Research Article

Speech Perception in Classroom Acoustics by Children With Hearing Loss and Wearing Hearing Aids

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Purpose: The classroom acoustic standard ANSI/ASA S12.60-2010/Part 1 requires a reverberation time (RT) for children with hearing impairment of 0.3 s, shorter than its requirement of 0.6 s for children with typical hearing. While preliminary data from conference proceedings support this new RT requirement of 0.3 s, peer-reviewed data that support 0.3-s RT are not available on those wearing hearing aids. To help address this, this article compares speech perception performance by children with hearing aids in RTs, including those specified in the ANSI/ASA-2010 standard. A related clinical issue is whether assessments of speech perception conducted in near-anechoic sound booths, which may overestimate performance in reverberant classrooms, may now provide a more reliable estimate when the child is in a classroom with a short RT of 0.3 s. To address this, this study compared speech perception by children with hearing aids in a sound booth to listening in 0.3-s RT.
Method: Participants listened in classroom RTs of 0.3, 0.6, and 0.9 s and in a near-anechoic sound booth. All conditions also included a 21-dB range of speech-to-noise ratios (SNRs) to further represent classroom listening environments. Performance measures using the Bamford–Kowal–Bench Speech-in-Noise (BKB-SIN) test were 50% correct word recognition across these acoustic conditions, with supplementary analyses of percent correct.
Results: Each reduction in RT from 0.9 to 0.6 to 0.3 s significantly benefited the children's perception of speech. Scores obtained in a sound booth were significantly better than those measured in 0.3-s RT.
Conclusion: These results support the acoustic standard of 0.3-s RT for children with hearing impairment in learning spaces ≤ 283 m[3], as specified in ANSI/ASA S12.60-2010/Part 1. Additionally, speech perception testing in a sound booth did not predict accurately listening ability in a classroom with 0.3-s RT.
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The classroom acoustic standard of ANSI/ASA 12.60-2010/Part 1 (American National Standards Institute/Acoustical Society of America, 2010) added a required classroom reverberation time (RT) for children with hearing impairment in core learning spaces ≤ 283 m[3] (e.g., ≤ 12.0 × 7.9 × 3.0 m), which was not in the previous standard, ANSI S12.60-2002 (American National Standards Institute, 2002). The earlier ANSI-2002 standard required a single classroom RT of 0.6 s in that size classroom for all students without specifying hearing ability. The more recent ANSI/ASA-2010 standard states in Section 5.3 and Table 1 that core learning spaces ≤ 283 m[3] (≤ 10,000 ft[3]) be adaptable to an RT of 0.3 s and, in Annex, Commentary 5.3.1, that an RT "of 0.3 s, shorter than stated in Table 1, is necessary for children with hearing impairment and/or other communicative issues." Peer-reviewed, published data prior to this article are not available on children using hearing aids and the potential benefits to their perception of speech in 0.3 as compared to 0.6-s RT. The only support for a classroom RT of 0.3 s for children with hearing aids is preliminary data published in conference proceedings (Iglehart, 2007, 2008a, 2008b).

The benefits gained from control of classroom reverberation and noise to various degrees have been well supported by published data. A child's academic progress depends on acoustic access to teachers and class discussions. Classroom noise and reverberation have often been measured as excessive and varying widely during the school day (e.g., Knecht, Nelson, Whitelaw, & Feth, 2002; Larsen & Blair, 2008; Shield & Dockrell, 2008). Excessive reverberation temporally overlaps or smears acoustic details of

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speech features, while the amplitude and timing of noise may further mask these details. Studies of the effects of RT or the combined effects of reverberation and noise on children's perception of speech have focused largely on children with typical hearing (e.g., Lewis, Manninen, Valente, & Smith, 2014; Neuman & Hochberg, 1983; Neuman, Wróblewski, Hajicek, & Rubinstein, 2010; Wróblewski, Lewis, Valente, & Stelmachowicz, 2012; Yacullo & Hawkins, 1987; Yang & Bradley, 2009). Often reported were decreased speech perception scores with increased RT, which could be offset to a limited extent by higher speech-to-noise ratios (SNRs), suggesting that both reverberation and background noise need reduction in classrooms. Studies of children with typical hearing, however, often used different RT conditions and thus varied between their reports on the shortest RT for optimal perception of speech (0.68-s RT: Yang & Bradley, 2009; 0.6 s: Iglehart, 2016; 0.4 s: Finitzo-Hieber & Tillman, 1978; 0.3 s: Neuman et al., 2010; 0.0 s: Neuman & Hochberg, 1983; Wróblewski et al., 2012; Yacullo & Hawkins, 1987).

Children also demonstrate greater susceptibility to distortion and masking of acoustical information than adults, with younger children experiencing the most difficulty. This susceptibility has been attributed largely to age-related developmental effects and the cognitive demands of school lessons, as described by others (e.g., Corbin, Bonino, Buss, & Leibold, 2016; Johnson, 2000; Klatte, Lachmann, & Meis, 2010; Koopmans, Goverts, & Smits, 2018; Leibold, 2017; Nábělek & Robinson, 1982; Neuman et al., 2010; Wróblewski et al., 2012). The focus of those studies, as well, has been on children with typical hearing.

Children with hearing loss and wearing hearing aids face further obstacles in the classroom compared to those with typical hearing. Hearing loss reduces auditory access to some speech features more than others, such as segmental more than suprasegmental, and this distortion often increases with degree of hearing loss (Blamey et al., 2001; Boothroyd, 1984; Buss, Hall, & Grosse, 2004). For example, based on results from 120 children with hearing loss of 55 dB HL and greater and listening through headphones, Boothroyd (1984) reported that speech perception scores fell to 50% for consonant place with hearing loss beginning at 75 dB HL, initial consonant voicing with a hearing loss of 85 dB HL, and so forth. Hearing aids can improve audibility but not necessarily overcome deficits in discrimination observed with sensorineural hearing loss (Boothroyd, 1984; Finitzo-Hieber & Tillman, 1978; McCreery et al., 2015). In addition to reporting on children with typical hearing, Finitzo-Hieber and Tillman (1978) provided substantial data on the effects of acoustics on speech perception by children with hearing loss. These 12 children, ages 8–13 years, wore a monaural hearing aid provided by the study and were chosen for their good perception of speech. Their mean scores improved significantly with each reduction in RT from 1.2 to 0.4 to 0.0 s and, separately, with each increase in SNRs from 0 to +6 to +12 dB to quiet. The effects of reverberation and noise were significantly greater for the children with hearing loss compared to those with typical hearing in the study. For example, in quiet with a decrease

in RT from 1.2 to 0.0 s, the percentage point improvement in speech perception scores for the children with typical hearing was 18.0, while for those using a hearing aid, it was 38.0. When noise levels improved from 0 dB SNR to quiet and RT remained at 0.0 s, the percentage point improvement in mean score by the children with typical hearing was 34.3, and for the children using a hearing aid, it was 44.0. In a combination of RT shortened from 1.2 to 0.0 s and increased SNR from +6 dB to quiet, the percentage point improvement in mean score for the children with typical hearing was 40.3, and for the children with a hearing aid, it was 56.0. The children with one hearing aid, however, could possibly have performed in reverberation better if binaural amplification had been used (children with typical hearing: Neuman & Hochberg, 1983; adults with hearing aids: Nábělek & Pickett, 1974; adults with typical hearing: Cox, DeChicchis, & Wark, 1981).

Other than those provided by Finitzo-Hieber and Tillman (1978), there are few data on the effects of various classroom reverberant conditions on speech perception scores by children with hearing loss wearing hearing aids. Picard and Bradley (2001) noted that the effects of reverberation and noise are relatively less well understood in regard to children with hearing loss compared to those with typical hearing. Subsequent studies on speech perception in reverberation by children with hearing loss have addressed those with cochlear implants (Iglehart, 2016; Neuman, Wróblewski, Hajicek, & Rubinstein, 2012). The focus of studies involving children with hearing aids has largely been to determine the benefits to speech perception with the use of assistive devices (e.g., personal sound field or FM systems; Anderson & Goldstein, 2004; Anderson, Goldstein, Colodzin, & Iglehart, 2005; Pittman, Lewis, Hoover, & Stelmachowicz, 1999). Other published reports have advocated for good acoustics for children with hearing loss but did not provide data on the effects of classroom RTs on speech perception by these children (e.g., Crandell & Smaldino, 2004; Guenther & Adrian, 2000).

Reduction of classroom RT to the relatively short 0.3 s raises a related audiologic clinical issue. Parents' and teachers' understanding of the ability to perceive speech by a child with hearing loss may be informed by audiologic clinical results often obtained in a near-anechoic sound booth. Only one study has compared speech perception performance, by children with hearing aids, between an anechoic environment and a reverberant listening environment. Finitzo-Hieber and Tillman (1978) reported a significant difference in mean scores between listening in an anechoic condition and in 0.4-s RT. With only this one study involving children with hearing aids, reports on children with typical hearing, listening in anechoic conditions and in a short RT, may help provide some suggestion of performance patterns across these listening conditions. The results reported, though, have not been consistent across these studies. For example, Wróblewski et al. (2012) found significant differences in scores for children with typical hearing listening in anechoic conditions as compared to 0.4-s RT. On the other hand, Finitzo-Hieber and Tillman comparing

scores between an anechoic condition and 0.4-s RT and Iglehart (2016) comparing scores between a near-anechoic condition and 0.3-s RT both testing children with typical hearing found nonsignificant differences in scores. The limited number of studies involving children with hearing aids and the mixed results across studies involving children with typical hearing suggest the need to examine further whether clinical results obtained in a sound booth may predict performance in the short RT of 0.3 s.

This article, therefore, addresses the following questions:

1. Does reduction in classroom RT to 0.3 s from 0.6 s, as required by ANSI/ASA S12.60-2010/Part 1, benefit speech perception performance by children with hearing loss wearing hearing aids?

2. Do clinical results for children with hearings aids listening in a near-anechoic sound booth predict speech perception performance in an acoustically well-treated classroom with an RT of 0.3 s?

Method

Participants

Six girls and four boys (M_{age} = 11.4 years, age range: 7.1–16.0 years) had hearing loss and wore hearing aids (first hearing aid use: M_{age} = 2.7 years, age range: 0.3–5.0 years). Table 1 provides participant age, hearing thresholds, make and model of hearing aid(s), and other demographic information. Audiograms provided by the parents

were the source of the hearing thresholds. These audiograms dated an average of 4.7 months (range: 0.1–14.5 months) prior to testing. Pure-tone threshold averages (PTAs) unaided across 500, 1000, and 2000 Hz served to classify the hearing abilities of the children (Northern & Downs, 1991; Schauch & Nelson, 2015). Hearing loss for four participants (Nos. 1, 3, 5, and 6; see Table 1) was profound (> 70 dB HL PTA) in one ear and severe in the other (51–70 dB HL PTA). Two children (Nos. 4 and 7) had a severe loss in both ears. Two children (Nos. 2 and 10) had a moderate loss (30–50 dB HL PTA) in both ears. One child (No. 9) had a moderate loss in one ear and a slight loss (16–25 dB HL PTA) in the other. One child (No. 8) had a profound loss in one ear and normal hearing (< 16 dB HL PTA) in the other. These last two children had hearing configurations above 2000 Hz in the better ear, which were precipitously falling (Schauch & Nelson, 2015), and thus had challenges in perception of speech beyond the descriptors of slight loss or normal hearing.

Eight children wore binaural hearing aids, and two (Nos. 3 and 8) wore monaural hearing aids. Binaural amplification is known to improve the perception of speech in reverberation relative to monaural fittings (Nábělek & Pickett, 1974). This factor was not addressed, however, in this article as the primary focus was the listening performance by a group of children with hearing aids in the RTs specified in the ANSI/ASA-2010 standard.

Audiograms and/or reports indicated that the hearing losses in all amplified ears were sensorineural. Identification of hearing loss for two children was at birth; for one child,

Table 1. Background information on participants.

Participants				Hearing thresholds (dB HL)						Hearing aids	Age first aided	Cause of hearing loss
				Hz								
No.	Age (years)	Gender	Ear	250	500	1000	2000	3000	4000	Make and model		
1	7.1	F	R	50	55	55	65	—	70	Oticon Tego Pro	2.5	Pendred syndrome
			L	65	65	70	100	115	110	Oticon SUMO DM		
2	8.3	M	R	20	25	40	55	45	40	Oticon Epoq XW	5.0	Genetic
			L	25	30	40	55	45	40	Oticon Epoq XW		
3	8.4	M	R	35	50	60	55	65	60	Phonak Savia Art 311 dSZ	2.0	Mondini malformation
			L	50	80	85	85	—	85	Unaided		
4	8.9	F	R	45	45	55	60	—	60	Oticon Tego Pro	0.3	Connexin 26 mutation
			L	45	50	60	70	—	65	Oticon Tego Pro		
5	11.3	F	R	30	55	65	85	—	85	Phonak Savia 311 dSZ	2.5	Unknown
			L	45	55	75	85	—	100	Phonak Savia 311 dSZ		
6	11.9	F	R	75	80	85	95	95	95	Phonak Naida V SP Jr.	2.5	Pendred syndrome
			L	70	75	75	45	70	60	Phonak Naida V SP Jr.		
7	12.9	F	R	60	60	60	55	—	55	Oticon Tego Pro Power	0.3	Genetic
			L	50	55	55	55	—	50	Oticon Tego Pro Power		
8	14.5	M	R	35	15	10	5	55	60	Phonak Exelia M	1.5	Large vestibular aqueduct syndrome
			L	65	85	75	80	75	80	Unaided		
9	14.7	F	R	10	10	20	65	—	65	Siemens Pure 500	6.0	Unknown
			L	10	5	15	50	—	55	Siemens Pure 500		
10	16.0	M	R	20	25	50	45	—	45	Oticon Epoq	5.0	Unknown
			L	25	35	60	50	—	45	Oticon Epoq		

Note. All hearing losses in aided ears were predominantly sensorineural. All hearing aids were postauricular (behind-the-ear). Em dashes indicate information not available. F = female; R = right; L = left; M = male.

by the age of 1.5 years; for four children, by the age of 2.5 years; for one child, by the age of 5 years; for another, by the age of 6.7 years; and for one child, the age of identification was unknown. Each child to be included in this study met the criterion of ability to correctly perceive words-in-sentences ≥ 80% with the Bamford–Kowal–Bench Speech-in-Noise (BKB-SIN) test (Etymotic Research, Inc., 2005) while listening in ≤ +21 dB SNR and in the classroom with an RT of 0.3 s. Since the primary test environment was a classroom, with ancillary testing in a sound booth, the most efficient and nonstressful use of time for each child was to incorporate the test of this ≥ 80% criterion for perception into her session in the classroom. If a child did not meet this criterion, testing continued, but her results were not included in this article. Always of concern was the length of time a child could be expected to attend to testing throughout an entire session. Whenever a child asked to stop testing, the entire session ended immediately and the results discarded as incomplete.

Participant recruitment was through parents of students attending schools in the region including the Clarke School, through siblings of participants who wore cochlear implants in a related study, and through word of mouth. American English was the primary language of all participants. All but one participant (No. 9) had no suspected or diagnosed attention-deficit disorder or learning disability. This one participant had attention-deficit/hyperactivity disorder, which the parent reported as successfully managed through medication. Approval for this study for human subjects' protection was obtained from the Smith College Institutional Review Board.

Test Materials

Speech perception ability was measured with the BKB-SIN test, which contains 36 lists in 18 pairs, with either eight or 10 sentences per list, with each sentence containing three to four target words. The BKB-SIN compact disc presents speech on one channel with background noise (four-talker babble) on a second channel. The SNR of the first sentence is +21 dB, with 3-dB decreases with each subsequent sentence in the list. To score performance in a list, the BKB-SIN user manual (Etymotic Research, Inc., 2005, p. 23) states that "the starting point (21 dB) plus half of the step size (1.5), plus the extra word in the first sentence… equals 23.5. SNR-50 is 23.5 minus the total number of words repeated correctly" or SNR-50 = (23.5) − (# Correct) = x dB. The list-pair SNR-50 score is the average of the SNR-50 scores from the two lists in a pair and represents the SNR at which the listener correctly perceived 50% of the words.

In this study, data collection focused on the number of words perceived correctly in each sentence at each SNR within each RT. These data served two analyses. The first analysis was as prescribed in the BKB-SIN user manual, with adjustments made to reflect each participant's listening ability in reverberation and noise. These adjustments to SNR-50 score were based on start SNRs considered appropriate for each participant. The term *start SNR* in this

article refers to the SNR used for the first sentence in a list. Though the BKB-SIN test always presents the first sentence in +21 dB SNR, at the time of data collection in this study, there were no published data for the BKB-SIN test to suggest for any group of listeners a single start SNR for listening in reverberation. Anecdotal evidence suggested that a start SNR of +21 dB for children wearing hearing aids could lead to extended ceiling effects and failure to capture the full performance range of many individuals. The use of adaptive start SNRs helped avoid this anticipated effect on scores. A downside, however, was that the same 21-dB range would not apply across all participants. This would result in within-group missing data at some SNRs and thus reduced N for some analyses. The adaption of the start SNR was made in each reverberant condition.

For an appropriate adaption, the start SNR needed to be high enough to capture the participant's best scores while low enough to reveal the listener's full range of listening ability as SNRs declined through presentation of each list. An appropriate start SNR was when the participant missed no more than two target words in the first three sentences across the two lists in a pair; performance then declined with each subsequent 3-dB decrease in SNR and was near or at 0% correct for words in the last two sentences presented in the lowest SNRs. The use of start SNRs other than +21 dB required adjustments to the SNR-50 formula provided by the BKB-SIN user manual. When it was necessary with some participants to raise or lower the start SNR from 21 dB, the formula used was SNR-50 = (23.5) − (# Correct) + (Start SNR − 21) = x dB. For example, when the start SNR was 18 dB, the adjustment to SNR-50 was calculated from 18 dB − 21 dB = −3 dB, and the value −3 was included as SNR-50 = (23.5) − (# Correct) + (−3) = x dB. When a participant required a start SNR of +24 dB, the scoring formula was SNR-50 = (23.5) − (# Correct) + (3) = x dB.

The second analysis was of participants' mean score at each SNR within each RT. This analysis, as in the first one, included the participants' adaptive start SNRs. These scores were labeled in this study as RT-SNR scores and measured as percent correct, which allowed calculations of performance intensity for additional insights (Boothroyd, 2008). This analysis required lists of equal length for consistent test conditions within and between participants. It was necessary, therefore, to delete Sentences 9 and 10 in List Pairs 1–8 to ensure that all lists had eight sentences. For consistency in test conditions, both the first and second analyses included lists with these sentences deleted. As described by M. Skinner (personal communication, December 10, 2006), Sentences 9–10 in the longer lists were presented under the poorest SNRs, which would result in scores near 0%. The removal of these sentences, therefore, would likely have no significant effect on test scores. These two last sentences also could have potentially discouraged some of the children in this study and thus reduced validity and reliability. Assessments in the sound booth usually used the first three list pairs. Testing in the classroom randomized the order of the remaining of the 18 list pairs within and

across the RT conditions and within and across participants. A child listened to a list pair only once.

The BKB-SIN user manual states that test reliability increases with the administration of additional list pairs, and the increase slows substantially after three list pairs. This study used three list pairs to improve reliability while avoiding excessive test time. Each child's attention to the listening task for an entire session and avoidance of potential fatigue were considered paramount when testing with three list pairs per RT condition. Some degree of acclimatization and/or learning effect could possibly occur across the list pairs. An analysis of changes in score within each set of three list pairs, from the first to second to third of each list pair, across the classroom RTs and participants indicated an average change in score of −0.5 dB SNR-50, which was nonsignificant in repeated-measures analysis of variance, $F(2, 52) = 0.67$, $p = .5127$.

Procedure

Each participant aged ≥ 8 years listened to three list pairs of the BKB-SIN test in each RT. The ancillary testing in the sound booth usually took place before testing in the classroom and helped indicate an appropriate start SNR in the classroom, usually the same start SNR as in the sound booth or 3 dB higher. Each SNR-50 score was an average of SNR-50 scores from the three list pairs presented in each RT. Each RT-SNR percent correct score, on the other hand, was the average of percent correct scores across six sentences all presented in the same RT and SNR condition across three list pairs. The six sentences contained a total of 18–24 target words, depending on the number of words per sentence. The SNRs of the remaining seven sentences in a list subsequent to the start SNR were almost always the same across participants. The result was that, though the start SNR may not have been the same for each participant, the second analysis was based on scores from SNRs in which all the children were tested (0, +3, +6, +9, +12, and +15 dB) across all four RT conditions. As a result, there were no missing data points in the analyses.

The one participant aged < 8 years listened to only two list pairs for each RT to limit testing to less than 8 min to avoid fatigue or flagging attention (Hnath-Chisolm, Laipply, & Boothroyd, 1998). Each SNR-50 score was an average over two list pairs, and each RT-SNR percent correct score was an average over four sentences containing a total of 12–16 target words. The test of this child with fewer test items may have increased statistical variability compared to the other nine participants (Etymotic Research, Inc., 2005). The use of two list pairs, however, may likely have decreased variability over the use of one list pair as suggested in the BKB-SIN test manual for routine clinical tests.

Most participants needed start SNRs other than the +21 dB provided by the BKB-SIN test. Two participants (Nos. 7 and 10) needed one start SNR of +15 dB in all the classroom RTs and sound booth. One participant (No. 9) had one start SNR of +18 dB in the classroom and +15 dB

in the sound booth. One participant (No. 8) had one start SNR of +18 dB in the classroom and sound booth. Two participants (Nos. 2 and 3) had start SNRs of either +21 or +18 dB in classroom RTs, depending on the list pair, and +18 dB in the sound booth. Four participants (Nos. 1 and 4–6) in all four RTs had one start SNR of +21 dB.

The two scorers separately marked each target word in each sentence in the classroom as either correct or wrong. In posttest comparisons of the scorers' score sheets, both scorers had to have judged a participant's response correct for it to be considered correct. If one scorer marked a word as correct and the other scorer marked the same word as not correct, the lower score was recorded, and the two scorers were recorded as disagreeing on the sentence score. If a scorer marked one word in a sentence as incorrect but the other scorer marked a different word as incorrect, both words were scored as incorrect, and the scorers were recorded as disagreeing on the sentence score. The two scorers agreed on number of words correct in 97.8% of the sentences across all the participants' responses in all conditions in the classroom. The author was always one of the scorers, and the second scorer was one of four people, all familiar with the children's speech. Scorers judged a participant's misarticulation as correct only if it had been observed in earlier conversations and could be considered to represent a correct response. The scorer in the booth always scored the same child in the classroom.

Test Rooms

The test classroom—10.0 (L) × 6.7 (W) × 3.4 (H) m— had a total volume of 223.4 m^3 (see Figure 1). Walls were plaster with blackboards and closed windows, the ceiling was plaster, and the floor was polished hardwood with a small, nonpadded carpet. Each participant sat at a small desk approximating the center of the second row of a classroom and facing the speech loudspeaker. This loudspeaker was 1.5 m above the floor, approximating the head position of a teacher when standing 0.7 m from the front-center of the room and 3.0 m in front of the participant. One of four noise loudspeakers faced each of the four corners of the room, 0.9 m from each corner and 1.5 m above the floor. Two response scorers sat to the right and left of the participant. The audiologic test booth (International Acoustic Chamber, Inc.)—1.9 (L) × 1.8 (W) × 2.0 (H) m—had a total volume of 6.8 m^3. Each participant sat in the booth 0.9 m from, and facing, speech and noise loudspeakers located immediately right and left of 0° azimuth and 1.0 m above the floor.

RTs

The number and location of acoustic panels (All Noise Control, 2007; Model ANC-600) determined the classroom RT. The panels were light weight, were covered entirely by the manufacturer in nylon fabric to facilitate handling and durability, and included grommets near the fabric edges for hanging on wall hooks when necessary. A change

Figure 1. The arrangement of the classroom with the student located near the center of the room, seated at a desk; two adult scorers were seated to the right and left. The speech loudspeaker was 0° azimuth to the student, with four noise loudspeakers, one facing each corner. The room also contained an alcove and several floor and wall cabinets. Reprinted from Iglehart (2016).
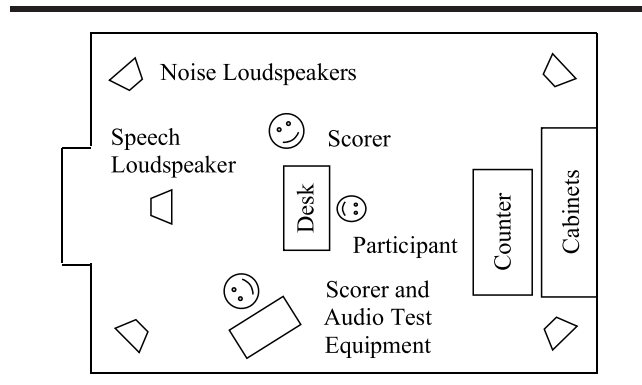
in panels from one RT condition to the next took 12–15 min and allowed the participant a break. The RT was 0.9 s with no panels; 0.6 s with 12 panels hanging on the walls just below ceiling height; and 0.3 s with a total of 50 panels, 34 hanging on the walls just below ceiling height, eight near floor level, and eight on the floor. Each panel was 0.6 × 1.8 m, with manufacturer's noise reduction coefficients of 1.15–1.25. The measured RT of the audiologic sound booth was 0.059 s and is described in this article as near anechoic.

The 0.9-s RT condition approximated the longer midrange of reported classroom RTs (Bradley, 1986; Crandell & Smaldino, 1994; Knecht et al., 2002; MacKenzie & Airey, 1999). The 0.6- and 0.3-s RT conditions addressed the requirements in the ANSI/ASA-2010 standard. The presentation order of the three RTs was counterbalanced within the group. The participants listened in the classroom beyond the acoustical critical distances calculated from measurements made within each RT.

Speech and Noise Levels

A potentiometer on an audiometer (at first, a Grason-Stadler 10 and, later in the classroom, a Grason-Stadler 16) controlled the level of target speech from the BKB-SIN test compact disc. A sound field system (Phonic Ear 210) amplified the signal through the one speech loudspeaker (Phonic Ear 578-S). The calibration noise on the BKB-SIN compact disc measured at the seated participant's midhead position, 1.0 m above the floor, was the basis for speech and noise level measurements. The calibration speech level was 59.5 dBA_{Leq} in 0.6-s RT. The speech presentation levels in participant testing ranged from 58.2 to 60.8 dBA_{Leq}. The range was due to effects of changes in RT. This range approximated the average level of 60.1 dBA (range: 56.9–69.6 dBA) reported by Picard and Bradley (2001) in a review of seven studies that measured a total of 183 teachers' voice levels. Four of the studies reported a fixed measurement

distance of either 2 or 3 m in the classroom, with the distance in three studies reported as varied or not specified.

The second channel of the audiometer controlled noise levels through a second sound system (Phonic Ear 210) and the four noise loudspeakers (Phonic Ear 578-S) described earlier. Head movements by the author sitting at the participants' position did not result in audible variations in noise level, which otherwise could have been caused by acoustic enhancement or cancelation effects among multiple direct and reflected signals. Listening checks at the speakers and the participants' position indicated equal noise levels from all directions. Nontest background noise measured before and after testing was < 35 dBA.

SNR, RT, and Spectra Measurements

The RT and speech and noise levels were measured with a Larson Davis System 824 (Type 1) sound-level meter. The RT measurements used the 824 meter's automatic RT60 algorithm and its preconfigured settings listed in the 824 Reference Manual, with "RT60 dB Down" set to "30 dB" (Larson Davis, Inc., 2004). Measurements in the classroom followed procedures in the 824 Reference Manual settings menu labeled as *RT60-A*, which were designed for steady-state triggering noise. Speech spectrum noise from the BKB-SIN compact disc, amplified through the speakers in each of the four corners of the room, acoustically excited the classroom (Etymotic Research, Inc., 2005). This noise, amplified to 90 dBA when measured at the participants' seat, was abruptly terminated to initiate decay and the triggering of the meter's measurement of RT. Measurements in the sound booth followed procedures labeled in the Reference Manual as RT60-B, which were designed for impulsive noise. Measurement was triggered by slapping two boards together, which created sufficient noise spectrum and decay in the small space to confirm the booth RT.

Each RT calculation was an average of one-third octave measurements at 500, 1000, and 2000 Hz. Please see Supplemental Material S1 for calculations of RTs. This study followed procedures in ANSI S12.60-2002 as, at the time of testing, ANSI/ASA S12.60-2010 had not yet been published. Procedures for RT measurements were those required in ANSI S12.60-2002 Table 1 and Annex E4.3. Table 1 requires octave averages at 500, 1000, and 2000 Hz to determine a classroom RT. Annex E4.3, however, refers to procedures in ASTM C423 Appendix X2, which require, among other procedures, one-third octave measurements (American Society for Testing and Materials Standards, 2002). This study combined both requirements and used one-third octave measurements at 500, 1000, and 2000 Hz. David Lubman, co-chair of the ANSI S12.60-2002 Working Group (personal communication, June 12, 2019), described, in his opinion, the use of one-third octave measurements as a nonsubstantial infraction of the procedures in Table 1 of the ANSI-2002 standard as one-third octave measurements would produce very similar results as octave measurements

in the relatively short RTs used in this study at the frequencies of 500, 1000, and 2000 Hz.

This study also followed other ANSI-2002 standard requirements such as the room must be unoccupied, windows closed, no loose clothing in the room, and ASTM requirements of at least five reverberation tests at a microphone position, with the following exception. The exception was that both ANSI and ASTM standards called for reverberation tests at multiple positions due to multiple locations of children in a regular classroom environment. In this study, however, only one child would be present at one location, so RT measurements were made only at the participant's head position.

Speech and noise-level measurements, based on 20-s LeqA, were made to 0.1 dB at the beginning of and periodically confirmed throughout the study. Each SNR was then rounded to the nearest decibel. Measurements with a calibrated Type 2 meter at the test midposition of a participant's head verified speech and noise levels before and after each session. When pre- and posttest levels differ more than 1.0 dB, the results for that child were discarded. Every few weeks, a more detailed check of sound levels was made. This check was to confirm that intentional increases and decreases in potentiometer settings for each channel, speech and noise, resulted in the same change (within ±0.1 dB) in sound level at the participant's head position. All such checks revealed no loss in accuracy in the potentiometers for these 10 participants.

The spectrum of noise varied from speech in the classroom and, separately, in the sound booth by 0.0 dB (within ±0.7 dB at each octave from 250 to 4000 Hz). The speech, and separately the noise, spectra varied between the classroom and the sound booth by 0.0 dB (within ±2.0 dB at each octave). All spectral outputs of speech and noise, therefore, were essentially the same.

Effects of RT on SNR

A change in RT, and thus acoustic panels, affected noise levels more than speech (see Table 2). This was likely due to relatively close locations of some acoustic panels to noise speakers. This change had the potential to confound the effects of RT with SNR on participants' scores. To prevent this, corresponding adjustments to noise levels maintained SNRs across changes in RT. For example, a change

in RT from 0.3 to 0.9 s increased speech levels by 2.6 dB and noise by 5.7 dB, for a net change in SNR of −3.1 dB. A subsequent 3-dB decrease in noise level counteracted the net change and thus maintained the original SNR.

Results

SNR-50 Scores

The mean SNR-50 score in 0.9-s RT was 7.87 dB (SD = 3.16 dB); in 0.6 s, 5.77 dB (SD = 2.68 dB); in 0.3 s, 4.76 dB (SD = 2.08 dB); and in the sound booth, 1.90 dB (SD = 2.22 dB; see Figure 2). The first analysis of results from RT conditions, three in the classroom and one in the sound booth, used a repeated-measures design with four levels of RT with SNR-50 scores as the dependent variable. The main effect of RT on speech perception was significant, $F(3, 27) = 54.81$, $p < .0001$. The change in mean score with each shortening of RT was significant in post hoc analysis (Fisher's least significance difference): from 0.9 to 0.6 s, $p = .0001$; from 0.6 to 0.3 s, $p = .0399$; and from 0.3 s to sound booth, $p < .0001$.

RT-SNR Percent Correct Scores

The second analysis of data allowed calculations of performance–intensity functions plotted in Figure 3. The online Supplemental Material S2 provides mean, standard deviation, and N for scores from 0 to +18 dB SNR by RT. Additionally, the second analysis used a 4 × 6 repeated-measures design with four levels of RT and six levels of SNR with RT-SNR percent correct scores as the dependent variable. The six levels of SNR were ones in which all 10 participants were tested across the four RT conditions. The main effect of RT on speech perception scores was significant, $F(3, 27) = 37.24$, $p < .0001$. The main effect of SNR was also significant, $F(5, 45) = 121.67$, $p < .0001$. The interaction between RT and SNR was significant, $F(15, 135) = 1.97$, $p = .0214$, possibly due to converging scores

Figure 2. Calculated speech-to-noise ratios (SNRs) for SNR-50 in three classroom reverberation times and in the sound booth. Error bars represent standard errors.
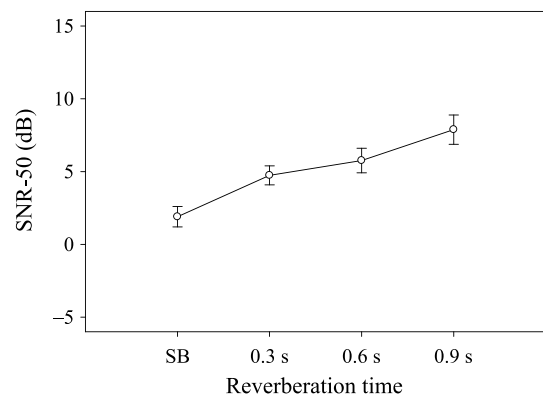
Table 2. Changes in speech and noise levels resulting from changes in reverberation time (RT).

RT (s)	Speech	Noise	Change in RT	Speech	Noise	SNR[a]
0.9	60.8	61.3	Change to 0.6	−1.3	−1.7	+0.4
0.6	59.5	59.6	Change to 0.3	−1.3	−4.0	+2.7
0.3	58.2	55.6	Change to 0.9	+2.6	+5.7	−3.1

Note. SNR = speech-to-noise ratio (dBA).

[a]These net changes in SNR with each change of RT were removed by adjustments in noise levels, thereby keeping SNRs constant across changes in RT.

Figure 3. Mean scores plotted as performance–intensity curves by reverberation time (RT) and speech-to-noise ratio when listening in the classroom. Error bars represent standard errors.
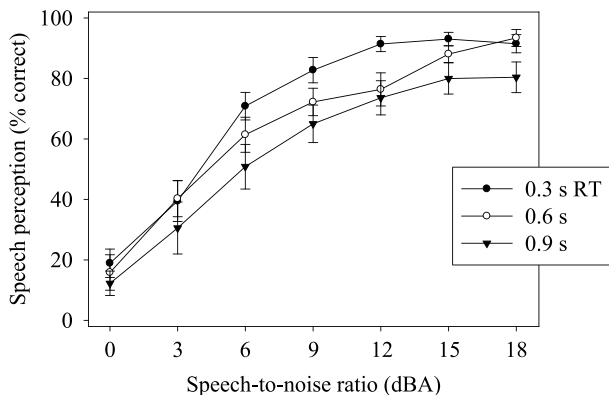
in apparent floor and ceiling effects at the most and least difficult SNRs.

Post hoc analyses of the effects between RT and SNR on percent correct scores in the classroom revealed several interesting facts. First, a single-step change in either RT or SNR alone yielded a significant change in scores in only 37% of comparisons. For example, within 0.6-s RT, the change in mean score with an improvement in SNR from +6 to +9 dB was nonsignificant ($p = .0559$), while an improvement from +3 to +6 dB was significant ($p = .0003$). Similarly, for example, within +12 dB SNR, shortening RT from 0.9 to 0.6 s yielded a nonsignificant change in score ($p = .6214$), while a shortening from 0.6 to 0.3 s resulted in a significant change ($p = .0085$). Second, and in contrast, each 3-dB increase in SNRs from 0 to +3 to +6 to +9 to +12 to +15 dB, in combination with one single-step reduction in RT from 0.9 to 0.6 to 0.3 s, yielded highly significant improvements in all scores (all $ps ≤ .0082$), with the exceptions of a significant change from 9 dB SNR in 0.9-s RT to 12 dB SNR in 0.6-s RT ($p = .0443$) and a significant change from +12 dB SNR in 0.9-s RT to +15 dB SNR in 0.6-s RT ($p = .0112$). An example of these changes is the 19.2 percentage point improvement in scores from 72.2% in 0.6-s RT and +9 dB SNR to 91.4% in 0.3-s RT and +12 dB SNR. A classroom mean score of > 90% correct did not occur in 0.9-s RT at any SNR and did occur in 0.6-s RT at only the highest SNR and at more, and lower, SNRs in 0.3-s RT (see Figure 3 and Supplemental Material S2).

Discussion

1. *Does reduction in classroom RT to 0.3 s from 0.6 s, as required by ANSI/ASA S12.60-2010/Part 1, benefit speech perception performance by children with hearing loss wearing hearing aids?*

Each reduction in RT from 0.9 to 0.6 to 0.3 s significantly improved speech perception overall for these children with hearing aids. The sample size in this study and the ranges of hearing loss and chronological ages across the participants may limit the generalizability of these results to all children who use hearing aids. These findings, at the same time, support in ANSI/ASA S12.60-2010/Part 1 the standard's Table 1, Footnote e, and Section 5.3.2 requirement that "core learning spaces ≤ 283 m^3 (≤ 10 000 ft^3) shall be readily adaptable to allow reduction in reverberation time to 0.3 s" and in Annex B, Commentary-5.3.1, the statement that "a reverberation time of 0.3 s…is necessary for children with hearing impairment and/or other communicative issues." This study provides the first peer-reviewed and published data to compare the performance of children with hearing aids listening in these two RTs provided in the ANSI/ASA-2010 standard. Finitzo-Hieber and Tillman (1978), the only other peer-reviewed, published study to measure speech perception performance by children with hearing loss and wearing hearing aids in the classroom-like RTs, compared scores in 1.2- to 0.4-s RT.

Evidence of the benefit of shortening RT from 0.6 to 0.3 s based solely on SNR-50 scores in the first analysis was significant, though not as strong a comparison as between 0.9- and 0.6-s RT (or between 0.3-s RT and the sound booth). Since each SNR-50 score represents the one SNR at which a listener is calculated to perceive 50% of words correctly, the analyses of SNR-50s in this study focused only on the effects of RT. The second analysis, using percent correct scores and performance–intensity functions, examined combined effects of RT and SNR. These analyses revealed that, when participants scored well in 0.6-s RT, for example, ≥ 85%, they also scored comparatively well in 0.3-s RT and, importantly, in approximately 3- to 6-dB more challenging noise conditions. For example, in 0.6-s RT and +18 dB SNR, participants scored > 90% correct, while in 0.3-s RT, they attained similar scores in both +15 and +12 dB SNR. This advantage provided by the shorter RT is notable in light of the reported noise levels in everyday classrooms.

From another perspective in this study, a little more than a third of the 3-dB increases in SNR alone or single-step changes in RT alone produced significant improvement in scores. Finitzo-Hieber and Tillman (1978), on the other hand, reported significant improvements in scores by the children with the hearing aid with every step in SNR and, separately, every step in RT. This difference in findings may have been due to Finitzo-Hieber and Tillman's step size in SNRs and RTs that was numerically twice the size as those in this study.

2. *Do clinical results for children with hearings aids listening in a near-anechoic sound booth predict speech perception performance in an acoustically well-treated classroom with an RT of 0.3 s?*

The children's mean speech perception performance in the sound booth was significantly better, by 2.86 dB SNR-50, than that observed in 0.3-s RT in the classroom. Comparisons of percent correct scores at specific SNRs in the sound booth to the score at the same SNR in 0.3-s RT offer another perspective (see Supplemental Material S2). Scores obtained in SNRs below apparent ceiling

effects, 0, +3, +6, and +9 dB, averaged 18.6% higher in the sound booth compared to results in 0.3-s RT in the classroom, with the largest difference of 31.4% at +3 dB SNR. These findings from both analyses suggest that clinical results obtained in near-anechoic conditions may likely overestimate speech perception abilities of children with hearing aids in 0.3-s RT. The sizes of standard deviations in both SNR-50 and RT-SNR scores, however, suggest caution in applying these averages to any one child.

At the time of this writing, the author could find no published study using SNR-50 scores from children wearing hearing aids to compare reverberant and nonreverberant listening conditions. The RT-SNR percent correct scores allow an alternative means of comparison. Finitzo-Hieber and Tillman's (1978) data permitted a within-SNR (0, +6, and +12 dB and quiet) comparison of scores obtained in 0.4-s RT, which, in the anechoic condition, improved by 9.3 percentage points (range: 7.3–11.2). A similar analysis in this study, limited to SNRs of 0, +6, +12, and +18 dB for the sake of comparison to listening conditions of 0.3-s RT and the sound booth, revealed a similar average improvement in scores of 11.0 percentage points (though a wider range: 3.3–26.9). Any comparison must be made in light of methodical differences between the Finitzo-Hieber and Tillman study and the present one such as differences in RT test conditions.

A consistent pattern emerged across studies in which children with hearing aids perceived speech in reverberation and noise better than those with cochlear implants and, as expected, with greater difficulty than those with typical hearing. In a near-anechoic listening condition, 10 children with typical hearing ages 5–15 years in Iglehart (2016) scored −0.5 dB SNR-50. As cited earlier and in similar listening conditions, the children with cochlear implants in the Iglehart study scored 7.4 dB SNR-50, while those in Neuman et al. (2012) similarly scored 5.82 dB SNR-50. The children with hearing aids in this study scored 1.90 dB SNR-50, a performance between children with typical hearing and those with cochlear implants.

This performance pattern continued in reverberant conditions. When listening in 0.3-s RT, Neuman et al. (2010) reported that 63 children ages 6–12 years and nine adults with typical hearing had an SNR-50 score of 2.7 dB. Iglehart (2016) reported that 23 children with typical hearing ages 5–16 years listening in 0.3-s RT had an SNR-50 score of −2.5 dB. Iglehart also reported that 23 children with cochlear implants ages 5–16 years had an SNR-50 score of 9.7 dB. The 10 children with hearing aids in this study scored 4.76 dB SNR-50. In 0.6-s RT, the same cohort with typical hearing in the study of Neuman et al. scored 3.4 dB SNR-50. The 23 children with typical hearing in the Iglehart study scored −2.3 dB SNR-50, while the 23 children with cochlear implants scored 10.9 dB SNR-50. Neuman et al. (2012) reported that the children with cochlear implants cited earlier scored 10.25 dB SNR-50. In this study, participants with hearing aids scored 5.77 dB SNR-50. In 0.9-s RT, Iglehart found that the children with typical hearing scored −0.6 dB SNR-50, while those with cochlear implants

scored 14.0 dB SNR-50. The children with hearing aids in this study scored 7.87 dB SNR-50.

Most test sessions were conducted after school, which limited each child's and parent's time. It was not possible, therefore, to add audiometric testing to confirm the hearing thresholds reported on the most recent audiogram available to this study or to electroacoustically test each child's hearing aid(s) for appropriateness of fit. The extent is not known to which possible changes in hearing status after each participant's audiogram was recorded may have affected results in this study. Not known, as well, is the percentage of students in classrooms on any given day who have appropriately fitted hearing aids, or the proportion who need updated adjustments, or the extent to which the suitability of amplification used by participants in this study may have reflected those with hearing aids in typical classrooms. The extent to which the quality of hearing aid fittings interacts with acoustics requires further study.

An issue may arise with the use of 0.3-s RT for children with hearing loss when children with typical hearing are also present in the classroom. Early sound reflections (< 50 ms) have been reported to benefit the perception of speech (e.g., Bradley & Sato, 2003; Lochner & Burger, 1964; Yang & Bradley, 2009), and shortening RTs may potentially reduce these early reflections significantly enough to affect listening. Other studies, however, have shown that reductions in RT caused no significant change in scores by children with typical hearing—from 0.4 to 0.0 s (Finitzo-Hieber & Tillman, 1978) or from 0.6 to 0.3 s (Iglehart, 2016; Neuman et al., 2010)—or, depending on comparisons, a reduction to 0.0-s RT had either no effect or improved children's scores (Wróblewski et al., 2012).

This study used the BKB-SIN test for several reasons. The use of multitalker babble in the test may better represent classroom noise compared to speech-shaped noise; the test presents a range of SNRs common to, or better than, most classrooms; and the test includes a sufficient quantity of sentence lists to cover all test conditions without repetition. The BKB-SIN test, however, presents each sentence list in SNRs progressing only from high to low values. Anecdotal observations outside this study suggest that this progression may cause some listeners to prematurely give up as sentences in a list become increasingly difficult to hear, possibly producing poorer scores compared to a test with adaptive procedures (e.g., Hearing in Noise Test for Children; Nilsson, Soli, & Gelnett, 1996). As well, future studies including the beneficial effects of speech reading and other visual cues may likely yield a more complete understanding of speech perception in classroom reverberation. Also of need in investigation is whether children with hearing loss exert greater listening effort as RT and noise increase, thus adding further cognitive load in understanding teachers and peers compared to those with typical hearing (e.g., Johnson, 2000; Klatte et al., 2010; Leibold, 2017; Nábělek & Robinson, 1982; Neuman et al., 2010; Wróblewski et al., 2012).

This study modified the BKB-SIN in several, nonvalidated ways. The SNR-50 is the only validated score in the BKB-SIN test and not the RT-SNR percent correct

scores with the resultant performance–intensity functions used in this study and by others (Neuman et al., 2010; Wilson, McArdle, & Smith, 2007; Wróblewski et al., 2012). The BKB-SIN also is validated with lists of eight and 10 sentences, not with the equalized length of all lists to eight sentences used in this study; with a start SNR of +21 dB, not with the use of adaptive start SNRs; and for use with noise, but not with noise and reverberation. The results of the study should be interpreted with caution in light of these changes to the validated use of the test.

Hearing aid technology can help improve speech perception in challenging acoustic conditions through the use of directional microphones and FM systems (e.g., Anderson et al., 2005). FM systems can help improve speech perception in noise and likely reduce the detrimental effects of reverberation. This is accomplished by reduction in the functional distance between talker and listener to well within the acoustical critical distance in any classroom. Some limitations, however, are FM access only to the talker with the microphone and FM reliability as an electronic system undergoing wear-and-tear from the children who use it.

Several aspects of the test conditions did not represent a classroom of children. The listening position was always both close (3.0 m) to the speech source and unchanging. The test classroom also was occupied by only three people, with noise of consistent spectrum and specific levels coming equally from all directions and with consistent RTs. One or more of these acoustically related factors would often change in a classroom of children. This study also measured the perception of only familiar words in simple sentences, while children in the classroom must perceive speech in a rich and ever-evolving linguistic environment.

The use of 50 acoustic panels to reduce RT in the study's classroom to 0.3 s may appear impractical for many classrooms. The test classroom, however, intentionally lacked acoustic ceiling tiles so that the resultant RT of 0.9 s could represent acoustics reported in classrooms, as well as contribute to the continuum of performance data obtained in 0.6- and 0.3-s RT. Several other similarly sized classrooms in the host school had acoustic ceiling tiles and a limited number of acoustic wall panels located conveniently between black/white boards, banks of windows, and large wall displays; the RTs measured close to 0.3 s. This relatively short RT may likely be readily attainable in other classrooms and without interference in room function.

The American Speech-Language-Hearing Association (2018) cites +15 dB SNR as a listening condition for children with typical hearing to "fully" perceive spoken messages in the classroom. Participants in this study demonstrated significant improvements of > 90% perception of speech in +15 dB SNR in the classroom, but only in 0.3-s RT. This necessity for both high SNRs and short RTs is consistent with observations from other studies of children with hearing loss listening in noise and low reverberation (children with hearing aid: Finitzo-Hieber & Tillman, 1978; children with cochlear implants: Iglehart, 2016). Though this study's small sample size and ranges of hearing loss and ages may limit the generalizability of these results to all children who use hearing aids, a growing body of evidence on speech perception by children with hearing loss supports the requirement of 0.3-s RT in ANSI/ASA S12.60-2010 and, as ASHA addresses, SNRs of at least +15 dB.

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