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TECHNICAL NOTE

The Effect of Classroom Acoustic Treatment on Listening, Learning, and Well-being: A Scoping Review

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Abstract

Classrooms are important learning spaces, however, the acoustic conditions in these spaces can often be suboptimal. The aim of this scoping review, which used the PRISMA-ScR protocol, was to understand what is known from the literature about the effect of classroom acoustic treatment on students' listening, learning, and well-being. Thirteen papers from the database searches were deemed relevant for the review. Information on the years of publication of the papers, the population studied, the types of acoustic treatment used, the measures and methods used to assess the effect of acoustic treatment, and the outcomes of the papers was gathered. Seven of the 13 studies reported positive effects of classroom acoustic treatment on student's speech perception, attention, and well-being. Five studies reported both positive effects and no effect depending on the measure, condition, or population. The remaining study reported a negative effect of classroom acoustic treatment on children's speech perception and listening effort. These findings suggest that the effect of ceiling and/or wall absorbers/diffusers on sound and reverberation in the room can help students' speech perception, attention, reading, and well-being, but they may also reduce the speech transmission index resulting in increased listening effort. The limitations of the reviewed studies and avenues for future research on the effect of acoustic treatment on a broader range of listening, learning, and well-being outcomes for students are discussed.

Keywords Classroom acoustics · Acoustic treatment · Reverberation · Listening · Learning · Well-being

1 Introduction

Classrooms are vital learning spaces, whether it be for preschool children, primary school children, high school students, or university/adult students. Recent reviews on the effect of classroom acoustic conditions on primary school children's listening, learning, and well-being have shown that poor acoustic conditions can negatively affect their speech perception, listening comprehension, literacy skills, numeracy performance, cognition, behaviour, physical health, and mental well-being [1–8]. Therefore, it is important that the acoustic environment provides support for learning.

Acoustic conditions that are important to consider in the design of classrooms are noise and reverberation. Penetration of external noise into the classroom can be an issue in schools built in high traffic areas or under flight paths. Internal noise from heating, ventilation, and air-conditioning systems and other equipment can also be problematic. Additionally, child-generated noise can be an issue. This is especially due to modern teaching methods that place a greater focus on group work activities which makes up around 50% of teaching time [9, 10] and have higher noise levels than lecture-style or independent learning [11, 12]. Furthermore, open plan innovative learning environments are growing in popularity [10], and these have higher intrusive noise levels than traditional classrooms [12]. Properties of the room, such as the reverberation time, can exacerbate the effect of noise. Many classroom are reported to have long reverberation times due to the building materials used and overall design of the classroom (see [13] for a review). Other acoustic parameters that are important to consider are the early decay time (EDT), speech clarity (C50), definition (D50), useful-to-detrimental ratio (U50), sound strength (G), and the speech transmission index (STI).

Due to the negative effect of poor classroom acoustic conditions on speech perception, there are several recommendations for what acoustic conditions should be

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achieved. For example, the Australian/New Zealand Standard AS/NZS2107:2016 suggests that noise levels should be 35–45 dBA and reverberation times for typically sized classrooms should be around 0.4–0.5 s [14]. A 2016 review of national and international standards and recommendations in the research literature synthesised results and proposed the following recommendations for primary schools: unoccupied noise levels should be < 30 dBA, occupied noise levels should be < 50 dBA, reverberation times should be 0.4 s, SNRs should be at least + 15 dB, and the STI should be > 0.75 [13]. A recent 2022 review of acoustical parameters that influence students' performance suggests that for children under 12 years, noise levels should be ≤ 35 dBA, reverberation times should be 0.6 s, SNRs should be ≥ + 12 dB, and STIs should be > 0.65. For students aged 12 years and over, noise levels should be ≤ 40 dBA, reverberation times should be 0.7 s, SNRs should be ≥ + 12 dB, and STIs should be > 0.60 [7].

One way to modify the acoustic environment to achieve these recommendations is via acoustic treatment. In classrooms, this is mostly achieved by installing absorbers and/or diffusers on the ceiling and walls. But how effective is this acoustic treatment in improving students' listening, learning, and well-being? The aim of this scoping review was to synthesise and systematically map research that has assessed the effect of classroom acoustic treatment on students' listening, learning, and well-being across the learning life span and to identify gaps in the research literature to inform future research. A scoping review approach rather than a systematic review approach was chosen as the method of synthesis as the purpose of the review fitted the criteria of a scoping review. According to Munn et al., the aim of a scoping review is "to identify the types of available evidence in a given field; to clarify key concepts/definitions in the literature; to examine how research is conducted on a certain; topic or field; to identify key characteristics or factors related to a concept; as a precursor to a systematic review; and to identify and analyse knowledge gaps" (pg. 2) [15]. The following research question was formulated: What is known from the literature about the effect of classroom acoustic treatment on students' listening, learning, and well-being?

2 Method

2.1 Protocol

The Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [16] was the protocol used for this scoping review. The PRISMA extension for scoping reviews website can be found at http://www.prisma-statement.org/Extensions/ScopingReviews.

2.2 Eligibility Criteria

The peer-reviewed papers had to meet the following criteria to be included in the review: (i) conduct a study in either the field or the laboratory with human participants on the effect of classroom acoustic treatment on listening, learning, or well-being, and (ii) have the full text in English available.

2.3 Information Sources

To identify potentially relevant documents, Scopus and Web of Science bibliographic databases were searched. The final search results were exported into .csv files where duplicates were removed.

2.4 Search

A comprehensive search of Scopus and Web of Science was conducted on 29th July 2022 to identify the effects of classroom acoustic treatment on listening, learning, and well-being. The search term was *classroom AND ("acoustic treatment" OR "acoustic insulation" OR "acoustic absorption" OR "acoustic intervention") AND (listen* OR intelligibility OR "speech perception" OR comprehen* OR communicat* OR learn* OR read* OR writ* OR spell* OR math* OR cognit* OR atten* OR memor* OR behav* OR health OR well-being OR "quality of life" OR annoy* OR disturb*).* No publication date restrictions were applied.

2.5 Selection of Sources of Evidence

All publications identified in the searches were evaluated for potentially relevant publications by the titles, and then abstracts and full texts when needed.

2.6 Data Charting Process

Data charting refers to how relevant information from the papers was extracted. Data from eligible studies were charted to capture the relevant information on key study characteristics on the effect of classroom acoustic treatment on listening, learning, and well-being.

2.7 Data Items

Data were abstracted on the following characteristics: the population studied, the measures and methods used to assess listening, learning, and well-being outcomes, and the effect of classroom acoustic treatment on students' listening, learning, and well-being outcomes.

2.8 Synthesis of Results

Studies were grouped by the outcome explored and summarised according to the effect of the acoustic treatment on students' listening, learning, and well-being.

3 Results

3.1 Selection and Characteristics of Sources of Evidence

The search and selection process of the papers to be included in the review is shown in Fig. 1. A total of 69 papers (46 after removing duplicates) were returned in the searches. These were vetted for relevance via reading the title, abstract, and when needed for clarification, the full text. Thirteen papers were deemed relevant for the review. The general information for the 13 papers is shown in Table 1, and the publication years are shown in Fig. 2. The majority of papers have been published since 2015.

3.2 Population

The age groups studied are shown in Table 2. There were studies from each of the age groups of preschool children, primary school children, high school students, and university/adult students. All studies included children/students who are typically found in mainstream classrooms, i.e. no studies assessed children/students with specific special educational needs.

3.3 Acoustic Treatment

The acoustic treatment used for the interventions in each study is shown in Table 1. All studies used absorbers/diffusers on the ceiling and/or walls.

3.4 Measures and Methods

The outcomes assessed are shown in Table 2. These include measures of speech perception via a test, measures of speech perception via a questionnaire, measures of attention, measures of reading, and measures of well-being. The specific measures and methods used to assess these outcomes are summarised for each study in Table 1.

3.5 Outcomes

Figure 3 shows an overview of the results according to the reverberation time change from the acoustic treatment as reverberation time was the most reported acoustic parameter. It can be seen in the majority of papers that decreasing the reverberation time improved performance on the outcome assessed. However, one study did show a negative effect and five studies showed no effect for certain measures/populations. The following sections describe the outcomes of the studies in more detail.

3.5.1 Speech Perception (Test)

Amlani and Russo [17] assessed primary school children's word recognition and listening effort in an auralised classroom with and without acoustic treatment on the walls. The reverberation time of the classroom without acoustic treatment was 0.82 s, and with acoustic treatment, it was 0.55 s (see Table 1 for changes in other acoustic parameters). Children completed the word recognition and digit recall tasks while wearing insert earphones that presented the stimuli in four different seating positions in the classroom. The approximate STI values for each seating position pre- vs. post-treatment from closest to furthest from the target signal were 0.85 vs. 0.83, 0.62 vs. 0.59, 0.46 vs. 0.39, and 0.35 vs. 0.24 (i.e. the acoustic treatment decreased the STI at all four seating positions). The authors found that the children's word recognition and digit recall decreased with acoustic panels installed in all seating positions and decreased as the distance from the target signal increased. The authors concluded that the acoustic panels had a negative effect as they resulted in increased listening effort.

Astolfi et al. [18] assessed primary school children's speech intelligibility in a classroom before and after acoustic treatment on the ceiling and walls. The reverberation time of the classroom without acoustic treatment was 1.6 s, and with acoustic treatment, it was 0.4 s. The authors found that speech intelligibility improved by around 10% when traffic noise outside the of the building was the noise source across the range of -15 to + 6 dB SNR, but there was no significant difference when the babble noise located in the middle of the classroom was the noise source.

Pekkarinen and Viljanen [19] assessed the effect of wall and ceiling acoustic treatment on speech discrimination in high school students. The reverberation time of the classroom without acoustic treatment was 1.7 s, and with acoustic treatment, it was 0.7 s. The authors found that sentence, word, and nonsense word discrimination increased with acoustic treatment in all three listening conditions (quiet, + 2 dB SNR, and + 7 dB SNR). The authors concluded that acoustic treatment could improve the quality of communication in the classroom.

Peng et al. [20] assessed the effect of acoustic ceiling tiles on primary school children's speech intelligibility. The reverberation time of the classroom without acoustic treatment was 0.8–1.4 s, and with acoustic treatment, it was 0.5–0.8 s (see Table 1 for changes in other acoustic parameters). The

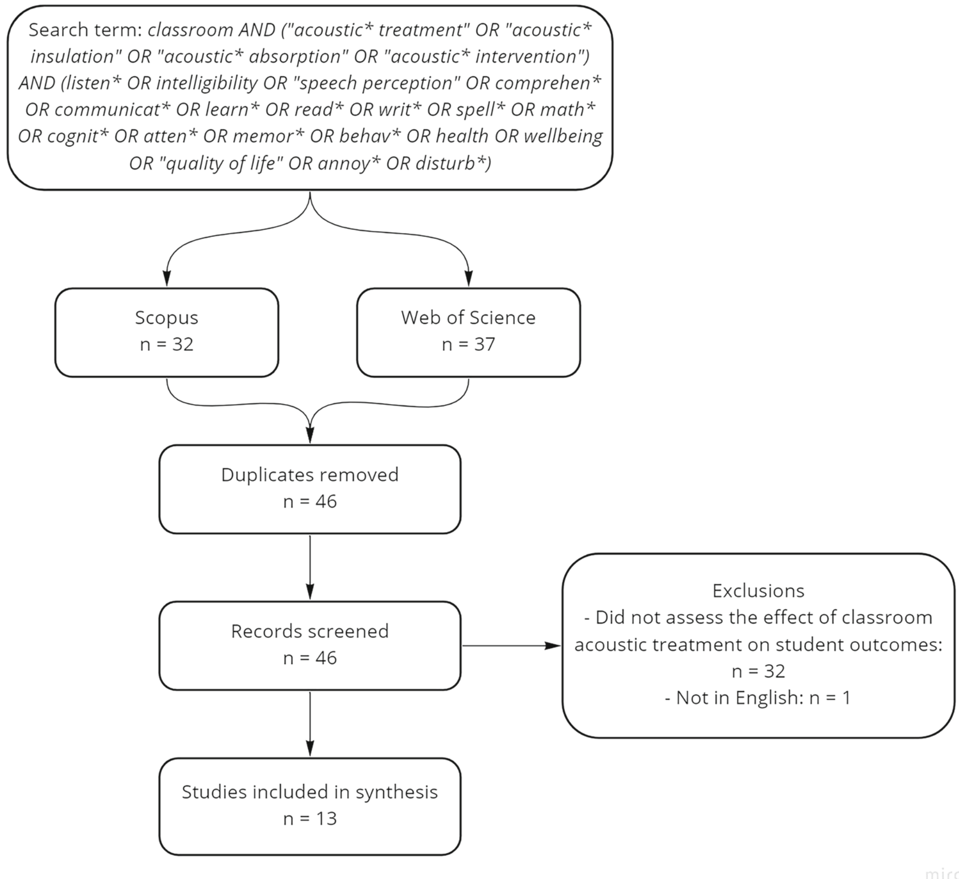

Fig. 1 Search and selection process for the papers to be included in the review

authors found that speech intelligibility scores improved for all grades in all four seating positions examined after installation of acoustic treatment. Subjective questionnaire responses also showed improvements in speech perception and the acoustic conditions of the classroom. The authors concluded that the acoustic treatment significantly improved the acoustic environment of the classroom.

Peng et al. [21] also assessed the effect of acoustic ceiling tiles in two classrooms on primary school children's speech intelligibility. The reverberation time of the classrooms without acoustic treatment was 1.1–1.7 s, and with acoustic treatment, it was 0.5–0.9 s (see Table 1 for changes in other acoustic parameters). Speech intelligibility scores were significantly better with acoustic treatment. Additionally, 86.4% of children said that they could hear the teacher more clearly in Classroom A after installation of the acoustic treatment, and 53.8% reported this for Classroom B (the decrease in reverberation time and increase in C50 were larger in Classroom A).

Scoczynski Ribeiro et al. [22] assessed the effect of wall panels on university students' speech intelligibility where the reverberation time was reduced from 1.32 s to 1.11 s (see Table 1 for changes in other acoustic parameters). The authors found that speech intelligibility scores improved with acoustic treatment for the seat furthest away from the speech source but were no different for closer seats.

Visentin et al. [23] assessed the effect of wall acoustic treatment on university students' speech intelligibility and listening effort. Auralised classrooms using signals from acoustic simulations of a university classroom played via headphones were created with the acoustic treatment reducing the reverberation time from 1.21 s to 0.81 s. No difference in speech intelligibility scores or subjective listening effort was found with acoustic treatment, however, reaction times were shorter with acoustic treatment than without acoustic treatment.

3.5.2 Speech Perception (Questionnaire)

Pirila et al. [24] assessed primary school children's experience of sound during lessons pre- and post-acoustic treatment on the ceiling and rear wall. The change in reverberation time or any other acoustic parameter was not reported. The subjective questions were related to the teacher's voice (e.g. clarity, loudness) and noise. Overall, the authors found improved experiences of the sound environment after the acoustic intervention for children in Grade 6 but not Grade 2 and 3.

Table 1 General information for the 13 papers included in the review and the effect of the acoustic treatment

Outcome	Authors	Aim	Population	Classroom dimensions	Acoustic treatment	Acoustic changes	Measure	Effect of acoustic treatment		
								Negative	None	Positive
Speech perception (test)	Amlani & Russo (2016) [17]	To assess the effect of acoustic treatment on speech transmission and listening effort	Primary school Children in Grade 3 (n = 27)	**Dimensions:** 7.9 m × 6.7 m × 3.5 m **Volume:** 185.255 m^3 **Seating positions:** Stimuli recorded at four locations (Seat 1: 1.91 m, Seat 2: 3.59 m Seat 3: 5.74 m, Seat 4: 7.22 m)	**Type:** Audimute Acoustical Absorption 2″ Eco-c-Tex Wall/Ceiling Tile; Audimute, Cleveland, OH **Noise reduction coefficient (NRC):** 1.00 **Number:** 12 panels measuring 4 ft (1) × 2 ft (w) × 2 ft (d) **Positioning:** Five acoustic panels along each of two sidewalls separated by 1.5 ft and centred on the wall. Two acoustic panels along the back wall equidistant between the window and sidewall	**Ambient noise level:** Pre = 40.1 dBA; post = 39.3 dBA **Reverberation time:** Pre = 0.82 s; post = 0.55 s **Speech transmission index (STI):** Seat 1: pre = 0.85, post = 0.83; Seat 2: pre = 0.62, post = 0.59; Seat 3: pre = 0.46, post = 0.39; Seat 4: pre = 0.35, post = 0.24	**Primary task:** Monosyllabic word recognition (recordings made with a Knowles Electronics Manikin for Acoustic Research and played over earphones) **Secondary task:** Digit recall (to measure listening effort)	x[a]		
	Astolfi et al. (2012) [18]	To assess speech intelligibility in classrooms including one before and after acoustic treatment	Primary school Children in Grade 2–5 (n = 983)	**Dimensions:** 6.8 m × 6.7 m × 4.3 m **Volume:** 193 m^3 Height reduced to 3.8 m after acoustic installation	**Type and positioning:** Porous sound absorption material (rock-wool panels) placed on the ceiling and the upper part of the back and lateral walls. Plaster board panels placed on the lower part of the walls Plaster board panel of 7m^2 inserted into the flat absorbing ceiling above the teacher's desk to increase early speech sound reflections	**Reverberation time:** Pre = 1.6 s; post = 0.4 s	Diagnostic rhyme test played through a head and torso simulator with traffic noise outside the building (-16 to + 18 dB SNR), and with babble noise in the centre of the classroom (-15 to + 20 dB SNRs)		x[b]	x[b]
	Pekkarinen & Viljanen (1990) [19]	To investigate the effect of acoustic treatment on speech discrimination	High school Children aged 15 to 16 years (n = 152)	**Dimensions:** 9.5 m × 6.5 m × 3.5 m **Volume:** 216.125 m^3 **Seating positions:** Closest was 2 m from loudspeaker. Other positions not reported	**Type:** Mineral wood panels (50 mm thick) **Coverage:** 20 m^2 on back wall and 40 m^2 on ceiling	**Reverberation time:** Pre = 1.7 s; post = 0.7 s	Sentences, words, and nonsense words played via loudspeaker in the classroom with background noise played through a loudspeaker next to it in quiet, and at + 2 and + 7 dB SNR conditions			x[c]

Table 1 (continued)

Outcome	Authors	Aim	Population	Classroom dimensions	Acoustic treatment	Acoustic changes	Measure	Effect of acoustic treatment		
								Negative	None	Positive
	Peng et al. (2015) [20]	To investigate the effect of acoustic ceiling tiles on children's speech intelligibility	Primary school Children in Grade 2, 4, and 6 (n = 48)	**Dimensions:** 9.35 m (l) 7.90 m (w) 3.70 m (h) **Volume:** 273.3 m^3 **Seating positions:** Four locations around the classroom (distances not reported)	**Type:** Mineral-fibre acoustic ceiling tiles with 1.5 cm thickness were installed on the ceiling (Brand: Armstrong; Model: School Zone Smart **NRC:** > 0.60 **Ceiling attenuation class (CAC):** 33 **Positioning:** On the ceiling with a 53 cm height cavity above the ceiling tiles	**Early decay time (EDT):** Pre = 0.8–2.2 s; post = 0.5–1.2 **Reverberation time (T30):** Pre = 0.8–1.4 s; post = 0.5–0.8 s **Mid-frequency Definition (D50):** Pre = 0.3–0.5; post = 0.5–0.85 **Mid-frequency Clarity:** Pre = -4.5–2; post = 0.5–7 dB. **Speech transmission index:** Pre = 0.55, post = 0.74	Mandarin Chinese rhyme test word lists played through a loudspeaker at the front of the classroom at + 20 dB at 1 m Children also completed a questionnaire			x[d]
	Peng et al. (2020) [21]	To compare the acoustic conditions and speech perception in children in two classrooms before and after acoustic treatment	Primary school Children in Grade 6 (n = 16)	**Dimensions:** Classroom A: 9.35 m × 7.90 m × 3.70 m; Classroom B: 8.70 m × 7.30 m × 3.45 m **Volume:** Classroom A: 273.30 m^3; Classroom B: 219.12 m^3 **Seating positions:** Four locations around the classroom (distances not reported)	**Type:** Mineral-fibre acoustic ceiling tiles with 1.5 cm thickness were installed on the ceiling (Brand: Armstrong; Model: School Zone Smart **NRC:** > 0.60 **Ceiling attenuation class (CAC):** 33 **Positioning:** On the ceiling with a 53.5 cm height cavity above the ceiling tiles	**Reverberation time (T30):** Pre = 1.1–1.7 s; post = 0.5–0.9 s) **Clarity:** Pre = -5–0; post = 0–7 dB) **Speech transmission index:** pre = 0.55–0.58, post = 0.74–0.75 **Background noise level:** Pre = 40.8–43.3 dBA; post 38.3–40.9 dBA	Mandarin Chinese rhyme test word lists played through a loudspeaker at the front of the classroom at 65 dBA dB at 1 m Children also completed a questionnaire			x
	Scoczynski Ribeiro et al. (2021) [22]	To assess the effect of wood-based composites on classroom acoustic conditions and speech intelligibility	University Students aged 18 + years (n = 18)	**Dimensions:** 7.10 m × 9.80 m × 3.25 m **Volume:** 226.13 m^3 **Seating positions:** Four locations around the classroom	**Type:** Wood-Wool Cement Board 50 mm thick **Positioning:** 12 wood-based panels (0.60 × 1.20 m) attached to the back and side wall	**Reverberation time (T20):** Pre = 1.32 s; Post = 1.11 s **Speech transmission index:** Pre = 0.57–0.61; post = 0.62–0.65	Word discrimination test played over headphones		x[e]	x[e]

Table 1 (continued)

Outcome	Authors	Aim	Population	Classroom dimensions	Acoustic treatment	Acoustic changes	Measure	Effect of acoustic treatment		
								Negative	None	Positive
	Visentin et al. (2018) [23]	To assess speech intelligibility and listening effort in auralised classrooms with and without acoustic treatment	University Students aged mean 25 years (n = 21)	**Dimensions:** 7.29 m × 7.62 m × 3.55 m **Volume:** 198 m^3 **Seating positions:** Two locations 2.5 m and 5.5 m from the speech source	Auralised treatment of the lateral wall	**Reverberation time (T20):** Pre = 1.21 s; Post = 0.81 s **Noise level:** Pre = 60.8–62 dBA; post = 58.7–60.9 dBA **Signal-to-noise ratio:** Pre = -0.1–0.6 dB; post = -0.3–0.1 dB **Speech transmission index:** Pre = 0.42–0.49; post = 0.45–0.52	Diagnostic Rhyme Test played over headphones where accuracy and response time were measured. Stationary noise played at 0 dB SNR Subjective listening effort questionnaire		x[f]	x[f]
Speech perception (questionnaire)	Pirila et al. (2020) [24]	To improve experiences of listening and voice ergonomics in classrooms	Primary school Children in Grade 2, 3, and 6 (n = 50)	Not reported	**Type:** Acoustic panels (not specified) **Positioning:** Ceiling and rear wall	Not reported	Questionnaire developed for the study on the experiences of the sound environment		x[g]	x[g]
	Arvidsson et al. (2021) [25]	To evaluate speech perception for three different configurations using absorbers and diffusers	Adults (ages not reported)	**Dimensions:** 7.32 m × 7.57 m × 3.50 m with absorbent ceiling at 2.7 m **Volume:** 193.94 m^3 **Seating positions:** Three locations around the classroom (approx. 2–6 m from the source)	**Configuration 1:** Ceiling-only treatment (52 m^2) **Configuration 2:** Ceiling plus porous 40 mm absorbers were mounted on two perpendicular walls (9 m^2) **Configuration 3:** Ceiling plus diffusers that diffuse high frequencies and absorbs low frequencies (9 m^2)	Acoustic treatment in configurations 2 and 3 decreased **reverberation time** (1 = 0.8–0.95 s; 2 = 0.45–0.95 s; 3 = 0.5–0.75 s), slightly decreased **sound strength**, and increased **C50** (1 = 1–5 dB; 2 = 1–8 dB, 3 = 2–7 dB). See supplementary material in [25] for detailed graphs	Participants rated sound quality and attributes and ranked their preferred listening environments			x

Table 1 (continued)

Outcome	Authors	Aim	Population	Classroom dimensions	Acoustic treatment	Acoustic changes	Measure	Effect of acoustic treatment		
								Negative	None	Positive
Attention	Castro-Martinez et al. (2016) [26]	To examine the effect of noise, reverberation, and acoustical barriers on student's attention	University students (n = 141)	**Dimensions:** 8 m × 6 m × 5 m **Volume**: 240 m^3	**Type:** Modular panels made with trapezoidal wood filled with fibreglass used as absorbers and diffusers **Positioning:** On a wall	**Reverberation time:** Pre = 2 s; post = 1.2 s	Questionnaire where participants chose words belonging and not belonging to the class Looking away measure			x
Reading	Bronzaft (1981) [27]	To assess the impact of classroom noise reduction on the reading scores of children in classrooms next to train tracks	Primary school Children in Grade 2 to Grade 6 (n = 955)	Not reported	**Type:** Track rubber pads installed in container plates to replace the steel tie-plates normally used to hold rails to the ties	**Noise level:** Pre = 89 dBA; post: 81–86 dBA	California Achievement Test (reading comprehension and vocabulary)			x
Well-being	Persson Way & Karlberg (2021) [28]	To study the association between an acoustic intervention and children's perceptions of and reactions to sounds in their preschool environment	Preschool Children aged 4–6 years (n = 61)	Not reported	Changed floor mats from traditional plastic to plastic mats designed to reduce impact sounds Added damping cushions under chairs Installed sound-absorbing tiles on the ceilings and some walls	**Noise level:** Pre = 85 dBA; post = 83 dBA **Reverberation time:** Pre = 0.3–0.5 s; post = 0.1 s **C50:** Pre = 8–10 dB; post = 11–13 dB **D50:** Pre = 86–89%; post = 92–95%	Inventory of Noise and Children's Health interview with the children		x[h]	x[h]
	Polewczyk & Jarosz (2020) [29]	To investigate whether and to what extent the acoustic treatment of the school rooms influenced students' and teachers' assessment of changes in different aspects of their performance and well-being	Primary school Children in Grade 2 to Grade 8 (n = 378)	**Floor surface area:** between 31.3 m^2 and 72.3 m^2 (63% between 59.0 m^2 and 67.0 m^2). **Height:** 3.0 m before the treatment	**Type:** 100 mm thick glasswool tiles **Ceilings:** Tiles covering from 43.4% to 50.6% of the ceiling area installed around the perimeter of the rooms **Walls:** Tiles covering from 12.4% to 14.1% of the total wall area mounted on two the rear wall and one side walls with panels covering the entire available surface of these walls higher than 2 m	**Reverberation time:** Pre = 0.8–2.5 s; post = 0.5–0.8 s **STI:** Pre = 0.47–0.52; post = 0.70–0.72	Teacher rating: Rating of children's physical and mental aggression via the Acoustic Change Feelings Scale (ACFS-T) (no reference provided) Child rating: ACFS-S (no reference provided)			x

[a]Word recognition and digit recall decreased with acoustic panels and as the distance from the target signal increased
[b]Speech intelligibility improved with acoustic treatment in traffic noise over the range of -15 to + 6 dB SNR but not babble noise
[c]Sentence, word, and nonsense word discrimination increased with acoustic treatment in all three listening conditions (quiet, + 2 dB SNR, and + 7 dB SNR)
[d]Speech intelligibility scores improved for all grades in all seating positions after installation of acoustic treatment. Questionnaire responses also showed improvements in speech perception and acoustic conditions
[e]Speech intelligibility scores improved with acoustic treatment for the seat furthest away from the speech source but were no different for closer seats
[f]No difference in speech intelligibility scores or subjective listening effort with acoustic treatment, but reaction times were shorter with acoustic treatment
[g]Experiences of the sound environment improved after the acoustic intervention for children in Grade 6 but not Grade 2 and 3
[h]See Table 5 in Persson Way & Karlberg [28] for specific results

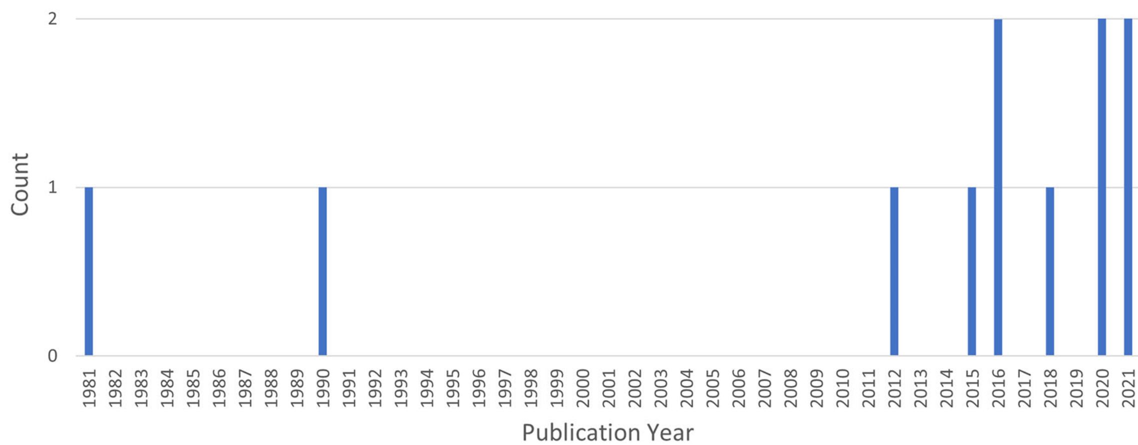

Fig. 2 Publication years of the 13 papers included in the review

Table 2 Distribution of studies by age and outcome measure

	Number of papers by age group				
Outcome	Preschool	Primary School	High school	University/Adults	Total
Speech perception (test)	0	4	1	2	7
Speech perception (questionnaire)	0	1	0	1	2
Attention	0	0	0	1	1
Reading	0	1	0	0	1
Well-being	1	1	0	0	2
Total	1	7	1	4	13

Arvidsson et al. [25] assessed adults' ratings of sound quality and attributes and ranked their preferred listening environments in auralised classrooms played over headphones with an absorbent ceiling only (reverberation time of 0.8–0.95 s), an absorbent ceiling plus absorbers (reverberation time of 0.45–0.95 s), and an absorbent ceiling plus diffusers (reverberation time of 0.5–0.75 s) (see Table 1 for changes in other acoustic parameters). Overall, an absorbent ceiling plus absorbers was preferred (which had the lowest mid-frequency reverberation times (T20), the highest C50 and the lowest G), followed by an absorbent ceiling plus diffusers, then an absorbent ceiling only. The authors suggest that C50 > 8 dB is required to obtain satisfactory sound quality.

3.5.3 Attention

Castro-Martinez et al. [26] assessed university student's performance on an objective attention test in a treated and untreated room. The reverberation time of the classroom without acoustic treatment was 2 s, and with acoustic treatment, it was 1.2 s. The authors found that students in the treated classroom performed better on measures of attention. The authors concluded that taking measures to decrease the reverberation time of classrooms positively affects students' attention.

3.5.4 Reading

Bronzaft [27] assessed the reading ability of primary school children in classrooms located next to train tracks before and after the installation of rubber pads which reduced the noise level from 89 to 81–86 dBA inside the classroom when a train was passing (there were approximately 15 trains per school day). The children's reading results were compared to children in classrooms away from the train tracks. Initially before acoustic treatment, the children in the classrooms next to the tracks performed more poorly than the children on the quieter side. However, after the acoustic treatment was installed, the children performed equally as well as the children on the quieter side.

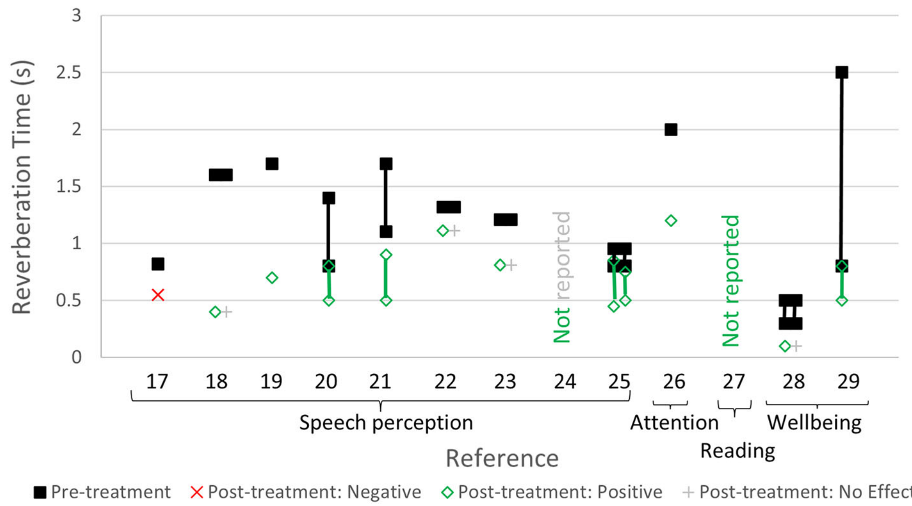

Fig. 3 Outcomes of studies according to the reverberation time change from acoustic treatment. Lines represent range of reverberation times. Numbers on the horizontal axis are the reference numbers

3.5.5 Well-being

Persson Way and Karlberg [28] assessed the effect of an acoustic intervention in preschools on children's well-being. The reverberation time of the classroom without acoustic treatment was 0.3–0.5 s, and with acoustic treatment, it was 0.1 s (see Table 1 for changes in other acoustic parameters). The authors found that the change in the internal noise levels generated by the children after the acoustic intervention was associated with a 31% reduction in children's perception of scraping and screeching sounds and a 29% reduction in the frequency of reported stomach ache as reported on a visual five-point Likert scale. The authors concluded that the effect of the acoustic intervention was perceived by the children even though there was only a 2 dB difference in noise levels.

Polewczyk and Jarosz [29] assessed the change in performance and well-being in primary school children after the installation of acoustic treatment in classrooms which reduced the reverberation times from 0.8–2.5 s to 0.5–0.8 s (see Table 1 for changes in other acoustic parameters). The authors found improvements in the children's performance (e.g. listening, concentration) and well-being (a reduction in the teachers' perceived level of children's physical and mental aggression) with the acoustic treatment.

4 Discussion

The aim of this scoping review was to synthesise research that has assessed the effectiveness of classroom acoustic treatment for improving students' listening, learning, and well-being. Thirteen papers met the criteria to be included in the review covering a range of ages and outcomes.

4.1 Main Findings

Seven of the 13 studies reported positive effects of classroom acoustic treatment on student's speech perception, attention, and well-being. Five studies reported both positive effects and no effect depending on the measure, condition, or population. The remaining study reported a negative effect of classroom acoustic treatment on children's speech perception and listening effort. Given that most studies reported positive effects of classroom acoustic treatment, acoustic treatment is likely to be a good way of altering the acoustics of classrooms to aid listening, learning, and well-being. However, care needs to be taken as it may reduce speech transmission and increase listening effort. Therefore, it is important that techniques such as modelling and auralisation are used when designing and retrofitting classrooms with acoustic treatment so that an optimal listening environment can be created.

4.2 Limitations

There are several limitations in the reviewed studies. First, let us consider the limitations of the studies assessing listening. Regarding speech perception test measures, five of the seven studies measured the effect of the acoustic treatment on speech perception in a lecture-style learning scenario [17, 19–22]. While this is an important scenario, a substantial amount of time is also spent in group work where students are listening to their peers [9, 10]. The two studies that did consider group work still had the source as the teacher standing at the front of the classroom rather than the source being the peers within the group [18, 23]. Therefore, more research is needed on this scenario. Additionally, Amlani and Russo [17], Peng et al. [20], Peng et al. [21], and Scoczynski Ribeiro et al. [22] did not incorporate noise in their studies and only examined the effect of acoustic treatment in quiet. Pekkarinen and Viljanen [19] and Visentin et al. [23] did incorporate noise in their study, however, the generated noise used was not realistic classroom noise. Astolfi et al. [18] did use classroom noise based on ~ 20 children chatting so this was realistic classroom noise, however, it was played from the middle of the classroom rather than all around the classroom. Therefore, there is a gap in understanding the effect of acoustic treatment when realistic classroom noise is present. Regarding speech perception measured via a questionnaire, a limitation is that these questionnaires can be subject to response bias, so it would have been beneficial to have also assessed speech perception via a test in these studies and compared results. Additionally, questionnaires may not be feasible or reliable methods of getting data for young children.

Regarding learning, there were only two studies that assessed this outcome, and these assessed the learning process of attention and the academic outcome of reading. Therefore, there is a large gap on how classroom acoustic treatment affects other learning outcomes and processes for students of different ages.

Regarding well-being, there were only two studies that assessed this as an outcome. The study by Polewczyk and Jarosz [29] only assessed mental and physical aggression, and the results were difficult to interpret as the authors reported that "prevalence of physical aggression during breaks was rated as "very often" or "often" by 36.4% (before) and 15.9% (after) of teachers" (pg. 414), however, Fig. 12 only has the end points of the scale marked as "always" and "never". Persson Way and Karlberg [28] assessed both emotional well-being (sad or angry reactions to sounds) and physical well-being (psychosomatic symptoms). However, this was only in preschool children and only used subjective questionnaires which may be subject to response bias.

These limitations present many opportunities for future research avenues. These are outlined in the following section.

4.3 Future Research

Avenues for future research are outlined below according to the outcomes of listening, learning, and well-being. This section finishes with general considerations relevant to each of the outcomes.

4.3.1 Listening

The nine studies returned in the search that assessed the effect of classroom acoustic treatment on students' listening all assessed speech perception. While this is an important starting point, there is a need for studies to assess higher-order listening processes such as listening comprehension and communication. According to Kiessling et al. [30], comprehending goes beyond hearing and listening. It is "the reception of information, meaning, or intent" (pg. 93). Communication is "the transfer of information, meaning, or intent between two or more people" (pg. 93). Communication requires participation. Both listening comprehension and communication skills are vital in the classroom for learning to take place, therefore, it is important that future research addresses the effect of classroom acoustic treatment on these skills to find the optimal acoustic conditions needed and how to achieve them.

4.3.2 Learning

The only two papers assessing learning that were found in the scoping review assessed the learning process of attention and the academic outcome of reading. Therefore, there is a need for research on other cognitive processes such as memory, and learning outcomes such as literacy and numeracy performance. There is also a need for studies on learning behaviours such as motivation and persistence. As classrooms are the primary environment that learning takes place in, it is of great importance that we understand how classroom acoustic treatment may be able to enhance learning outcomes.

4.3.3 Well-being

Both of the studies on the effect of classroom acoustic treatment on well-being used subjective measures of well-being which can be subject to response biases. Therefore, there is a need for studies to use objective physiological measures. For example, cortisol levels that measure stress levels could be a potential physiological measure that could be used. Additionally, there is a need to expand on emotional well-being in future studies to also include mental health such as anxiety and depression which is a growing and very current area of concern.

4.3.4 General Considerations

There are several considerations that need to be taken into account when assessing the effect of classroom acoustic treatment on all of the above outcomes. These include the types of acoustic treatments used, the acoustic parameters assessed, the classrooms activities undertaken, the age of the learners, and the capabilities of the students.

Regarding the types of acoustic treatment, variables such as the material, thickness, sound absorption properties (such as the noise reduction coefficient (NRC)), and whether it is an absorber or diffuser and at what frequencies are all important to consider. Additionally, the effect of placement of the treatment such as on the ceiling, walls, or other places, and how much of the surfaces are covered are also important to evaluate. Techniques such as modelling and auralisation can be used when designing or retrofitting classrooms with acoustic treatment so that an optimal listening environment can be created. These techniques are often used by acoustic engineers in the industry, so it would be beneficial for these findings to also be published in the academic literature, and for research studies to be conducted in collaboration with acoustic engineers and a multidisciplinary research team to determine how the classroom listening environment affects children's learning and well-being.

When assessing the acoustic effect of the acoustic treatment, it is important that different types of acoustic parameters are measured such as the reverberation time over different frequencies, EDT, C50, D50, U50, G, and STI. Assessing the impact of differences in these parameters may provide helpful insights into what acoustic conditions are needed to aid listening, learning, and well-being.

It is also essential that the effect of acoustic treatment on a range of classroom activities is assessed. The three main classroom activities are lecture, group work, and independent work, so it is important to understand what acoustic treatment is best for each of these activities. It is also essential that the acoustic conditions, such as noise that is present in these activities, are as realistic as possible.

Additionally, it is vital that the full age range of learners is assessed, from preschool children to adult learners. It is likely that the acoustic conditions needed will vary across the age-span as children develop neurologically. For example, children's speech perception improves as they get older and does not reach adult-like performance in noise and reverberation until the late-teenage years [31]. Therefore, younger children may need more favourable classroom acoustic conditions than older children and adults.

Finally, it is important that future research assesses the effect of classroom acoustic treatment on students with special educational needs. All studies in the scoping review assessed students typically found in mainstream classrooms so it is assumed that the majority of these students were typically developing. Specific studies on students with special educational needs are needed. This includes students with hearing loss who have poorer speech perception in noise than their typically hearing peers [32], students who are non-native listeners who have poorer listening comprehension than native listeners [33], and students with autism spectrum disorder who exhibit more repetitive behaviours in noisy classrooms compared to quiet classrooms [34],

5 Conclusions

This scoping review found that the effect of classroom acoustic treatment such as ceiling and/or wall absorbers/diffusers on sound and reverberation in the room can help students' speech perception, attention, reading, and well-being. However, it is important to consider how the acoustic treatment affects the speech transmission index as more absorption in a classroom may result in lower speech transmission and increased listening effort. As only 13 studies were found in this review, there are many avenues for future research to better understand the effect of classroom acoustic treatment on a broader range of listening, learning, and well-being outcomes and how acoustic treatment can be implemented to improve these outcomes.

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