]	Measurements of indoor environmental conditions in Italian classrooms and their impact on childrens comfort	2015	Indoor and Built Environment	Comfort; Global ranking; Indoor environmental quality; Long-term measurements; Schools; Survey	Google Scholar
De Giuli V. et al.[89]	Measured and perceived environmental comfort: Field monitoring in an Italian school	2014	Applied Ergonomics	Indoor environmental quality; Occupant satisfaction; School	Scopus
Di Perna C. et al.[90]	Ventilation strategies in school buildings for optimization of air quality, energy consumption and environmental comfort in mediterranean climates	2011	International Journal of Ventilation	Air changes; Carbon dioxide; Energy consumption; Environmental comfort; Indoor air quality; Occupied classrooms; Particulate matter; Questionnaires; Retrofitting; monitoring; Schools; Ventilation	Scopus
Corgnati S. et al.[91]	Thermal comfort in Italian classrooms under free running conditions during mid seasons: Assessment through objective and subjective approaches	2009	Building and Environment	Thermal comfort; Thermal acceptability; Thermal preference; Adaptive models; Classrooms	Google Scholar

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2.2. *Qualitative synthesis of data*

The existing literature is reviewed and analyzed by distinguishing the papers according to two domain:

- Combined effect;
- Only one effect.

Table 3 shows the characteristics of included studies in qualitative synthesis.

Table 3. Characteristics of the 42 studies included in this systematic review. The following information is given: 1) Author [Ref], 2) Case study (type and number of schools), 3) Data collection (type of measurement or subjective evaluation or both), 4) Combined effect (where IEQ= Indoor environmental quality, IAQ= Indoor air quality, A= Acoustic and I= Lighting), 5) Effect considered in each study.

Authors	**Case study**	**Data collection**	**Combined effect (IAQ+IEQ+A+I)**	**Effect Considered**
Moschella A. et al.[52]	Primary school (1)	Lighting levels, luminance distribution, average daylight factor and daylight autonomy	No	I
Ferrari S. et al.[53]	Primary schol (1) Secondary school (1)	CO2 concentrations	No	IAQ
Pittana I. et al.[54]	School (3)	Globe temperature, indoor air temperature (Tair), relative humidity (RH), air velocity, Total Volatile Organic Compounds (TVOC), CO2, CO, horizontal illuminance level and Aweighted equivalent sound pressure level (LA,eq)	Yes	
Visentin C. et al.[55]	Primary schol (1)	LA,eq and intelligibility	No	A
Babich F. et al.[56]	High school (1) Primary school (1) Middle school (1)	TAir, Tglobe, RH, pair and CO2	No	IAQ + IEQ
Lo Verso V.R.M. et al.[57]	Kindergarten (1) Middle school (1)	integrative lighting, non-visual effect of light and circadian measures	No	I
Di Loreto S. et al.[60]	Secondary school (4) Primary school (3) University (1)	LA,eq, Reverberation time and intelligibility (measurement and predictive methods)	No	A

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Table 3. *Cont.*

Authors	Case study	Data collection	Combined effect (IAQ+IEQ+A+I)	Effect Considered
Torriani G. et al.[59]	Primary school (4) Middle schools (2) High school (1) University (3)	Indoor air temperature, Outdoor air temperature, Globe-thermometer temperature, Relative humidity, Air velocity, CO2, Subjective evaluation (PMV,PPD)	No	IAQ + IEQ
Di Loreto S. et al.[58]	Secondary school (4) Primary school (3) University (1)	STI (measurement and predictive methods)	No	A
Visentin C. et al.[44]	Primary schol (3)	LA,eq (dB), RT time, C50 and subjective evaluation (auditoty test)	No	A
Albertin R. et al.[61]	University (1)	CO2	No	IAQ
Rubino C. et al.[62]	University (1)	LA,eq, Reverberation time, Absorption and Scattering Coefficients	No	A
Visentin C. et al.[63]	Primary schol (3)	Subjective evaluation of intelligibility	No	A
Astolfi A.[64]	Primary school	Intelligibility	No	A
Croce P. et al.[65]	University (1)	C50 and STI (predictive methods)	No	A
Vettori G. et al.[66]	Primary schol (1)	Subjective evaluation of intelligibility	No	A
Astolfi A. et al.[67]	Primary schol (1)	Speech communication, Sound level meters, Sound source perception and Speech intelligibility	No	A
De Salvio D. et al.[68]	University (2)	LA,eq, Reverberation time and statystical analysis	No	A
Lamberti G. et al.[69]	Kindergarten (4) Primary school (40) Secondary school (39) University (60)	thermal comfort and indoor environmental quality	No	IEQ
Zinzi M. et al.[70]	School (1)	TAir, Top and CO2	No	IAQ + IEQ
Naddeo A. et al.[71]	University (8)	Subjective evaluation of air quality, air teperature , ventilation and lighting	No	IAQ + IEQ + I
Lo Verso V.R.M. et al.[72]	University (5)	Subjective evaluation of air quality, air teperature , ventilation and lighting	No	I
Leccese F. et al.[73]	University (5)	Subjective evaluation of air quality, air teperature , ventilation and lighting	No	IAQ + IEQ + I
Avella F. et al.[74]	Kindergarten (2) High school (7) Secondary school (1)	air temperature, relative humidity and CO2	No	IAQ + IEQ
Leccese F. et al.[75]	University (1)	lighting	No	I

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Table 3. *Cont.*

Authors	Case study	Data collection	Combined effect (IAQ+IEQ+A+I)	Effect Considered
Lauría A. et al.[76]	Primary schol (55)	RT and absorbition area	No	A
Balocco C. et al.[77]	Hight school (1)	Air temperature	No	IAQ
Pistore L. et al.[78]	Secondary school (1)	Subjective evaluation of thermal comfort	No	IEQ
Fabozzi M. et al.[79]	University (1)	Thermal comfort and subjective evaluation of thermal perception	No	IEQ
Berardi U. et al.[80]	University (1)	C50 and STI	No	A
Leccese F. et al.[81]	University (1)	RT and STI	No	A
Lassandro P. et al.[82]	Hight school (1)	CO2 concentration, lighting and thermal	No	IAQ + IEQ + I
Buratti C. et al.[83]	University (1)	Thermal, acoustic and ligthing parameters	No	IEQ + A + I
Castilla N. et al.[84]	University (2)	Subjective evaluation of lighting	No	I
Balocco C. et al.[85]	Hight school (1)	CFD Transient Simulations of the Indoor Air Flow Pattern	No	IAQ
Ricciardi P. et al.[86]	University (1)	Thermal, acoustic and ligthing parameters	No	IEQ + A + I
Loreti L. et al.[87]	Secondary school (1)	Acoustical, thermal, indoor air, lighting and subjective evaluation	Yes	
De Giuli V. et al.[88]	Primary schol (3)	Air temperature, relative humidity, CO2 concentration, illuminance and subjective evaluation	No	IAQ + IEQ + I
De Giuli V. et al.[89]	Primary schol (1)	Air temperature, relative humidity and CO2 concentration	No	IAQ + IEQ
Di Perna C. et al.[90]	Secondary school (1)	Indoor air quality and subjective evaluation	No	IAQ + IEQ
Corgnati S. et al.[91]	University (2)	Thermal comfort and subjective evaluation of indoor environmental quality	No	IEQ

3. Analysis and discussion

Our meticulous examination has brought to light notable deficiencies in the present methodologies employed for the design, deployment, and documentation of multi-domain studies.

- Standards and types of measures:

The first subsection meticulously elucidates the prevailing standards and diverse types of measures employed across the available articles. This scrutiny aims to bring clarity to the methodologies and metrics adopted in existing research, providing a foundation for a comprehensive understanding of the varied approaches utilized to assess multi-domain aspects within educational environments.

- Cross-sectional summary of results:

In the second subsection, we present a cross-sectional synthesis of results obtained from the examined studies. This summary distills key findings, offering a panoramic view of outcomes across different domains. By juxtaposing and interlinking these results, we aim to unveil patterns, gaps, and potential avenues for further exploration, thereby contributing to the ongoing discourse on the quality and depth of research in this domain. This dual-sectioned approach serves to not only critique the existing state of multi-domain studies but also to provide a constructive framework for enhancing the rigor and comprehensiveness of future research initiatives.

3.1. The assessment of indoor comfort: italian regulations, monitoring and instrumentation

Recently, there has been a notable advancement in the establishment of standards that specifically focus on defining and ensuring Indoor Environmental Quality (IEQ).

The main goal is to promote strategies aimed at the improvement of indoor air quality in schools, which will result in a significant health benefit for students, as well as teaching, technical and administrative staff, as highlighted in the Prime Ministerial Decree of 26 July 2022[92].

In the 2022 revision of CAM Edilizia[93], the UNI EN 16798-1[94] standard is cited as a reference for thermo-hygrometric comfort and air quality.

These standards[94,95] play a crucial role in outlining acceptable ranges for various parameters that directly impact the overall comfort and well-being of individuals within indoor spaces.

These parameters encompass a range of factors influencing indoor conditions, such as temperature, humidity, air quality, lighting, and acoustics.

The reference standards for determining the air flow are the Ministerial Decree of 18 December 1975[96] and the UNI 10339[97].

The DM 18/12/75 establishes, depending on the type of school and classroom, the value of the air exchange coefficient n, expressed in 1/h, for the calculation of the air flow to be provided to the environment concerned. This coefficient should be multiplied by the internal volume of the environment to determine the flow rate to be provided according to regulations (eq.1).

The values of the coefficient n are given in paragraph 5.3.12. of DM 18/12/75.

Indicators for assessing the indoor acoustic quality of buildings are described in Appendix C of UNI 11367:2023[98] "Indications for the assessment of the indoor acoustic characteristics of rooms" which provides the recommended values of the parameters Reverberation time, C50 and STI in relation to environments used for speech or sports activities.

The internal acoustic characteristics of confined environments are also dealt with in the UNI 11532-1[99], "Internal acoustic characteristics of confined environments-Design methods and evaluation techniques-Part 1: General requirements" and UNI 11532-2[100], "Internal acoustic characteristics of confined environments-Design methods and evaluation techniques-Part 2: School sector".

The refinement of these standards reflects an evolving understanding of the intricate interplay between environmental factors and human comfort.

By setting clear benchmarks and acceptable limits for each of these parameters, the standards aim to provide guidelines that contribute to creating indoor environments conducive to optimal comfort, health, and productivity.

3.2. Cross-sectional summary of results

A comprehensive analysis of the data collected in this review, focusing on the educational landscape of multiple institutions. A diverse range of schools have been examined:

- Kindergarten (4): Nursery school or preschool for young children.
- Primary School (123): Elementary school, typically covering grades from first to fifth.
- Middle School (4): Intermediate school, generally including grades from sixth to eighth.
- Secondary School (12): High school, encompassing grades from 9th to 12th.

- University (44): Higher education institution offering undergraduate, master's, and doctoral programs.

For each article, the highlighted emphasis has been placed on identifying which parameter, in accordance with Italian legal standards, was selected to evaluate comfort in schools. Specifically, the focus has been on the effects related to Indoor Environmental Quality (IEQ), Indoor Air Quality (IAQ), Illumination (I), and Acoustics (A), and how these parameters have been combined.

Figure 2 presents the percentage of combined and not combined effects for the analysis.

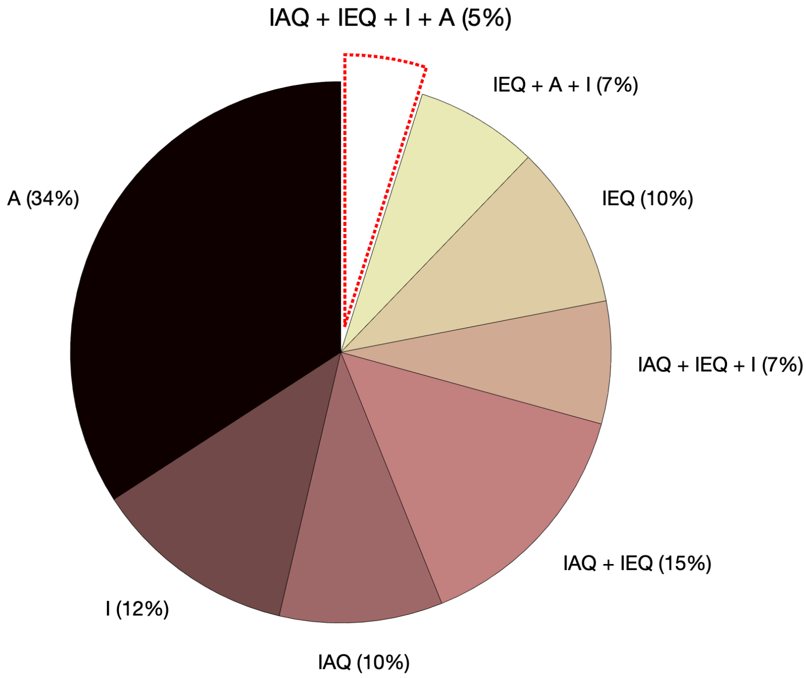

Figure 2. Percentage of combined and uncombined effects in the analysis.

From the figure, it is evident that only 5% of the considered studies took into account all effects when evaluating comfort in schools. Studies that also take into account only acoustics (34%), IEQ combined with lighting and acoustics (7%) do not consider air quality, and vice versa.

In recent years, there has been a growing focus from regulatory authorities on creating healthier and more comfortable school environments. Laws and regulations have been introduced with the aim of ensuring optimal conditions for the learning and work of students and staff.

During this period of regulatory change, the direct impact on research has been evident. Various research groups have felt compelled to explore a broader range of topics related to the internal comfort of schools. Moving away from monothematic approaches, research has expanded to consider elements such as air quality, lighting, and space design, thus promoting a holistic approach to well-being in schools.

In fig. 3 , it is clearly highlighted how research in this field has undergone a notable transformation over time. Initially focused on specific themes, investigations have gradually shifted towards a holistic perspective, delving into aspects such as air quality, lighting, and space design. This change has been closely guided by regulations aimed at improving environmental conditions within schools.

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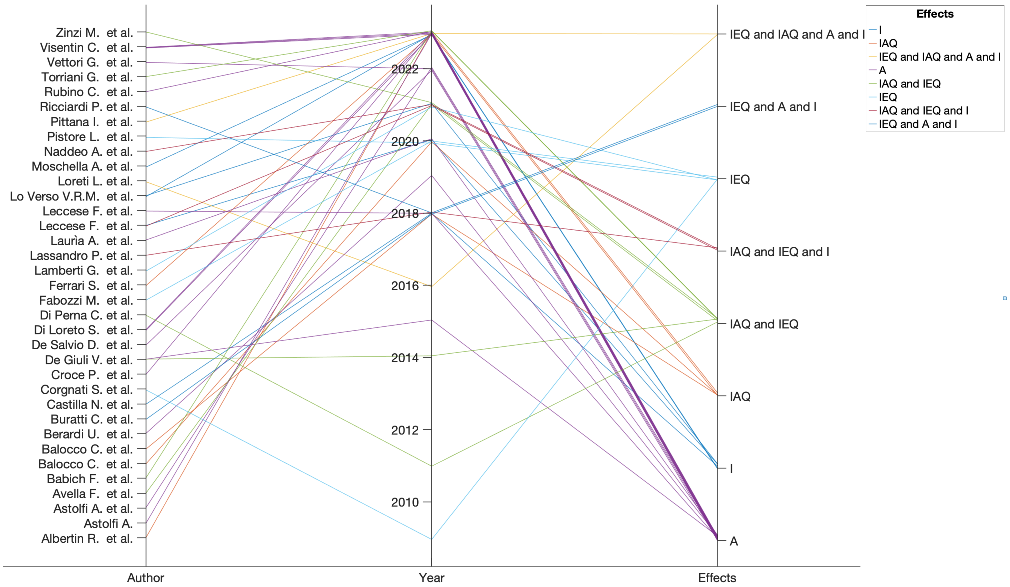

Figure 3. Shifting perspectives: school environmental research trends.

Observing the graph, one can grasp key trends reflecting the diversification of research topics over the years. This broader approach reflects the direct impact of regulations, which have stimulated a more comprehensive and in-depth perspective on well-being in schools.

As we closely examine the evolution of research on the environmental quality in schools, it's worth noting that one of the emerging areas of interest is acoustics.

It is noteworthy that a predominant majority of studies selected for this review seem to concentrate their efforts on assessing speech intelligibility or characterizing the classroom in terms of its sound insulation. However, to provide a more comprehensive view of the research landscape, we have conducted an analysis of the distribution of these focuses. The following graph illustrates the percentages of studies dedicated to speech intelligibility, sound insulation, and other related factors, offering insights into the prevailing emphasis within the existing literature.

Figure 4 presents the distribution of research focus in acoustic studies.

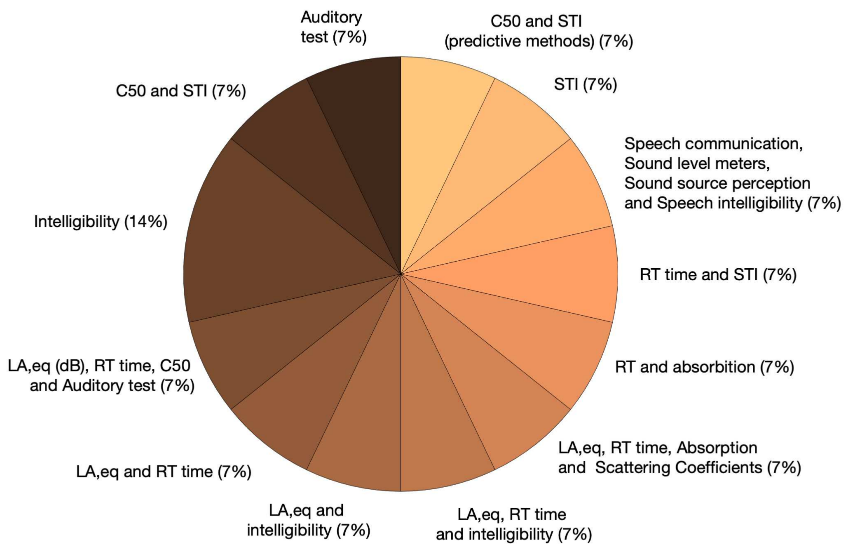

Figure 4. Distribution of research focus in acoustic studies.

While these are undoubtedly critical aspects of acoustic design there seems to be a noticeable gap concerning the comprehensive reference to the measurement and design of noise generated by air exchange systems. This oversight is particularly significant as the noise emanating from these systems can significantly impact the learning environment within educational facilities.

The identified lack of consideration for air quality in studies focusing on acoustics and vice versa raises a pertinent concern, particularly in the context of potential health implications.

It is noteworthy that the heightened vocal effort exerted by teachers, stemming from inadequate acoustical design within educational spaces, might inadvertently contribute to the dispersion of airborne particles, including potential viruses.

In the pursuit of optimal learning environments, where both the physical and mental well-being of students and educators are paramount, it becomes imperative to address the interconnectedness of acoustic conditions and air quality. A comprehensive approach to the design and maintenance of school facilities should encompass both elements to mitigate potential health risks.

4. Conclusions

The experiences of individuals within built environments are intricately shaped by diverse environmental factors, including visual, thermal, acoustic, and air quality stimuli. Despite the extensive literature on these multi-domain exposures, a lack of consistency in methodological approaches and study reporting hampers direct comparisons and meta-analyses.

To address this challenge and bolster future research, this work advocates for increased multi-domain studies and underscores the importance of systematic and transparent study design, conduct, and documentation. To facilitate future research endeavors, a set of quality criteria is proposed for the design and reporting of multi-domain studies.

The critical review of existing literature, guided by these criteria, provides valuable guidelines and recommendations for upcoming studies. The identified quality criteria cover study setup, deployment, analysis, and outcomes, emphasizing the need for consistent terminology and reporting styles. Unveiling various shortcomings in the current approach, the review signals the imperative for enhanced quality in future research.

The ultimate goal is to consolidate knowledge on multi-domain exposures, facilitating integration into regulatory resources and guidelines, which currently predominantly rely on single-domain knowledge.

Within the intricate tapestry of environmental factors, the role of acoustics emerges as particularly pivotal. Acoustic conditions wield a profound influence on the well-being, concentration, and overall experiences of individuals within built environments. Yet, amidst the array of multi-domain exposures, acoustics often stands as an underappreciated protagonist.

Effective communication, crucial for educational and professional settings, relies inherently on the clarity and intelligibility of sound. The acoustic environment of a space significantly shapes this communication, influencing not only verbal exchanges but also the cognitive load placed on individuals. Poor acoustics can lead to increased stress, diminished focus, and compromised learning outcomes.

Recognizing the critical interplay between acoustics and human experiences, our call for enhanced multi-domain studies extends a special emphasis on the need for rigorous exploration of acoustic parameters. A comprehensive understanding of how acoustic conditions intersect with other environmental stimuli is vital, as it contributes not only to the enrichment of scientific knowledge but also to the development of targeted interventions for creating healthier and more supportive built environments.

In light of the identified shortcomings and the imperative for enhanced quality in research efforts, we underscore the urgency of prioritizing acoustic considerations within the broader multi-domain discourse. By doing so, we pave the way for a more holistic and nuanced comprehension of the intricate relationships that govern our experiences within the built environment.

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Abbreviations

The following abbreviations are used in this manuscript:

IEQ Indoor Environmental comfort
IAQ Indoor air quality
A Acoustic comfort
I Ligthing comfort

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