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Review Article

Systematic Review of Literature on Speech Intelligibility and Classroom Acoustics in Elementary Schools

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ABSTRACT

Purpose: Good verbal signals and low background noise are key factors for all children to maximize understanding of what is being taught. Classroom shape, surroundings, and even furnishings change how the environment "sounds" and how speech is "heard" in the classroom. Classroom acoustics is perhaps one of the most important, but often least considered, factors when designing a classroom. This systematic review aimed to characterize the relationship between intelligibility of speech and room acoustics in elementary schools based on the available evidence.
Method: Eligible studies were identified using two computerized databases: PubMed and Scopus. In total, 23 publications met our inclusion criteria: (a) Participants must have been from elementary schools, (b) acoustic characterization of the classroom must have been provided, (c) intelligibility tests must have been performed, and (d) articles were written in English.
Results: After identifying the parameters and tests used to quantify the intelligibility of speech, the speech intelligibility scores were analyzed in relation with acoustical parameters found in the articles, particularly signal-to-noise ratio and speech transmission index. Our results highlighted the negative effect on intelligibility associated with poor transmission of the speech and poor classroom acoustics caused by long reverberation times and high background noise.
Conclusion: Good classroom acoustics is needed to improve speech intelligibility and, therefore, increase children's academic success.

Good verbal signals and low background noise are key factors for all children in order to maximize understanding of what is being taught. Classroom shape, surroundings, and even furnishings change how sound "sounds" and how speech is "heard" in the classroom. Although, classrooms should be designed to facilitate children in understanding speech, discriminating words, and recalling information, when classroom acoustics is not ideal, children may have difficulty with reading, spelling, paying attention during the lesson, and concentrating (Shield et al., 2015). Poor classroom acoustics may also impact children's behavior (Shield et al., 2015). It is estimated that children spend 45%–65% of their day at school listening; therefore, it is essential that they can hear and understand their teacher and classmates' speech (Rosenberg et al., 1999). Speech intelligibility, that is, the amount of speech that is understood by the listener (International Organization for Standardization [ISO], 2003), is affected by several factors including the level and characteristics of background noise and/or other competing speakers and the acoustical features of the room, particularly the reverberation time (RT; Bradley, 1986).

Noise in classrooms can be attributed to various sources such as outside noise; noise from building services such as heating, light, and ventilation; noise from technology;

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and noise from the children, which is considered the most disturbing (Astolfi et al., 2012). Noise in the classroom negatively impacts children's speech perception and, as a consequence, their academic achievement (Crandell & Smaldino, 2000; Klatte et al., 2010; Maxwell & Evans, 2000). It is also important to underline that even though young children are more impacted by noise than older students and adults (Johnson, 2000), they are also the student group generating the highest level of noise (Jamieson et al., 2004).

Speech intelligibility also depends on the acoustical features of the room, particularly the RT, and the quality of speech transmission in the room described by acoustical parameters such as speech transmission index (STI) and signal-to-noise ratio (SNR). RT is defined as the time required for a steady-state sound pressure level in an enclosed space to decay by 60 dB, measured from the moment the sound source is switched off (ISO, 2008). RT can impede speech perception by creating a sound tail that masks important cues for speech understanding such as duration and rhythm (Lecumberri et al., 2010). Typical values for the classroom setting range from 0.4 to 1.2 s (Crandell & Smaldino, 2000); however, the American National Standards Institute (ANSI, 2010, ANSI/ASA S12.60) suggests an RT of 0.6 s in unoccupied classrooms. Longer RTs would result in degraded speech signals (Dockrell & Shield, 2006). STI measures the transmission quality of the speech signal, and it has been shown to be a good predictor of room acoustics, reverberation, and additive noise (Steeneken & Houtgast, 1980, 1982). According to the International Electrotechnical Commission (IEC, 2020), STI values between 0.75 and 1 are considered excellent, followed by good (0.6–0.75), fair (0.45–0.6), poor (0.3–0.45), and bad (0–0.3). The difference between the level of speech and the level of background noise in the classroom can be quantified with SNR. When the noise level exceeds the signal level, important linguistic information is masked, leading to a negative correlation between high SNR values and speech intelligibility and academic performance (Caviola et al., 2021; Connolly et al., 2019; Picard & Bradley, 2001; Prodi, Visentin, Borella, et al., 2019; Rudner et al., 2018). The typical SNR present in a classroom environment has been reported to vary between −7 and +5 dB (Crandell & Smaldino, 2000). To ensure that children benefit from optimal speech understanding, the literature suggests an SNR of +15 dB throughout the classroom (American Speech-Language-Hearing Association, 2005). Good classroom acoustical design is critical to enabling children to receive an appropriate education. An unfavorable acoustic environment interferes with the transmission of a clear signal, preventing children from receiving accurate information and thus negatively impacting their understanding and academic performance (Flexer, 2004). The architectural features that should be taken into account in a classroom design include (a) the shape and the volume of the room avoiding curved or too long, narrow, or high spaces to prevent concentration of sound; (b) furniture placement and the use of appropriate absorbing materials to decrease noise, unwanted reflections, and echo especially in the ceiling and in the back of the room; (c) appropriate choice of window and door frames to reduce the discomfort from external noise; and (d) HVAC systems designed to limit the production of excessive noise.

Assessing speech intelligibility in elementary school is challenging in many aspects. It is critical to use a test that includes vocabulary and response modalities appropriate for children (Cienkowski et al., 2009). Among the studies analyzed in this systematic review, commonly used tests to assess speech intelligibility among children include the Word Intelligibility by Picture Identification (WIPI; Ross & Lerman, 1970) Test, the Test for Reception of Grammar (TROG; Bishop, 2013), and the Diagnostic Rhyme Test (DRT; ANSI S3.2-1960; ANSI, 1960). In addition, the Chinese Word Recognition Test (Standardization Administration of China, 1985; Standardization of Ministry of Electronics and Industry, 1984) is used to assess speech intelligibility for young native Chinese speakers. The WIPI Test evaluates the ability of children, between 5 and 11 years old, to identify speech (Ross & Lerman, 1970). The test is made of four 25-item word lists and two lists of foil items. After hearing the cue word, the child can choose the item among six pictures (Ross & Lerman, 1970). The TROG Version 2 assesses the understanding of grammatical contrasts for children ages 4 to 18+ years. After presenting the stimulus, children can choose between four pictures with lexical and grammatical foils (Bishop, 2013). The DRT is an ANSI standard test to evaluate speech intelligibility (ANSI S3.2-1960; ANSI, 1960). Upon hearing the stimulus, children are asked to choose between two pictures that differ only in their initial consonant (Greenspan et al., 1998). The Chinese Word Recognition Test is made of 25 five-word rows. The words are monosyllabic and similar sounding (Peng et al., 2015). For the DRT and the Chinese Word Recognition Test, the age range for which the tests are intended is not clearly specified. To administer the test, researchers choose vocabulary appropriate for the participants involved in their research.

To date, there has not yet been a systematic review of the literature concerning the relationship between speech intelligibility and classroom acoustics for elementary children. The goal of this systematic review is to synthesize the findings of previous studies that connect speech intelligibility data collected in elementary classrooms with the acoustical parameters of the classrooms in order to determine the effects of noise and classroom acoustics on speech intelligibility. We expect a gap in children's performance according to their age as the ability to recognize degraded speech increases linearly until the age of 10 years due to limited development of the necessary auditory recognition skills (Corbin et al., 2016; Eisenberg et al., 2000; Flaherty et al., 2021; Leibold & Buss, 2013). For this reason, it is crucial to investigate acoustics, especially in elementary school classrooms, since evidence has shown that classroom sound quality is often unsuitable for learning (Mealings, 2016).

Method

Literature Search

Eligible studies were identified through a search in two databases: Scopus (Elsevier), which provided studies in a time range between 1956 and March 2020, and PubMed/MEDLINE (National Library of Medicine), which covered articles from 1971 to March 2020. The same search string was used for both databases: (School OR classroom OR teach*) AND (Acoustics OR Noise OR Reverberation) AND (Speech AND Intelligibility OR comprehension OR perception OR reception threshold). The databases were consulted in April 2020. The inclusion criteria consisted of studies on speech intelligibility performed in elementary schools and a description of acoustic characterization of the classroom and intelligibility tests administered to the children.

Publication Selection

The bibliography that emerged from the databases after the removal of duplicates included 5,587 studies. As a second step, the authors screened titles and abstracts based on the following eligibility criteria: (a) The participants in the study had to be elementary school children, (b) the acoustic characterization of the classroom had to be described, (c) the children had to have performed an intelligibility test in a classroom whose description and scores were reported in the article, and (d) the article had to be written in English. The application of the eligibility criteria to the titles and abstracts led to a total of 32 articles. Articles were excluded because they presented research on a topic different from the scope of this review, or because the experiments were conducted outside the classroom environment, or a wider age range was analyzed without reporting the results grouped by age. After a review of the full-text articles by two of the authors, we excluded four articles because no intelligibility tests were performed, one article because no acoustic measurements were performed, and three others because the measurement was conducted in university classrooms. Therefore, there were 23 full-text articles included in the qualitative assessment. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2009 flow diagram in Figure 1 shows the process of literature search regarding intelligibility in elementary schools.

Data Extraction

Table 1 shows the extracted data from all the 23 full-text articles included. The data extracted were authors and titles, year of publication of the journal article, the country where the study was conducted, and the language used to perform the intelligibility test.

In addition, Table 2 shows data about sample size (in terms of either participants or classrooms), the number of participants divided by gender and the average age of the participants or the grades from which they belonged, and the parameters to define speech intelligibility in classrooms. These definitions concern (a) the objective parameters used to characterize classroom acoustics and speech transmissions, such as noise level (n = 23), STI (n = 5), SNR (n = 15), and RT (n = 17), and (b) the list of different tests performed by children to obtain the intelligibility score, such as the WIPI Test (n = 5), the TROG (n = 1), the DRT (n = 2), and the Chinese Word Recognition Test (GB 4959/SJ2467-84; n = 5). Two of the authors collected the data for Tables 1 and 2.

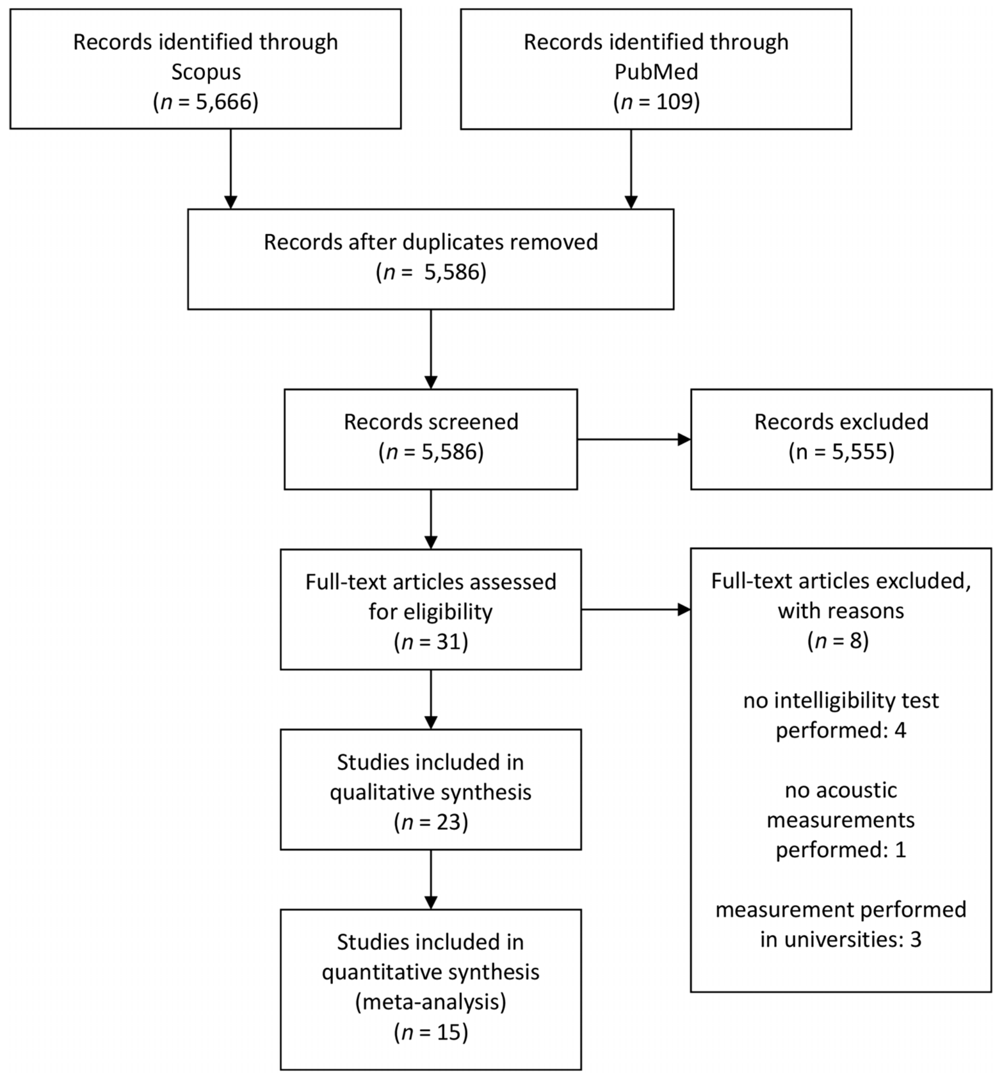
Article Quality Assessment

To assess the validity of the selected studies, two of the authors individually used the Quality Assessment Tool for Quantitative Studies (Moher et al., 2009) to evaluate the merit of the selected studies. The assessment is divided into eight categories: (a) selection bias, (b) study design, (c) confounders, (d) blinding, (e) data collection methods, (f) withdrawals and dropouts, (g) intervention integrity, and (h) analysis appropriate to questions. Each category receives a score of 1 (*strong*), 2 (*moderate*), or 3 (*weak*) to indicate the strength of quality. Our analyses only included scores from the first six categories (1–6) to calculate an overall quality score. The overall quality score was computed by the number of "weak" ratings obtained in the various categories. Studies were rated as "strong" if none of the categories were rated as "weak," they were considered "moderate" if only one category was rated as "weak," and they were considered "weak" if two or more categories were rated as "weak." During the individual evaluation, the agreement between the two authors was 91.7%. Then, the two authors compared and discussed the quality of the articles to validate the scores, based on the methodology described above, and reached 100% agreement.

Meta-Analysis

A random-effects meta-analysis was performed to combine results from different articles grouped by factors of interest. The intelligibility scores were grouped by grade level, SNR, RT, and STI. Only 15 of the 23 articles showed the results of intelligibility tests as a function of age and speech parameters and were therefore included in the meta-analysis. All the analyses were conducted using the software R 3.6.0

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2009 flow diagram of search and selection of articles for review.



where a linear model was built in order to describe the relationship between intelligibility scores and the acoustic parameters.

Results

In this review, 23 full-text articles were evaluated: All publications, except one (Bovo & Callegari, 2009), measured speech intelligibility with a one-time survey study design. In these studies, a test was administered, and the intelligibility scores were evaluated against the acoustic parameters of the classrooms. As shown in Table 2, the sample size for each study varied widely from 22 children to 983 for a total of 5,315 participants plus 43 classes, for which the number of children was not specified. The age of the children included only elementary school children, ranging from 5 to 12 years.

Definition of Intelligibility

To measure speech intelligibility, the authors of the studies used two factors: (a) the measurement of acoustic parameters in classrooms and (b) the administration of intelligibility tests to children. Regarding the acoustic parameters, the effect of noise on intelligibility has been studied in all 23 articles. A variety of noise sources were used in the studies: natural noise coming from outside (e.g., car, airplane, or railway traffic) or from inside the building (e.g., ventilation or heating), teaching aids (e.g., computers), and artificially created noise to generate different listening conditions during tests (e.g., babble noise, activity noise, speech-shaped noise), which simulate the noise caused by children during lessons. In addition, noise was used in 14 cases to calculate the SNR (Bovo & Callegari, 2009; Bradley & Sato, 2004, 2008; Houtgast, 1981; Jamieson

Table 1. Identification of the studies by ID, title, author, year, country of publication, and language of the intelligibility test.

ID	Title	Author	Year	Country	Test language
20	The effect of ambient noise on speech intelligibility in classrooms	T. Houtgast	1981	Netherlands	Dutch
53	Speech recognition in noise and reverberation by school-age children	W. S. Yacullo & D. B. Hawkins	1987	United States	English
8	Speech recognition by grades 1, 3 and 6 children in classroom	J. S. Bradley & H. Sato	2004	Canada	English
24	Speech intelligibility of young school-aged children in the presence of real-life classroom noise	D. G. Jamieson, G. Kranjc, K. Yu, & W. E. Hodgetts	2004	Canada	English
15	Acoustical barriers in classrooms: The impact of noise on performance in the classroom	J. E. Dockrell & B. M. Shield	2006	United Kingdom	English
9	The intelligibility of speech in elementary school classrooms	J. S. Bradley & H. Sato	2008	Canada	English
6	Effects of classroom noise on the speech perception of bilingual children learning in their second language: Preliminary results	R. Bovo & E. Callegari	2009	Italy	Italian
54	Effects of room acoustics on the intelligibility of speech in classrooms for young children	W. Yang & J. S. Bradley	2009	Canada	English
27	Effects of classroom acoustics on performance and well-being in elementary school children: A field study	M. Klatte, J. Hellbrück, J. Seidel, & P. Leistner	2010	Germany	Dutch
4	Subjective and objective speech intelligibility investigations in primary school classrooms	A. Astolfi, P. Bottalico, & G. Barbato	2012	Italy	Italian
50	Experimental investigation of the effects of the acoustic conditions in a simulated classroom on speech recognition and learning in children	D. L. Valente, H. M. Plevinsky, J. M. Franco, E. C. Heinrichs-Graham, & D. E. Lewis	2012	United States	English
39	On the perception of speech in primary school classrooms: Ranking of noise interference and of age influence	N. Prodi, C. Visentin, & A. Feletti	2013	Italy	Italian
51	Using personal response systems to assess speech perception within the classroom: An approach to determine the efficacy of sound field amplification in primary school classrooms	D. A. Vickers, B. C. Backus, N. K. Macdonald, N. K. Rostamzadeh, N. K. Mason, R. Pandya, J. E. Marriage, & M. H. Mahon	2013	United Kingdom	English
42	Effect of classroom acoustics on the speech intelligibility of students	A. T. V. Rabelo, J. N. Santos, R. C. Oliveira, & M. D. C. Magalhães	2014	Brazil	Portuguese
34	Chinese speech intelligibility and its relationship with the speech transmission index for children in elementary school classrooms	J. Peng, N. Yan, & D. Wang	2015	China	Chinese
31	The development of the Mealings, Demuth, Dillon, and Buchholz Classroom Speech Perception Test	K. T. Mealings, K. Demuth, J. Buchholz, & H. Dillon	2015	Australia	English
36	Effect of different types of noises on Chinese speech intelligibility of children in elementary school classrooms	J. Peng, H. Zhang, & N. Yan	2016	China	Chinese
35	Investigation of Chinese word recognition scores of children in primary school classroom with different speech sound pressure levels	J. Peng, C. Wang, P. Jiang, & S. K. Lau	2016	China	Chinese
37	Chinese speech intelligibility of children in noisy and reverberant environments	J. Peng & S. Wu	2018	China	Chinese
46	Is children's listening effort in background noise influenced by the speaker's voice quality?	B. Sahlén, M. Haake, H. von Lochow, L. Holm, T. Kastberg, K. J. Brännström, & V. Lyberg-Åhlander	2018	Sweden	Swedish
45	Listening comprehension and listening effort in the primary school classroom	M. Rudner, V. Lyberg-Åhlander, J. Brännström, J. Nirme, M. K. Pichora-Fuller, & B. Sahlén	2018	Sweden	Swedish
41	Investigating listening effort in classrooms for 5- to 7-year-old children	N. Prodi, C. Visentin, A. Peretti, J. Griguolo, & G. B. Bartolucci	2019	Italy	Italian
33	A virtual speaker in noisy classroom conditions: Supporting or disrupting children's listening comprehension?	J. Nirme, M. Haake, V. Lyberg Åhlander, J. Brännström, & B. Sahlén	2019	Sweden	Swedish

Table 2. Description of the sample size for each study and list of the acoustic parameters and tests used to define speech intelligibility.

	Participants			Definitions	
ID	Sample size	Gender	Mean age	Acoustic parameters	Tests
20	270	Not specified	Not specified; range of 7–12 years old	Reverberation time (RT), road traffic noise, signal-to-noise ratio (SNR)	CVC words—Articulation Loss of Consonant
53	32	13 males; 19 females	9 years 3 months	RT, SNR, 12-talker babble	Speech stimuli from sentence material by Blair
8	43 classrooms	Not specified	Not specified; Grades 1, 3, and 6	RT, C_{50}, SNR, noise level (NL)	The Word Intelligibility by Picture Identification (WIPI) Test
24	40	Not specified	Not specified; range of kindergarten–Grade 3 (5–8 years)	NL, SNR	Sixty words (24 monosyllables, 12 spondees, 12 trochees, 12 trisyllables)
15	158	67 males; 91 females	8 years 6 months	Children's babble noise, NL	Verbal tasks, arithmetic, nonverbal tasks
9	388	Not specified	Not specified; Grades 1, 3, and 6 (6, 8, and 11 years)	SNR, C_{50}, early decay time (EDT), RT, NL	WIPI Test
6	21	14 males; 7 females	8 years 6 months	SNR to obtain 50% intelligibility (speech reception threshold), NL	List of Italian words
54	234	Not specified	Not specified; 77 Grade 1, 75 Grade 3, 65 Grade 6, and 17 adults	RT, SNR, C_{50}, NL	WIPI Test
27	398	197 males; 201 females	8 years 6 months	RT, SNR, NL	Phonological processing task, questionnaire
4	983	Not specified	Not specified; range of Grades 2–5 (7–10 years)	RT, STI, EDT, C_{50}, 3 conditions of noise	Diagnostic Rhyme Test (DRT)
50	90	Gender not specified—50 children; 40 adults	Children 8–12 years; adults 25–75 years	RT, NL, SNR, EDT, C_{50}	Sentence recognition task: 50 meaningful sentences + 18 comprehension questions
39	822	Not specified	Not specified; ages 6–10 years	3 types of noises (babble and activity, tapping, traffic), RT, speech transmission index (STI)	WIPI Test, DRT
51	44	24 males; 20 females	Not specified; Grades 2 and 3	RT, sound-field amplification, NL	Chear Auditory Perception Test
42	273	123 males; 150 females	9 years 4 months	Equivalent sound pressure level (Leq), T30, STI	Adapted speech recognition percentage index test
34	480	Not specified	Not specified; Grades 2, 4, and 6	STI, EDT, RT, C_{50}, speech-shaped noise, SNR	Chinese rhyme test word list
31	22	9 males; 13 females	Not specified; kindergarten students	NL	Online 4-picture choice speech perception task
36	60	Not specified	Not specified; Grades 2, 4, and 6	RT, EDT, C_{50}, C_{80}, SNR, and 5 noise conditions (traffic noise, fan noise, babble noise, Chinese speech-shaped noise)	Mandarin Chinese test word list
35	30	Not specified	Not specified; Grades 3 and 5	RT, NL, speech sound pressure level, BNL, SNR	Mandarin Chinese test word list
37	480	Not specified	Not specified; Grades 2, 4, and 6	Speech-shaped noise, RT, BNL, SNR	Chinese rhyme test word list
46	93	41 males; 52 females	8 years 8 months	NL, response time	Test for Reception of Grammar
45	245	117 males; 128 females	Not specified; all 8 years	SNR, babble noise	Passage comprehension module of the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4), Wechsler Intelligence Scale for Children
41	117	Not specified	Not specified; range of 5–7 years	RT, Laeq, STI	WIPI Test
33	55	21 males; 34 females	8 years 6 months	Mode of presentation (audio-only, audiovisual), auditory setting (quiet, multitalker babble noise)	CELF-4

Note. CVC = consonant–vowel–consonant; BNL = background noise level.

et al., 2004; Klatte et al., 2010; Peng, Wang, et al., 2016; Peng & Wu, 2018; Peng et al., 2015; Peng, Zhang, & Yan, 2016; Prodi, Visentin, Peretti, et al., 2019; Valente et al., 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). The RT was calculated in 16 out of the 23 studies to verify the influence of classroom characteristics on intelligibility (Astolfi et al., 2012; Bradley & Sato, 2004, 2008; Houtgast, 1981; Klatte et al., 2010; Peng, Wang, et al., 2016; Peng & Wu, 2018; Peng et al., 2015; Peng, Zhang, & Yan, 2016; Prodi et al., 2013; Prodi, Visentin, Peretti, et al., 2019; Rabelo et al., 2014; Valente et al., 2012; Vickers et al., 2013; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). Regarding the intelligibility tests, mainly three tests were carried out: the WIPI Test (five studies: Bradley & Sato, 2004, 2008; Prodi et al., 2013; Prodi, Visentin, Peretti, et al., 2019; Yang & Bradley, 2009), the DRT (two studies: Astolfi et al., 2012; Prodi et al., 2013), and the Chinese Word Recognition Test (for Chinese language; four studies: Peng, Wang, et al., 2016; Peng & Wu, 2018; Peng et al., 2015; Peng, Zhang, & Yan, 2016). A complete list of all the intelligibility tests used in the studies is provided in Table 2.

Intelligibility and Acoustics

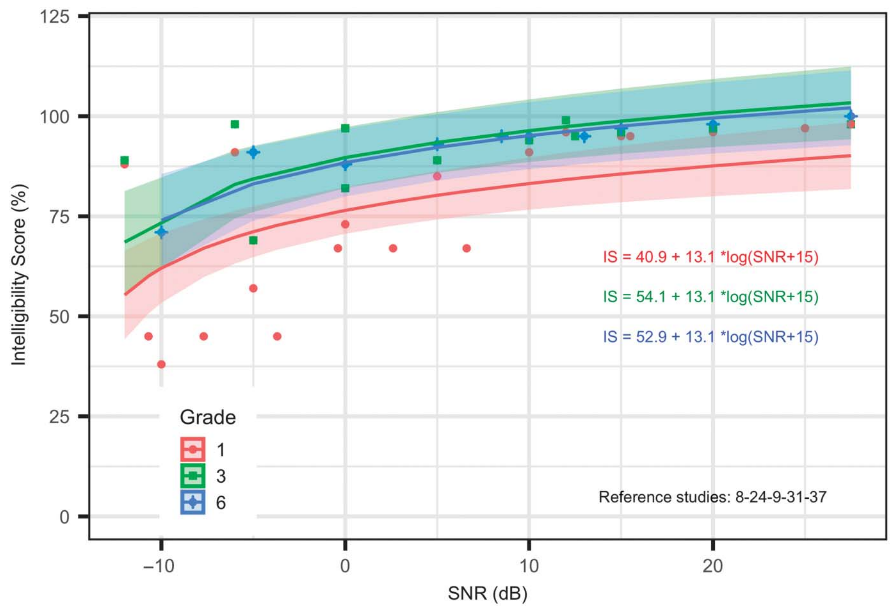
Fifteen studies demonstrated the results of intelligibility tests as a function of speech parameters; this is the reason why they were selected for the meta-analysis. Ten studies reported the relationship between SNR and the percentage of the intelligibility score (Bradley & Sato, 2004, 2008; Jamieson et al., 2004; Mealings et al., 2015; Peng, Wang, et al., 2016; Peng & Wu, 2018; Peng, Zhang, & Yan, 2016; Prodi et al., 2013; Valente et al., 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). The remaining five described intelligibility as percent-correct scores compared to the STI (Astolfi et al., 2012; Peng et al., 2015; Prodi, Visentin, Peretti, et al., 2019; Rabelo et al., 2014). The following tables report the values collected from the studies, whereas the figures show the regressions resulting from the model applied to the data. Five studies presented the results of the intelligibility score as a function of SNR (see Table 3). The analyses were carried out based on grade level. In order to consider the situation at the beginning, halfway through, and at the end of elementary school, Grades 1, 3, and 6 were taken into account. The choice to analyze different grade levels stems from studies showing a different development in children's speech recognition performance, which increases linearly until they reach 10 years of age (Corbin et al., 2016; Flaherty et al., 2021; Leibold & Buss, 2013). To build the graph (see Figure 2), +15 was added to the logarithmic function in order to shift the curve for all the results to be positive. This mathematical transformation was needed because the logarithm of a negative number is not defined in the real numbers. Because first graders have been in school for fewer years, it is expected that on equal SNR conditions, they will have lower speech intelligibility performance compared to third and sixth graders. The ability to develop auditory recognition to identify spectrally degraded speech takes more than 7 years because of limited linguistic and cognitive knowledge due to limited experience (Eisenberg et al., 2000).

Table 3. Database association between intelligibility score and signal-to-noise ratio (SNR).

		Parameters	
Study ID	Grade	SNR (dBA)	Intelligibility score (%)
8	1	15.50	95
		27.5	98
	3	12.50	95
		27.5	98
	6	8.50	95
		27.50	100
24	1	Quiet	96
		0.00	97
		−6.00	91
		−12.00	88
	3	Quiet	99
		0.00	97
		−6.00	98
		−12.00	89
9	1	−10	38
		−5	57
		0	73
		5	85
		10	91
		15	95
		20	96
		25	97
	3	−5.00	69
		0.00	82
		5.00	89
		10.00	94
		15.00	96
		20.00	97
	6	−10.00	71
		−5.00	91
		0.00	88
		5.00	93
		10.00	95
		15.00	97
		20.00	98
31	1	6.60	67
		2.60	67
		−0.40	67
		−3.70	45
		−7.70	45
		−10.70	45
37	6	13.00	95

The association between SNR and the intelligibility of speech as a percent-correct score is shown in Figure 2, comparing first, third, and sixth grades (Bradley & Sato, 2004, 2008; Jamieson et al., 2004; Mealings et al., 2015; Peng & Wu, 2018). Grade 1 had the lowest intelligibility scores compared to Grades 3 and 6 at equal SNR. Even with high SNR values, Grade 1 children did not reach 100% intelligibility. The other groups of children (Grades 3 and 6) showed similar trends of intelligibility versus SNR. Positive SNR led to intelligibility higher than 90% and reached 100% at 20 dB of SNR.

Figure 2. Linear model between signal-to-noise ratio (SNR) and the intelligibility of speech as a percent-correct score (intelligibility score [IS]) calculated with the intelligibility tests, grouped by grade (Grades 1, 3, and 6). The 95% confidence interval is represented by the shaded regions. Reference Study ID: 8, 24, 9, 31, 37.



Five studies presented the results of the intelligibility score reporting the SNR and RT measurements (see Table 4; Peng, Wang, et al., 2016; Peng, Zhang, & Yan, 2016; Valente et al., 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). Three studies showed that both SNR and RT were alternately varied to assess the variations on the intelligibility score (Valente et al., 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). Another study showed that the intelligibility score was measured as a function of two RTs without variation of SNR (Peng, Zhang, & Yan, 2016). Finally, one study reported the values of SNR and RT needed to reach 95% of the intelligibility score (Peng, Wang, et al., 2016).

A threshold value of 0.61, the standard value indicated for classrooms (ANSI, 2010), was used to divide the cases. RTs within the standard recommendation were classified as "within the limit." RTs higher than the standard recommendation were classified as "above the limit." RTs above the standard limits correspond to lower intelligibility scores. In Figure 3, the relationship between the SNR and the intelligibility score is grouped by classrooms with RTs within and above the threshold value of 0.61 (Peng, Wang, et al., 2016; Peng, Zhang, & Yan, 2016; Valente et al., 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). With RTs above the limit, the model showed that an intelligibility score of 100% is not achieved even with high SNR values. It also showed that values above 90% are achievable with SNR above 15 dB regardless of RT. For shorter RTs, the model showed that intelligibility exceeds 90% from SNR equal to 2 dB and reaches 100% with values above 16 dB. The last five studies considered in the meta-analysis expressed the score of intelligibility according to the STI (see Table 5). In this case, the results were grouped because the studies analyzed different grades. Figure 4 shows the association between the percentage of intelligibility scores and the STI. Intelligibility scores greater than 90% are achieved with STI values greater than 0.56 (Astolfi et al., 2012; Peng et al., 2015; Prodi, Visentin, Peretti, et al., 2019; Rabelo et al., 2014).

Article Quality Assessment

The 23 articles selected for quality assessment were independently evaluated by two of the authors using the Effective Public Health Practice Project Quality Assessment Tool for Quantitative Studies criteria. After a discussion about disagreements on two articles between the two authors who performed the quality assessment, all articles were assessed as "weak." This was mainly because, except for one article designed as a case–control study, 22 articles had a study design of a one-time survey. Participants were generally described as having normal hearing. Additionally, blinding for examiners and participants was not described, which made the confounders and blinding sections "weak."

Discussion

This review highlighted the strong correlation between the classroom acoustical environment and speech intelligibility.

Table 4. Database association between intelligibility score, signal-to-noise ratio (SNR), and reverberation time.

Study ID	Parameters		
	SNR (dBA)	Intelligibility score (%)	Reverberation time (s)
53	6.0	85.4	0.04
	2.0	50.5	0.04
	6.0	36.8	0.80
	2.0	16.9	0.80
54	−5	78	0.30
	−2	81	0.60
	0	82	0.90
	2	82	1.20
	−7	76	Direct sound (0.00 s)
	−1	86	Direct sound + early reflections (0.05 s)
	−2	87	0.30
	−2	75	0.90
	−2	75	1.20
50	7	95.5	1.50
	10	98.3	1.50
	7	97.5	0.60
	10	99.2	0.60
	7	95.5	1.50
	10	98.3	1.50
	7	98.7	0.60
	10	100.0	0.60
36	10	90	0.83
	10	80	1.30
35	11.8	95	0.46
	23.2	95	0.46
	16.2	95	0.46
	15.8	95	0.46
	12.8	95	0.46
	21.0	95	0.81
	21.7	95	0.81
	21.0	95	0.81
	20.6	95	0.81
	17.6	95	0.81
	27.4	95	1.30
	27.0	95	1.30
	24.0	95	1.30
	8.70	95	0.46
	4.70	95	0.46
	4.30	95	0.46
	1.30	95	0.46
	10.0	95	0.81
	17.1	95	0.81
	16.7	95	0.81
	13.7	95	0.81
	15.4	95	1.30
	20.0	95	1.30
	25.1	95	1.30
	24.7	95	1.30
	21.7	95	1.30

All of the studies under investigation quantified speech intelligibility by administering intelligibility tests and measuring classroom acoustic parameters. Mainly three tests were administrated to assess speech intelligibility in classrooms: the WIPI Test, the DRT, and the Chinese Word Recognition Test. Regarding room acoustics, the parameter common to all studies was background noise from both natural and artificial sources, together with RT. In the majority of the studies, the intelligibility scores were expressed as functions of the objective parameters SNR and STI. These two parameters have been confirmed to be good predictors of speech intelligibility since the SNR considers the intensity of the speech compared with the intensity of the background noise (Crandell & Smaldino, 2000) and STI includes SNR and classroom acoustics (Steeneken & Houtgast, 1980, 1982).

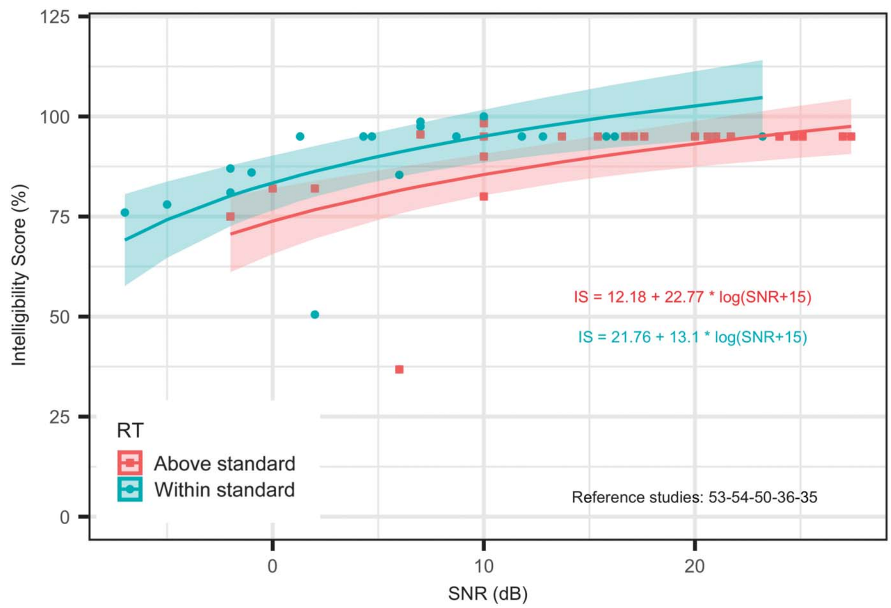
As shown in previous studies, speech intelligibility increased as children's age increased (Corbin et al., 2016; Flaherty et al., 2021; Leibold & Buss, 2013). This was expected, as previous literature has reported that young children are more impacted by noise than older students and adults (Jamieson et al., 2004). With the development of the auditory cortex, children between 6 years of age and adolescence mature in their ability to listen under different conditions (Werner, 2007). However, they are not as consistent as adults in categorizing speech sounds, especially in the presence of noise and high RT, which can cause masking or distortion of acoustic cues. The evaluation of the studies in this review further highlighted this conclusion. First-grade children did not achieve 100% intelligibility scores even in the presence of high SNR. The results between Grades 3 and 6 highlighted a similar trend reaching a 100% intelligibility score starting from 20 dB of SNR. This result is also accentuated by the fact that first graders have spent fewer years in school, so their performance is lower because of the restricted linguistic and cognitive knowledge they have acquired (Eisenberg et al., 2000).

Although RT was calculated in 16 studies, the relationship with intelligibility test scores was not calculated in most cases. However, five studies (Peng, Wang, et al., 2016; Peng, Zhang, & Yan, 2016; Valente et al., 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009) showed that long RTs (above the recommended value of 0.6 s) do not allow a 100% intelligibility score, which is instead reached with an SNR of 15 dB in the case of short RTs. Although previous literature reported that SNR typically ranges between −7 and +5 dB in school environments (Crandell & Smaldino, 2000), long RTs are a degrading condition that requires higher SNR levels, especially considering that typical values of RT in classrooms can reach 1.2 s (Crandell & Smaldino, 2000).

Finally, although according to the IEC (2020) that values of STI between 0.45 and 0.6 are considered "fair," the studies included in this review demonstrated that a high intelligibility score (e.g., 90%) can be reached with STI as low as 0.56. On the other hand, values lower than 70% of intelligibility score are reached for STI values lower than 0.10 rated as "bad" by the standard (IEC, 2020). Unfortunately, only five studies reported intelligibility scores as a function of STI, limiting the accuracy of the reported relationship.

It should be taken into consideration the different nature of the languages used for the intelligibility tests.

Figure 3. Linear model between the signal-to-noise ratio (SNR) and the percentage of the intelligibility score (IS), grouped according to reverberation time (RT). The threshold to divide the RTs is 0.61 s, the standard value indicated for classrooms (ANSI, 2010). Values lower than 0.61 are "within the standard." The 95% confidence interval is represented by the shaded regions. Reference Study ID: 53, 54, 50, 36, 35. T_{30} = reverberation time.



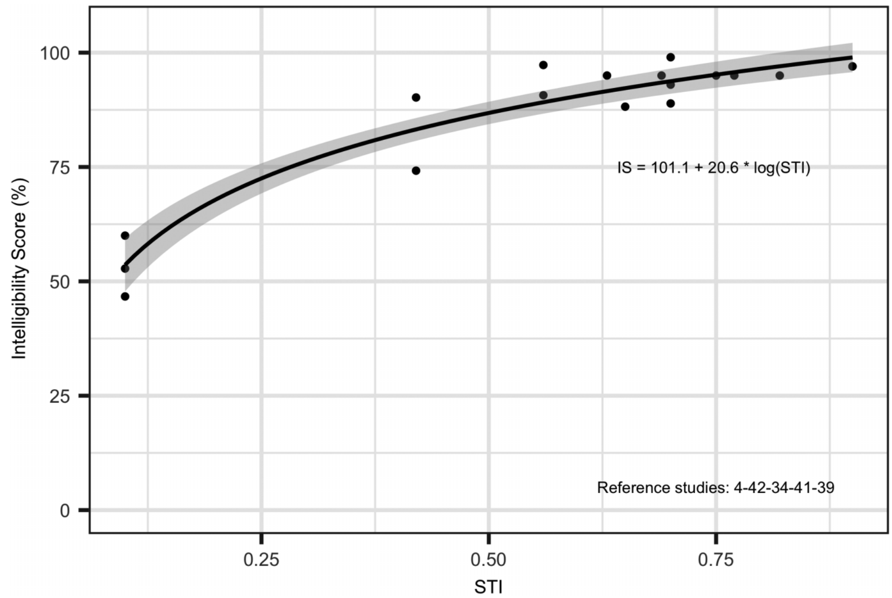
Indeed, these languages have different characteristics: English is a stress-timed language, which means that stressed syllables are pronounced at a regular cadence whereas unstressed syllables are shortened to fit this rhythm. Italian, on the other hand, is a phonetic language, which therefore has a direct relationship between the spelling of words and their pronunciation. Finally, Chinese is a tonal language. In this case, the pitch is used to distinguish and give a different meaning to the words. The work of Kang (1998) showed that acoustics can have a different influence on speech intelligibility, depending on the language in which the test is administered. Intelligibility scores showed that, in the presence of longer RTs, Chinese language intelligibility is slightly higher than English language intelligibility. On the other end, slightly higher intelligibility scores were obtained with the English language tests under the same noise conditions. Although the results of this review are consistent across language testing, consideration should be given in classroom design to what acoustic parameters can support better understanding for the children for whom it is intended.

Table 5. Database association between intelligibility score and speech transmission index (STI).

		Parameters	
Study ID	**Grade**	**STI**	**Intelligibility score (%)**
4	2	0.82	95.00
		0.90	97.00
	4	0.77	95.00
		0.90	97.00
42	4	0.65	88.19
34	2	0.75	95.00
	4	0.69	95.00
	6	0.63	95.00
41	0	0.56	90.70
		0.42	74.20
	1	0.56	97.30
		0.42	90.20
39	All	0.10	60.00
		0.70	88.90
		0.10	46.70
		0.70	99.00
		0.10	52.80
		0.70	93.00

The current systematic review had several limitations. First, the low number of articles constrains the generalizability of the results. In the experimental designs of the included studies, the lack of blinding and explanation of confounding variables impacted their strength, thus narrowing the conclusions that can be drawn across the studies. The quality assessment showed the critical aspects of studies conducted on speech intelligibility in elementary school. The type of design used for these studies was usually the one-time survey, which made these studies weak. Most studies reported speech intelligibility as a percent-correct score, whereas some of them reported average scores without a reference range. This made it impossible to compare results across studies. Different types of background noise (babble noise, cafeteria noise, traffic noise, etc.) were used to simulate the acoustic environment of a

Figure 4. Linear model between the speech transmission index (STI) and the percentage of the intelligibility score (IS). The 95% confidence interval is represented by the shaded regions. Reference Study ID: 4, 42, 34, 41, 39.



classroom. This may affect the relationship between STI and speech intelligibility score. Although our approach was to evaluate the intelligibility scores derived from the studies, the intelligibility tests used sometimes have different purposes and structures resulting from adaptation to different languages. The WIPI Test is used to evaluate children's ability to identify speech, the TROG is administrated to assess understanding of grammatical contrast, the DRT is an ANSI standard test to evaluate speech intelligibility in choosing between rhyming words, and the Chinese Word Recognition Test is performed to evaluate the ability to discriminate monosyllabic similar-sounding words. This variability may have an influence on the intelligibility scores obtained from each test. The articles in the meta-analysis assessed speech intelligibility at the word level. The ISO (2003) compared different methods to assess speech intelligibility as a function of STI. The results showed that, among adults, intelligibility based on sentence recognition for STI is higher than 0.3 compared to intelligibility scores based on single-word recognition, and vice versa. We hypothesize that this will be the case for children as well, but more evidence should be provided on this topic. Finally, the articles included in this systematic review analyzed the effect of classroom acoustics on speech perception for elementary students. Even if not selected due to the age range, it is worthy to mention three studies including students with hearing loss with an age range between 6 and 16 years (Iglehart, 2004, 2016, 2020). These studies showed that hard of hearing students need a better acoustic environment in order to support their learning. Iglehart (2004, 2016, 2020) successfully demonstrated that to reach the same intelligibility score, hard of hearing students need shorter RTs and lower background noise compared to normal-hearing peers. This is in agreement with the ANSI standard (ANSI/ASA S12.60; ANSI, 2010) that suggests a more favorable classroom acoustic environment for children with auditory issues (e.g., RT shorter than 0.3 s) is needed. They also showed that both hard of hearing and normal-hearing students benefit from sound-field systems to overcome the obstacle of poorer speech understanding, and this is especially important to achieve the acoustic quality needed by hard of hearing children. Therefore, hard of hearing students are expected to achieve lower intelligibility scores on equal acoustics conditions and would require a separate analysis and consideration.

Future studies should consider a more standardized approach for speech intelligibility testing. This will allow the possibility to combine results from different studies and analyze combined factors. In addition, the characterization of the classroom acoustics should include all the parameters of interest for speech transmission. Finally, to make these assessments more robust, future research should investigate the intelligibility of speech in a longitudinal way, to better understand the development of hearing ability over age.

Conclusions

This systematic review aims to synthesize the findings from previous literature describing the relationship between speech intelligibility and classroom acoustic parameters in elementary schools. Although the quality assessment revealed weaknesses in the included studies, especially due to the one-time survey design, this review established a basis for implementing research on the effect of noise and classroom acoustics on speech intelligibility.

Speech intelligibility was primarily assessed using three tests (WIPI Test, DRT, and Chinese Word Recognition Test as specified by GB 4959 or SJ2467-84). As supported by prior literature, measures of STI and SNR were used as predictors of speech intelligibility. The main findings of this systematic review confirmed that, at equal SNR, the intelligibility scores increase with age, indicating that higher values of SNR are required to achieve the same percentage of intelligibility when the RT is higher than the recommended value of 0.6 s and showed that STI values rated as "fair" allow a high percentage of intelligibility.

In conclusion, optimal classroom acoustics will improve speech intelligibility, which may increase children's academic success, as increased noise levels have been associated with decreased concentration and increased negative behaviors in children. The results obtained have provided a first analysis that can be generalized to all elementary school children, helping direct future projects to minimize the effect of poor acoustics on children comprehension.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article. All databases for analysis are provided in Tables 3, 4, and 5.

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References

American National Standards Institute. (1960). *American standard method for measurement of monosyllabic word intelligibility* (ANSI S3.2-1960).

American National Standards Institute. (2010). *American national standard acoustical performance criteria, design requirements, and guidelines for schools* (ASA/ANSI S12.60).

American Speech-Language-Hearing Association. (2005). *Acoustics in educational settings: Technical report*. https://specialedlaw.blogs.com/home/files/AcousticsTR.pdf

Astolfi, A., Bottalico, P., & Barbato, G. (2012). Subjective and objective speech intelligibility investigations in primary school classrooms. *The Journal of the Acoustical Society of America, 131*(1), 247–257. https://doi.org/10.1121/1.3662060

Bishop, D. (2013). *Test for Reception of Grammar*. https://www.pearsonclinical.co.uk/Psychology/ChildCognitionNeuropsychologyandLanguage/ChildLanguage/TestforReceptionofGrammar(TROG-2)/TestforReceptionofGrammar(TROG-2).aspx

Bovo, R., & Callegari, E. (2009). Effects of classroom noise on the speech perception of bilingual children learning in their second language: Preliminary results. *Audiological Medicine, 7*(4), 226–232. https://doi.org/10.3109/16513860903189499

Bradley, J. S. (1986). Speech intelligibility studies in classrooms. *The Journal of the Acoustical Society of America, 80*(3), 846–854. https://doi.org/10.1121/1.393908

Bradley, J. S., & Sato, H. (2004). Speech recognition by grades 1, 3 and 6 children in classrooms. *Canadian Acoustics, 32*(3), 26–27.

Bradley, J. S., & Sato, H. (2008). The intelligibility of speech in elementary school classrooms. *The Journal of the Acoustical Society of America, 123*(4), 2078–2086. https://doi.org/10.1121/1.2839285

Caviola, S., Visentin, C., Borella, E., Mammarella, I., & Prodi, N. (2021). Out of the noise: Effects of sound environment on maths performance in middle-school students. *Journal of Environmental Psychology, 73,* 101552. https://doi.org/10.1016/j.jenvp.2021.101552

Cienkowski, K. M., Ross, M., & Lerman, J. (2009). The Word Intelligibility by Picture Identification (WIPI) Test revisited. *Journal of Educational Audiology, 15,* 39–43.

Connolly, D., Dockrell, J., Shield, B., Conetta, R., Mydlarz, C., & Cox, T. (2019). The effects of classroom noise on the reading comprehension of adolescents. *The Journal of the Acoustical Society of America, 145*(1), 372–381. https://doi.org/10.1121/1.5087126

Corbin, N. E., Bonino, A. Y., Buss, E., & Leibold, L. J. (2016). Development of open-set word recognition in children: Speech-shaped noise and two-talker speech maskers. *Ear and Hearing, 37*(1), 55–63. https://doi.org/10.1097/AUD.0000000000000201

Crandell, C. C., & Smaldino, J. J. (2000). Classroom acoustics for children with normal hearing and with hearing impairment. *Language, Speech, and Hearing Services in Schools, 31*(4), 362–370. https://doi.org/10.1044/0161-1461.3104.362

Dockrell, J. E., & Shield, B. M. (2006). Acoustical barriers in classrooms: The impact of noise on performance in the classroom. *British Educational Research Journal, 32*(3), 509–525. https://doi.org/10.1080/01411920600635494

Eisenberg, L. S., Shannon, R. V., Schaefer Martinez, A., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *The Journal of the Acoustical Society of America, 107*(5), 2704–2710. https://doi.org/10.1121/1.428656

Flaherty, M., Libert, K., & Monson, B. B. (2021). Extended high-frequency hearing and head orientation cues benefit children during speech-in-speech recognition. *Hearing Research, 406,* 108230. https://doi.org/10.1016/j.heares.2021.108230

Flexer, C. (2004). The impact of classroom acoustics: Listening, learning, and literacy. *Seminars in Hearing, 25*(02), 131–140. https://doi.org/10.1055/s-2004-828664

Greenspan, S. L., Bennett, R. W., & Syrdal, A. K. (1998). An evaluation of the Diagnostic Rhyme Test. *International Journal of Speech Technology, 2*(3), 201–214. https://doi.org/10.1007/BF02111208

Houtgast, T. (1981). The effect of ambient noise on speech intelligibility in classrooms. *Applied Acoustics, 14*(1), 15–25. https://doi.org/10.1016/0003-682X(81)90040-2

Iglehart, F. (2004). Speech perception by students with cochlear implants using sound-field systems in classrooms. *American Journal of Audiology, 13*(1), 62–72. https://doi.org/10.1044/1059-0889(2004/009)

Iglehart, F. (2016). Speech perception in classroom acoustics by children with cochlear implants and with typical hearing. *American Journal of Audiology, 25*(2), 100–109. https://doi.org/10.1044/2016_AJA-15-0064

Iglehart, F. (2020). Speech perception in classroom acoustics by children with hearing loss and wearing hearing aids. *American Journal of Audiology, 29*(1), 6–17. https://doi.org/10.1044/2019_AJA-19-0010

International Electrotechnical Commission. (2020). *Sound system equipment. Part 16: Objective rating of speech intelligibility by speech transmission index* (IEC 60268-16).

International Organization for Standardization. (2003). *Ergonomics—Assessment of speech communication* (ISO 9921:2003). https://www.iso.org/standard/33589.html

International Organization for Standardization. (2008). *Acoustics—Measurement of the reverberation time of rooms with reference to other acoustical parameters* (ISO 3382:2008). https://www.iso.org/standard/36201.html

Jamieson, D. G., Kranjc, G., Yu, K., & Hodgetts, W. E. (2004). Speech intelligibility of young school-aged children in the presence of real-life classroom noise. *Journal of the American Academy of Audiology, 15*(7), 508–517. https://doi.org/10.3766/jaaa.15.7.5

Johnson, C. E. (2000). Childrens' phoneme identification in reverberation and noise. *Journal of Speech, Language, and Hearing Research, 43*(1), 144–157. https://doi.org/10.1044/jslhr.4301.144

Kang, J. (1998). Comparison of speech intelligibility between English and Chinese. *The Journal of the Acoustical Society of America, 103*(2), 1213–1216. https://doi.org/10.1121/1.421253

Klatte, M., Hellbrück, J., Seidel, J., & Leistner, P. (2010). Effects of classroom acoustics on performance and well-being in elementary school children: A field study. *Environment and Behavior, 42*(5), 659–692. https://doi.org/10.1177/0013916509336813

Lecumberri, M. L. G., Cooke, M., & Cutler, A. (2010). Non-native speech perception in adverse conditions: A review. *Speech Communication, 52*(11–12), 864–886. https://doi.org/10.1016/j.specom.2010.08.014

Leibold, L. J., & Buss, E. (2013). Children's identification of consonants in a speech-shaped noise or a two-talker masker. *Journal of Speech, Language, and Hearing Research, 56*(4), 1144–1155. https://doi.org/10.1044/1092-4388(2012/12-0011)

Maxwell, L. E., & Evans, G. W. (2000). The effects of noise on pre-school children's pre-reading skills. *Journal of Environmental Psychology, 20*(1), 91–97. https://doi.org/10.1006/jevp.1999.0144

Mealings, K. T. (2016). *Classroom acoustic conditions: Understanding what is suitable through a review of national and international standards, recommendations, and live classroom measurements*. The 2nd Meeting of the Australasian Acoustical Societies, Australia. https://www.acoustics.asn.au/conference_proceedings/AASNZ2016/

Mealings, K. T., Demuth, K., Buchholz, J., & Dillon, H. (2015). The development of the Mealings, Demuth, Dillon, and Buchholz Classroom Speech Perception Test. *Journal of Speech, Language, and Hearing Research, 58*(4), 1350–1362. https://doi.org/10.1044/2015_JSLHR-H-14-0332

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA statement. *BMJ, 339,* b2535. https://doi.org/10.1136/bmj.b2535

Nirme, J., Haake, M., Lyberg Åhlander, V., Brännström, J., & Sahlén, B. (2019). A virtual speaker in noisy classroom conditions: Supporting or disrupting children's listening comprehension? *Logopedics Phoniatrics Vocology, 44*(2), 79–86. https://doi.org/10.1080/14015439.2018.1455894

Peng, J., Wang, C., Jiang, P., & Lau, S. K. (2016). Investigation of Chinese word recognition scores of children in primary school classroom with different speech sound pressure levels. *Applied Acoustics, 110,* 235–240. https://doi.org/10.1016/j.apacoust.2016.03.026

Peng, J., & Wu, S. (2018). Chinese speech intelligibility of children in noisy and reverberant environments. *Indoor and Built Environment, 27*(10), 1357–1363. https://doi.org/10.1177/1420326X17716236

Peng, J., Yan, N., & Wang, D. (2015). Chinese speech intelligibility and its relationship with the speech transmission index for children in elementary school classrooms. *The Journal of the Acoustical Society of America, 137*(1), 85–93. https://doi.org/10.1121/1.4904519

Peng, J., Zhang, H., & Yan, N. (2016). Effect of different types of noises on Chinese speech intelligibility of children in elementary school classrooms. *Acta Acustica united with Acustica, 102*(5), 938–944. https://doi.org/10.3813/AAA.919008

Picard, M., & Bradley, J. S. (2001). Revisiting speech interference in classrooms [Revisando la interferencia en el habla dentro del salón de clases]. *Audiology, 40*(5), 221–244. https://doi.org/10.3109/00206090109073117

Prodi, N., Visentin, C., Borella, E., Mammarella, I. C., & Di Domenico, A. (2019). Noise, age, and gender effects on speech intelligibility and sentence comprehension for 11- to 13-year-old children in real classrooms. *Frontiers in Psychology, 10*. https://doi.org/10.3389/fpsyg.2019.02166

Prodi, N., Visentin, C., & Feletti, A. (2013). On the perception of speech in primary school classrooms: Ranking of noise interference and of age influence. *The Journal of the Acoustical Society of America, 133*(1), 255–268. https://doi.org/10.1121/1.4770259

Prodi, N., Visentin, C., Peretti, A., Griguolo, J., & Bartolucci, G. B. (2019). Investigating listening effort in classrooms for 5- to 7-year-old children. *Language, Speech, and Hearing Services in Schools, 50*(2), 196–210. https://doi.org/10.1044/2018_LSHSS-18-0039

Rabelo, A. T. V., Santos, J. N., Oliveira, R. C., & Magalhães, M. D. C. (2014). Effect of classroom acoustics on the speech intelligibility of students. *Revista da Sociedade Brasileira de Fonoaudiologia, 26*(5), 360–366. https://doi.org/10.1590/2317-1782/20142014026

Rosenberg, G. G., Blake-Rahter, P., Heavner, J., Allen, L., Redmond, B. M., Phillips, J., & Stigers, K. (1999). Improving Classroom Acoustics (ICA): A three-year FM sound field classroom amplification study. *Journal of Educational Audiology, 7,* 8–28.

Ross, M., & Lerman, J. A. Y. (1970). A picture identification test for hearing-impaired children. *Journal of Speech and Hearing Research, 13*(1), 44–53. https://doi.org/10.1044/jshr.1301.44

Rudner, M., Lyberg-Åhlander, V., Brännström, J., Nirme, J., Pichora-Fuller, M. K., & Sahlén, B. (2018). Listening comprehension and listening effort in the primary school classroom. *Frontiers in Psychology, 9,* 1193. https://doi.org/10.3389/fpsyg.2018.01193

Sahlén, B., Haake, M., von Lochow, H., Holm, L., Kastberg, T., Brännström, K. J., & Lyberg-Åhlander, V. (2018). Is children's listening effort in background noise influenced by the speaker's voice quality? *Logopedics Phoniatrics Vocology, 43*(2), 47–55. https://doi.org/10.1080/14015439.2017.1324914

Shield, B., Conetta, R., Dockrell, J., Connolly, D., Cox, T., & Mydlarz, C. (2015). A survey of acoustic conditions and noise levels in secondary school classrooms in England. *The Journal of the Acoustical Society of America, 137*(1), 177–188. https://doi.org/10.1121/1.4904528

Standardization Administration of China. (1985). *Methods of measurement for the characteristics of sound reinforcement in auditoria* (GB 4959: 1985).

Standardization of Ministry of Electronics and Industry. (1984). *Test methods for Chinese articulation in communication equipment* (SJ2467: 1984).

Steeneken, H. J., & Houtgast, T. (1980). A physical method for measuring speech-transmission quality. *The Journal of the Acoustical Society of America, 67*(1), 318–326. https://doi.org/10.1121/1.384464

Steeneken, H. J., & Houtgast, T. (1982). Some applications of the speech transmission index (STI) in auditoria. *Acta Acustica united with Acustica, 51*(4), 229–234.

Valente, D. L., Plevinsky, H. M., Franco, J. M., Heinrichs-Graham, E. C., & Lewis, D. E. (2012). Experimental investigation of the effects of the acoustical conditions in a simulated classroom on speech recognition and learning in children. *The Journal of the Acoustical Society of America, 131*(1), 232–246. https://doi.org/10.1121/1.3662059

Vickers, D. A., Backus, B. C., Macdonald, N. K., Rostamzadeh, N. K., Mason, N. K., Pandya, R., Marriage, J. E., & Mahon, M. H. (2013). Using personal response systems to assess speech perception within the classroom: An approach to determine the efficacy of sound field amplification in primary school classrooms. *Ear and Hearing, 34*(4), 491–502. https://doi.org/10.1097/AUD.0b013e31827ad76f

Werner, L. (2007). What do children hear? How auditory maturation affects speech perception. *The ASHA Leader, 12*(4), 6–33. https://doi.org/10.1044/leader.FTR1.12042007.6

Yacullo, W. S., & Hawkins, D. B. (1987). Speech recognition in noise and reverberation by school-age children. *Audiology, 26*(4), 235–246. https://doi.org/10.3109/00206098709081552

Yang, W., & Bradley, J. S. (2009). Effects of room acoustics on the intelligibility of speech in classrooms for young children. *The Journal of the Acoustical Society of America, 125*(2), 922–933. https://doi.org/10.1121/1.3058900