# The Assistive Benefits of Remote Microphone Technology for Normal Hearing Children With Listening Difficulties

Lucy Shiels, Dani Tomlin, and Gary Rance



**Objectives:** Children often present with listening difficulties (LiD) but with normal sound detection thresholds. These children are susceptible to learning challenges, and struggle with the suboptimal acoustics of standard classrooms. Remote microphone technology (RMT) is one way to improve the listening environment. The aim of this study was to determine the assistive potential of RMT for speech identification and attention skills in children with LiD, and to investigate whether the benefits obtained by these children were greater than for those with no listening concerns.

**Design:** A total of 28 children with LiD and 10 control participants with no listening concerns aged 6 to 12 years were included in this study. Children attended two laboratory-based testing sessions, where their speech intelligibility and attention skills were behaviorally assessed with and without the use of RMT.

**Results:** There were significant improvements in speech identification and attention skills when RMT was used. For the LiD group, use of the devices improved speech intelligibility to being comparable or better than control abilities without RMT. Auditory attention scores also improved from being poorer than controls without RMT to comparable to control performance with device assistance.

**Conclusions:** Use of RMT was found to have a positive effect on both speech intelligibility and attention. RMT should be considered a viable option for addressing common behavioral symptoms of LiD, including for the many children that present with concerns of inattentiveness.

**Key words:** Attention, Listening difficulties, Pediatric, Remote microphone technology, Speech intelligibility.

**Abbreviations:** AAA = American Academy of Audiology; ADHD = attention deficit hyperactivity disorder; AP = auditory processing; APD = auditory processing disorder; ASD = autism spectrum disorder; ASHA = American Speech-Language-Hearing Association; BSA = British Society of Audiology; CALIS = Child Anxiety Life Interference Scale – Child Version; IVA-QS = integrated visual and auditory continuous performance task – quick screen; LiD = listening difficulties; LIFE-R = listening inventory for education – revised student appraisal; RMT = remote microphone technology; SNR = signal-to-noise ratio.

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## INTRODUCTION

In school classrooms, reverberation times and noise levels rarely meet recommended standards, often leading to adverse listening conditions (Howard et al. 2010). Distance can increase difficulty, as students must be seated within 2 m of their teacher to overcome the negative effects of reverberation (Keith & Purdy 2014). A recent trend in schools is replacing traditional enclosed classrooms with open plan learning environments (Mealings et al. 2015), which can add further acoustic challenge. In these settings, large numbers of students sharing a space and participating in group activities results in even higher levels of intrusive speech noise (Mealings et al. 2015).

Suboptimal classroom acoustics make learning particularly challenging for children with compromised listening abilities (Keith & Purdy 2014). Dillon and Cameron (2021) describe listening difficulties (LiD) as "an umbrella term for observed or self-reported difficulties in understanding or responding to auditory stimuli, especially speech" (p. 1098). While the most recognized cause of LiD is peripheral hearing loss, similar presentations frequently occur in children with clinically normal sound detection thresholds (Hind et al. 2011). Normal hearing individuals with LiD most commonly have trouble understanding speech in noise or reverberation (Dawes & Bishop 2010; Moore 2012; Boothalingam et al. 2019; Moore et al. 2020; Dillon & Cameron 2021). Additional symptoms can include poor localization of sounds, difficulty following rapid speech, frequent requests for repetition, inappropriate comments in conversation, inattentiveness, and academic concerns related to spelling, reading, and learning (Dillon & Cameron 2021). Collectively, these reported behaviors have been described as auditory processing disorder (APD) (American Speech-Language-Hearing Association 2005; American Academy of Audiology 2010; British Society of Audiology 2018); however, challenges with auditory processing (AP) are not the only possible cause. Symptoms could instead be attributed to cognitive deficits (e.g., memory or attention), language deficits, or a combination of factors (Dillon & Cameron 2021). The neurological domains that contribute to listening are not isolated in function, making it challenging for audiologists to appropriately assess, diagnose, and manage symptoms.

Appropriate audiological management of children with LiD is complex given the wide scope of underlying deficits potentially causing presenting difficulties (Petley et al. 2021). As recognized by the British Society of Audiology (2018), a top priority of further research is to explore intervention options that address the specific listening needs of the individual. The same report statement summarizes that the current management strategies can be seen to fall into three key areas: auditory training, compensatory strategies, and modification of the listening environment. Environmental modification improves access to important auditory information by either enhancing the target signal or the acoustics of the listening environment. The use of personal remote microphone technology (RMT) in the classroom is one way to improve the signal accessibility. These devices consist of two components: ear-level receivers worn by the listener and a microphone/transmitter worn by a primary speaker (usually a teacher). The use of RMT improves the signal-to-noise ratio (SNR) the child receives, which can bypass challenges as a result of noise, reverberation, and distance (Keith & Purdy 2014). Although audiologists often consider RMT as a suitable intervention for children who present

Department of Audiology and Speech Pathology, University of Melbourne, Parkville, Victoria, Australia.







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with LiD, there is currently no consensus on which clinical presentations warrant the recommendation or the best methods to measure outcomes from device use (Smart et al. 2018).

For school-aged children, the main disadvantage of LiD is the reduced ability to understand speech in acoustically challenging circumstances (Dawes & Bishop 2010; Moore 2012; Boothalingam et al. 2019; Moore et al. 2020; Dillon & Cameron 2021). Therefore, it is unsurprising that most studies investigating the effects of RMT have primarily focused on the assistive and associated learning benefits in the classroom setting. When wearing receivers, children have consistently been found to have improved speech perception in quiet and background noise. Although RMT can overcome acoustic barriers for any user, significantly greater improvements have been measured in those with LiD compared to controls with no auditory concerns (Johnston et al. 2009; Rance et al. 2010; Schafer et al. 2013; Rance 2014). Research on children who received a diagnosis of APD has reported average aided gains in noise of 13% in word discrimination (Smart et al. 2018) and 10 dB in reception thresholds for sentences (Johnston et al. 2009), with similar results obtained by other populations who commonly experience LiD including those with attention deficit hyperactivity disorder (ADHD) (Schafer 2013; Schafer 2014), autism spectrum disorder (ASD) (Schafer 2013; Rance 2014; Schafer 2014), and Friedreich Ataxia (Rance et al. 2010). RMT use during laboratory-based measures has also been found to reduce the negative impacts of noise on cortical auditory-evoked potential amplitudes and latencies (Smart et al. 2018), indicating an advantage in adverse listening conditions can be measured both behaviorally and electrophysiologically. In addition to clinical findings, questionnaire results from teachers, parents, and students indicate positive outcomes regarding classroom engagement and academic performance (Friederichs & Friederichs 2008; Johnston et al. 2009; Smart et al. 2018; Stavrinos et al. 2020). Notable improvements have related to perceived listening ability, on-task behaviors, following instructions, contributions to class discussion, appropriateness of answers to questions, and learning outcomes.

Compared to children with no auditory concerns, those who experience LiD are more likely to exhibit concentration issues including impaired auditory attention and inhibitory control (Allen & Allan 2014). Increased attentiveness is another reported improvement from RMT intervention; however, supporting evidence is currently limited. To date, no studies have attempted to behaviorally measure the impact of device use on attention skills, but questionnaire findings suggest benefit during RMT use. Friederichs and Friederichs (2008) investigated the use of RMT over a 12-month period in 10 children with symptoms of APD, many of whom had a diagnosis of ADHD. Teachers reported a significant attentional benefit; however, parental responses to the same questionnaire showed no improvement. The authors suggested this inconsistency was due to the devices predominantly being used at school; therefore, significant changes in behavior were more likely to be observed by educators.

Diminished psychosocial health is another consequence of the communication challenges experienced by children with LiD (Kreisman et al. 2012). Children who have received a diagnosis of APD are reported to exhibit higher rates of social stress, anxiety, depression, and self-esteem issues compared to their peers (Johnston et al. 2009). There is some evidence to suggest that improving the listening environment with RMT may result in positive change to psychosocial status. Johnston et al. (2009) used the Behavioral Assessment System for Children questionnaire to measure emotional and social abilities in children with a diagnosis of APD before and at the conclusion of an RMT trial. At the post-trial, subjects self-rated themselves as significantly less likely to experience problems relating to locus of control, depression, anxiety, and interpersonal relationships. Another study investigated the associations between functional listening ability and stress in children with ASD (Rance et al. 2017). By measuring salivary cortisol levels, they showed a significant reduction in listening-related stress when subjects wore RMT in a structured listening situation. These findings indicate that enhancing the auditory environment may have broader impacts on overall wellbeing and health.

Although RMT is increasingly being utilized by students with normal audiograms in today's classrooms, there is clinical confusion regarding which presentations of LiD should be recommended device use. Given parents commonly report concerns of inattentiveness and distractibility to audiologists assessing this population (Dawes & Bishop 2009), it is important to consider the potential benefits of audiological intervention for addressing these symptoms. Previous literature regarding RMT trials has documented improvements for a range of auditory behaviors; however, the impact of device use on auditory attention skills has not yet been explored. The purpose of the current study was to investigate the assistive potential of RMT use for speech identification in noise, auditory attention, and visual attention skills in normal-hearing children with LiD. Based on previous research, it was predicted that speech identification and auditory attention skills would improve when the children with LiD were using RMT, but that visual attention skills would remain unchanged. A secondary aim was to investigate the difference in behavioral benefits for the LiD group compared to a group of children who had no listening concerns. It was anticipated that all children would benefit from device use, but the improvements would be significantly greater for those with evidence of LiD.

## MATERIALS AND METHODS

The protocol for this research was approved by the Human Research Ethics Committee of The University of Melbourne (Ethics identification number: 1999857.1).

### Participants

Thirty-eight primary school-aged children were enrolled in the study. All participants were required to have normal pure-tone hearing thresholds (screened at octave frequencies from 250 Hz to 8 kHz at 10 dBHL in a sound-attenuated booth) and normal middle ear function bilaterally (type A tympanograms and present ipsilateral acoustic reflexes at 1 kHz bilaterally). None had neurodevelopmental diagnoses or learning disabilities, and all used English as their primary language.

Twenty-eight of the children (17 males) had reported LiD and were recruited through the University of Melbourne Audiology Clinic following a behavioral assessment of listening skills. Average age at assessment was 8 years; 6 months ± 1 year; 7 months; and ranged from 6 years, 0 months to 12 years, 6 months. Initial assessment included measures of temporal sequencing (frequency pattern test; Musiek 1994), binaural integration (dichotic digit test; Musiek 1983), temporal resolution (gaps in noise; Musiek et al. 2005), binaural interaction (listening in spatialized noise-sentences test; Cameron & Dillon 2007), and sustained auditory attention (integrated visual and auditory continuous performance task – quick screen (IVA-QS); Sandford & Anton 2014). For each of these assessments, *z* scores were calculated based on age-specific, normative data from published resources (Cameron & Dillon 2007; Sandford & Anton 2014; Tomlin et al. 2014, 2015), expressing performance as difference from the mean in standard deviation (SD) units. Scores falling two or more SDs below age-based mean were regarded as abnormal. Selection for the study was not based on having a diagnosis of APD due to the lack of universally accepted diagnostic criteria (Moore 2018), and because the cause/s of poor test performance could not be conclusively attributed to deficits in AP. Instead, children with behavioral evidence of LiD, as measured by abnormal performance on at least one test, were considered eligible for recruitment. No children scored significantly outside normal limits on the temporal resolution task. A summary of the deficits identified for the other listening tasks can be seen in Table 1.

An additional group of 10 children (five males) with normal sound detection thresholds were recruited as controls through word-of-mouth in the community. Inclusion criteria were no parent-reported concerns regarding listening, attention, or academic progress. Average age at assessment for the control group was 9 years; 1 month ± 2 years; 0 months; and ranged from 6 years, 6 months to 10 years, 4 months.

To evaluate baseline difficulties of the two groups, each participant (n = 38) completed two questionnaires. Perceived classroom listening challenge was measured using the Listening Inventory for Education – Revised Student Appraisal questionnaire (Anderson et al. 2011), which quantifies the child's degree of listening difficulty in 15 classroom, school and social listening scenarios. Participants with LiD had significantly lower scores than controls, indicating they perceived more listening challenges [$t(18) = -6.69$, $p < 0.001$, $d = 2.37$].

The Child Anxiety Life Interference Scale – Child Version (Lyneham et al. 2013) was used to assess anxiety-related life interference/impairment. The Child Anxiety Life Interference Scale – Child Version includes nine questions regarding anxiety levels in four situations at home and five situations outside the home. Children in the LiD group rated their anxiety-related life impairment as greater than controls for situations outside home [$t(28) = 3.38$, $p = 0.02$, $d = 1.08$], but not when considering home-based scenarios [$t(13) = 1.40$, $p = 0.18$, $d = 0.60$].

All parents who agreed to having their child participate signed written consent informing them of the research purpose, details of their child's involvement, and the possible benefits and risks of involvement in the study.

## Procedure

Behavioral assessments were administered at the University of Melbourne Audiology Clinic in a realistic, simulated classroom environment with an unoccupied noise level of 42 dBA and unoccupied reverberation time of 0.78 sec. Each child was required to participate in two, 1-hr sessions scheduled ~2 weeks apart. At the beginning of session one, participants were fit bilaterally with RMT to be worn during behavioral testing. At each visit, assessments of speech identification and attention

**TABLE 1. Deficits identified in each participant of the listening difficulties group**

| Subject | Age | Gender | Temporal Sequencing | Binaural Integration | Binaural Interaction | Sustained Auditory Attention |
|---|---|---|---|---|---|---|
| 1 | 9 yrs; 10 mos | M | | ✓ | | |
| 2 | 7 yrs; 10 mos | M | | | | ✓ |
| 3 | 8 yrs; 1 mo | M | | | ✓ | |
| 4 | 12 yrs; 6 mos | M | ✓ | | | ✓ |
| 5 | 8 yrs; 4 mos | M | | | ✓ | |
| 6 | 8 yrs; 2 mos | F | | | | ✓ |
| 7 | 10 yrs; 2 mos | F | | | ✓ | |
| 8 | 12 yrs; 5 mos | F | | ✓ | ✓ | ✓ |
| 9 | 8 yrs; 1 month | F | | ✓ | | |
| 10 | 9 yrs; 5 mos | F | ✓ | ✓ | | |
| 11 | 7 yrs; 10 mos | M | | | | ✓ |
| 12 | 9 yrs; 6 mos | M | | | | ✓ |
| 13 | 8 yrs; 11 mos | F | ✓ | | | ✓ |
| 14 | 8 yrs; 10 mos | M | | ✓ | | |
| 15 | 9 yrs; 10 mos | M | ✓ | | | |
| 16 | 7 yrs; 11 mos | F | | ✓ | | |
| 17 | 7 yrs; 2 mos | M | | ✓ | | ✓ |
| 18 | 10 yrs; 7 mos | F | ✓ | | | |
| 19 | 7 yrs; 6 mos | M | ✓ | ✓ | | |
| 20 | 7 yrs; 4 mos | F | ✓ | ✓ | | |
| 21 | 6 yrs; 11 mos | M | | | | ✓ |
| 22 | 6 yrs; 6 mos | F | | | ✓ | ✓ |
| 23 | 8 yrs; 2 mos | F | | | ✓ | ✓ |
| 24 | 7 yrs; 10 mos | M | ✓ | ✓ | ✓ | ✓ |
| 25 | 7 yrs; 8 mos | M | ✓ | | | ✓ |
| 26 | 7 yrs; 11 mos | M | | | | ✓ |
| 27 | 6 yrs; 0 mos | M | | | | ✓ |
| 28 | 6 yrs; 6 mos | M | | | | ✓ |

*✓, deficit identified.*

in noise were either undertaken with or without RMT, and the order of device condition was randomized across the two sessions to account for any potential learning effects. A total of 14 of the LiD group and five of the controls completed assessments in session one without RMT, and session two using the devices. The remaining participants from each group completed testing in the opposite order.

### RMT Fitting

Participants were fit bilaterally with Phonak Roger Focus II receivers that were wirelessly connected to a Phonak Roger Touchscreen Microphone transmitter. Fitting of the devices followed standard clinical procedures. To check the comfort of receiver volume, the examiner wore the transmitter while standing 1 m from the participant and spoke at a level of ~50 dBA (as measured on a sound level meter set to fast). The participant was asked to listen to the examiner and rate volume comfort using a 5-point scale from 'much too soft' to 'much too loud'. Volume was adjusted in 2 dB steps until the participant subjectively rated the comfort of the examiner's voice as 'just right'. Receivers were then locked at this level for behavioral testing. Most participants found the default Roger Focus volume comfortable (LiD n = 17; control n = 9). For the remaining participants, volume setting was decreased for seven (LiD n = 6; control n = 1) and increased for five (LiD n = 5; control = 0). Mean adjustments were $0.3 \pm 3.1$ dB and $-0.2 \pm 0.6$ dB for the LiD and control groups, respectively.

Device use was limited to the laboratory-based behavioral testing for the control group. The LiD group were permitted to take the devices home for a 2-week, school-based trial between the two laboratory visits; however, outcomes from this trial period were beyond the scope of the current study. Twenty-six of the 28 LiD families opted into the 2-week trial.

### Behavioral Assessments

For behavioral testing, a Behringer Monitor MS16 speaker presented test materials sourced from a HP Probook laptop. Four additional Behringer Monitor MS16 speakers were connected to a Dell Latitude E6540 laptop and played four-talker babble noise from the four corners of the room (see Figs. 1 and 2). The Touchscreen Microphone was positioned 20 cm below the target speaker to replicate the recommended distance from a wearer's mouth in everyday use (Rance et al. 2010).

Open-set speech intelligibility in noise was measured using the AzBio sentences test (Spahr et al. 2012), which has been recognized as a reliable and valid tool when used on listeners with normal hearing (Schafer et al. 2012). This test comprises 10 lists including 20 sentences each and spoken by four different talkers (two male and two female talkers). Participants were required to repeat each sentence, and a percentage of correctly identified words was calculated by the examiner. At each session, participants completed two AzBio lists positioned 1.5 m from the target speaker and another two lists at 5 m away to account for different seating locations in a classroom (i.e. front and back). Signal and noise levels for each condition were calibrated at the listener's head position and were selected to reflect a typical range of noise levels and SNRs measured in primary-school classrooms (Crandell & Smaldino 2000; Howard et al. 2010). Parameters for each AzBio listening condition are summarized in Table 2. The examiner was positioned within 1 m of the participant for all AzBio testing to enable clear perception and reliable scoring of verbal responses.

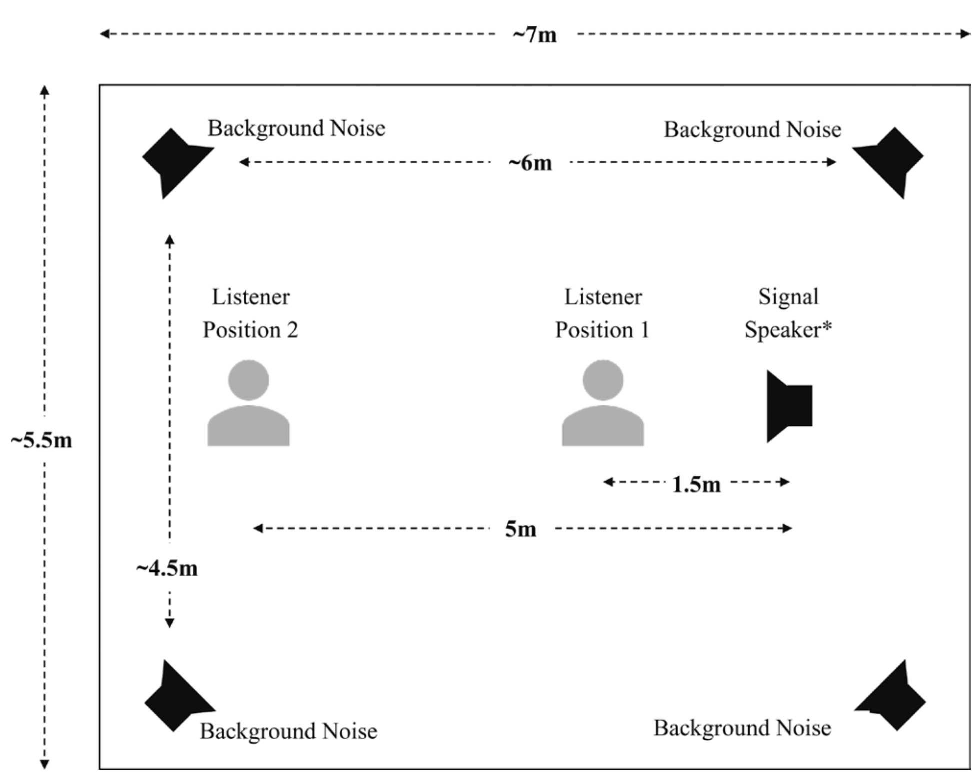


Fig. 1. Room setup for the AzBio Sentences Test. *Touchscreen Microphone positioned 20 cm below the signal speaker. cm indicates centimeters; m, meters.

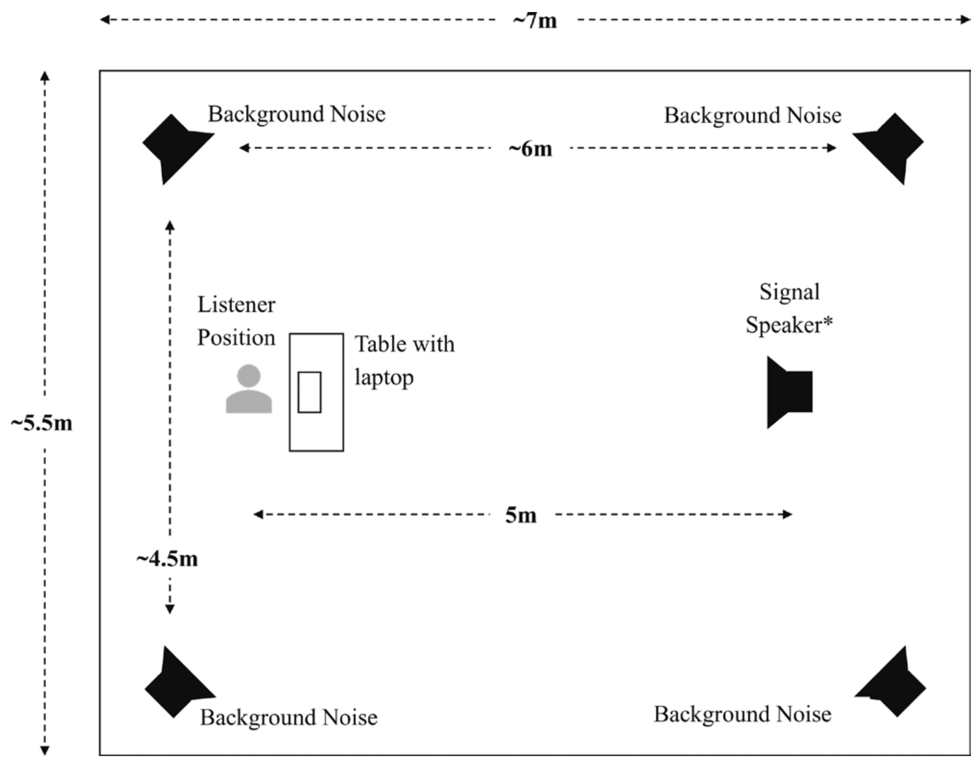


Fig. 2. Room setup for the IVA-QS. *Touchscreen Microphone positioned 20 cm below the signal speaker. cm indicates centimeters; IVA-QS, Integrated Visual and Auditory Continuous Performance Task – Quick Screen; m, meters.



Auditory and visual attention were measured using the IVA-QS (Sandford & Anton 2014). The IVA-QS requires participants to click a computer mouse when the number one is seen or heard but to ignore any number two stimuli for a period of 8 min. IVA-QS was completed on a laptop positioned 5 m from the target speaker (see Fig. 2). Auditory stimulus was calibrated to reach the listener's head at a level of 50 dBA, while the four corner speakers provided diffuse background noise (four-talker babble) at an equivalent level (0 dB SNR). Although the LiD group had previous exposure to the IVA-QS during their enrollment assessment, this initial attempt was completed in quiet under headphones as opposed to the simulated classroom setup that was utilized for research purposes. IVA-QS performance is divided into five subscales: full scale, auditory, visual, sustained auditory, and sustained visual attention. The auditory and visual attention scores are derived from vigilance, focus, and speed measures. Vigilance is evidenced by two different types of errors of omission during the test, speed reflects the average response time for correct responses, and focus measures the total variability of mental processing speed for correct responses. Full scale attention is based on a combination of the global auditory and visual attention scores. Finally, the sustained attention subscale for each modality provides a global measure of the ability to reliably and accurately respond to stimuli under low demand conditions, as well as sustain attention and be flexible under high demand conditions when stimuli change.

## Data Analysis

Data were analyzed by the first and final authors using Minitab software. Mixed effects repeated measures analysis of variance (ANOVA) was performed with subject group (LiD/control) as the between-subject factor and test order (first/second session), device condition (with/without RMT), and SNR (+12, +5, 0, and −10 dB) as within-subject factors. Fixed effects were followed up with post hoc analyses using Tukey pairwise comparisons and simultaneous tests for differences of means. Separate ANOVAs were performed for the AZBio and for the IVA-QS scores. Model assumptions were checked using residual plots and were met across all analyses.

# RESULTS

## Open-Set Speech Intelligibility in Noise

All participants (n = 38) completed assessments of speech intelligibility with and without the use of RMT.

**TABLE 2. AzBio listening conditions**

| Distance (m) | Signal Level* (dBA) | Noise Level* (dBA) | SNR at Listener's Head |
|---|---|---|---|
| 1.5 | 62 | 50 | +12 |
| 1.5 | 70 | 65 | +5 |
| 5 | 50 | 50 | 0 |
| 5 | 55 | 65 | −10 |

*Calibrated at the listener's head position.
dBA, A-weighted decibel; SNR, signal-to-noise ratio.

### Summary of Main Effects

Table 3 summarizes the repeated-measures ANOVA findings for the speech intelligibility assessment. AZBio scores were affected by subject group, device condition, and SNR. Significant interactions were also seen between subject group and device condition, device condition and SNR, and group and SNR. There was no significant difference in behavioral performance between test orders.

In general, AZBio scores decreased as the SNR decreased [$t(251) \geq 6.75$; $p < 0.001$] and increased with RMT use [$t(251) = 17.91$; $p < 0.001$]. There was a significant interaction between SNR and treatment condition indicating that RMT benefit depends on difficulty of the listening scenario. With the exception of +12 dB SNR, AZBio scores were significantly higher in all SNR conditions when listeners were using RMT.

At the group level, AZBio scores were significantly lower for participants with LiD compared to the control [$t(36) = -3.20$; $p = 0.003$]. While participants with LiD performed significantly worse than the control group in the unaided condition [$t(43.55) = -3.70$; $p = 0.001$], there was no significant difference when listeners were using RMT [$t(43.55) = -8.47$; $p = 0.086$]. Group performance also differed depending on the listening condition, as indicated by the interaction between subject group and SNR. While both groups generally yielded poorer performance as the SNR decreased, similar results were achieved in the 0 and 5 dB SNRs for the LiD group, and in the 5 and 12 dB SNRs for the controls.

### LiD Group

Speech intelligibility of the LiD group was impacted by increasing noise and distance. Mean scores were poorer as SNR levels decreased when listening at both distances of 1.5 m [$t(251) = 9.91$; $p < 0.001$] and 5 m [$t(251) = 15.09$; $p < 0.001$]. As demonstrated in Table 4, utilization of RMT yielded speech intelligibility benefits across all SNRs aside from in the easiest condition of 12 dB SNR. At 1.5 m, the improvement in the SNR of 5 dB increased scores to being comparable to performance in the easier SNR of 12 dB. Despite increased performance with RMT in both conditions at 5 m, speech intelligibility remained poorer in the −10 dB SNR compared to the 0 dB SNR [$t(251) = 3.49$; $p = 0.046$].

### Control Group

Unlike the children with LiD, when listening at 1.5 m from the target speaker, speech intelligibility for the control group was unaffected by decreasing the SNR from 12 dB to 5 dB. However, at 5 m, scores were poorer in the −10 dB SNR compared to the 0 dB SNR [$t(251) = 8.00$, $p < 0.001$], consistent with findings from the LiD group. Mean benefits from RMT use for the controls are listed in Table 4. As can be seen, scores remained unchanged in the 1.5 m conditions but improved with device use at 5 m. With the benefits yielded at 5 m, there were no longer differences in performance at the 0 dB and −10 dB SNRs, meaning scores were less impacted by increasing the noise level.

### Group Comparisons

Comparisons of the speech intelligibility benefits obtained from RMT use for both the control and LiD groups are demonstrated in Figure 3. Without RMT, the LiD cohort had poorer speech identification in the 5 dB SNR at 1.5 m [$t(97.24) = -4.94$; $p < 0.001$], but the scores achieved across the other SNRs were similar between the groups. Comparing LiD performance with RMT to control performance without RMT revealed that scores increased to being

**TABLE 3. Repeated-measures ANOVA results for the AZBio sentences test**

| Effects | $DF_{Num}$ | $DF_{Den}$ | *F*-Value | *p* |
|---|---|---|---|---|
| Group | 1.00 | 36.00 | 10.23 | 0.003 |
| Device condition | 1.00 | 251.00 | 320.71 | >0.001 |
| Test order | 1.00 | 251.00 | 1.54 | 0.216 |
| SNR | 3.00 | 251.00 | 155.13 | >0.001 |
| Group × device condition | 1.00 | 251.00 | 4.70 | 0.031 |
| Group × SNR | 3.00 | 251.00 | 3.68 | 0.013 |
| Device condition × SNR | 3.00 | 251.00 | 66.29 | >0.001 |
| Group × device condition × SNR | 3.00 | 251.00 | 0.95 | 0.417 |

*$DF_{Num}$, numerator degrees of freedom; $DF_{Den}$, denominator degrees of freedom; SNR, signal-to-noise ratio.*

**TABLE 4. Mean AZBio scores with and without RMT**

| SNR (dB) | Mean ± SD (%) Without RMT | Mean ± SD (%) With RMT | Mean ± SD (%) Benefit With RMT | DF | Simultaneous 95% CI | *T*-Value | Adjusted *p* |
|---|---|---|---|---|---|---|---|
| LiD group | | | | | | | |
| -10 | 20.96 ± 11.70 | 70.91 ± 17.33 | 49.95 ± 16.26 | 251.00 | (41.49–58.40) | 20.44 | >0.001 |
| 0 | 57.82 ± 14.65 | 79.44 ± 12.88 | 21.61 ± 14.81 | 251.00 | (13.16–30.07) | 8.85 | >0.001 |
| 5 | 56.13 ± 17.55 | 77.53 ± 11.24 | 21.40 ± 13.58 | 251.00 | (12.94–29.86) | 8.76 | >0.001 |
| 12 | 80.34 ± 11.70 | 83.38 ± 11.88 | 3.03 ± 10.96 | 251.00 | (–5.42 to 11.49) | 1.24 | 0.997 |
| Control group | | | | | | | |
| -10 | 34.45 ± 10.97 | 80.76 ± 14.80 | 46.31 ± 16.77 | 251.00 | (32.40–60.74) | 11.38 | >0.001 |
| 0 | 67.14 ± 12.69 | 84.75 ± 14.68 | 17.61 ± 10.50 | 251.00 | (3.70–32.04) | 4.37 | 0.002 |
| 5 | 80.54 ± 13.69 | 89.67 ± 8.64 | 9.13 ± 7.41 | 251.00 | (–4.78 to 23.56) | 2.29 | 0.628 |
| 12 | 92.21 ± 8.66 | 93.37 ± 6.86 | –1.16 ± 4.54 | 251.00 | (–12.75 to 15.59) | 0.35 | 1.000 |

*CI, confidence interval; dB, decibel; DF, degrees of freedom; LiD, listening difficulties; RMT, remote microphone technology; SNR, signal-to-noise ratio.*

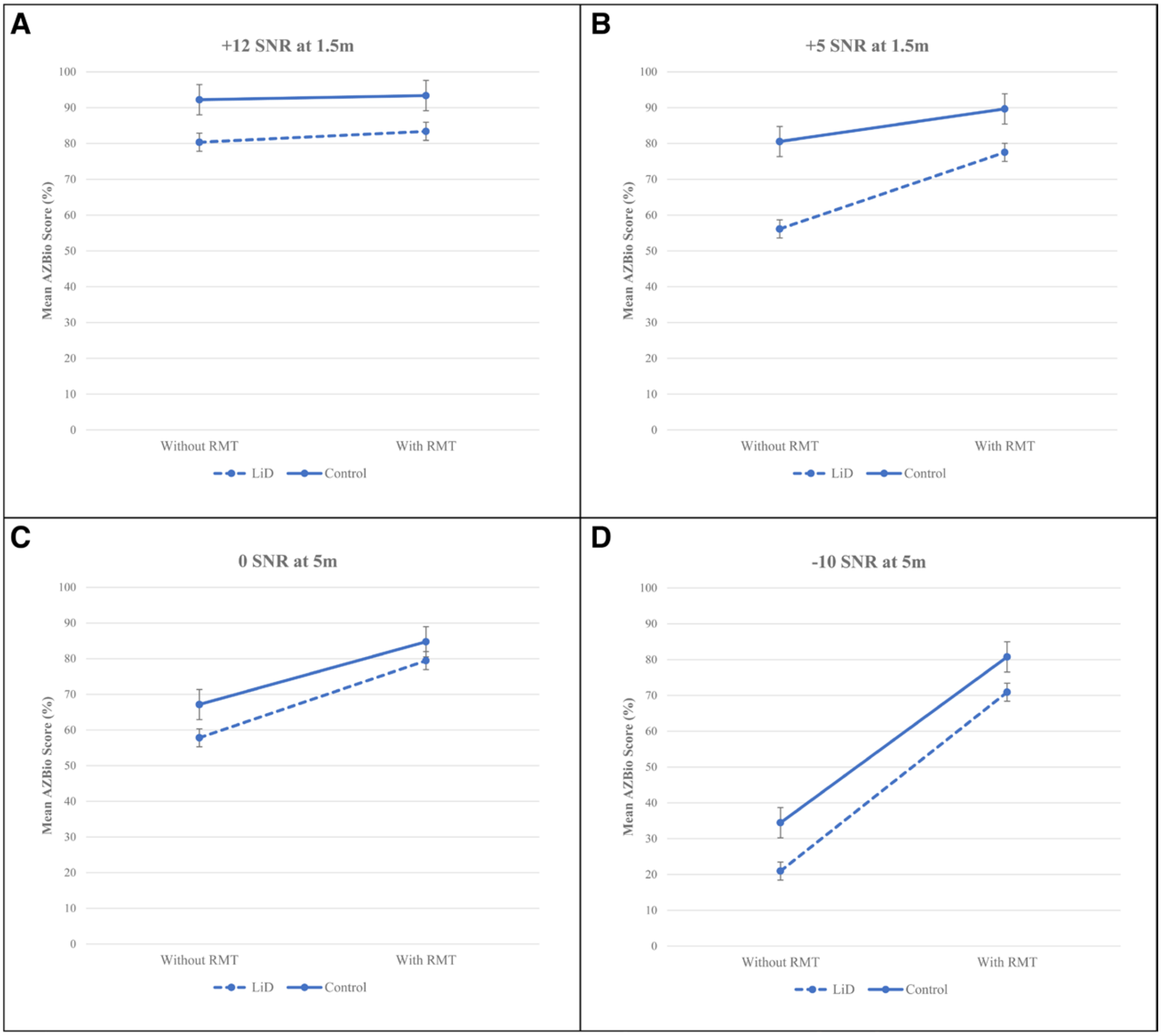


Fig. 3. Mean AzBio test scores for the LiD (n = 28) and control (n = 10) groups with and without RMT in listening conditions (A) +12 dB SNR at 1.5 m, (B) +5 dB SNR at 1.5 m, (C) 0 dB SNR at 5 m, and (D) −10 dB SNR. Error bars represent the SE of the mean. dB indicates decibels; LiD, listening difficulties; m, meters; n, number of participants; RMT, remote microphone technology; SNR, signal-to-noise ratio.

similar in the 5 dB SNR, remained comparable in the 12 dB and 0 dB SNRs, and resulted in the LiD group outperforming the controls in the −10 dB SNR [$t(97.24) = 7.45$; $p < 0.001$]. Comparisons of the mean improvements attained by each group showed no difference in benefit in the 12 dB, 0 dB, or −10 dB SNRs. However, at 5 dB SNR, RMT use yielded a larger benefit for the LiD group than the controls [$t(27) = -16.26$; $p < 0.001$].

### Attention in Noise

All participants completed attention testing; however, an error in the laboratory setup invalidated the data obtained from the first 10 children assessed with LiD. The remaining LiD subjects (n = 18) and all control subjects (n = 10) were included in the following analyses.

### Summary of Main Effects

The repeated-measures ANOVA findings for the attention assessment can be found in Table 5. Main effects on IVA-QS scores included group, device condition, test order, and IVA-QS subscale, as well as an interaction between group and device condition.

Performance was generally better for the controls compared to the LiD group [$t(24.95) = 4.06$; $p < 0.001$], and increased with device use [$t(197.88) = 3.07$; $p = 0.002$]. However, the degree of benefit from RMT varied between the two groups. RMT did not impact performance for the controls, but resulted in improved scores for the LiD subjects [$t(198.63) = 6.12$; $p < 0.001$]. Auditory scores were found to be poorer than visual scores for both the attention [$t(198.74) = 4.85$; $p < 0.001$] and sustained attention [$t(198.74) = 5.76$; $p < 0.001$] subscales. Scores were also highest during the first as opposed to the second test session [$t(197.88) = -4.17$; $p < 0.001$].

### LiD Group

Without device assistance, the LiD group had poorer attention [$t(199.43) = 4.62$; $p = 0.001$] and sustained attention

[$t(199.43) = 5.49$; $p < 0.001$] toward auditory stimuli compared to visual stimuli. Table 6 summarizes the benefits yielded from wearing RMT. Significant attention improvements were evident for the auditory subscales, but not for the visual subscales. The enhanced concentration on auditory stimuli from RMT use meant that there were no longer differences in the level of attention or sustained attention directed toward the two sensory modalities.

### Control Group

In contrast to the LiD findings, attention was similar toward auditory and visual stimuli for the control subjects. Table 6 compares the mean scores obtained with and without RMT. Device utilization resulted in no changes to the scores obtained across all IVA-QS subscales.

### Group Comparisons

Comparisons between the two groups for each IVA-QS subscale can be seen in Figure 4. Without RMT, the LiD group had poorer scores for full scale [$t(79.33) = 4.47$; $p = 0.002$], auditory [$t(71.10) = 5.00$; $p < 0.001$], and sustained auditory attention [$t(71.10) = 5.49$; $p < 0.001$), but not for visual or sustained visual attention. For the LiD group, the improvements in scores with RMT use increased performance to match that of the controls without RMT across all subscales: full scale, auditory, sustained auditory, visual, and sustained visual. The benefit obtained from device utilization was greater for the LiD group compared to the controls for full scale [$t(20) = 2.45$; $p = 0.024$], auditory [$t(25) = 3.23$; $p = 0.003$], and sustained auditory attention [$t(24) = 2.96$; $p = 0.007$]. However, device benefit was the same for both the groups for the visual and sustained visual subscales.

## DISCUSSION

In school-aged children, the presence of LiD can have negative consequences for speech understanding, attention, educational outcomes, and psychosocial wellbeing (Keith & Purdy 2014). The current study aimed to determine the assistive potential of RMT use for speech identification and attention skills in normal-hearing children with LiD, and to investigate whether the benefits obtained by these children were greater than those with no listening concerns.

### Speech Intelligibility in Noise

Children with LiD demonstrated poorer speech intelligibility in noise compared to those with no listening concerns. Consistent with previous literature (Johnston et al. 2009; Smart et al. 2018), enhancing the acoustic signal with RMT resulted in improved speech identification. Benefits were applicable at various SNRs and distances that are representative of usual listening conditions in a classroom setting. American Speech-Language-Hearing Association (2005) recommends classroom SNRs should be at minimum +15 dB for students with normal hearing. Realistically, schools present more difficult situations with typical SNRs ranging from −7 to +5dB, and often nearing 0 dB (Howard et al. 2010). Distance from the teacher can add further acoustic strain depending on individual seating position.

**TABLE 5. Repeated-measures ANOVA results for the IVA-QS**

| Effects | $DF_{Num}$ | $DF_{Den}$ | F-Value | *p* |
|---|---|---|---|---|
| Group | 1.00 | 24.95 | 16.49 | >0.001 |
| Device condition | 1.00 | 197.88 | 9.45 | 0.002 |
| Test order | 1.00 | 197.88 | 17.42 | >0.001 |
| IVA-QS subscale | 4.00 | 198.14 | 14.74 | >0.001 |
| Group × device condition | 1.00 | 197.84 | 23.51 | >0.001 |
| Group × IVA-QS subscale | 4.00 | 198.14 | 2.18 | 0.072 |
| Device condition × IVA-QS subscale | 4.00 | 197.39 | 0.33 | 0.856 |
| Group × device condition × IVA-QS subscale | 4.00 | 197.39 | 0.88 | 0.479 |

*ANOVA, analysis of variance; $DF_{Den}$, denominator degrees of freedom; $DF_{Num}$, numerator degrees of freedom; IVA-QS, integrated visual and auditory continuous performance task – quick screen.*

**TABLE 6. Mean IVA-QS scores with and without RMT**

| IVA-QS Subscale | Mean ± SD Without RMT | Mean ± SD With RMT | Mean ± SD Benefit With RMT | DF | Simultaneous 95% CI | *T*-Value | Adjusted *p* |
|---|---|---|---|---|---|---|---|
| LiD group | | | | | | | |
| Full scale attention | 63.00 ± 20.94 | 80.39 ± 19.33 | 17.39 ± 35.39 | 198.06 | (−1.65 to 36.43) | 3.28 | 0.122 |
| Auditory attention | 56.23 ± 20.11 | 74.14 ± 22.78 | 17.91 ± 27.62 | 197.49 | (1.45–34.37) | 3.91 | 0.018 |
| Sustained auditory attention | 50.29 ± 22.89 | 68.34 ± 26.31 | 18.08 ± 34.76 | 197.49 | (1.62–34.54) | 3.95 | 0.015 |
| Visual attention | 79.23 ± 16.52 | 87.55 ± 18.66 | 8.32 ± 31.19 | 197.80 | (−10.29 to 26.94) | 1.61 | 0.988 |
| Sustained visual attention | 77.61 ± 22.41 | 84.78 ± 15.26 | 7.17 ± 32.67 | 197.80 | (−11.45 to 25.79) | 1.38 | 0.998 |
| Control group | | | | | | | |
| Full scale attention | 98.38 ± 16.68 | 95.72 ± 16.94 | −2.67 ± 8.24 | 197.29 | (−23.79 to 18.46) | −0.45 | 1.000 |
| Auditory attention | 94.48 ± 17.94 | 90.72 ± 18.80 | −3.77 ± 13.55 | 197.29 | (−24.89 to 17.36) | −0.64 | 1.000 |
| Sustained auditory attention | 92.28 ± 17.08 | 86.02 ± 21.44 | −6.27 ± 13.74 | 197.29 | (−27.39 to 14.86) | −1.07 | 1.000 |
| Visual attention | 100.68 ± 14.84 | 100.92 ± 15.50 | 0.23 ± 9.45 | 197.29 | (−20.89 to 21.36) | 0.04 | 1.000 |
| Sustained visual attention | 100.28 ± 13.86 | 97.02 ± 16.10 | −3.27 ± 9.90 | 197.29 | (−24.39 to 17.86) | −0.56 | 1.000 |

*CI, confidence interval; DF, degrees of freedom; IVA-QS, integrated visual and auditory continuous performance task – quick screen; LiD, listening difficulties; RMT, remote microphone technology.*

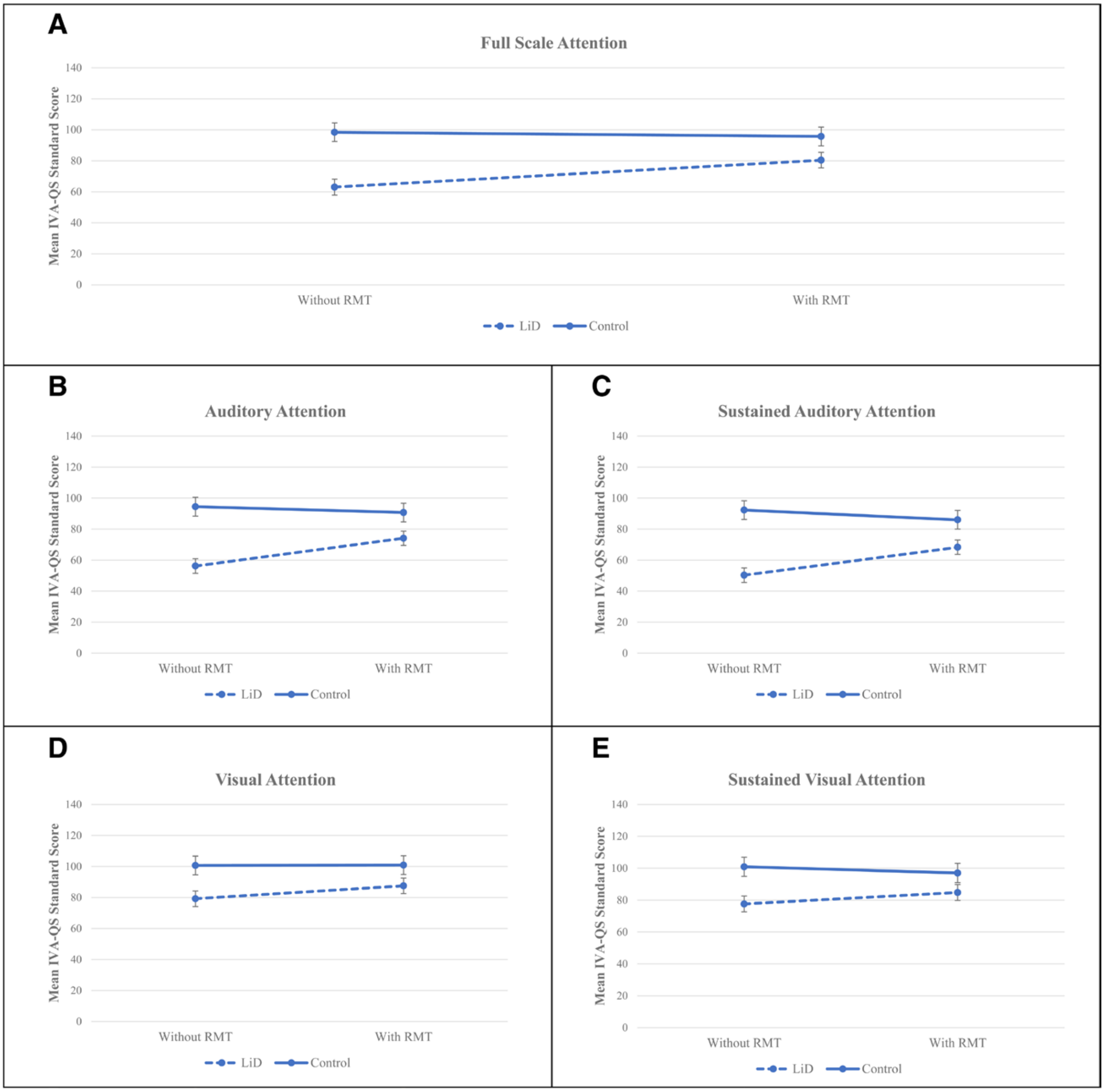


Fig. 4. Mean IVA-QS scores for the LiD (n = 18) and control groups (n = 10) with and without RMT for the (A) full scale attention, (B) auditory attention, (C) sustained auditory attention, (D) visual attention, and (E) sustained visual attention subscales. Error bars represent the SE of the mean. IVA-QS indicates Integrated Visual and Auditory Continuous Performance Task – Quick Screen; LiD, listening difficulties; n, number of participants; RMT, remote microphone technology.

To account for these factors, the current study measured speech intelligibility in the near and far fields and at varied SNRs from −10 to +12 dB. No benefit was obtained from device use in a +12 dB SNR, indicating this condition reflects optimal acoustics that are unlikely to disrupt signal perception. However, at lower SNRs (0 dB SNR or less), both groups showed significant device-related speech perception improvements. This emphasizes the importance of considering acoustic modifications in classrooms where SNRs typically surpass 0 dB, as impaired understanding is unlikely to apply exclusively to students with LiD in these circumstances.

While speech intelligibility was impacted by noise level and distance, differences in scores depending on the listening condition parameters were less apparent when participants were using RMT. Furthermore, scores for the LiD group improved to be comparable to controls in SNRs of 0, 5 and 12 dB, and exceeded control performance in the most difficult listening condition of −10 dB SNR. This suggests that for children with LiD, device use can overcome acoustic barriers in standard classrooms, enabling access to vital speech information that may be otherwise missed. Previous studies using fixed-intensity stimuli have assessed speech perception at a single distance and SNR of 0 dB (Rance et al. 2010; Rance 2014; Smart et al. 2018). Although this effectively simulates a difficult scenario, it fails to consider the potential advantage in alternative circumstances. The current findings indicate that even children presenting with LiD that are positioned toward the front in relatively quiet classrooms may be suitable candidates for RMT.

### Attention in Noise

Children with LiD commonly experience inattentiveness and have been found to have impaired sustained auditory attention compared to typically developing children (Allen & Allan 2014). This was certainly evident in the current study with participants in the LiD group demonstrating poorer attention in noise skills compared to the controls.

Previous research investigating the benefits of RMT have used questionnaire ratings to quantify changes in attention (Friederichs & Friederichs 2008), which has yielded inconsistencies depending on responder (i.e., parent versus teacher). To our knowledge, the current study is the first to behaviorally measure attention skills while children are wearing RMT. Enhancing the SNR (through device use) resulted in significantly improved auditory and sustained auditory attention results.

The assistive benefit obtained by the LiD group increased attention scores to being comparable to the abilities of controls across all subscales. In contrast to the speech intelligibility findings that indicate at least some degree of benefit for all wearers of RMT, improvements for attention may be specific to those with LiD. This is particularly important considering the substantial number of normal-hearing children who present with listening concerns related to a lack of focus on verbal instruction (Dawes & Bishop 2009). When these symptoms are identified, clinicians should consider RMT a viable intervention option.

Although we believe this to be the first study to test attention of children when aided with RMT, others have attempted to behaviorally measure a therapeutic effect on unaided ability over time (Smart et al. 2018; Stavrinos et al. 2020). No significant changes in auditory attention or sustained auditory attention were found after 5 and 6 months of wearing RMT in the classroom, suggesting the passive nature of device use is unlikely to produce lasting changes to higher order function. Based on these findings, device use may provide assistive support in the classroom, without having long-term implications on concentration. However, given the average use time of RMT is over 2 years (Hoen et al. 2010), additional research implementing longer trial periods is required to further investigate the possibility of neuroplastic development.

### Clinical Implications

Although RMT is frequently recommended for children with LiD, there is currently no consensus regarding the suitability for specific clinical presentations. Rosenberg (2002) proposed RMT should only be considered appropriate for those with specific deficits relating to listening ability in noise, and that alternative auditory concerns should be considered a contraindication to fitting (Rosenberg 2002). This is a theoretical model lacking evidence, and if used clinically could risk neglecting RMT as a management strategy for others who may benefit. Contrasting Rosenberg (2002), broader practice guidelines put forward by American Academy of Audiology (2008) indicate candidacy may be appropriate for any child with hearing, listening, or learning problems. More recently, studies have investigated amplification in children who meet the diagnostic criteria for APD (American Speech-Language-Hearing Association 2005), without considering the specific deficits in each participant (Johnston et al. 2009; Smart et al. 2018; Stavrinos et al. 2020). The present study did not recruit based on this arbitrary criterion but instead considered any child with at least one listening-related deficit as eligible. Of the 28 recruited into the LiD group, only five would have fulfilled the American Speech-Language-Hearing Association (2005) diagnostic criteria for APD (falling >2 SDs outside the normal range on two or more traditional AP assessments). Most participants were instead considered eligible based on either isolated deficits in AP, auditory attention challenges, or a combination of both, and all participants gained substantial assistive benefits from device use. If solely basing clinical decisions on whether the traditional criteria for APD is met, many children could suffer from ineffective management of their symptoms due to not ‘fitting a box’. When determining appropriate intervention for a child with LiD, it is important that audiologists consider a holistic approach with focus on presenting concerns in addition to test results.

### Limitations and Future Research

While the current study exclusively recruited neurotypical participants, many other pediatric populations may be afforded attention benefits from RMT. There is substantial evidence supporting an increased prevalence of auditory and attention deficits in children diagnosed with neurodevelopmental conditions including ASD, ADHD, and Language Disorders (Schafer et al. 2013; Rance 2014; Schafer et al. 2014). In subjects with at least one of these diagnoses, Schafer et al. (2014) measured a significant reduction in observed off-task behaviors while they were wearing RMT, many of which related to distractibility and focus. Teacher questionnaire responses have also indicated increases in the attention span of children with ADHD while they are utilizing RMT (Updike 2006; Schafer et al. 2014). Given these findings, future research should consider measuring attention skills with RMT in a broader population of children with LiD to determine whether similar outcomes are applicable in the presence of developmental comorbidities.

Recruitment in the present study included a broad group of children with LiD who presented with a range of auditory skill deficits. As a result, assistive benefits of the entire group were considered without investigating outcome variations depending on clinical presentation. This is an important area for future research given the findings may highlight clinical indicators when deciding whether RMT is an appropriate intervention. However, categorizing individuals into groups based on deficits may prove difficult, particularly for those who perform outside normal limits on more than one task.

Additional limitations related to the study design. First, the assessor was not blinded to device condition when scoring the AZBio Sentences Test. The presence of free field background noise could confound perception of participant responses; therefore, future research should use a blinded study design and consider utilizing a second assessor to control scoring reliability. Additionally, calibrations at the microphone position were not conducted to check for variations in signal transmission during each AZBio condition. Although volume of both the target speech and background noise were adjusted to simulate increased teacher vocal effort amongst significant noise (Crukley et al. 2012), future studies should consider only changing background noise volume to vary SNR so the level transmitted via RMT is controlled.

## CONCLUSIONS

Findings of the present study support the use of RMT as an intervention for children with normal hearing and LiD. Use of the devices was found to improve speech intelligibility and attention in noise skills. This study demonstrated significant benefits in neurotypical children with a range of LiD without considering individual patterns of processing deficit. Future research should consider differences in outcomes depending on clinical presentation and comorbid conditions to determine which children with LiD will benefit most from a remote-microphone intervention.

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Address for correspondence: Lucy Shiels, Department of Audiology and Speech Pathology, University of Melbourne, 550 Swanston Street, Carlton, VIC, 3053, Australia. E-mail: shiels.l@unimelb.edu.au

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