Impact of classroom acoustic conditions on children with ASD: insights from a neuroarchitectural perspective in a preliminary study in Pakistan

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Abstract

Purpose – Children with autism spectrum disorder (ASD) are affected by challenging acoustic conditions in classrooms due to altered sensory processing. Current guidelines on classroom acoustics lack established standards specifically for children with ASD. The aim of this preliminary, exploratory study is to examine the potential correlation between classroom acoustical parameters upon ASD children's sensory behaviour from a neuroarchitectural perspective, testing threshold value for reverberation time (RT) = 0.4s, mid-frequency (Tmf).

Design/methodology/approach – In a single-case experimental design study A-B-A, data from four ASD children in two classrooms with varying RT (ranging from 1.1 to 0.4 s) was analysed.

Findings – The overall findings for ASD ($N = 4$) indicated the potential significance of acoustic intervention impact on repetitive, ear-covering and loud vocalising behaviours. The RT modulation, when decreased to 0.39 Tmf, indicated a promising positive correlation on the sensory behaviour frequency.

Research limitations/implications – The generalizability of the results was delimited by small sample size and a specific ASD population conducted in a single educational context of a classroom setting in Pakistan. Further research is required to determine and test the most effective acoustic conditions for a classroom environment that reduces sensory disruptions and promotes learning.

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Practical implications – The findings provide exploratory evidence on the impact of classroom acoustics on the sensory behaviours of children with ASD.

Originality/value – Overall, the research underscores the significance and potential of establishing evidence-based guidelines for RT and noise thresholds in educational environments tailored to children with ASD.

Keywords Autism, Classroom acoustics, Reverberation time, Sensory behaviours, Neuroarchitecture, Pakistan

Paper type Research paper

Introduction

Autism spectrum disorder (ASD) is characterised by a range of challenges, including difficulties in social interaction, communication, sensory processing and the presence of repetitive behaviours or restricted interests (American Psychiatric Association, 2013). Individuals with ASD experience varying degrees of sensory dysfunction that affects their ability to modulate environmental signals, primarily auditory and visual (Bogdashina, 2003). These challenges further affect how individuals with ASD interpret environmental stimuli (Gaines *et al.*, 2016). A recent study found that classroom participation of ASD children may be disproportionately affected by the physical classroom environment, compared with family or individual characteristics, demonstrating the importance of a conducive physical environment (Li *et al.*, 2024).

In a seminal study by Caniato *et al.* (2022), individuals with ASD demonstrate heightened sensitivity to loud and background noise, which emerged as the most significant source of stress among the four environmental domains examined. Consistent with this, a high proportion of children with ASD (88%) reflected the problem of auditory sensitivity from a qualitative study of classroom environmental experiences of children (Howe and Stagg, 2016).

Understanding the importance of the auditory environment for children with ASD is critical for promoting communication, learning and emotional stability (Keith *et al.*, 2019). Evidence from the literature supports that children with ASD exhibit distinct behaviours responding to certain auditory stimuli. These behaviours often manifest as repetitive movements such as hand-flapping, rocking, spinning and ear-covering, as well as crying, meltdowns and wandering away to locate the source of the sound (Stiegler and Davis, 2010; Kanakri, 2017b). This indicates a strong correlation between ASD diagnosed children and the sensory impact of acoustics on their resultant behaviours.

Key studies have found that specific physical design modifications such as using sound-absorbing materials or creating compact, acoustically calibrated spaces can positively impact auditory sensory processing and well-being in children with ASD by mitigating classroom noise (Mostafa, 2014; Kinnealey *et al.*, 2012; Ueno *et al.*, 2019). However, few empirical studies dealt with the specificity of physical classroom design for children with ASD and its relationship with children's noise-regulatory acoustic comfort in educational settings (Caniato *et al.*, 2022; Dargue *et al.*, 2021).

Clearly defined acoustic standards specifically tailored to ASD remain lacking. Although proposed thresholds for noise level, clarity, definition and reverberation time (RT, time for sound reflections to decay by 60 dB in a space) exist (Hewitt, 2022; BB-93, 2015; Canning *et al.*, 2015; Zaniboni and Toftum, 2023), these require empirical validation. Most studies rely on subjective assessments rather than objective acoustic or behavioural data, making effective evaluation difficult. In a recent seminal systematic review, Qutub *et al.* (2024) analysed indoor environmental quality parameters in classroom settings and their impact on the behaviour of students with ASD. The review synthesised eleven studies on classroom acoustics; however, only one specifically examined the relationship between RT and behavioural responses. This specific study, conducted in Japan by Ueno *et al.* (2019), found a statistically significant association between RT modulation and behavioural outcomes, although assessments relied primarily on subjective observations.

Some countries have adapted their educational building standards to meet the needs of children with specialised requirements by implementing lower noise levels and shorter RTs. Unfortunately, in Pakistan, apart from classrooms designed for hearing-impaired students, specialised accommodations for children with ASD are largely absent. Moreover, there is a lack of reliable autism prevalence data, limited awareness and resources (Asghar *et al.*, 2023; Ashraf *et al.*, 2022) and the broader neglect of sensory-inclusive design practices and policy. The present preliminary study underscores the critical need for architectural interventions that foster supportive educational and therapeutic environments for individuals with autism.

This preliminary study contributes to addressing this gap by providing initial, exploratory empirical evidence to support the development of evidence-based acoustic design guidelines for ASD classrooms. It defines and tests a potential threshold value for RT in classroom environment for children with ASD. It examines the association between the classroom acoustic parameters, RT, A-weighted equivalent sound level (LAeq) and A-weighted, sound level exceeded for 90% of the measurement period (LA90) levels, upon ASD children's sensory behaviour in a classroom.

Auditory sensory modulation and input processing

For children with ASD, challenges in sensory modulation can hinder the interpretation of environmental input, contributing to repetitive behaviours and reduced engagement in educational tasks. Sensory regulation is a fundamental neurological process governing how children absorb organise and respond to information (Anzalone and Lane, 2012).

Within this broader sensory context, auditory processing differences are particularly significant. Autistic individuals demonstrate altered auditory processing within speech-relevant frequencies, including reduced cochlear responses around 1 kHz (Bennetto *et al.*, 2017). As most speech intelligibility information lies within the 500–4,000 Hz range (Bottalico and Murgia, 2023) and speech-in-noise difficulties have been documented in autism (Ruiz Callejo and Boets, 2023), acoustic conditions within the mid-frequency band (approximately 500–2,000 Hz) may be particularly important for classrooms designed for children with ASD as well as inclusive classroom settings. Accordingly, mid-frequency RT (Tmf) was calculated from the 500–2,000 Hz octave bands in line with Building Bulletin 93 for the present study. Research further suggests that physical design modifications that improve acoustic conditions may reduce sensory-related behavioural dysregulation (Kinnealey *et al.*, 2012).

Neuroarchitecture and theoretical foundations for translation

Understanding the neurobiological mechanisms associated with autism may inform more effective therapeutic approaches, support translational design and provide deeper insight into the disorder's origins. According to Sternberg and Wilson (2006), environmental variables can elicit neurological and physiological reactions that contribute to emotional and behavioural dysregulation.

In this context, a recent narrative review suggests that peripheral hearing sensitivity in individuals with autism is generally comparable to that of neurotypical populations (Poulsen *et al.*, 2025). Auditory hypersensitivity, therefore, appears to reflect differences in central auditory processing, including atypical neural responses and altered temporal processing, which have been documented in autism (Haesen *et al.*, 2011). These variations suggest that sound regulation difficulties may originate at multiple levels of the auditory pathway. From a built-environment perspective, these insights imply that poorly controlled acoustic conditions may disproportionately increase cognitive and sensory load. Therefore, classroom design should move beyond general noise reduction measures to incorporate frequency-sensitive and regulation-supportive acoustic strategies. Such approaches should align with neurodevelopmental processing differences in autism and may support sensory regulation and associated behaviours within the learning environment. Building on this foundation, Ayres (1974) developed a neuroscience-informed Sensory Integration (SI) framework grounded in principles of neural plasticity, active engagement and the structured organisation of environmental input to support adaptive neural development. This framework informs the present study's linkage between behaviour and learning in children with ASD. Contemporary interpretations of SI theory emphasise the dynamic interaction between experience-dependent neuroplasticity, emotional state and environmental input in shaping behavioural responses (Lane *et al.*, 2019). Accordingly, architectural design informed by neuroarchitecture principles may be strategically used to positively influence learning, behaviour and emotional regulation (Eberhard, 2009).

In relation to sensory characteristics in ASD, children frequently exhibit atypical sensory processing, with a substantial proportion demonstrating hyper- or hypo-responsive reactions to environmental stimuli (Robertson and Baron-Cohen, 2017). Extending this to educational contexts, modulation of auditory conditions may support more regulated sensory input for children with ASD. Such environmental adjustments may contribute to improved sensory processing, emotional regulation and learning engagement.

Despite this, auditory or acoustic interventions that promote learning, reduce sensory stress and support well-being among children with ASD remain relatively underexplored. Further investigation in natural school settings is needed to evaluate how acoustic modifications influence auditory-related stress and sensory behaviours (Dargue *et al.*, 2021). Empirical evidence supporting this direction is emerging. For example, Rance *et al.* (2017) found that remote microphone use in school-aged children with ASD improved listening, social participation and communication, while reducing salivary cortisol levels. However, specific teaching pedagogy, assessment and intervention requirements remain insufficiently addressed in existing studies (Kanakri, 2017b; Martin, 2014; James, 2010).

Classroom acoustics

The acoustic environment of a room is primarily determined by RT, which is the duration it takes for the sound pressure to decay by 60 dB, measured in seconds from its high point until it declines (Crandell and Smaldino, 2000; Kristiansen *et al.*, 2016). The effect of prolonged reverberation has a significantly greater impact than most other variables that determine a building's acoustics (Klatte *et al.*, 2010). Longer RTs can make spoken words more difficult to understand, as reverberation degrades speech by smearing temporal and spectral cues within the speech frequency range, thereby increasing listening effort and perceptual uncertainty (Klatte *et al.*, 2013). In addition, long RTs allow incidental sounds, such as fidgeting or furniture movement, to persist and accumulate, increasing overall classroom noise levels. Behavioural responses, including raised vocal effort in reverberant conditions, may further contribute to this escalation (Lubman and Sutherland, 2002). More recent classroom research highlights the interaction between acoustic conditions and student behaviour in shaping classroom noise environments (Mealings *et al.*, 2024).

Research further indicates that classrooms with RTs approaching 1.0 s were associated with reduced well-being and less positive social relationships between students and teachers (Klatte *et al.*, 2010). In this regard, it is important to evaluate the most prevalent pedagogy of structured learning in a one-to-one teacher–student ratio for children with ASD in a classroom environment. This teaching approach minimises physical distance to less than 2 m and has been proven effective in reducing teachers' acoustical signals (James, 2010). However, even with this approach, internally generated sounds, noise build-up and reflection in the classroom can still be detrimental to ASD children's classroom instruction processing and sensory behaviour.

It was hypothesised that children with ASD would exhibit increased sensory behaviours under longer RT and higher background noise, particularly during group activities. Given the interrelation of RT and ambient noise (Klatte *et al.*, 2010), their combined effects were considered. Unlike prior research focused on communicative outcomes, this study examines RT in relation to sensory emotional behavioural responses.

Research questions

This study aimed to investigate the relationship between classroom acoustical environment and delineated sensory response behaviours in children with ASD. It addresses the following main research question:

> Q: What is the correlation between the classroom acoustic parameters, such as long and short RT and the background noise LAeq and LA90, with delineated sensory response behaviours in children with ASD? Further subdivided into three questions:

RQ1. Does there exist an association between the acoustic variable (RT) and the repetitive behaviour of children with ASD in the classroom environment?

RQ2. Does there exist an association between the acoustic variable (RT) and the ear-covering behaviour of children with ASD in the classroom environment?

RQ3. Does there exist an association between the acoustic variable (RT) and the loud vocalising behaviour of children with ASD in the classroom environment?

Objectives

- To examine the correlation between the prevailing unconditioned classroom RT (Tmf 1.11s) and correlates LAeq and LA90 pressure levels upon individually targeted sensory response behaviours in children with ASD through a single-case experimental design (SCED) methodology.
- To examine the ramifications of the classroom sensory condition upon the ($N = 4$) individual sensory response behaviours through SCED methodology.
- To test the hypothesis through the impact of the return-to-baseline Phase A, prevailing unconditioned classroom RT (Tmf 1.11s) upon the ($N = 4$) sensory behaviours.

Methodology

Research design

The SCED (A-B-A) baseline, intervention and withdrawal of intervention design was objectively selected for its reliability and suitability for the low-incidence ASD population in this study. It accounted for behavioural heterogeneity and variability in children with ASD (Hammond and Gast, 2010; Kazdin, 2003). The design enabled replication of intervention effects across participants, settings and behaviours. It was also appropriate for reversible behaviours, allowing return to baseline following withdrawal (Barlow and I-Iersen, 1984) and helped control for history and maturation effects (Hitchcock *et al.*, 2010). The individual unit of analysis was particularly salient for examining and interpreting multilevel sensory behaviours in children with ASD (Louis *et al.*, 2000). The construction of the research design was thus based on the following criteria:

- Heterogeneity in children with ASD
- Suitability for special education and classroom settings
- Listening to children with impaired or non-verbal communication

Participant

Four male students with ASD aged between 9 and 11 years were selected for this study. The purposive sampling of subjects for this research was limited to male students, as there were no female students present in the research classroom. An essential rationale for this is the higher prevalence of ASD in males compared with females, with a ratio closer to 3:1 (Loomes *et al.*, 2017), though this difference may partly reflect underdiagnoses and differing presentations in females (Lockwood Estrin *et al.*, 2021).The socioeconomic evaluation of the participating children demonstrated the mixture of upper, middle- and lower-class strata of families from the city of Lahore in the Punjab Province. The ethnic, cultural, religious or racial configuration make-up was composite, indicating no significant socio-cultural factor of diversity. All four students had a confirmed diagnosis of ASD. They were assigned an acronym to maintain confidentiality and the sensitive nature of this study based on ethical considerations. The student's details are presented in the following section.

Student ABD (male, age 10 years)

Student ABD was a 10-year-old boy (first of two siblings) at the time of the experiment. School medical records indicate he was diagnosed at age 5 with DSM-5 Criteria 299.00 (F84.0) ASD following a standardized Childhood Autism Rating Scale (CARS) assessment by a neurodevelopmental paediatrician and was assessed as having moderate autism. Observed sensory challenges included distraction by noise, transient sounds and peers' tantrums, which led him to leave his seat and wander, with difficulty settling and refocusing on tasks. He demonstrated limited attention span and difficulty remaining seated, with frequent stereotypical behaviours including jumping, circling, finger flicking, ear-covering and making loud noises. He often gazed at the ceiling, walls or his fingers while engaging in repetitive movements, repeatedly played with specific musical toys and had limited social skills with no verbal communication. He produced spontaneous loud vocalisations and could make limited requests using picture exchange communication system (PECS).

Student IBT (male, age 10 years)

Student IBT was a 10-year-old boy (third of three siblings) at the time of the experiment. School medical records indicate he was diagnosed at age 5 with 299.00 (F84.0) ASD (moderate autism) by a clinical psychologist following behavioural rating and developmental profile assessment. He was extremely sensitive to loud noise, tipped his chair to elicit loud sounds, used words repetitively and was distracted by nearby toys and desk objects. He displayed frequent challenging behaviours, including rocking, ear-covering, making loud noises and striking out at others and required strong encouragement to remain attentive and on task. He showed an obsessive tendency to hold paper and plastic bags and had a distinctive pattern of smiling, giggling and making eye contact. His limited verbal skills were characterised by functional limitations and echolalia, including repetitive words, short phrases and vocal sounds.

Student MOH (male, age 9 years)

Student MOH was a 9-year-old boy (second of three siblings) at the time of the experiment. School records indicate he was diagnosed at age 5 with 299.00 (F84.0) ASD following a standardised CARS assessment by a neurodevelopmental paediatrician and was assessed as severely autistic. He exhibited acute sensitivity to noise (e.g. toy music, crying, thrown objects, impulsive movements), avoided social contact and group activities and was highly distractible, particularly by peers' crying or meltdowns. He frequently wandered in class and displayed self-stimulatory behaviours, including rocking, finger flicking, ear-covering and making loud noises. He required frequent prompting to maintain attention and remain on task.

Student SHA (male, age 11 years)

Student SHA was an 11-year-old boy (third of three siblings). School medical records indicate he was diagnosed at age 3 with 299.00 (F84.0) ASD following a standardised CARS assessment by a neurodevelopmental paediatrician and was assessed as having severe autism. He was unable to remain seated or focused on assigned tasks, often disturbing peers and required constant prompting to complete activities. He frequently mouthed toys and displayed persistent, energetic, impulsive behaviours, including on-the-spot jumping, rocking, ear-covering and mouthing. He enjoyed climbing furniture and completing puzzles. His limitations included minimal social skills and no verbal communication; he produced spontaneous repetitive loud vocalisations, with or without covering his mouth and was able to make limited requests using PECS.

Setting

This research was carried out in a purpose-built school in Pakistan for children with autism. The study focused on a particular classroom within the school, which catered to children with ASD between the ages of 9 and 11. The classroom had a staff-to-student ratio of 1:1 and utilised the treatment and education of autistic and related communication handicapped children (TEACCH) teaching method as its primary approach. The classroom was staffed with two teachers and six assistants, who were responsible for a total of six students. Of the six students initially enrolled, two were unable to complete the study due to illness and unforeseen travel commitments. Data were therefore analysed for the four participants who completed the study. Physical classroom featured brick walls up to the windowsill, gypsum wallboard from windowsill to ceiling, linoleum flooring with partial carpeting, wooden doors, double-glazed windows with sandwich blinds, aluminium frames and a suspension ceiling of 2' × 4' gypsum board tiles fixed to an iron truss system. The classroom had a floor area of 44.4 m^2 and a clear floor to false ceiling height of 3.0 m.

Activity

The selected social group activity was conducted in a group arrangement around a single large C-shaped PVC table seating the children and the moderating teacher (see Figure 1). A photographic activity schedule with visual cues in a ring binder was used to initiate group interaction, requiring students to perform activities corresponding to the images. The tasks

Figure 1. Classroom before acoustic treatment
Source: Authors' own work

targeted listening, imitation, attention, turn-taking, sharing materials and waiting for their turn.

Research classroom floor plan detail

Procedure

The study was conducted over six consecutive weeks, excluding Friday half-days, weekends and the pilot period, encompassing three two-week phases: (A1) baseline data collection, (B) intervention (installation of sound-absorption wall panels) and (A2) return-to-baseline withdrawal (removal of sound-absorption wall panels). Children's daily routines were maintained throughout to preserve normalcy and consistency. Potential confounding classroom factors were controlled through consistent staffing, unchanged routines and stable classroom conditions (furniture layout, lighting, noise, temperature and number of students). In addition, a two-day desensitisation phase was implemented when transitioning from Classroom A to intervention Classroom B.

Ethical considerations

Informed written consent was obtained from the parents and caregivers of all participants in the study. In addition, informed written consent for publication was also obtained from the legal guardian.

Pilot study

Before commencing the pilot study, teachers filled out the requisite standardised teacher's school companion sensory profile questionnaire (Dunn, 2006) to provide insights and contextual information in relation to the four ASD students' sensory profiles. A three-day pilot study (15 h of observation) was conducted before baseline Phase A1. During this period, delineated sensory behaviours were observed in each child with ASD, and participant-specific observable operational definitions were finalised (Table 1), detailing the behavioural topography of the three delineated behaviours. Anecdotal reports from the classroom teacher identified social group activities as the noisiest periods, associated with increased disruptive and non-attending behaviours, as well as instances of classroom withdrawal; similar patterns were observed in the pilot study. Hence, group activity session was selected based on the teacher's account and pilot study observations.

Table 1. Dependent variable participant-specific

Participants	Behavioural variable	Behavioural topography
ABD	Ear-covering	Touching or covering one or both ears
	RB	Two or more instances of jumping, rocking or finger flickering
IBT	Ear-covering	Touching or covering one or both ears
	Loud noise	Two or more instances of making spontaneous, loud, meaningless sounds
	RB	Two or more instances of rocking back and forth or side to side
MOH	Ear-covering	Covering one or both ears with hands or elbow
	RB	Repetitive arm or hand movements, back and forth movement, jumping or flickering fingers
SHA	Ear-covering	Touching or covering one or both ears
	Loud noise	Loud, spontaneous, meaningless sounds
	RB	Jumping on the spot, rocking back and forth, repetitive hand or arm movement

Source(s): Authors' own creation

Outcome measures

Independent variable

This study examined the independent variable of classroom mid-frequency RT (Tmf; 500–2,000 Hz), defined as the average RT across the 500 Hz, 1 kHz and 2 kHz octave bands and its correlated LAeq (equivalent continuous noise level) and LA90 (statistical average noise level). These were measured and verified during group activity lessons, with daily noise measurements recorded throughout Phases (A) and (B) and numerically averaged to obtain representative values.

Dependent variable: behaviour observation and dimension

The frequency of the targeted behaviour ASD ($n = 4$) was delineated and categorised (see Table 1). These recorded behaviours were obtained by counting the occurrence of each incidence within a time frame. Video recordings were conducted for the behaviour observations to monitor and analyse the participant's stimuli response in classroom group activity sessions.

Each observational session lasted approximately 5–10 min, though exact durations occasionally varied due to participant heterogeneity and differences in response latency. Brief, repeated sessions enabled consistent measurement across acoustic conditions while accommodating students' attention spans and natural classroom activity schedule. This approach aligns with SCED methodology and ASD classroom research practices, supporting reliability and ecological validity (Ledford and Gast, 2024).

Therefore, the frequency rate of behaviour (FRB) of the four participants was calculated by each participant's behaviour occurrences (BO) observed empirically and divided by the length of observed time (LOT) for rate per minute: [FRB = BO/LOT]. The session variability factor was addressed by deducting the participant's unexpected non-attendance during the session divided by the (LOT). The repeated behaviour within the first 3 s of observation recording was omitted.

Instruments

Sound-level metre NTI XL2 acoustic analyser with M4260 omni directional microphone was used for acoustics and noise measurement, LAeq and RT. The RT was measured in an unoccupied designated classroom, pre- and post-intervention. RT was measured at five classroom positions (centre and four corners). An impulsive source (clapping boards) was used, ensuring a signal-to-noise ratio of at least 25 dB above the background level (35 dBA). The microphone was positioned approximately 1 m above the floor and at least 1 m from reflective surfaces. Measurements were conducted during weekends with only one operator present to minimise disturbance. RT60 values were derived from T20 decay measurements. Results were averaged across the five positions and mid-frequency RT (500–2,000 Hz) was subsequently calculated. RT frequency data set was analysed using NTI Data Explorer software 365. For the video recording, two IP HD Logitech C90 Pro Webcams were installed in the observational classrooms in the group activity area to record the four participants' sensory behavioural responses. The webcam's video recording data were obtained initially from the OBS software, whose recording analysis was done by the Interac-Mangold behaviour observation software for data structuring and analysis of behavioural data.

Intervention investigated

The acoustic panels were locally fabricated using 50 mm yellow fibreglass wool with a silver backing. While comparable 50 mm fibreglass boards (e.g. Owens Corning 703) are rated at NRC ≈ 1.0 under laboratory conditions, the panels in this study were conservatively assumed to have an NRC of 0.90–0.95. The glass wool was enclosed within a 2-inch timber frame and covered with breathable fabric on both the front and back to allow sound transmission into the absorber. Panels were designed in varied sizes to suit the available wall areas, matching the classroom room interior colour scheme for minimal visual change. In addition to the partially carpeted floor and classroom furnishings in place, a total, 313 ft^2 of acoustic wall treatment was installed, representing approximately 36% of the total wall surface area. Panels were mounted using D-ring hangers, with a 1-inch air gap maintained behind each panel to enhance low-frequency absorption and overall acoustic performance (see Figure 2).

Data analysis

Firstly, the RT and correlates LAeq and LA90 levels representative data were collected before and post-installation modification of classroom environment acoustic conditions compared and analysed. Secondly, each individual subject ($n = 1$) data were collated and their representation was analytically and comparatively drawn, demonstrating the significance of intervention relative to each ASD child within the phase and across phases. Analytical evaluation was conducted using visual graphical, Levels of change, trend,

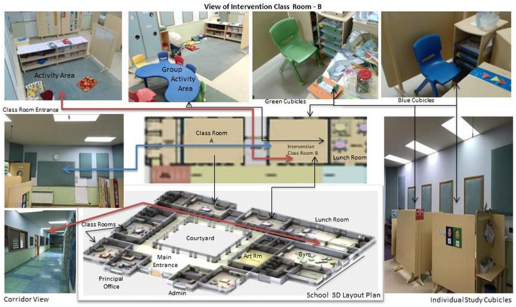


Figure 2. Classroom after acoustic treatment
Source: Authors' own work

immediacy and consistency. Effect size metrics (Tau-U and non-overlap of All Pairs [NAP]) were calculated for individual ASD participants to strengthen result credibility. Descriptive statistics (mean, range and standard deviation) for sensory behaviours are presented in Tables 3–5 to support overall interpretation.

Procedural fidelity

Procedural fidelity for individual participants during this study across phases is presented in Table 6. There was an inadequate outcome measure for loud vocalising behaviour for two participants, ABD and MOH. These were, therefore, validly omitted from the study part.

Reliability and social validity

The inter-observer agreement (IOA) was recorded for each targeted behaviour during Phases (A1-B-A2) for 25% of the sessions. The agreements for the behaviour event data recording were converted into percentages by the ratio: smaller/larger agreements. An IOA within the range of 87%–92% was established. Towards the termination of the final research, a teacher's survey questionnaire was requested to be filled out for social validity. The survey response reflected strong concordance and acceptance of the acoustical modification.

Habilitative validity

To confirm the study's habilitative validity, the acoustic panels were donated to the school and a post-summer break follow-up assessed intervention maintenance. The school principal confirmed their reinstallation and continued maintenance in the same classroom and a staff survey was conducted, which indicated positive perceptions of the intervention's effectiveness and a desire to continue its use to support improved classroom behaviour.

Results

Overall findings for the ASD group ($n = 4$) indicate promising trends, suggesting a potential effect of the acoustic intervention on repetitive behaviours, ear-covering and loud vocalisations.

Effect of acoustical treatment on classroom group activity noise levels

This examination directed the investigation of significant differences in group activity noise levels measured in relation to the RT. The group activity duration ranged between 5 and 10 min, and the noise levels were measured each day for the duration of the two weeks in the Phases A and B sessions and numerically averaged for analysis. The ambient noise level mean LAeq during Phase (A1) was 75.8A-weighted decibel level (dBA) and the mid-frequency (Tmf) RT was 1.11 s, exceeding the value recommended by the BB93 standards. During Phase (B), the acoustic treatment condition resulted in the mean LAeq levels of 64.0 dBA (see Table 2) and the

Table 2. Classroom average noise level before and after acoustic refurbishment

	Average LAeq dB		Average LA90 dB		Average LAF max dB		Average LAF min dB	
Noise condition	Before	After	Before	After	Before	After	Before	After
Group activity lesson time (10 min) Occupied with HVAC	75.8 (3.5*)	64.1 (3.6)	65.1 (3.0)	52.2 (6.9)	96.9 (3.8)	85.3 (6.2)	47.2 (2.9)	41.3 (1.5)

Note(s): *The number in the bracket represents the standard deviation
Source(s): Authors' own creation

Table 3. Inter-subject differential statistics for repetitive behaviour

	Descriptive parameters						Statistical parameters	
	Baseline A1		Intervention B		Return to Baseline A2			
Participant	Behaviour frequency mean	Level	Behaviour frequency mean	Level	Behaviour frequency mean	Level	NAP (%)	TAU
ABD	2.0	2.05	0.5	0.55	1.4	1.30	93	–
IBT	1.6	1.60	0.9	0.80	1.4	1.50	96	–
MOH	1.0	1.10	0.4	0.50	1.1	0.75		The Tau-U (fully corrected) shows systematic change during the B versus A1 condition only
SHA	0.9	0.85	0.2	0.15	0.9	0.85		The Tau-U (fully corrected) shows systematic change

Source(s): Authors' own creation

Table 4. Inter-subject differential statistics for ear-covering behaviour

	Descriptive parameters						Statistical parameters	
	Baseline A1		Intervention B		Return to Baseline A2			
Participant	Behaviour frequency mean	Level	Behaviour frequency mean	Level	Behaviour frequency mean	Level	NAP (%)	TAU
ABD	0.2	0.30	0.1	0.05	0.2	0.20	95	–
IBT	0.3	0.20	0.17	0.10	0.2	0.20	71	–
MOH	0.4	0.30	0.3	0.30	0.5	0.45	63	
SHA	0.3	0.20	0.1	0.10	0.2	0.15	–	The Tau-U (fully corrected) shows no systematic change

Source(s): Authors’ own creation

Table 5. Inter-subject differential statistics for loud vocalising

	Descriptive parameters						Statistical parameters	
	Baseline A1		Intervention B		Return to Baseline A2			
Participant	Behaviour frequency mean	Level	Behaviour frequency mean	Level	Behaviour frequency mean	Level	NAP (%)	TAU
IBT	1.3	1.10	0.5	0.50	1.7	1.90	–	The Tau-U (fully corrected) shows a positive correlation through systematic change
SHA	0.5	0.45	0.07	0.05	0.6	0.55	–	The Tau-U (fully corrected) shows systematic change

Source(s): Authors’ own creation

Table 6. Treatment fidelity

Participant	Fidelity (%)	Explanation
ABD	93	Absent One session, attended 23 out of 24 sessions
IBT	79	Absent 5 sessions, attended 19 out of 24 sessions
MOH	79	Absent 4 sessions and non-attending 1 session, attended 19 out of 24 sessions
SHA	100	No absentees attended all 24 sessions

Source(s): Authors' own creation

RT of 0.39 s (see Table 7). The octave-band RT decreased at 250 Hz (0.98–0.47 s) and at 125 Hz (0.73–0.57 s), with no meaningful change at 63 Hz.

The acoustic treatment condition reflected a significant transformation range of 11 dBA. The LA90 also reflected a significant average during group activity lessons in which the background noise levels decreased from 65.0 dB LA90 to 52.1 dB LA90. The post-intervention phase (B) reflected a significant reduction in the social group activity LA90 and LAeq levels. This finding conformed to the research indicators depicting the acoustic treatment effect on classroom activity LAeq and LA90 levels (Kristiansen *et al.*, 2016). It demonstrated that the higher the LAeq unoccupied levels and RT, the higher the LAeq and LA90 during the actively occupied classroom lesson due to the carryover effect of the consistent ambient and background noise levels during the unoccupied condition (Shield *et al.*, 2015).

The association between reverberation time, noise levels and repetitive behaviour in children with autism spectrum disorder

The first sub-question investigates the correlation between the acoustic variable RT and the children's ($n = 4$) repetitive behaviour during the classroom condition in Phases A1-B-A2. Among the four participants, ABD's sensory outcome demonstrated consistent stability across all three markers. The visual analysis, statistical parameters and interpretation of the descriptive mean values indicated a significant positive impact of the Phase B acoustic intervention. Participant IBT and MOH data outcomes reflected an overall promising correlation but included considerable variability across all three markers. Participant SHA's data demonstrated consistent variability in the Baseline Phases A1 and A2.

The acoustic conditioning in Phase B intervention, RT (0.39 s) Tmf and, LAeq (64.1) and LA90 (52.2), indicated a positive correlation on the overall decrease of repetitive behaviour frequency for all four participants. However, some variability was observed, but in general, the non-overlapping percentage, levels and trends data and the descriptive mean value demonstrated stability and consistency of decreased behaviours (see Table 3).

Table 7. Classroom reverberation times and mid frequency (tmf) pre and post-acoustic modification

	500		1,000		2,000		Tmf (500–2,000 Hz) Seconds	
Frequency (Hz)	Before	After	Before	After	Before	After	Before	After
RT60	1.12	0.41	1.16	0.40	1.07	0.35	1.11	0.39

Source(s): Authors' own creation

In comparison, in Phases A1 and A2, which maintained RT (1.11 s) and LAeq (75.1) and LA90 (65.1), there were significant effects of increased repetitive behaviours for all four participants (see Figure 3).

The association between reverberation time, noise levels and ear-covering behaviour in children with autism spectrum disorder

The second sub-question (b) investigated if an association existed between the acoustic variable RT and the ear-covering behaviour in children with ASD in the classroom environment. Results for one participant ABD indicated a strong direct impact of acoustic intervention across all three markers: visual analysis, NAP percentage and descriptive mean results, reflecting an overall decrease in ear-covering behaviour. However, for participants IBT and MOH results were partially positive. The results for participant IBT indicated a positive response only during the first comparison baseline phase and intervention phase; during the second comparison intervention phase and withdrawal Phase A2, the data suggested that weak or no impact was observed with NAP 63% of all data pairs. The results for participant MOH indicated a positive response only during the second comparison baseline Phase A2 and intervention Phase B. During the first comparison of intervention phase B and withdrawal baseline Phase A1, data was suggestive of weak or no impact with NAP 63% of all data pairs. Results for the participant SHA showed weak or no direct effect of the intervention on ear-covering behaviour.

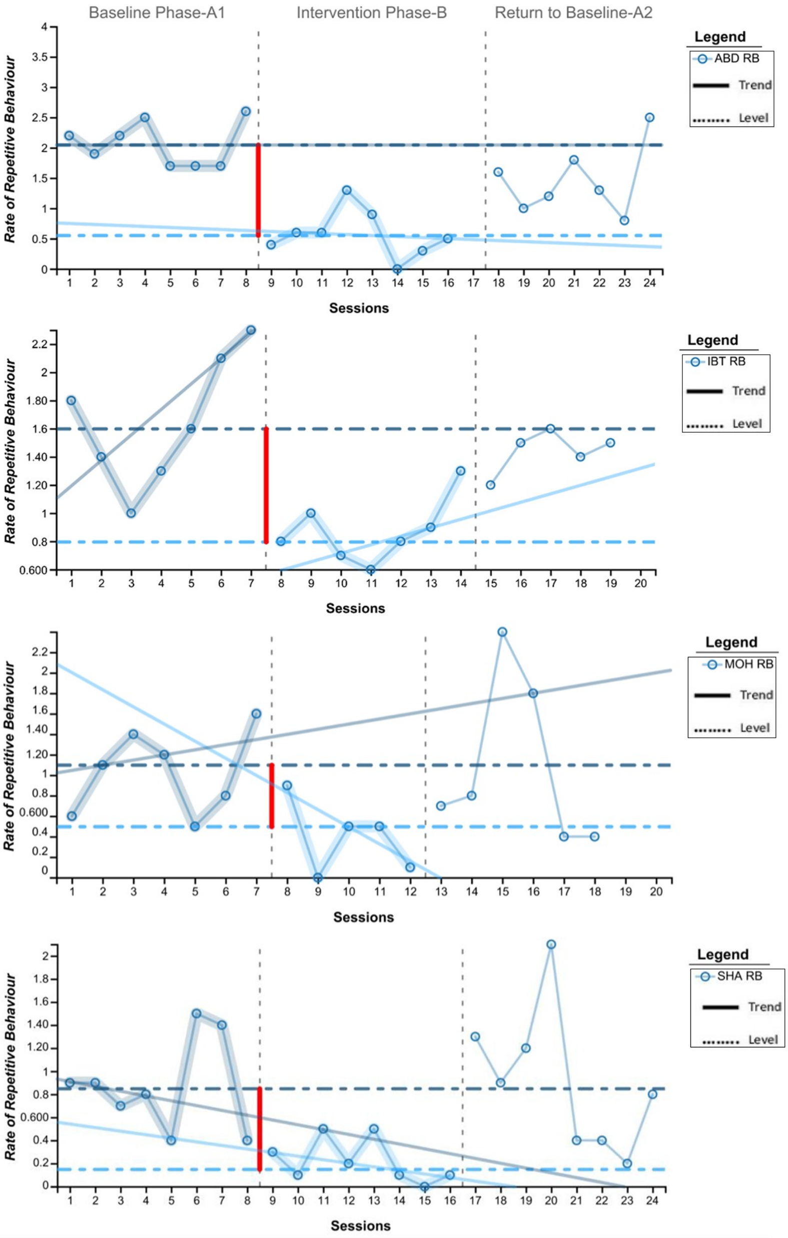
Although the visual analysis does not show much impact based on supplementary descriptive mean values, the author feels that there might be some impact reliably present which is demonstrated through a decrease in ear-covering behaviour during the intervention phase (see Figure 4). All Four participants ($n = 4$) data depicted variability of the ear-covering behaviour continuum during the overlap, trends and levels. However, the descriptive mean values were stable and demonstrated a consistent decrease during the intervention condition compared with the baseline conditions for all the participants (see Table 4). Overall, positive correlation results of ear-covering behaviour through intervention conditions of RT (0.39 s) Tmf, LAeq 64.08 and LA90 52.2 contrasted with the baseline Phases A1 and A2 RT (1.11 s) with LAeq (75.1) and LA90 (65.1) showed congruence.

The association between reverberation time, noise levels and loud vocalising in children with autism spectrum disorder

The third sub-question (C) investigated whether an association existed between acoustic variable RT and loud vocalising behaviour in children with ASD in the classroom environment. The participants' IBT and SHA results showed a strong impact of the acoustic intervention across the three markers, visual analysis (see Figure 5), Tau and descriptive mean value, and there was an overall decrease in loud vocalising behaviour during Phase B (see Table 5). For the participant, MOH and ABD outcomes remain indeterminate due to findings of idiosyncratic trends. Nonetheless, the impact of the acoustic intervention on loud vocalising behaviour is noteworthy, with a 50% positive result in only two participants. Although limited, this data is still valuable. One plausible explanation for this outcome lies in the heterogeneous behavioural responses of children with ASD, given their unique and individual characteristics.

Discussion

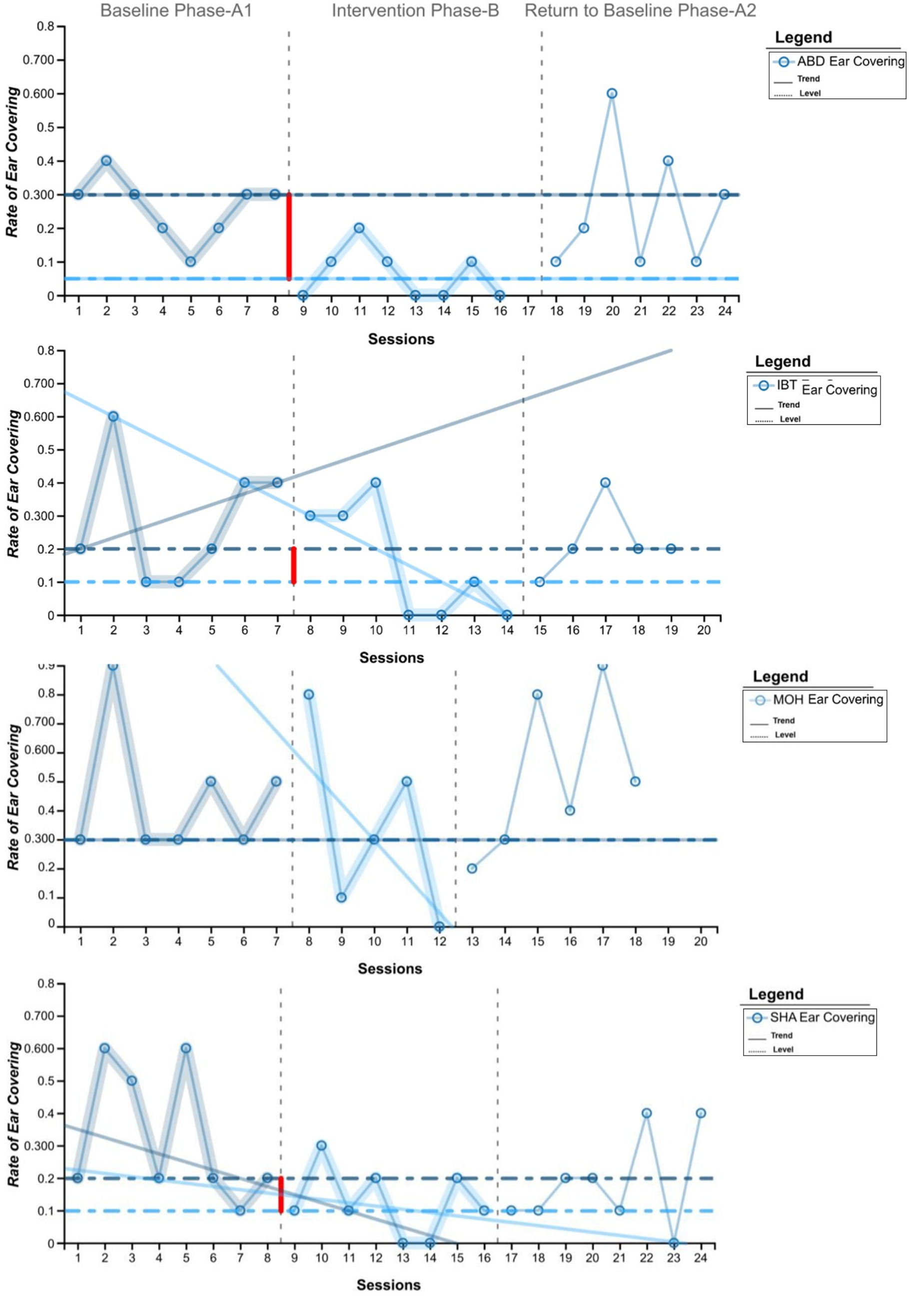
The focus of this study is to examine the impact of long (1.11 s) and short (0.39 s) RT upon sensory response behaviours, ear-covering, repetitive and loud vocalising in children with ASD. The findings from this study underscore the complexity of ASD, showing a differential



Comparison of Phases BA

Figure 3. Rate of repetitive behaviour across phases and participants

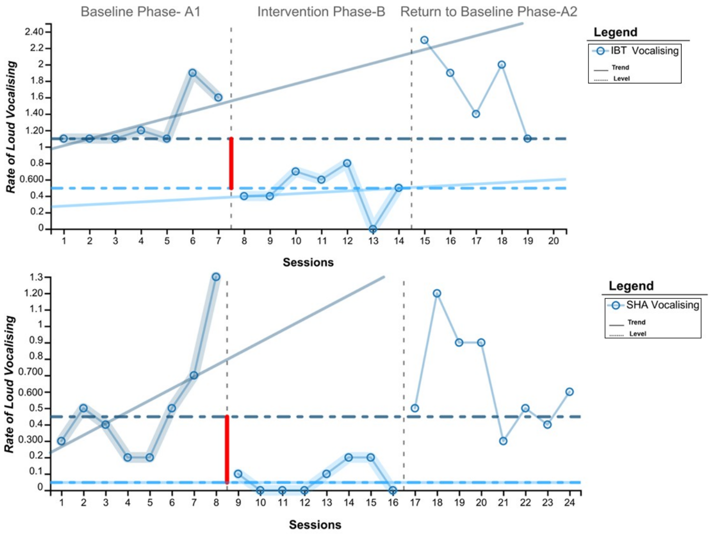
Source: Authors' own work



Comparison of Phases BA

Figure 4. Rate of ear-covering across phases and participants

Source: Authors’ own work



Comparison of Phases BA

Figure 5. Rate of vocalising across phases and participants

Source: Authors' own work

frequency reduction in sensory response behaviours individually for participants and specific behaviour profiles, such as repetitive behaviour, which was most frequent under the existing acoustic conditions RT (1.11 s) and demonstrated the most noticeable positive correlation response under improved acoustics RT (0.39 s), followed by ear-covering and loud vocalisation. This complexity likely reflects the interaction of environmental, neurobiological and cognitive factors in autism (Keith *et al.*, 2019; Goncalves and Monteiro, 2023).

Moreover, a delayed immediacy response, as evidenced in some participants' marked behaviours, was an expected outcome common within naturalistic settings. Following the behavioural improvements observed during the intervention phase (B), the variability in the withdrawal Phase (A2) likely reflects participants' sensitivity to the removal of acoustic modifications rather than random instability. A possible explanation for this could be partial adaptation, adaptive neural recalibration (Rankin *et al.*, 2009) or individual sensory and auditory processing differences in ASD affecting behavioural responses (Goncalves and Monteiro, 2023; Poulsen *et al.*, 2025), However, some variation may also stem from contextual factors or any coincidental events. Future replications with additional reversal phases are recommended to enhance reliability and generalizability of the findings.

While these preliminary results align with seminal research identifying noise and acoustics as predominant environmental factors that trigger sensory–modulatory behaviours in children with ASD (Kanakri, 2017b; Howe and Stagg, 2016; Ashburner *et al.*, 2008,), the present study extends this understanding by proposing a potential RT threshold that may inform acoustic design practices for ASD.

Although classroom acoustic performance is evaluated using mid-frequency RT (BB-93, 2015), spectral balance remains relevant in autism settings. While 250 Hz is not a compliance parameter, it reflects low-mid frequency reverberant persistence that may affect noise build-up and auditory comfort. More stringent limits (≤0.7 s at 250 Hz; ≤ 1.0 s at 125 Hz) have been proposed for special educational classrooms and small-group instruction rooms (James and Canning, 2010). Given decreased sound tolerance in autism (Williams *et al.*, 2021), low-mid frequency control may, therefore, represent an important design consideration alongside speech-band targets (≤0.4 s) Tmf. In this study, 250 Hz was analysed diagnostically. RT decreased at 250 Hz (0.98–0.47 s) and at 125 Hz (0.73–0.57 s), with no meaningful change at 63 Hz. This spectral pattern suggests improved low-mid frequency reverberation control and offers contextual insight when interpreting associated behavioural outcomes. However, given the study's exploratory scope, small sample size and short observation period, the findings are preliminary and should be interpreted as indicative rather than conclusive. The results of the three sub-questions are further detailed in the subsequent discussion.

Repetitive behaviour

In the first sub-question (a), the findings for repetitive behaviour showed a significant positive correlation response across all four participants. This finding, the most prevalent and frequent among the other two delineated behaviours, underscores the importance of classroom sensory conditioning through acoustic modulation in reducing repetitive behaviours for children with ASD. Similarly, this finding aligns with the study by Kanakri *et al.* (2016), which, using a quasi-experimental design, reported a correlation between repetitive behaviours and classroom noise levels exceeding 35 dB. However, the absence of a control group and reliance on A-weighted noise levels and RT reporting limited detailed spectral analysis and causal interpretation.

Ear-covering behaviour

In the second sub-question (b), the results of ear-covering behaviour were promising among three (ABD, MOH and IBT) out of four participants, indicative of a positive correlational response to acoustic conditioning. This deduction is consistent with the seminal observational research examining the effect of noise/acoustics on the frequency of ear-covering behaviour in children with ASD in noisy and quiet classrooms (Kanakri *et al.*, 2016). These results are also consistent with important findings in the research, including evading and hiding from the source of noise emission and covering ears (Stiegler and Davis, 2010).

Vocalising behaviour

In the third sub-question (c), the study yielded promising results regarding the impact of acoustic intervention on participants' IBT and SHA markers. Therefore, it is crucial to consider the heterogeneity in ASD when aiming to enhance acoustics to support children on the spectrum in a classroom setting. However, the intervention positively affected loud vocalising behaviour in two participants, representing a 50% success rate. It is worth noting that children with ASD exhibit diverse and unique behavioural responses; a reason for this outcome could be attributed to children's idiocentric heterogeneity, as no two children with ASD are similar (American Psychiatric Association, 2013; Gabriels and Hill, 2002; Caniato *et al.*, 2022). The findings are consistent with the effect of noise and classroom acoustics on the frequency of children's repetitive vocalising behaviours (Kanakri *et al.*, 2016).

Implications

This research contributes to understanding the global acoustic sensitivity assessment in educational settings for children with ASD. It is relevant for architects, designers and policymakers seeking to improve the sensory experience, well-being and learning outcomes of children with ASD. By generating preliminary experimental evidence from Pakistan, this study addresses a major research gap. It contributes to both regional and global discourses on acoustic design for autism, offering initial insights from an underrepresented diverse socio-cultural and economic context, underscoring the universality of the issue. This research emphasises the significance of calibrated acoustics in classrooms to minimise sensory behaviour among children with ASD and proposes a potential threshold range of 0.39–0.4 s, (Tmf) for RT based on the initial empirical evidence from this experimental study. The findings also underscore the cost-effective design of locally sourced acoustic panels that can be implemented to address acoustic conditions, leading to classroom designs that meet the specific requirements of children with ASD in Pakistan, underdeveloped nations and worldwide. Despite its limited scope, this study provides meaningful evidence to inform future research and supports the development of specific acoustic design guidelines for educational environments for children with ASD. It further provides multidisciplinary insights into the relationship between sensory dysfunction, the built environment and learning in children with ASD, considering individual profiles and pedagogical approaches.

Limitations and future studies

The generalizability of the findings is limited by the small sample size, short observation periods and focus on a specific low-incidence ASD population within a single educational context of classroom. Maximum unoccupied RT 0.4 s mid-frequency (Tmf) threshold, supported by general guidelines, the British Standards Institution and Building Bulletin (BB93) for children with neurodiverse needs and sensory differences in learning spaces (Hewitt, 2022; BB-93, 2015; Canning *et al.*, 2015) was tested in this study as the structured acoustic intervention in classroom for children with ASD. In the present study the nature and scale of the acoustic panels limited the flexibility of the intervention, preventing the gradation of RT levels. As such, the study compared only two conditions: the presence and absence of structured acoustic intervention.

Future studies could introduce graded variations in RT and incorporate objective behavioural measures to further examine the relationship. Replication of this study with additional phases using the A-B-A SCED and the multiple base line design is recommended to build on the current preliminary exploratory findings and enhance their generalizability and reliability. Moreover, future studies could incorporate larger participant cohorts, multi-site trials and cross-cultural replication to validate these findings across diverse educational settings. In addition, researchers could explore correlations between children's physiological and neurological markers and varying classroom acoustic conditions, implementing a multidisciplinary approach that draws upon architecture, special education, neuroscience and environmental psychology.

Conclusion

The primary conclusion of this study, which aimed to examine the impact of classroom acoustic conditioning on sensory behaviours in children with ASD, suggests maintaining a mid-frequency (Tmf) RT of ≤0.4 s across 500, 1,000 and 2,000 Hz may be beneficial. In addition, attention to low-mid frequency reverberation around 250 Hz offers contextual insight when interpreting associated behavioural outcomes and may support auditory sensory comfort within the classroom environment. Accordingly, classroom design should move beyond general noise reduction to adopt frequency-sensitive acoustic strategies aligned with neurodevelopmental differences in autism to support sensory regulation and behaviour.

As such conclusions are drawn from a limited sample of individuals with ASD within the scope of this study, the generalizability of the results remains limited and the findings should therefore be considered indicative rather than definitive. Moreover, as supported by previous research and this study, it is evident that the reverberation and noise levels are closely related. It emphasises the need to use effective methods to modify physical classroom acoustics, RT and background noise levels to support auditory sensory processing in children with ASD. Overall, the study highlights the importance of developing evidence-based guidelines for RT and noise thresholds in educational environments for children with ASD.

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