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Ten questions concerning autism and auditory accessibility in buildings[☆]

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ABSTRACT

The ten questions in this paper discuss how the auditory experience of autistic individuals is related to the built environment, integrating perspectives from practitioners and researchers in acoustical engineering, audiology, soundscapes, psychology, architecture, and indoor environment. Autism is a neurodevelopmental disability associated with, as one of its main characteristics, hypo- or hypersensitivity to sensory stimuli. In the built environment, the sensory profile of autistic individuals is directly impacted by thermal, visual, and (the main topic of this paper) acoustical design. However, research on creating more acoustically-inclusive equipment or spaces for this population is still limited, leading to shortcomings in existing acoustic design standards, which do not consider such sensory processing differences. The paper highlights the limitations of current acoustic standards, which are based on neurotypical hearing models, and advocates for inclusive design practices that prioritize the needs of autistic individuals. We also present the shift from a purely medical model to a more nuanced approach that includes discussing ethical research practices, autism as a social concept, appropriate language, and disability rights. Key recommendations include participatory research, flexible acoustic environments, and the adoption of universal design principles to create spaces that accommodate sensory diversity, ensuring both functionality and well-being.

1. Introduction

The design of buildings has profound implications for human well-being, influencing comfort, functionality, and accessibility. While architectural and acoustic considerations have historically centered on the needs of the general population, emerging research highlights the importance of inclusive design for neurodivergent individuals, particularly autistic persons.

Autism is a neurodevelopmental disability that influences how a person interacts with the world. For example, differences in interaction style may lead to issues when socializing and communicating, especially in interactions with non-autistic (also referred to as allistic) individuals. A second key aspect of the autistic experience is different sensory processing compared to the general neurotypical population. These differences span both hyper- and hyposensitivity: responses of greater or lesser intensity to sensory stimuli such as lights, sounds, tastes, textures/touch, and smells. Hypersensitivity can be linked to increased anxiety and avoidance when the sensory experience is negative [1] and prolonged seeking when the experience is positive [2]. At the same time, hyposensitivity can cause the need for an exaggerated sensory stimulus, e.g., loud sounds and bright lights.

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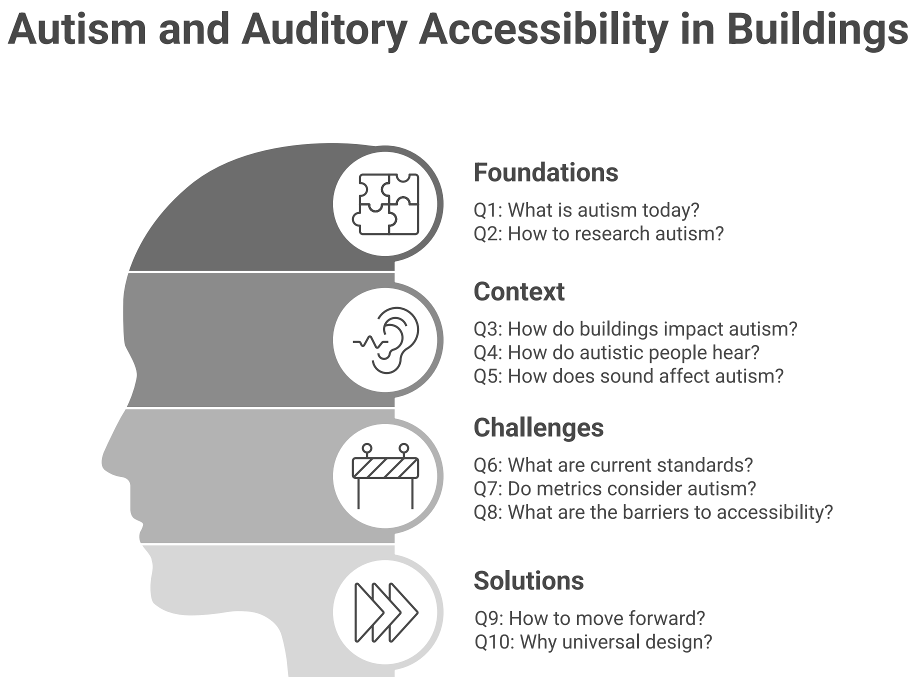

Fig. 1. Graphical abstract.

These unique sensory processing differences can make certain environments overwhelming or under-stimulating. This affects autistic people's interaction with indoor spaces and their overall quality of life. Auditory processing, in particular, presents distinct challenges, with many autistic individuals experiencing hypersensitivity to noise, difficulty distinguishing speech from background noise, or discomfort in acoustically reflective spaces. These factors underscore the need to develop environments that accommodate various sensory needs, ensuring both functionality and well-being.

This paper addresses key questions regarding the relationship between autism and auditory accessibility in buildings, focusing on how acoustic environments can be adapted to better support autistic individuals. The contemporary understanding of autism and how it shapes research methodologies is an open issue. As such, the present paper also discusses the shift from a purely medical model to a more nuanced, participatory approach that values autistic voices and lived experiences. The answers are based on a combination of general literature review, expert opinions, and participatory research involving autistic individuals.

Given the increasing recognition of the importance of auditory accessibility, we assert the need to revisit existing standards and design guidelines. Such guidelines set the standard for the whole population, but rarely include autistic needs.

Alongside this call to action, we acknowledge the challenges to implementing effective acoustic interventions and the barriers to long-term success. These barriers often include a lack of awareness, insufficient policy frameworks, and economic constraints, all of which hinder the widespread adoption of inclusive design principles.

Furthermore, strategies to advance auditory accessibility in architectural practice and policy are absent. This emphasizes the need to incorporate universal design principles as a means to create environments that accommodate diverse sensory needs. Universal design principles advocate for spaces that are inherently accessible to all individuals, reducing the need for retroactive modifications, and fostering inclusivity from the outset.

The present paper addresses these issues by answering ten key questions with the following topics:

First, we consider how autism is viewed nowadays (Q1) and how researchers can promote appropriate and ethical autism research practices (Q2). Next, the relationship between autism and buildings is introduced (Q3), with a subsequent focus on the hearing experiences of autistic individuals and different aspects of buildings that might positively or negatively impact such experiences (Q4 and Q5). Current guidelines, metrics to account for autistic populations, and possible long-term barriers are then discussed to lay the foundations for practical solutions (Q6 to Q8). Lastly, we outline recommendations for moving auditory accessibility forward (Q9) and the value of universal design (Q10). An overview of the structure of this paper is presented in the graphical abstract (Fig. 1).

At the outset, we wish to note that while some of the terms included in this article are still used by some health professionals for diagnostic purposes, the definition of autism and its characteristics are being widely updated to avoid the use of ableist framings and to match the preferences of autistic people and the considerations of the autistic rights movement [3]. Most autistic individuals, including autistic autism researchers, link the pathology model and its characterization of autism as a 'deficit' to dehumanizing research rooted in denial of subjectivity, identity, and epistemic authority [4]. In their study, Botha and Cage [4] found that medicalized narratives were associated with higher ableist cues. They also found that the majority of autism researchers personally preferred the use of identity-first language ("autistic person") versus person-first language ("person with autism").

This interdisciplinary collaboration brings together expertise from acoustical engineering, architecture, psychology, audiology, and autism research across multiple countries. Each question was developed collaboratively, with author pairs taking initial responsibility for drafting responses based on their specialized knowledge, followed by iterative group review to ensure consistency and coherence. The answers synthesize current literature, expert knowledge, and emerging evidence from participatory research with autistic individuals.

Through this approach, we aim to bridge the gap between theory and practice, advocating for an evidence-based approach to designing environments that are inclusive, comfortable and accessible for all individuals, regardless of their sensory processing differences. In doing so, we seek to contribute to a broader movement toward designing spaces that respect and accommodate human diversity, ultimately enhancing the quality of life for autistic individuals and many others who benefit from improved auditory environments.

2. Questions

2.1. What is autism today?

Answer:

Our collective understanding of autism is evolving. The key to this evolution has been a shift in focus away from autism as a disorder towards autism as a natural variation in human cognition.

Medical models describe autism as Autism Spectrum Disorder (ASD). The American Psychiatric Association's Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision (DSM-5-TR) [5] states that a diagnosis of ASD requires evidence of (1) persistent deficits in social communication and interaction (e.g., challenges in social-emotional reciprocity, non-verbal communication, and relationship building); and (2) restricted, repetitive patterns of behavior, interests, or activities (e.g., repetitive movements or speech, insistence on sameness, intense interests, and - as noted in our introduction - unusual sensory responses). These symptoms must be present from early development (early childhood); cause significant impairment in social, occupational, or other important areas of functioning; and not be better explained by intellectual disability or global developmental delay [5]. Assessments for ASD vary by region but often involve a range of tests and observations performed by a lead practitioner (such as a pediatrician or psychiatrist) or a multidisciplinary team (such as a pediatrician, psychiatrist, psychologist, speech pathologist, and other healthcare professionals). In some cases, a diagnosis of ASD can be offered as Level 1 (requiring support), Level 2 (requiring substantial support), or Level 3 (requiring very substantial support) [5].

Neurodiversity paradigms focus on the lived experiences of autistic individuals to describe autism as a neurological difference within the variation of human cognition [6,7]. These paradigms are underpinned by the social models of disability, recognizing the status of disability, and relating the major disabling aspects of autism to societal factors [8]. This has allowed the well-being and autonomy of autistic individuals to be prioritized by demanding societal adjustments that ensure inclusion over therapeutic treatments that risk exclusivity and psychological harm [9]. The neurodiversity movement has also amplified autistic voices in research to better serve the interests and well-being of autistic individuals without suppressing their traits or characteristics [4].

Both medical models and neurodiversity paradigms of autism highlight the wide range of strengths and challenges for autistic individuals that need to be understood and accommodated on an individual basis [10–18]. Some commonly identified characteristics in autistic people are:

1. heightened sensitivity to sensory input such as sound, light, or textures;
2. exceptional attention to detail and the ability to notice subtle patterns and recall intricate information;
3. strong visual and spatial abilities;
4. an ability to focus intensely on areas of interest, leading to extensive knowledge of specific topics; logical and analytical thinking ideal for systematic problem-solving, data analysis, and mathematical reasoning; and remarkable creative talent in areas such as art and music;
5. challenges with traditional verbal communication (sometimes requiring alternative methods of communication) and with non-autistic social cues and societal norms that affect non-autistic social interaction.

In specific environments and situations, a higher capacity to perceive, analyze, and process information from the environment can lead autistic people to feel highly overwhelmed, leading to "shutdowns" (disconnection from the environment to protect from more external inputs) and/or "meltdowns" (externalization of the state of sensory overwhelm). Possessing such high capacity can also place higher long-term demands on energy levels, which can lead to burnout, difficulties with unexpected events, and ongoing challenges to the autistic person's sensory needs and preferences.

Our evolving understanding of autism underscores the need to understand the lived experiences of autistic individuals in their words and the words of those they trust [19]. Only by understanding these experiences can we celebrate the unique strengths and perspectives that autistic individuals bring to society and foster more inclusive and accepting environments that are both acceptable and accessible to all.

2.2. How can researchers promote appropriate and ethical autism research practices?

Answer:

Promoting suitable practices in autism research and discourse requires a multi-dimensional, inclusive, and ethically grounded approach. Building on Q1's discussion of evolving autism understanding, appropriate and ethical practices in autism research require addressing historical biases while implementing participatory methodologies. Studies have disproportionately focused on autistic children [20], with gender and racial biases remaining prevalent [21]. These disparities stem from male-centric diagnostic criteria and underreporting in diverse populations [22–26]. Given autism's complexity beyond simplified diagnostic levels [27,28], it would be essential that all the subgroups (e.g., genders, ages, races, ethnicities, level of support, specific co-occurring conditions) are represented in research to have outcomes fostering design solutions that target the needs of the whole autistic population. Nevertheless, including an overall sample of the entire autistic population in a single study is not possible due to: (1) the necessity to design targeted experiments tailored to the specific needs of each group; (2) results from different subgroups likely being non comparable (due to the use of different methodologies); (3) practical impossibility to reach such a diverse sample with sufficient statistical power; (4) ethical barriers [29–32].

To ensure a comprehensive understanding of autism and indoor environments, multiple studies should be encouraged, targeting specific and diverse participant groups with distinct characteristics, allowing for meaningful comparisons across different samples or control groups. Researchers should clearly describe the demographic composition of the study samples acknowledging, in addition to gender and age of participants, co-occurring conditions, sensory profiles, and functional variability. The practical barriers to reaching a broader group should be outlined in the limitations, discussing how this aspect limits the generalization of results. In this way, dissemination and communication activities could raise awareness about the intrinsic diversity of the autism population, reducing the misconception that only certain categories can be autistic and fostering research involving more autistic groups.

Most research on indoor environments and autism is based on third-party observations or expert opinions from other fields, such as neurology and psychology. Therefore, design guidelines often rely on assumptions about sensory needs rather than empirical data from autistic individuals [33]. Studies show that autistic participants report more sensory challenges than informants recognize, highlighting the need to include their direct perspectives in research [19]. Despite the paradigm shift toward valuing autistic voices, practical barriers remain. Ethical constraints from the Helsinki Declaration [34] and misconceptions about self-awareness [35] may limit research participation of autistic individuals who, for example, face communication barriers [32]. For such a group, which includes non-verbal and non-speaking persons,[1] Augmentative and Alternative Communication (AAC) may be used [36]. AAC encompasses a variety of methods that go beyond the traditional reliance on speaking, hearing, and even verbal communication. A few examples of AAC techniques are: writing, sign language, text-to-speech and speech-to-text tools, as well as graphic symbols and pictograms. Specific simplified questionnaires (e.g., use of pictograms, Boolean questions such as "Is the noise too loud?") can be feasible solutions [37,38].

It is worth mentioning that vulnerable groups already communicate daily with individuals who are around them [31]. In some cases, the researchers and the autistic participants could benefit from a multidisciplinary team formed by individuals who are in direct contact with the them. These include other autistic persons, parents, professional caregivers, psychologists, psychiatrists, speech therapists, educators, and/or occupational therapists [39,40]. These individuals are essential in providing the right tools for effective communication, instead of being the single reference for the autistic person. The procedures could be designed with the aid of multidisciplinary teams [41], providing valuable insights for researchers in areas such as engineering and architecture.

In order to ensure relevance, effectiveness, and applicability, participatory and bottom-up approaches should be used for the design of research activities [42]. Especially when direct involvement of autistic researchers cannot be ensured [43], caregivers and/or autistic participants should be involved while developing the protocol. This approach involves clearly communicating the research objectives, outlining procedures, and emphasizing the mutual benefits, such as enhancing scientific understanding and improving the quality of life for autistic individuals. Participants should be informed of their rights (e.g., to withdraw from the experiment at any point without consequences) and allowed to visit the research facilities before the experiment [44]. Their considerations and suggestions should be taken into account in the experimental design. To operationalize these principles, strategies developed by McDonald et al. [45] for research with the participation of adults with intellectual disabilities (ID) could be adapted for autistic individuals with or without ID. These strategies include ([45], page 6): "have team members with skills in communicating with adults with ID; have multiple people explain the study; demonstrate study procedures; provide time to think between sharing study information and asking prospective participants to make a consent decision (this may include multiple points of contact prior to making a decision); in-person meetings; provide individualized accommodations; conduct in a familiar and comfortable setting and attend to sensory environment". Such practices not only reduce potential distress but may also foster trust and engagement, ultimately leading to more accurate and meaningful data. Finally, to promote the engagement of the target population, the research findings should be published in accessible formats [46] and results should be shared with autistic communities, and not only academic audiences.

Future research about non-invasive methodologies should be encouraged. One example is the use of wearable technologies capable of detecting physiological indicators of stress, such as heart rate and electrodermal activity (EDA) [47]. The galvanic skin response (GSR), a widely recognized EDA measure, is considered a gold standard for assessing sensory reactivity in autistic populations, as it quantifies changes in skin conductance associated with emotional and sensory stimuli [48]. Elevated GSR levels may reflect heightened sensory or emotional responses. In addition to physiological monitoring, improvements in subjective assessment tools are necessary prior to their application with autistic adults. Nicolaidis et al. [49] highlight that many existing survey instruments contain complex vocabulary, ambiguous phrasing, and figurative language, which can lead to confusion and anxiety among participants. To address these issues, the authors recommend providing contextual explanations, using simplified and direct language, and incorporating visual aids to support comprehension. Researchers should adopt the language preferences expressed by the autistic community, as discussed in Q1, ensuring respectful and ethical research practices [4].

2.3. What aspects of the built environment might impact the experience of autistic persons?

Answer: Historically, buildings have been planned primarily to cater to neurotypical populations, with little consideration given to the needs of neurodivergent individuals, including those on the autism spectrum [50]. In fact, autistic individuals exhibit different sensory processing patterns [50–52], with a potentially strong impact on their perception of Indoor Environmental Quality (IEQ). For this reason, such environments can present significant challenges, either limiting access or creating overwhelming experiences when accessed [53]. This can contribute to feelings of marginalization due to unequal access to resources [54].

Hearing is often considered the most impactful sensory modality in terms of autistic sensitivities [29,53]. Unexpected noises and high-intensity or high-pitched sounds can be distressing, potentially triggering misophonia or hyperacusis [55–57]. Additionally, difficulties with sensory gating may cause background noise and reverberation to interfere with speech intelligibility [33,50,58,59]. Despite the prominence of auditory sensitivity, which is indeed the main focus of this paper, other IEQ and design factors may also have a heightened impact on the well-being of autistic individuals compared to the general population. This is partly due to the multi-domain nature of IEQ, where interactions among comfort domains collectively shape indoor well-being [60,61]. For instance, synesthesia, where stimulation in one sensory modality triggers perception in another, such as seeing numbers as colors, has a reported prevalence of 18.6% in the autistic population, nearly three times higher than in non-autistic individuals [62]. This may intensify cross-modal interactions or amplify the influence of non-auditory stimuli on acoustic perception.

Moreover, the literature widely recognizes that autistic individuals often experience heightened sensitivities across multiple sensory modalities, which can significantly influence their perception of IEQ [63–65]. Visual environments may be overstimulating (e.g., flickering lights, excessive brightness, glare, and complex patterns) or understimulating (e.g., dim lighting, monotonous environments, and shadowy areas) [33,50,59]. Furthermore, differences in melatonin production make daylight exposure a critical factor in regulating the sleep-wake cycle in autistic individuals [66–68]. In addition to the documented higher sensitivity in acoustic and visual domains, autistic people commonly experience heightened thermal sensitivity, often perceiving uncomfortable thermal conditions as more extreme [44], and may be negatively affected by certain indoor odors, including fragranced consumer products [69].

Other design elements that may disproportionately affect autistic individuals include spatial layout, as complex configurations can induce anxiety and disorientation. Key considerations include zoning, spatial sequencing, and differentiation through color or ceiling height [50,59,70]. While sensory interactions can sometimes cause discomfort, they can also be harnessed to create engaging experiences. Cross-modal sensory affordances, for example, can be intentionally used to design environments where one sense stimulates another [71]. In this context, interactions between senses can create discomfort but can also be engaging. In relation to this aspect, a recent study conducted in a living

[1] Verbal communication refers to any communication using structured language, whether spoken, written, or signed. The term 'non-speaking' describes individuals who do not use oral speech but may communicate through writing, typing, sign language, or communication devices. 'Non-verbal' refers to individuals who do not use structured language in any form. It is important to note that many non-speaking autistic individuals are highly verbal through alternative communication methods.

laboratory found that access to a view out may help mitigate thermal discomfort in autistic adults [44]. Positive stimulation, including aesthetics, such as engaging design elements such as natural materials, indirect lighting, and curved surfaces, can aid restoration [50,72], and natural elements can promote healing indoors. However, current studies mainly focus on outdoor settings [50,73].

For these reasons, whether acoustic is the most impactful factor, proper IEQ design should address all comfort domains, as inadequate environments can lead to significant challenges. Sánchez et al. suggest that behaviors often seen as problematic may stem from environments lacking adaptability. Well-designed spaces can support autistic individuals by easing sensory processing and promoting autonomy [74]. Despite growing evidence of diverse needs, IEQ requirements for autistic individuals remain underexplored, and current standards are still based on data from the general population [33,75]. Although the United Nations calls for inclusive public spaces by 2030 [76,77], current design practices continue to prioritize physical accessibility for visible disabilities [50,74].

Further, while autistic people are more sensitive to the IEQ elements discussed above, the general population would likely benefit from autism-targeted improvements in indoor design [72]. However, there is also the potential for conflict between the needs of autistic and non-autistic space occupants. Further data is needed to help identify situations where accommodations might conflict, and allow exploration of strategies to resolve those conflicts.

2.4. How do autistic people experience hearing?

Answer: Autistic people report several different kinds of hearing differences compared to non-autistic people. These can lead to disadvantages or advantages, depending somewhat on context and environment. Hyperacusis (decreased tolerance of loudness) is experienced by 37%–45% of autistic people [57] compared to 0.2–17.2% of the general population [78]. Khalfa et al. found an increase in loudness growth curves of about 20 dB between small samples of autistic and non-autistic participants [79]. This substantial difference perhaps explains the frequent use of ear defenders by autistic people in noisy spaces like classrooms [2]. But even quiet sounds can be harder to habituate to for autistic people [80].

Pitch is fundamental to hearing [81]. A meta-analysis by Chen et al. concluded that autistic people exhibit enhanced pitch perception compared to non-autistic people [82]. The superiority includes more accurate relative pitch discrimination [83], better long-term melodic memory [84], and higher prevalence of absolute (perfect) pitch recognition (5%–11% vs < 0.01% in the general population) [85]. At the same time, perception of global structural features of music is preserved [86]. Not surprisingly, autistic traits are over-represented in professional musicians [87].

Speech perception in the presence of background noise is one of the most important functions of human hearing [88]. A systematic review of speech-in-noise research found differences between autistic and non-autistic participants when the background noise was speech babble [89]. A typical laboratory result is provided by Schafer et al. who reported that autistic children needed the speech level increased by 2.4 dB to match the performance of non-autistic children. In comparison, the performance gap for young adults was 0.7 dB [90]. These slight differences in laboratory tests are accompanied by significant but heterogeneous difficulties in everyday conversations [91].

Researchers trying to explain why greater sensitivity to pitch and level might coincide with difficulties in processing speech currently focus on two areas. At the behavioral level, judgments of the temporal order of auditory cues are worse in autistic people [92], and this seems to impair the ‘dip listening’ strategy used to glimpse speech when noise briefly dips [93]. At the neural level, researchers study an electroencephalographic phenomenon called mismatch negativity (MMN), an involuntary response to novelty in a series of sounds. Autistic people exhibit smaller and slower MMN responses to changes in speech [94] and tones, although effect sizes are small [95].

Not suppressing background sounds may also confer advantages in some situations. Remington and Fairnie found that autistic people were better at detecting a target sound against several competing sounds, and that the advantage increased with the complexity of the task [96]. Davies found that some autistic people reported a capacity for perceiving fine detail and structure in complex soundscapes and music [97].

No theory yet offers quantitative predictions of all the findings above. Perhaps the most promising is the predictive coding framework [98] – which states that the brain seeks to minimize the error between its sensory inputs and its prediction of the world [99]. It has been suggested that autistic brains place more weight on sensory input compared to previous experience [100]. More accurate autistic perception of the world may come at a cost, as autistic individuals may not automatically suppress large parts of the world – the background – making processing more cognitively expensive [101]. More work is needed to develop and apply this model.

2.5. How do acoustic aspects of the built environment impact the experience of autistic people?

Answer: Autistic individuals often experience buildings differently from their non-autistic peers. Recent interdisciplinary research indicates a common trend: acoustics emerge as one of the most significant stressors within various environments [102–105]. This fact has a direct impact on autistic people, where unsuitable daily life environments can result in high levels of stress and significant adverse effects on multiple aspects of personal, social, and professional life, health, and well-being [106,107].

The study of the acoustic aspects of buildings has traditionally been approached from two different viewpoints: “noisy space” and “quiet space” according to the number and level of sound stimuli (see, for example, [77,108]). In addition, acoustic environments are also perceived not only based on intensity, but also on contextual meaning, predictability, and emotional valence [109,110]. This is particularly relevant for autistic individuals, as research shows that background noise, particularly sudden, anthropogenic sounds and continuous, low-frequency noises, is a prominent source of distress for autistic people [29,30,53]. For example, Keith et al. [111] examined the effects of noise on autistic and non-autistic adolescents by asking participants to complete cognitive tasks of varying difficulty under different background noise conditions. The noise level (75 dB) and type (noises of children engaged in work and conversation) were selected to replicate the average volume and the intermittent characteristics of noise typically observed in a classroom. Findings indicated that the addition of noise had a slight negative impact on the performance of both groups. However, while heart rate for both groups increased with noise on the easier task, only autistic adolescents’ heart rates continued rising on the more difficult task. This suggests that the necessity to manage background sounds was only a significant additional stressor for this group. Spaces intended for high-focus activities would benefit from enhanced acoustic control, providing an environment conducive to concentration and reduced sensory overload [70].

Block [112] conducted a study that emphasized optimizing visual and acoustic comfort for autistic children in classroom settings. Results from this study indicated that reduced-stimulus environments, particularly those with minimal acoustic elements, can facilitate improved decision-making processes. The study identified background noises, including traffic and heating, ventilation, and air conditioning (HVAC) systems, which were found to particularly impair focus capabilities and comfort for autistic individuals. These experiences are also shared by autistic educators, whose perspectives have often been overlooked in research but who can encounter significant challenges due to inadequate acoustic conditions that can lead them to leave their careers [113].

The second aspect (quiet space) addresses the necessity of access to a tranquil environment. In this regard, Gaudion [114] underscores the importance of inclusive design approaches that specifically address sensory needs in autistic individuals, promoting sensory-friendly outdoor environments tailored for neurodivergent users. Creating "quiet" spaces does not necessarily require complete silence; the goal is to establish a sensorially positive environment that fosters relaxation and minimizes sensory stress. Sarrett [115] proposes that an adequate quiet space should feature low lighting, minimal noise, and be free of strong odors. In this view, high reverberation times (RT), low speech clarity (C50), and inadequate definition (D50) are consistently identified as factors that negatively impact autistic individuals in indoor environments, as well as other people with auditory differences.

Emerging evidence indicates that vibrant but positively perceived environments — those characterized by meaningful, rhythmic, or natural sounds — can be suitable, and even beneficial, for some autistic individuals in some specific contexts [116]. For example, dynamic acoustic settings may support engagement in educational or social spaces, provided they are not overwhelming. Conversely, for individuals with pronounced sensory sensitivities, calm and acoustically neutral environments remain essential to avoid sensory overload and foster a sense of control [117]. These contrasting needs underscore the importance of designing for sensory diversity, offering a range of acoustic scenarios, and allowing for user choice and modulation. Rather than aiming for generic acoustic solutions, inclusive design must adopt a pluralistic and flexible approach, accounting for the heterogeneity of autistic sensory profiles and prioritizing subjective experience alongside technical performance.

To address all these challenges, acoustic design can play a vital role in mitigating sensory overload by creating more auditory-accessible spaces as well as low-stimulus areas, such as designated quiet spaces, within environments prone to high auditory stimuli [118]. Experimental studies have shown that these improvements in acoustic environments yield tangible benefits in both behavioral and academic contexts [118]. Research with autistic children shows that the reduction of reverberation and background noise can positively influence behavior, mood, comfort, attention, academic performance, attendance, and engagement among autistic students or students with dyspraxia [2, 119].

In conclusion, ongoing research should be more coordinated in identifying specific thresholds tailored to acoustic and sensory needs for autistic users. This will offer an opportunity to enhance inclusion in buildings, addressing a vital aspect of well-being for all individuals.

2.6. What are current standards or guidelines for building acoustics?

Answer:

The acoustical design of buildings includes the analysis and coordination of architectural and engineering (structural, mechanical, electrical, plumbing, etc.) systems and components that make up a modern building and their impact on building occupants. Acoustical performance requirements in buildings vary significantly by region, country, and building type. While some jurisdictions mandate acoustic performance for specific building types such as multi-family housing, schools, and hospitals, coverage and stringency differ considerably across different regulatory frameworks.

Recent international reviews of acoustic codes and standards reveal this diversity [120,121]. Van Reenen and Manley, and Tardini et al. found that among over 50 countries surveyed, approximately 90% have building codes for schools, 85% have national standards, and 30% provide guidelines, but only about 55% explicitly mandate acoustic design and performance requirements.

In the United States, the International Building Code includes mandatory requirements for sound transmission in multifamily residential buildings (IBC Section 1206) and Enhanced Classroom Acoustics (IBC Section 1207) [122], though enforcement varies at state and local levels. European countries typically have more comprehensive acoustic requirements: the UK's Building Regulations mandate compliance with BB93 for schools [123], Germany applies DIN 18041 for classroom acoustics [124], and Norway requires "Class C" acoustic performance under TEK'10 [125]. Australia and New Zealand implement acoustic performance through AS/NZS 2107 standards [126], while Asian countries have developed region-specific criteria—Japan follows AIJ standards for school acoustics [127], China applies GB/T 50356 for auditoriums and GB 50118 for schools with NR-30 background noise limits [128,129], and Russia uses SP 254 and SP 275 standards for workplace and building acoustics [130,131]. Brazil follows NBR standards for acoustic performance, including NBR 10152 specifying a limit of 40 dBA ambient noise in classrooms [132].

Acoustical performance is typically measured through standardized metrics including reverberation time, background noise levels, sound transmission class ratings, and speech intelligibility indices. These measurements form the foundation for compliance verification and provide the quantitative basis for assessing whether built environments meet established criteria, though the specific metrics and target values vary significantly between jurisdictions.

A fundamental challenge is that there is no international agreement on acoustical performance criteria, and access to detailed standards from various nations can be difficult due to quantity, cost, and language barriers. This review focuses primarily on standards and codes accessible in English and those from countries where the authors have direct access to building code documentation.

The vast majority of acoustic standards currently in effect from the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), and the International Organization for Standardization (ISO) focus on measurement procedures of acoustical materials, assemblies, equipment, and building performance. Two notable exceptions include: ISO 23591:2021 Acoustic quality criteria for music rehearsal rooms and spaces [133], and ANSI/ASA S12.60/Part 1–2010 (R2020) Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent Schools [134].

These two standards illustrate the typical practice in the building design field: guidelines and performance criteria for buildings are separated by building use type. Unlike ISO 23591 and ANSI S12.60, acoustical criteria are typically included within more comprehensive building program documents instead of standalone acoustic guideline documents.

One example is the Facility Guidelines Institute (FGI) Guidelines for the Design and Construction of Hospitals [135], which includes a section on acoustic design requirements for hospitals, along with sections for all the architectural and engineering disciplines, in addition to specific healthcare-related specialty needs such as medical and laboratory equipment. Similar sector-specific guideline documents include the US Courts Design Guide [136] for the design and construction of federal courthouses in the United States and the US General Services Administration P100 Facilities Standards for the Public Buildings Service for government office buildings [137].

Sustainability programs and rating systems such as LEED (Leadership in Energy and Environmental Design), WELL, Green Globes, CHPS (Collaborative for High Performance Schools), and International Green Construction Code also include considerations for acoustical performance, typically within Indoor Environmental Quality sections. These commonly include background noise limits (typically 35-45 dBA), reverberation time requirements (usually 0.6–1.2 s depending on room volume and use), and sound isolation criteria (often STC-45 to STC-55 for wall assemblies) aimed at supporting occupant health and productivity.

However, a rarely stated assumption underlies these various standards and guidelines: they are largely based upon historically average human occupants with “normal” auditory sensitivities. While ANSI S12.60 includes some consideration for students with hearing differences, and the Americans with Disabilities Act of 1990 (ADA) requires assisted listening devices in assembly areas, explicit consideration for autistic populations remains rare in current building acoustic standards and codes, though some emerging guidelines are beginning to address this gap (as discussed in Q9).

2.7. To what extent do the acoustical metrics referenced in current research and guidelines/standards account for autistic populations?

Answer: Building on the research findings presented in Sections 2.4 and 2.5, which demonstrate that autistic individuals often experience hyperacusis, enhanced pitch perception, and difficulties with speech-in-noise processing, it becomes evident that current acoustic metrics may inadequately address these specific needs. For example, research shows that autistic individuals require quiet spaces with minimal noise [115] and experience distress from sudden, anthropogenic sounds [29,30,53], yet current NC curves and A-weighting systems may not adequately define what constitutes acceptable noise levels for this population, suggesting the need for more stringent criteria and metrics that account for sudden sound events rather than only steady-state levels.

Building on Q6’s analysis of current standards’ limitations, the question remains: which design metrics can appropriately account for autistic populations? Current acoustical metrics were developed using conventional hearing models with specific demographic limitations that become apparent when examining their methodological foundations [138].

For example, the A-weighting filter for sound pressure levels (i.e. dBA), intended to account for the sensitivity of the human ear to different frequency bands, was developed using equal loudness contours which account for only “otologically normal” persons in the age range from 18 years to 25 years [138,139]. At the time of writing, this age range is estimated only to describe 12% of the global population [76], and the proportion of “otologically normal” persons within that demographic is likely lower than 12% considering other kinds of aural diversity [140]. Moreover, despite being initially developed to model loudness perception, A-weighting is now also used to model many other types of human response to sound, including annoyance [141], risk of hearing damage [142], and cardiovascular disease [143].

Noise criterion (NC) curves are another metric commonly referenced in standards and design guides in the United States to assess indoor noise from HVAC equipment. NC curves were developed from the responses of participants who “felt that they were neither unusually sensitive nor insensitive to noise” and who “the great majority assessed their hearing as good” [144]. Further work is needed to determine if the NC curve system is appropriate to describe the auditory experience of autistic persons.

Another rating method in the United States is the Room Criteria (RC) methodology. Blazier [145] developed RC from HVAC noise level measurements in unoccupied buildings. Like NC, the RC contours were intended to evaluate spaces where HVAC systems were the primary noise source. Later, Blazier [146] suggested improvements to the RC methodology, which led to the development of the Room Criteria Mark II (RC Mark II) methodology. In the Mark II method, a quality assessment index (QAI) measures octave-band sound pressure level deviations from a neutral-sounding reference spectrum. In the RC Mark II system, a spectral identifier indicates whether a noise spectrum is imbalanced (low frequency, mid-frequency, and high frequency) or neutral. The inclusion criteria used to collect subjective responses from occupants does not appear to have been reported in any of Blazier’s published works [145,146], so it is unclear if the perspective of autistic persons was represented.

Common sources of environmental noise, such as traffic or aircraft noise, concentrate their sound power emissions at low and very low frequencies, which are not as heavily weighted by the dBA or NC systems. This, combined with constructive solutions such as windows and façades having lower sound insulation performance at these frequencies, can lead to great disturbance even when noise regulations are fulfilled [147]. Music from modern sound systems and impact noise from neighbors present similar issues, especially in lightweight buildings [148,149].

There is a historical call for changes in how low frequencies are measured and accounted for, not only for people who may be more sensitive to noise. The effects of low frequencies in the general population (e.g., annoyance, reduced concentration and sleep disturbances) are likely to be underestimated [150–154]. In response to this, some countries have proposed specific limits and “penalties” for certain third-octave bands and the use of units such as dBCs [155–157]. Reducing reverberation times at low frequencies has also been proposed to increase intelligibility in classrooms with children with hearing differences [158]. Considering that children do not belong to the “otologically typical” group, and, as mentioned in the UK’s Schools acoustics guidance [159], many infections can affect adults’ and children’s hearing, these recommendations could be helpful if applied to other indoor environments as well.

An additional limitation of current metrics is their tendency to assess acoustic parameters independently, without considering cumulative effects. Autistic individuals may experience compounded difficulties when multiple acoustic challenges co-occur—for instance, moderate background noise combined with high reverberation and occasional sudden sounds may create far more overwhelming conditions than predicted by evaluating each factor separately [107,108,160]. Addressing these limitations will require further work to explore how existing acoustical metrics can be successfully used or adjusted to account for the auditory experience of autistic persons, including the development of composite assessment approaches that consider acoustic environments as integrated systems.

2.8. What are the barriers to long-term success in implementing auditory environments that are accessible to autistic people?

Answer:

Despite growing recognition of the importance of making spaces more accommodating for autistic people, stakeholders often face significant barriers to achieving this goal. A primary obstacle is stakeholders’ limited understanding of autistic individuals’ specific needs (as outlined in Q3-Q5) [50], making it challenging to identify and prioritize appropriate design strategies.

Second, the regulatory gaps identified in Q6 create fundamental implementation barriers. Unlike other accessibility provisions mandated by building codes, acoustic accommodations for autistic populations remain largely optional. This lack of regulatory enforcement allows design interventions to be deprioritized during budget constraints and creates knowledge barriers among design professionals who have limited exposure to these approaches since they are not required for licensure.

Third, it is important to point out that economic factors and budgetary constraints also pose a significant barrier to accessibility. Incorporating additional acoustic treatments, sensory-friendly design elements, or other accommodations can be costly, hindering implementation, especially in resource-limited settings. Furthermore, potential conflicts may arise between accommodations for autistic individuals and other accessibility or design requirements. For instance, open-plan office layouts intended to promote collaboration can create uncomfortable acoustic environments for those with sensory sensitivities. Balancing these competing needs presents a challenge that requires careful consideration and creative solutions. Therefore, a shift toward research-informed, human rights-based, and interdisciplinary design approaches is essential to drive industry change, ensuring that accessibility is not treated as an afterthought but as a fundamental aspect of the built environment [161].

Fourth, even when autism-friendly spaces are created, there may be a fear that they will remain underutilized due to a lack of awareness or familiarity. Human behavior and social factors can also impede progress. For example, concerns about feeling unequally treated or fear of bullying may hinder the use of autism-friendly spaces, as well as pressure individuals to continue using regular spaces or events that can be highly disabling [106]. Also, resistance to change can deter the implementation and acceptance of such spaces. This apprehension can discourage further investment and commitment to such initiatives. Conversely, the absence of such spaces can perpetuate a cycle of underutilization, as autistic individuals may not have access to environments that meet their needs. Addressing these perceptions and fostering an inclusive mindset is crucial for the successful implementation and adoption of these spaces.

Lastly, non-comparable and non-inclusive data from post-occupancy evaluation (POE) and feedback mechanisms predicated on neurotypical respondents can also hamper long-term success. While an investigative or diagnostic POE would effectively capture input from all end users, triangulated against other methods such as observation or sensor data, the self-report surveys used vary from firm to firm and cannot be reliably compared or collated [162]. The self-report survey measures used in such POEs cannot be assumed to effectively gather and reliably measure input on the autistic experience [163]. There are design and post-occupancy evaluation frameworks (e.g. Autism ASPECTSS Index) that evaluate acoustic experience specifically with consideration of autistic individuals [164]. Moreover, research and projects focusing on built environments for autistic individuals may not always align with the priorities and needs expressed by the autistic community [165]. This misalignment can result in solutions that fail to address the most pressing concerns effectively. The participatory approaches detailed in Q2 are essential for ensuring autistic perspectives are accurately represented in design and decision-making processes [166].

Overall, by embracing a participatory approach and leveraging the expertise of autistic individuals, stakeholders can gain a deeper understanding of their unique sensory and environmental needs. This will enable the development of comprehensive guidelines, cost-effective solutions, and greater awareness and understanding.

2.9. How can communities move auditory accessibility in buildings forward?

Answer:

To advance auditory accessibility, the participatory research principles outlined in Q2 must be applied to design practice. Gaudion's work exemplifies how involving autistic adults with communicative differences in design processes leads to meaningful outcomes [114,167–171].

Early research, such as "Designing for autism spectrum disorders" by Gaines et al. [172] and the ASPECTSS© Autism Design Index developed by M. Mostafa [70,173], laid the groundwork for the development of better accessibility criteria for autistic individuals. Recent initiatives, particularly those that integrate the perspectives of people with lived experiences, continue to address key accessibility needs, including the creation of quiet spaces [174], adapting healthcare environments [15, 174], and addressing sensory needs in homes [175]. The inclusion of appropriate, accessible multisensory spaces could be also helpful in certain settings [176].

Practical design adaptations include optimizing lighting, aesthetics, and sound control. According to Black et al. [177], key recommendations include using simple spatial layouts, compartmentalizing and zoning spaces into specific activity sections, and providing retreat spaces.

According to the papers cited in Black et al. [177], soundproofing strategies are equally important. Acoustic paneling, sound-absorbing materials, and cavity wall systems can minimize intrusive background noise. Spatial sequencing, with buffer zones or transition areas, reduces sound transmission between spaces.

In addition to public spaces, work environments, and housing, it is equally important to focus on hospitality and leisure venues, which serve as key locations for socialization but can be acoustically-disabling for autistic individuals [106]. Initiatives like the Royal Albert Hall's efforts [178] and the Aural Diversity Network's inclusive concerts [179] demonstrate growing recognition. Similar efforts have improved accessibility in museums [180], academic conferences [181], and airports [182]. The importance of these efforts has been reinforced by a 2023 inquiry by the House of Lords Science and Technology Committee, which emphasized the detrimental effects of artificial light and noise on human health [183,184].

While technological solutions and space diversification can enhance accessibility in specific locations, they risk creating the segregated approaches that Q8 identified as problematic and Q10's universal design principles seek to avoid. Individual measures like sound masking technologies [185] or acoustic PECS [186] may be helpful for some users in specific circumstances, but do not address systemic exclusion from common areas like main halls, canteens, or offices [106,113,187].

Moreover, autistic individuals often view personal accommodations (earplugs, noise-canceling headphones) as coping strategies that highlight inadequate environmental design rather than genuine solutions [107,108]. While personalized acoustic treatments can offer localized benefits for users with different sensory profiles in shared spaces [188], the reliance on individual coping tools reflects a broader issue of environments requiring autistic individuals to adapt rather than being designed inclusively. Importantly, lived experiences of autistic people in this regard show that it is unfortunately common that individual measures involve risks such as stigma, forced disclosure, professional and personal repercussions, or social isolation, and are not always effective, accessible, or granted [106,107,189,190]. Universal accessibility should remain a guiding principle, aiming to reduce reliance on individual tools where possible. Universal design supports personalization when beneficial, and coping tools, like wearable devices, should be allowed if and when desired, without substituting thoughtful design strategies.

Building on Q6's analysis of current standards, emerging guidelines like the UK's PAS 6463 "Design for the mind – Neurodiversity and the built environment" offer important recommendations for acoustic inclusivity, though they remain non-mandatory [191]. Collaboration between standardization committees, researchers, and professionals is crucial to incorporate research and community-driven solutions into building standards, ultimately benefiting autistic individuals.

As noted in Q8, accommodating autistic needs must consider other disabilities, with conflicting requirements (e.g., lighting for low vision vs. light sensitivity [192]) highlighting the complexity of inclusive design. Moving forward requires integrating these practical approaches with the universal design principles discussed next to create truly inclusive built environments.

2.10. Why should we care about universal design in buildings?

Answer:

Ableism is a product of the belief in an ideal body. In the words of Disability Studies scholar, Fiona Kumari Campbell, "Ableism refers to a network of beliefs, processes, and practices that produces a particular kind of self and body (the corporeal standard) that is projected as the perfect, species-typical and therefore essential and fully human. Disability then is cast as a diminished state of being human" [193,194]. If a person does not have an ideal body, they are denied trivial experiences such as entering a building and managing to stay. In contrast to this ableist framework, universal design sees persons with disability (PWDs) as full participants of society, not a diminished type of human being, as it embraces disabilities as part of human diversity [195]. Understanding how pervasive ableism is in Western societies is the first step towards more inclusive practices like universal design.

Building on this inclusive philosophy, the concept of universal design arises from the need for an accessibility model that considers the different forms of human beings, "regardless of their age, size, ability or disability" [196]. This accessibility would be integrated into the structure of a space in an almost imperceptible way and would not need to be demanded by its users [197]. It would also go beyond what is required by law [198]. According to [197, pg. 8], the seven principles of universal design are: equitable use; flexibility in use; simple and intuitive use; perceptible information; tolerance for error; low physical effort; and size and space for approach and use.

Applying these principles to our specific context, acoustic environments can embody universal design through variable zones within buildings — quiet areas for focused work, moderate zones for collaboration, and dynamic spaces for social interaction — allowing occupants to choose environments matching their sensory needs without requiring disclosure or special accommodations.

This approach reflects the concept of universal design's alignment with the social model of disability: the environment creates disabling experiences for individuals with certain conditions and should be responsible for diminishing the barriers [199]. This opposes the idea that the condition itself is the main problem and something to be corrected at any cost (as stated by the medical model) [200]. Disabilities do not have just one appearance, and many of them will not be evident to an outsider. Individuals living with "invisible disabilities" (such as neurodivergence) are often misjudged and denied accommodations [201]. However, no one should be forced to disclose their disability to gain access. Genuine accessibility is accommodation without people having to ask. Universal design makes this possible.

The urgency of universal design becomes even more apparent when considering that not every PWD is born with a disability. A significant number of individuals have an acquired disability. Widespread phenomena such as pandemics, natural disasters, wars, and conflicts could also be responsible for a considerable amount of acquired disabilities. Long COVID, for example, is classified as a "mass disabling event" both by health professionals and the disability community [202] as it can cause, among other consequences, an average health loss of 21% of a person [203]. In addition, if society aims at longevity, it must also create accessible environments for older adults [204]. According to the United Nations, it is expected that by 2025, 1 in 6 people in the world will be over 65 years old [205]. Planning for universal design is planning for everyone's future.

3. Conclusion

Although participatory research and post-occupancy evaluations are beginning to emerge, the experiences of autistic persons within the built environment have not yet been widely adopted into design practice. Acoustical design criteria appear in codes and standards, but the metrics cited were developed within the conventional normal hearing model. More work is needed to explore how current metrics can be adjusted to consider a broader range of auditory experiences. In addition to these gaps, lack of awareness, conflicting needs, and economic constraints are potential barriers to adopting universal acoustical design measures.

Despite the barriers, there are also signs of progress. Participatory research efforts have helped to identify design considerations, such as quiet spaces, which can reduce sensory overload and produce positive occupant outcomes. Further work can help quantify the specific design thresholds that achieve positive outcomes and examine their application in spaces beyond the classroom, which was the focus of a considerable number of studies that we found and presented in this paper.

Several interconnected themes emerge across the ten questions addressed. The tension between standardization and personalization highlights the need for flexible, adaptive environments rather than rigid solutions. Current standards, based on neurotypical hearing models, inadequately serve autistic populations who demonstrate enhanced sensitivity to specific frequencies and greater difficulty with sensory gating. The critical importance of authentic participation by autistic individuals permeates every aspect of this field, from research methodologies through design implementation to post-occupancy evaluation. Environmental control emerges as a unifying principle, extending beyond simple volume controls to encompass choices between acoustic environments and the ability to modify overwhelming conditions.

It is fundamental to consider that, as in the case of non-autistic people, there exists a wide heterogeneity of sensory sensitivities and needs in autistic people. What may be optimal for one person may be disabling for another one or for the same person if certain elements of the design are rigid and imposed in type, timing, and intensity (e.g., in the case of background sounds). It is, therefore, important to provide an adequate degree of control over certain designs based on the addition of stimuli and the possibility for these designs to be reviewed through specific evaluation processes and modified if needed. In other words, universal acoustical design in buildings may not refer to some single ideal soundscape, but rather the provision of a range of sensory environments and the freedom for occupants to choose which environment suits their needs, or for the environment to adapt to their needs. This approach recognizes autism as part of human neurodiversity rather than a problem to be solved, emphasizing environmental responsibility for accessibility. Ultimately, such an inclusive acoustical design would promote well-being, comfort, and accessibility for all.

CRediT authorship contribution statement

Bruno S. Masiero: Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Fernanda Caldas-Correia:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Conceptualization. **Samuel H. Underwood:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Carmen Rosas-Pérez:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Alaa Algargoosh:** Writing – original draft. **Federica Bettarello:** Writing – original draft. **Marco Caniato:** Writing – original draft. **William J. Davies:** Writing – original draft. **David Manley:** Writing – original draft. **Anna Remington:** Writing – review & editing. **Anjana Sivakumar:** Writing – original draft. **Wayne J. Wilson:** Writing – original draft. **Luca Zaniboni:** Writing – original draft. **Lily M. Wang:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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