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Assistive technology evaluations: Remote-microphone technology for children with Autism Spectrum Disorder

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ABSTRACT

The goal of this study was to conduct assistive technology evaluations on 12 children diagnosed with Autism Spectrum Disorder (ASD) to evaluate the potential benefits of remote-microphone (RM) technology. A single group, within-subjects design was utilized to explore individual and group data from functional questionnaires and behavioral test measures administered, designed to assess school- and home-based listening abilities, once with and once without RM technology. Because some of the children were unable to complete the behavioral test measures, particular focus was given to the functional questionnaires completed by primary teachers, participants, and parents. Behavioral test measures with and without the RM technology included speech recognition in noise, auditory comprehension, and acceptable noise levels. The individual and group teacher (n = 8–9), parent (n = 8–9), and participant (n = 9) questionnaire ratings revealed substantially less listening difficulty when RM technology was used compared to the no-device ratings. On the behavioral measures, individual data revealed varied findings, which will be discussed in detail in the results section. However, on average, the use of the RM technology resulted in improvements in speech recognition in noise (4.6 dB improvement) in eight children, higher auditory working memory and comprehension scores (12–13 point improvement) in seven children, and acceptance of poorer signal-to-noise ratios (8.6 dB improvement) in five children. The individual and group data from this study suggest that RM technology may improve auditory function in children with ASD in the classroom, at home, and in social situations. However, variability in the data and the inability of some children to complete the behavioral measures indicates that individualized assistive technology evaluations including functional questionnaires will be necessary to determine if the RM technology will be of benefit to a particular child who has ASD.

Learner outcomes

1. The reader will be able to describe the potential benefit of remote-microphone systems for children with ASD.
2. The reader will be able to identify applicable questionnaires that will help professionals to better understand listening difficulties of children with ASD.

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3. The reader will be able to explain the behavioral test measures that may be used in assessing the potential benefit of remote-microphone systems in children with ASD.

1. Introduction

According to the American Psychiatric Association Diagnostic and Statistical Manual V (DSM; American Psychiatric Association, 2013), children diagnosed with autism spectrum disorder (ASD) exhibit deficits in social communication and social interaction as well as restrictive, repetitive patterns of behavior, interests, or activities. Additionally, in public educational settings, ASD is defined as a developmental disability that negatively impacts a child's educational performance, verbal and nonverbal communication, and social interactions (Individuals with Disabilities Education Act: IDEA, 2004). Children who are diagnosed with ASD often have difficulty with transitions and change and show hyper- or hypo-reactivity to sensory input, including auditory input. In particular, there is strong empirical evidence to support the presence of auditory dysfunction in children who are diagnosed with Autism Spectrum Disorder (ASD) (Alcántara, Weisblatt, Moore, & Bolton, 2004; Ashburner et al., 2008; Haesen, Boets, & Wagemans, 2011; Schafer, Mathews et al., 2014; Tomchek & Dunn, 2007). As a result, many children with ASD may require audiological management and special education support in order to address their auditory and other sensory processing difficulties.

When children with ASD are receiving special education support under IDEA, audiological management in the form of hearing assistive technology may be provided by the child's school district for use at school and at home. However, in most cases, the auditory deficits and the educational need for the technology must be documented prior to purchasing the hearing technology. Additionally, in many cases, documentation of benefit from the hearing technology is also required for the assistive technology to remain in the child's special education Individual Education Plan (IEP). The following introductory sections will highlight some of the auditory deficits experienced by children with ASD and will review existing evidence to support the use of assistive hearing technology for children with ASD.

1.1. Functional evidence: abnormal auditory behaviors

In numerous studies, parents of children with ASD report abnormal auditory processing and auditory responses (e.g., Ashburner et al., 2008; Egelhoff & Lane, 2013; Tomcheck & Dunn, 2007). In one representative study, the Short Sensory Profile (SSP) was completed by 400 parents of children diagnosed with ASD (Tomchek & Dunn, 2007). The study revealed that 58–79% of the children had abnormal auditory filtering, difficulty attending to auditory stimuli, were distractible or could not function in noisy environments, and were unresponsive to auditory stimuli. Auditory filtering is defined as the ability to hear, function, and complete tasks in the presence of background noise (Ashburner et al., 2008), and this skill is critical for hearing in real-world, noise-enriched environments. In a study by Ashburner et al. (2008) on 28 children with ASD, parents reported that auditory filtering was the most atypical sensory characteristic. In fact, the child's under-responsiveness and auditory filtering ability, which were poor for almost all children in the Ashburner study, were the most significant predictors of educational performance. Finally, on a questionnaire focused specifically on auditory function, parents of 165 children with ASD reported difficulty in background noise as one of the most common auditory issues (Egelhoff & Lane, 2013). Within this category, the majority of parents reported that the presence of noise results in difficulty responding, trouble focusing on tasks, attention problems, distractibility, and distress.

1.2. Behavioral evidence: poor speech recognition

In addition to the parental reports of abnormal auditory processing in their children with ASD, several studies show significantly poorer speech recognition in noise relative to age-matched neurotypical peers (Alcántara et al., 2004; Haesen et al., 2011; Rance et al., 2014; Schafer, Mathews et al., 2014). For instance, in one study, Alcántara et al. (2004) compared performance of high-functioning adolescents and young adults (20.9 years ± 11.1) diagnosed with ASD to neurotypical peers on a sentence-recognition task in three types of background noise (single-talker noise, speech-shaped noise with temporal dips, and speech-shaped noise with temporal and spectral dips (i.e., pitch changes)). The group of participants with ASD had average sentence thresholds in noise that were significantly worse, on the order of 2–3.5 dB, than their peers. This finding suggests that individuals with ASD need a substantially better (higher) signal-to-noise ratio (SNR) than neurotypical peers to identify at least half of the speech signal. In another study, Schafer, Mathews et al. (2014) found that children with ASD who were fairly high functioning and/or those with Attention-Deficit Hyperactivity Disorder (ADHD) had significantly poorer (higher) sentence-recognition thresholds in the presence of spatially-separated multi-talker babble ($M = -4.8$) compared to age-matched peers ($M = -10.6$). In a third study, Rance et al. (2014) examined word recognition in the presence of multi-talker babble, as well as temporal processing and spatial-listening ability in a group of 20 high-functioning children with ASD and in a control group. Average word recognition in noise was significantly poorer in the ASD group compared to the control group. In addition, on a functional questionnaire designed to assess auditory function, the high-functioning children with ASD reported significantly more difficulty in background noise, in reverberant environments, and when communicating with others.

Overall, children with ASD have significant perceptual difficulties when asked to repeat word and sentence stimuli in the presence of background noise. Therefore, assessments of speech recognition in noise in children with ASD may be a valuable tool in determining education need for hearing assistive technology. However, when considering the hierarchy of auditory-skill development, perception is only the gateway to comprehension (Erber, 1971). In other words, if a student is unable to perceive the speech signal from the teacher, there is a low probability that he or she will understand and follow verbal directions or auditory-based teaching. As a result, measures of comprehension may also contribute to the assessment of educational need for hearing assistive technology in children with ASD.

1.3. Management: ASD

Given the published evidence suggesting that children with ASD exhibit abnormal speech recognition performance, particularly in background noise, audiological management of this population in the educational settings is imperative. Deficits in noise are particularly concerning given the high levels of noise and poor acoustics encountered in typical classrooms (Cruckley et al., 2011; Knecht, Nelson, Whitelaw, & Feth, 2002; Nelson, Smaldino, Erler, & Garstecki, 2007). According to acoustical measurements by Knecht et al. and Nelson et al., typical classrooms do not meet the acoustical guidelines set forth by the American National Standards Institute (2010) or the American Speech-Language-Hearing Association (2005) for recommended SNR (+15 dB), unoccupied noise level (35 dBA), or reverberation time (less than 0.7 s). Furthermore, classrooms are dynamic where the actual SNR may range from −17.6 to +5 dB, and occupied noise levels may range from 60 to 80 dBA for 75% of the school day (Cruckley et al., 2011; Larson & Blair, 2008; Sanders, 1965).

For children with ASD who exhibit normal pure-tone hearing sensitivity, assistive technology in the form of remote-microphone (RM) technology may directly address hearing deficits in background noise and possibility overcome some hyper-sensitivity to background noise. RM technology consists of a frequency modulation (FM) or digital transmitter connected to a microphone worn by the primary talker or teacher as well as FM or digital receivers worn by the listener. The transmitter wirelessly sends the speech signal from the primary talker or signals from other auditory mediums (e.g., projector, audio player, television) directly to the child's receivers. As a result, the SNR at the child's ear is greatly improved over what would be obtained without hearing technology. Additionally, the negative effects of room reverberation and distance from the teacher/talker are greatly reduced. There are open-ear FM and digital receivers, with conservative volume levels, that are specifically designed for children with normal pure-tone hearing to allow natural sound from the environment, classmates, and other talkers to enter the ear canal.

There is growing evidence to support the use of RM technology in children with ASD (Rance et al., 2014; Schafer, Bryant et al., 2014; Schafer, Mathews et al., 2014). Schafer, Mathews et al. (2014) used an ABAB (alternating no-intervention and intervention trial periods) design to assess speech recognition in noise, classroom behavior, and teacher perceptions of auditory behaviors with and without the use of an FM system in seven high-functioning children diagnosed with ASD and four children with ADHD. These children attended a small private school for children with special learning needs. As mentioned previously (Section 1.2), the children with ASD and ADHD had significantly poorer speech-recognition performance in background noise when compared to neurotypical, age-matched peers. However, when the children with ASD used the FM system, their average speech recognition improved by 5.3 dB, which was equal to the performance of their peers. In addition, on-task behaviors and teacher-rated, auditory-listening behaviors significantly improved during two trial periods (2 weeks; 3 weeks) when the FM system was used in the classroom when compared to periods without the system.

In another study (Section 1.2), Rance et al. (2014) reported similar disparity in speech-recognition in noise performance between 20 high-functioning children with ASD and a control group. However, speech recognition significantly improved by an average of 17% (from 69 to 86%; SD = 10.1) when using the FM system. Additionally, the self-perceived listening difficulties of eight children who completed a six-week trial period decreased significantly when using the FM system while communicating and listening in noise and reverberation.

As stated previously, children with ASD who are receiving special education services may qualify for hearing assistive technology when educational need for the technology is documented. IDEA (2004) states educational need for assistive technology should be documented through a functional evaluation in the student's customary environment. However, the specific test measures that should be used for the functional evaluation are not well defined in IDEA, which likely stems from the fact that different measures would be required for different students, populations (e.g., hearing loss, ASD), and types of technology (i.e., communication device, hearing technology, etc.). Once educational need for the technology is documented, and the IEP team decides that the technology should be implemented, the RM technology may be used at school and also at home. Home use of the RM system would be indicated with the IEP team has confidence that the use of the device at home may facilitate continued growth on IEP goals and that it ensures a free and appropriate education. As a result, one goal of the present study is to identify functional questionnaires and behavioral measures that are feasible and efficient for use in the schools and at home when conducting an assistive technology evaluation with RM systems.

1.4. Study aims and hypotheses

The primary goal of the present study is to evaluate the potential individual and group benefits of RM technology in children diagnosed with ASD with functional levels across the spectrum. Previous investigations (Rance et al., 2014; Schafer, Mathews et al., 2014) included only children with ASD who were high-functioning and utilized mostly behavioral measures (auditory processing; speech recognition). The present study replicates some aspects of the previous studies; however, the present study includes children across the spectrum and focuses mainly on functional questionnaires from teachers and parents, which are one means of data collection for children who are unable to complete behavioral measures. For the children who were able, behavioral measures were conducted with and without the RM technology using one or more tests, which included speech recognition in noise, auditory comprehension in noise, and acceptable noise levels.

The secondary goal was to investigate individual performance on the various measures in order to (1) more closely examine single-subject performance across the measures and to (2) determine which measures may be helpful in documenting benefit from RM technology in home and public school-based environments. Most of the measures used in the present study were based on methods used successfully in previous investigations on children with various disorders (Rance et al., 2014; Schafer, Mathews et al., 2014; Schafer, Traber et al., 2014).

Overall, the investigators hypothesize that the RM technology will improve teacher, parent, and participant ratings on functional questionnaires and also performance on behavioral measures when compared to the no-device, baseline questionnaires and behavioral test measures. Furthermore, when examining the individual functional questionnaire data of children who received substantial benefit from the RM technology, there will be a consistent pattern of improvement across the functional questionnaires measures despite the fact that they were completed by different people. This hypothesis is based on the fact that most of the functional questionnaires assess listening ability across various environments and listening situations, with the exception of the SSP, which focuses more on auditory filtering and over-sensitivity to sound. Conversely, the investigators hypothesize varied patterns of improvement across the behavioral measures because some tasks may be difficult for children with ASD, and the measures assess three different constructs: (1) the ability to recognize sentences in background noise, (2) listening comprehension and working memory, and (3) tolerance or acceptance of background noise.

2. Methods

2.1. Participants

The methods and procedures for this study were approved by the Institutional Review Board at the University of North Texas. Parental consent, and when possible participant assent, was obtained from 17 children, but only 12 children were able to participate in the study. Five participants did not complete the study due to one or more of the following reasons: the inability to tolerate wearing the RM technology (n = 3); parent and teacher questionnaires were not returned following the trial period, and the child was unable to do behavioral testing (n = 1); or the child was identified with a profound sensorineural hearing loss during the study (n = 1). The three children who would not tolerate wearing the device included (1) a four-year-old girl with few spontaneous words who was enrolled in special education preschool, (2) a six-year-old boy with few spontaneous words who was enrolled in a self-contained classroom for academic courses, and (3) a child for which the family did not return the case history or functional questionnaires (age and level of function unknown). The common factors among the three of the children were their young age and delayed language.

Demographic information about the 12 participants who completed the study is provided in Table 1. Participants ranged in age from 6 to 17 years and were diagnosed with ASD as their primary disability. The examiners requested initial ASD diagnosis reports from the parents, and 6 of the 12 parents were able to provide them. For the six remaining participants, information about the age of diagnosis and the professional who made the diagnosis was obtained via parent case history. Information from the professional reports and the parent questionnaires suggested that the participants were diagnosed between the ages of two and six years by a pediatric neurologist (n = 2), licensed specialist in school psychology (n = 1), school diagnostician (n = 4), or a developmental pediatrician (n = 5).

As shown in Table 1, all 12 children had verbal abilities; however, the level of verbal ability varied substantially across participants. To provide a more complete description of each participant, the examiners of this study generated a 1–5 rating to describe the level of verbal ability observed during direct contact with the participant (i.e., hearing screening, behavioral testing, fitting of the device, and counseling on device use). Rating modifiers were the following levels: (1) primarily echolalic with few spontaneous words (n = 0), (2) produces one to three spontaneous words (n = 4), (3) produces novel sentences containing four or more words (n = 2), (4) produces two to three sentences (n = 3), and (5) conversational (n = 3). Again, the ratings provided in Table 1 are based on observations by the examiners and only represent behavior during the one to two test sessions during the study.

In all but one subject (#9), a behavioral pure-tone hearing test with frequencies ranging from 250 to 8000 Hz (Subjects 1, 3–8, 11) or objective hearing screening with distortion product otoacoustic emissions (OAE) was used to confirm normal hearing and cochlear function (Subject 2 and 12). In Subject 9, normal hearing thresholds could only be obtained in one ear before the child refused to complete further testing, including OAEs. However, her mother did not report any concerns about her hearing, denied any ear surgeries or chronic otitis media, and reported that she passed a previous hearing evaluation.

2.2. RM technology & equipment

All 12 participants were fit with a digital Phonak Roger inspiro transmitter synced to bilateral, digital Phonak Focus receivers with SlimTubes and open SlimTip domes (Fig. 1). These receivers are designed specifically for children with normal

Table 1
Participant Demographic Information.

Subject #	Age (yrs; mo)	Diagnoses	Age at ASD Diagnosis	Verbal Status: Level	School Classroom Environment	RM volume Right; Left
1*	17;2	ASD, ADHD, BD	6;0	Verbal: 5	Gen. ed. with support	+4; +2
2	6;0	ASD, VI	4;1	Verbal: 2	Gen. ed. with support	+6; +6
3*	9;3	ASD, LD	3;0	Verbal: 4	Gen. ed. with support	+6; +6
4*	7;3	ASD, ADHD, APD, LD	3;6	Verbal: 4	Gen. ed. with support	+6; +6
5*	6;4	ASD, VI	4;3	Verbal: 2	50/50 self contained & gen. ed.	+8; +6
6*	14;0	ASD	3;0	Verbal: 5	Self contained with gen. ed. specials	+6; +6
7*	13;3	ASD, ADHD	5;1	Verbal: 5	50/50 self contained & gen. ed.	+6; +6
8*	8;6	ASD, LD	3;6	Verbal: 3	Self contained in life skills classroom	+4; +4
9	7;6	ASD, LD	2;6	Verbal: 2	Gen. ed. with support	+6; +6
10*	7;6	ASD	2;0	Verbal: 4	Gen. ed. with support	+6; +6
11	6;5	ASD	1;10	Verbal: 3	Gen. ed. with support	+6; +6
12	5;1	ASD, LD	1;8	Verbal: 2	Gen. ed. with support	+6; +6
Average (SD)	9;8 (4;1)	–	3;4 (1;3)	–	–	+6; +6

Note. Asterisk next to subject # indicates children who were able to complete one or more of the behavioral measures; APD = auditory processing disorder; ASD = autism spectrum disorder; ADHD = attention-deficit hyperactivity disorder; BD = bipolar disorder; Gen. Ed. = General education classroom; LD = language disorder; Level = hierarchy of verbal abilities defined in text; RM = remote-microphone technology volume level; SD = standard deviation; Specials = art, physical education, music; VI = vision impairment.

pure-tone hearing thresholds, so they provide a safe and comfortable volume for the participants. Also, use of objective fitting verification was included to ensure an appropriate receiver volume for each participant and each ear, and real-ear, probe microphone-measures with the Audioscan Verifit (Dorchester, Ontario) were attempted and are described in the following section.

Behavioral testing was conducted in a double-walled sound booth. Test stimuli were presented with a GSI 61 audiometer (Eden Prairie, MN), Sony Compact Disc player (CDP-CE500), and two single-coned loudspeakers located at 0 (speech) and 180 (noise) degrees azimuth (Grason Stadler Standard). The participant was seated 3.54 ft (1.07 m) from each head-level loudspeaker. Pure-tone hearing testing was conducted with the same audiometer and supra-aural headphones (TDH-50). Calibration and stimuli intensity were determined using a sound-level meter (Larson-Davis 824, Depew, NY). When the RM system was used during behavioral testing, the transmitter microphone was placed on a stand six inches in front of the loudspeaker at 0° azimuth.

2.3. Fitting procedures: remote-microphone system

The tube length for each receiver was fit to the participant's ears with a Phonak measuring tool; dome size was selected based on otoscopic inspection. Once the devices were measured and fit to each ear, the volume of each receiver was adjusted according to output obtained via real-ear, probe-microphone measures. An extensive description of these procedures is

Fig. 1. (a) Phonak Roger inspiro transmitter and (b) digital Phonak Focus receiver.

available in Schafer, Bryant et al. (2014) and Schafer, Traber et al. (2014), but the overall goal of the procedure is to account for the child's ear canal size in order to select an appropriate volume level for the receivers. If a child had a particularly small ear canal, and the receiver was set to the manufacturer default setting, it is possible that the volume level could be too loud for the participant.

During the fitting, the examiner entered the child's hearing thresholds in the Verifit. Desired Sensation Level (DSL v5) prescriptive targets were then generated for conversational-level speech and estimated uncomfortable loudness levels. Two measures were conducted for each ear with the probe microphone placed in the child's ear canal. First, using a standard speech input (65 dB SPL), the examiner adjusted the volume of the receivers to match the DSL prescriptive target. Second, using a sequence of tone bursts (85 dB SPL), the examiner compared this maximum power output to estimated uncomfortable loudness levels. All but four participants (Subjects 2, 9, 11, 12) were able to tolerate the real ear measures. For these four participants, receiver volume was set to +6 for each ear, which is the average volume level determined for children in previous studies (Schafer, Bryant et al., 2014; Schafer, Traber et al., 2014).

According to the fitting data obtained from the eight participants, on average, the examiners were able to meet DSL prescriptive targets within ± 5 dB at 1000, 2000, 3000, and 4000 Hz (measurement 1), and the maximum power output for all ears never exceeded the estimated uncomfortable loudness level (measurement 2). The final receiver-volume settings for the participants are provided in Table 1.

2.4. Questionnaires and test measures

The goal of the functional questionnaires and behavioral test measures was to document the potential benefit of the RM technology in the children with ASD and to identify test measures that may be helpful for assistive technology evaluations under IDEA, which may initiate the use of RM technology at school and at home. The functional questionnaires relied on parent, teacher, and participant ratings of listening ease and difficulty in various environments. The behavioral measures were selected to represent auditory tasks that are common and required in school and home environments: speech recognition in noise (i.e., repeat/identify speech stimuli in the presence of background noise, listening comprehension/ auditory working memory, and acceptance of noise).

2.4.1. Functional questionnaires

A total of five questionnaires were given to teachers, parents, or participants to complete before and after a six-week trial period with the RM technology.

The two teacher questionnaires, which were completed by the child's primary teacher, included the Listening Inventory for Education-Revised (L.I.F.E.-R.; Anderson, Smaldino, & Spangler, 2012) and the Children's Auditory Performance Scale (C.H. A.P.S.; Smoski, Brunt, & Tannahill, 1998). The C.H.A.P.S., a 36-item questionnaire, is used to assess listening difficulties of a child compared to age-matched, typically-developing peers using a 7-point Likert scale (Smoski & Brunt, 1992). The scale ranges from *less difficulty than peers* (+1) to *cannot function at all* (−5). The questionnaire yields ratings from six listening conditions: noise, quiet, ideal, multiple inputs (i.e., auditory, visual, tactile), auditory memory (i.e., recalling spoken information), and auditory attention, all of which are required at school. According to the C.H.A.P.S. manual, the questionnaire has high test-retest reliability because a statistical comparison between two test sessions in 20 children yielded no significant differences in ratings. According to the normative data from 64 children with auditory processing disorders, which was published in the test manual, a rating below 1 as associate with a greater need for special support services and lower reading levels. This questionnaire is commonly used by audiologists to identify children with behaviors associated with an auditory processing disorder and was selected in the present study to examine listening ability in various environments at school. In Schafer, Mathews et al. (2014), the C.H.A.P.S. documented significantly less listening difficulty in children with ASD and ADHD when RM technology was used during a trial period at school relative to listening without the device.

The L.I.F.E.-R. depicts 15 school-based listening scenarios and requires teachers and students to rate listening performance for each scenario on a 5-point Likert scale ranging from *no challenge or very rare* (5) to *almost always challenged* (1). The participant also completed the student version of the L.I.F.E.-R. with help, as needed, from the parent, teacher, or investigator. This version provides a description of each situation as well as a photograph depicting the situation. As reported in the original L.I.F.E. manual, test-retest reliability is high for the student version of this questionnaire because a statistical comparison between two test sessions in 19 children yielded no significant differences in ratings. This questionnaire was selected for the present study because, in Schafer, Traber et al. (2014), the teacher L.I.F.E.-R. was used to document substantially less listening challenge when RM technology was used in the classroom.

The two parent questionnaires were the Children's Home Inventory for Listening Difficulties (C.H.I.L.D.; Anderson & Smaldino, 2011) and the auditory sections of the Short Sensory Profile (SSP; McIntosh, Miller, & Shyu, 1999). The C.H.I.L.D. is a 15-item questionnaire that uses an 8-point scale ranging from *hears and understands everything* (8) to *misses all of message* (1). This questionnaire has high test-retest reliability ($r = 0.82$) and is used to estimate the child's listening ability in typical family communication situations at home including situations in quiet, noise, at a distance, social, and media. This measure was used in a previous investigation on children with ASD to document significantly improved listening ability with RM technology at home and in social environments (Schafer, Traber et al., 2014).

The SSP is a screening tool used to gather information related to the child's sensory processing where the parent rates the child's auditory behaviors on a scale from *always displays the behavior* (5) to *never displays the behavior* (0). In this study, the parent only completed the two auditory sections of the SSP: Auditory Filtering (i.e., items 22–27) and Visual/Auditory Sensitivity (i.e., items 34–38). No test-retest reliability statistics were found for the SSP; however, test-retest reliability for a similar Infant/Toddler Sensory Profile measure, published by the SSP author (Dunn, 2002), ranges from 0.74 to 0.86. This questionnaire was selected for the present investigation because, based on previous a previous study on children with ASD (Ashburner et al., 2008), the auditory filtering section of this questionnaire correlates significantly with educational success.

2.4.2. Behavioral measures

The laboratory-based behavioral test measures included speech recognition in noise, auditory comprehension and working memory, and acceptable noise levels. All measures were conducted with and without RM technology; the order of the test measures was pseudo-randomized for each participant.

Speech recognition in noise was assessed with two list pairs of the Bamford-Kowal-Bench Speech-in-Noise test (BKB-SIN, 2005), which consists of sentences recorded in four-talker babble. The BKB sentences are presented at a fixed intensity 60 dBA with varying levels of background noise (pre-recorded SNRs on the compact disc) in order to estimate the child's 50% correct speech-in-noise threshold in dB. In other words, it estimates the SNR necessary for the child to repeat 50% of the key words correctly. For this test; lower thresholds (i.e.; more negative) represent better performance. The test-retest reliability on the BKB-SIN is high for two list pairs with a 95% confidence interval of 1.8 dB. The 95% critical difference necessary for determining statistical differences between test conditions is 2.5 dB for two list pairs. The BKB-SIN has been used in previous investigations to document improvements in speech recognition in noise in children with ASD and other auditory disorders (Schafer, Mathews et al., 2014; Schafer, Traber et al., 2014).

The child's listening comprehension and auditory memory was examined using the Ross Information Processing Assessment – Primary (RIPA-P; Ross-Swain, 1999). This assessment identifies and quantifies information processing skill impairments in children and involves at least three auditory skills: perception, memory, and comprehension. On this test, children were asked to recall auditory information and to answer simple questions on two sections of the RIPA-P. First, the *Immediate Memory* subtest required the child (1) to repeat digits, words, and sentences that varied in length and difficulty for item 1 through 12 (e.g., "Say this after me: After school, we have basketball practice."), (2) to recall details in a short story in item 13, and (3) to recall and follow motor commands (e.g., "Touch your nose, blink your eyes, and point to me,"). All 15 items on the *Recent Recall* subtest required the child answer questions about recent activities and facts (e.g., "What is the name of your school?"). Because most of the *Immediate Memory* subtest required children to repeat the stimuli heard, perception and auditory-working memory (i.e., short-term memory) are the main auditory skills tested. On the other hand, the *Recent Recall* subtest required the child to answer questions, which involved listening comprehension of the questions asked as well as perception and working memory. For each item, the examiner provides a score that ranges from 5, *a prompt and accurate response*, to 1, *error response or denial*. The scores for each condition were summed to calculate a raw score, with a higher score representing a greater number of accurate responses. Use of the standard scores provided in the test manual was not appropriate given the non-standardized test procedures used in this study, which are described below. Although no peer-reviewed publications on the RIPA-P were found, the test manual thoroughly examined the reliability and validity of the measure. According to the test manual, the test-retest reliability for this measure is high (correlation coefficient = 0.93–0.95), and content validity is well-documented through rationales for each subtest, outside reviews of test content, and item analysis procedures. Traditionally, this test is presented to a child using live-voice; however, for this study, the stimuli were recorded by a female talker and presented at 63 dBA in the presence of recorded multi-classroom noise at 60 dBA (+3 dB SNR; Schafer & Thibodeau, 2006; Schafer et al., 2012). The stimuli, which were burned on a compact disc, were presented in this format to ensure uniformity of the stimuli intensities presented to each participant. To determine if there were significant differences between the test conditions, the 95% confidence interval was estimated based on the mean difference between the conditions for each separate subtest (11.8 for Immediate Memory; 13 for Recent Recall) using *t* distribution (Gardner & Altman, 1986; Hintze, 2007). This calculation resulted in a 95% confidence intervals of 0.80–22.9 for the Immediate Memory subtest and −0.19 to 26.2 for the Recent Recall subtest. Although the investigators have not used this measure in a previous study, another measure of listening comprehension has been utilized and showed deficits relative to neurotypical peers (Schafer, Traber et al., 2014). The RIPA-P is more efficient (i.e., shorter administration time) relative to the previous measures used, which may make it more usable to school-based personnel.

The Acceptable Noise Level test (ANL, 2009; Nabelek, Tucker, & Letowski, 1991), which is recorded on compact disc, quantifies the level of noise a listener is willing to accept or "put up with" for a long period of time when listening to running speech. To obtain the ANL, the examiner, first, determines the listener's most comfortable listening level (MCL) for the recorded story using a loudness scaling chart with descriptors and faces (i.e., happy face when comfortable; sad faces when too loud or too soft). Next, while the story continues at MCL, background noise is introduced and adjusted to an intensity the listener is willing to "put up with" for a long time while still understanding and hearing the story. This noise level in dB represents the background noise level (BNL). The ANL is calculated by subtracting the BNL from the MCL (ANL = MCL-BNL). In this study, running speech was presented at 0° azimuth with background noise located at 180°. The test-retest reliability of the ANL in children is high (r = 0.95) according to a study by Moore, Gordon-Hickey, and Jones (2011). The SEM for the ANL test was calculated using the data from 34 children in the Moore et al. (2011) study. More specifically, the SEM was calculated by taking the square root of 1 minus the reliability estimate of 0.95 and multiplying this value (.05) by the standard deviation of the ANL scores for the 34 children (5.1). Using this formula, the SEM for the ANL is 1.1 dB. The ANL been used successfully in a previous investigation with children using hearing aids and RM technology (Schafer, Bryant et al., 2013; Schafer, Sanders et al., 2013) and was used in the present study because the investigators hypothesized that higher noise levels would be accepted when RM technology was in use.

2.5. Study procedures

2.5.1. Test session 1

After explaining study procedures and obtaining parental consent, parents were asked to complete a case history form as well as the baseline SSP and C.H.I.L.D. questionnaires. Participants were asked to sign an assent form and complete the L.I.F.E.-R. questionnaire, with assistance if necessary. These questionnaires provided the baseline of the child's auditory abilities prior to being fit with the RM technology. A folder containing instructions and a total of four questionnaires, two of the L.I.F.E.-R. and two of the C.H.A.P.S., was given to the parent to be delivered to the participant's teacher. In the instructions, teachers were asked to complete both questionnaires for a baseline measurement before the child wore the device and then to complete the same two questionnaires at the end of the study to represent the child's auditory performance with the device. Teachers were given a postage-paid envelope to return the questionnaires to the investigators.

After the session 1 paperwork, the participants completed hearing testing, the RM technology fitting, and probe microphone measures. The fitting was followed by the three behavioral measures. The order of the test condition (with or without RM technology) was counterbalanced across subjects and test sessions. For example, Subject 1 completed testing with the RM technology in test session 1 and without the technology in test session 2 while, Subject 2 completed the testing in the opposite order across the two sessions. After testing, the family was counseled and given written information on use, care, and maintenance of the RM technology.

2.5.2. Test session 2

In the second test session, the same parent and participant questionnaires were administered about performance with the RM technology. The same three behavioral test measures were also attempted with the participants. Participants returned the equipment and were compensated monetarily for their time and effort.

Although we attempted on multiple occasions to obtain completed questionnaires, some parents and teachers did not return one or more of the questionnaires. Additionally, some children were only able to complete one of the three behavioral measures because of task difficulty or inability to understand directions (Participants 2, 9, 10, 12). As a result, 8 of the 12 participants completed both test sessions. The sample size for each questionnaire and behavioral test will be provided in the results section.

3. Results

This study utilized a within-subjects, repeated-measures design for all functional questionnaires and test measures. Average ratings from each questionnaire were analyzed statistically, and effect sizes were also calculated. Individual data from the functional questionnaires is provided in Table 3. Given the smaller sample sizes for the behavioral data, the group

Table 2
Effect sizes (d) and variance (Var [d]) of Teacher, Participant, and Parent Questionnaires Between the No-Device and Remote-Microphone Technology Conditions.

Rater	Questionnaire	Condition	d	Var (d)
Teacher	Listening Inventory for Education-Revised (L.I.F.E.-R)	Total sum of ratings	0.84	0.13
	Children's Auditory Performance Scale (C.H.A.P.S.)	Noise	0.85	0.09
		Quiet	0.87	0.11
		Ideal	0.33	0.03
		Multiple Inputs	0.64	0.06
		Auditory Memory	0.61	0.06
		Auditory Attention	1.15	0.21
Participant	L.I.F.E.-R Student Version	Total sum of ratings	1.28	0.26
Parent	Children's Home Inventory for Listening Difficulties (C.H.I.L.D)	Quiet	1.35	0.18
		Noise	1.52	0.29
		Distance	1.53	0.27
		Social	1.22	0.25
		Media	0.55	0.07
	Short Sensory Profile	Auditory Filtering	1.19	0.13
		Visual/Auditory Sensitivity	0.74	0.10

Table 3
Individual Data and Group Ratings on Functional Questionnaires.

	L.I.F.E.-R Teacher		C.H.A.P.S. Teacher		L.I.F.E.-R. Child		C.H.I.L.D. Parent		SSP Aud. Filtering		SSP Aud. Sensitivity	
Subject	No RM	RM	No RM	RM	No RM	RM	No RM	RM	No RM	RM	No RM	RM
1	–	–	–	–	47	72	4.1	5.2	20	13	12	8
2	25	52	−3.1	−1.6	33	56	4.1	6.3	19	18	13	13
3	41	49	−1.4	−0.7	44	58	4.5	5.7	25	17	16	14
4	34	48	−2.9	−1.9	–	–	–	–	–	–	–	–
5	–	–	–	–	40	54	–	–	23	14	16	12
6	–	–	–	–	71	75	6.3	7.3	8	6	5	5
7	37	47	−2.5	−1.4	46	42	5.1	7.1	15	8	7	7
8	36	49	−1.4	−0.1	29	62	4.2	6.1	26	14	12	6
9	32	26	−0.6	−0.8	37	67	3.9	6.4	30	18	15	8
10	44	65	−2.4	−1.9	–	–	–	–	–	–	–	–
11	21	21	−1.1	0	53	48	3.1	6.1	25	13	12	11
12	35	35	–	–	–	–	–	–	–	–	–	–
Avg	33.9 (7.2)	43.9 (13.2)	−1.9 (.90)	−1.0 (.76)	44.4 (12.4)	59.3 (10.9)	13.0 (4.3)	18.7 (3.3)	21.2 (6.6)	13.4 (4.2)	12 (3.8)	9.3 (3.2)

Note. = questionnaire was not returned; C.H.I.L.D. = Children's Home Inventory for Listening Difficulties, 1 = know someone is talking but missed all of message, 8 = hear and understand every word; L.I.F.E.-R = Listening Inventory for Education-Revised, higher scores = less listening difficulty, lower score = more difficulty; C.H.A.P.S. = Children's Auditory Performance Scale, −5 = cannot function at all, +1 = less difficulty than peers; SSP = Short Sensory Profile, lower scores = better behavioral responses, higher scores = poorer behavioral responses.

data were not analyzed statistically. Instead, the individual data provided in Table 4 were examined to determine significant differences between the test conditions.

3.1. Teacher questionnaires

3.1.1. Group data

Table 3 provides the individual and average data from the nine teachers who returned the L.I.F.E.-R and the eight teachers who returned the C.H.A.P.S. Fig. 2 shows the average C.H.A.P.S. ratings for each separate listening condition. Questionnaires were not returned for Subjects 1 and 6 because the participants' teachers refused to use the RM technology at school, and one teacher did not return both questionnaires (Subject 12). On both questionnaires, the average level of listening difficulty or challenge decreased when using the RM technology as compared to the no-device ratings (higher ratings on both questionnaires indicated less difficulty).

To determine if there were significant differences between the device and no-device ratings, planned nonparametric tests were conducted for each listening condition with the Wilcoxon Signed-Rank Test. The analysis for the L.I.F.E.-R. ratings yielded significantly less listening difficulty with the RM technology over no device ($z = 2.3$, $p = 0.02$, two-tailed). The analyses for each listening condition on the C.H.A.P.S. suggested significant benefit of the RM technology in all conditions: noise ($z = 2.5$, $p = 0.01$, two-tailed), quiet ($z = 2.5$, $p = 0.01$, two-tailed), ideal listening situations ($z = 2.0$, $p = 0.05$, two-tailed), multiple inputs ($z = 2.5$, $p = 0.01$, two-tailed), auditory memory ($z = 2.3$, $p = 0.02$, two-tailed), and auditory attention ($z = 2.4$,

Table 4
Individual and Group Data on Behavioral Measures.

	Test Order		BKB-SIN		ANL		RIPA-P Immediate Memory		RIPA-P Recent Memory	
Subject	No RM	RM	No RM	RM	No RM	RM	No RM	RM	No RM	RM
1	1	2	−10.25	−10.5	0	−10	69	71	75	75
2	2	1	–	–	–	–	–	–	–	–
3	1	2	−4.25	−13.5	4	−10	51	66	63	70
4	2	1	−6.5	−5.5	–	–	35	39	30	43
5	1	2	5.75	0.75	15	5	23	29	15	31
6	2	1	−2.5	−6.75	8	10	53	55	52	60
7	1	2	−4.5	−8.25	–	–	51	71	68	72
8	2	1	7.25	−0.25	–	–	–	–	–	–
9	1	2	–	–	–	–	–	–	–	–
10	2	1	–	–	–	–	–	–	–	–
11	1	2	1.5	−6.75	11	0	21	55	25	68
12	2	1	–	–	–	–	–	–	–	–
Avg			−1.7 (5.4)	−6.3 (4.8)	7.6 (5.9)	−1.0 (8.9)	43.3 (17.6)	55.1 (16.1)	46.9 (23.5)	59.9 (16.6)

Note. Shaded regions represent substantial changes in ratings according to critical difference values, standard errors of measurement, or 95% confidence intervals (see Methods Section for details). = could not evaluate; ANL = Acceptable Noise Level test, low score = tolerates higher noise levels, higher score = tolerates less noise; BKB-SIN = Bamford-Kowal-Bench Speech-in-Noise Test, lower thresholds in dB are better; Diff = difference score; Ross Information Processing Assessment-Primary, higher standard score indicates better performance.

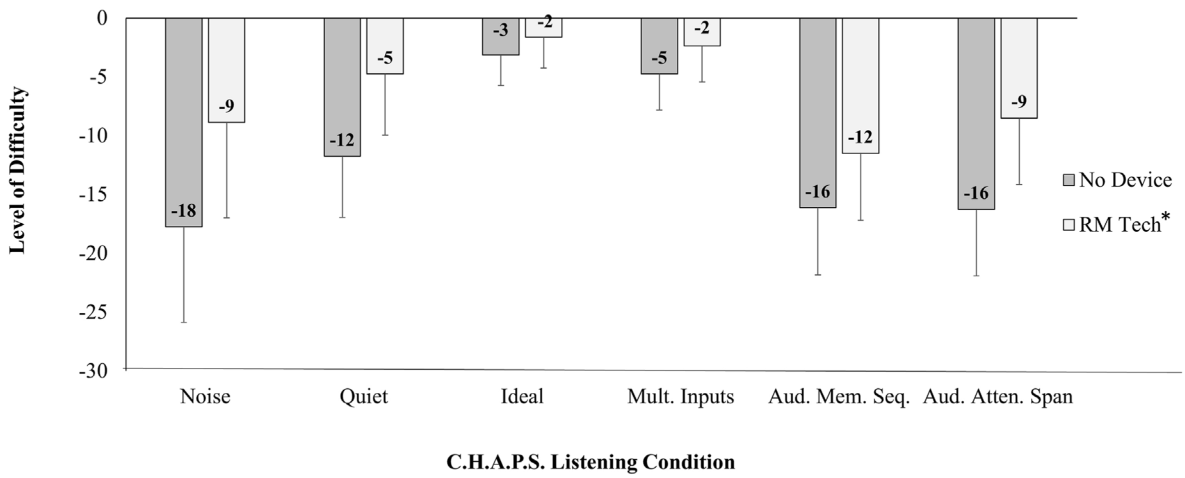

Fig. 2. Average ratings from nine teachers on the Children's Auditory Performance Scale (C.H.A.P.S.). Note. Vertical lines represent one standard deviation; asterisk represents significantly better performance, $p < 0.05$.

$p = 0.02$, two-tailed). Overall, the teachers perceived significant benefit of the RM technology in all school-based listening situations.

The magnitude of rating differences between the no-device and the RM technology conditions may also be examined by calculating the effect size (i.e., d) and variance

[Var (d)] between the two sets of conditions. This study utilized a within-subjects, repeated-measures design; therefore, there is a high probability that questionnaire and behavioral data from the no-device and remote-microphone conditions are highly correlated. As a result, modified effect size and variance formulas were used that were specifically designed for correlated measures (Dunlap, Cortina, Vaslow, & Burke, 1996). Traditional calculations of effect size, such as those proposed by Hedges and Olkin (1985), may overestimate the effect sizes in this study and only may be used with two independent samples. As shown in Table 2, the effect sizes for the teacher ratings on the teacher L.I.F.E.-R. and the C.H.A.P.S. are considered large according to Cohen (1988) with the exception of a medium effect size in the ideal listening condition on the C.H.A.P.S.

The average ratings for each listening situation showed the largest average differences (>4 rating number) in quiet, in noise, for auditory-memory sequencing, and for auditory attention span. Despite the large improvements on the C.H.A.P.S., however, the average ratings with the RM technology for all situations are still in the "at-risk" range for listening and learning difficulties according to the C.H.A.P.S. scoring figure.

3.1.2. Individual data and questionnaire items

When examining the individual data in Table 3 from the two teacher questionnaires, the same six participants showed changes in ratings from the no-device to the RM-technology conditions (Participants 2–4, 7–8, 10) of at least 8 scale points on the L.I.F.E.-R. and of at least 0.5 scale points on the C.H.A.P.S. The remaining children showed no change on these two questionnaires. When examining the individual teacher ratings from specific items on the L.I.F.E.-R., the largest rating changes (>1 rating number) occurred on items 1, 2, 8, 12, and 15. Items 1 and 2 asked teachers to rate the (1) student's ability to follow large group verbal instruction and (2) student's ability to follow verbal instruction when the teacher moves about the room. Items 8, 12, and 15 included statements about the student's (1) hesitation when volunteering to answer questions, (2) ability to attend to verbal instruction and understand when noise is present, and (3) overall rate of listening and learning in comparison to peers.

3.2. Participant questionnaire

3.2.1. Group data

Nine participants were able to complete the student version of the L.I.F.E.-R., which depicts each listening situation/scenario with color pictures. The participants who could not complete this questionnaire included Subjects 4, 11, and 12. Average ratings from the participants are provided in Table 3 and show substantially improved ratings with the RM technology over no device. According to statistical analysis performed with the Wilcoxon Signed-Rank Test, significantly better ratings were found with the RM technology over the no-device condition ($z = 2.1$, $p = 0.03$, two-tailed). As shown in Table 2, the effect size for this comparison was large.

3.2.2. Individual data and questionnaire items

According to the individual data provided in Table 3, all but two participants (7 and 11) show score changes (≥4 scale points) with the RM technology. When examining participant ratings from specific items on the L.I.F.E.-R. (Table 3), larger rating changes (>1 scale point) occurred on 9 of the 15 items on the questionnaire (2–4, 6, 10, 11, 13–15). As a result, the RM technology was helpful in most classroom situations including following verbal instruction with no visual cues, hearing in noise, and hearing in large groups. A comparison between the available teacher and participants ratings revealed similar findings for some participants, but not others. For example, in Participant 2, the teacher reported a 27-scale-point improvement on the L.I.F.E.-R. with RM technology while the participant reported a 21-scale-point improvement. Conversely, Participant 9's teacher reported a decline in performance on the L.I.F.E.-R while the participant reported large improvements.

3.3. Parent questionnaires

3.3.1. Group data

Average parent ratings are provided in Fig. 3 and Table 3 for the C.H.I.L.D. (n = 8) and in Table 3 for the SSP (n = 9). Only the nine parents who completed home-based trial periods completed the questionnaires, and as a result, ratings were not returned for Subjects 4, 11, and 12. The Wilcoxon Signed-Rank Test was used for ratings in each listening condition to determine if there were significant differences between the device and no-device ratings. The analyses for each listening condition on the C.H.I.L.D. suggested significant benefit of the RM technology in all conditions: quiet ($z = 2.5$, $p = 0.01$, two-tailed), noise ($z = 2.4$, $p = 0.02$, two-tailed), at a distance ($z = 2.4$, $p = 0.02$, two-tailed), in social situations ($z = 2.2$, $p = 0.02$, two-tailed), and for social media ($z = 2.2$, $p = 0.03$, two-tailed).

On the SSP, the Wilcoxon Signed-Rank Test was used to compare the no-device and RM technology ratings for the two listening areas. The analysis revealed that, with the RM technology, parents reported significantly less difficulty with auditory filtering ($z = 2.7$, $p = 0.01$, two-tailed) and less difficulty with visual/auditory sensitivity ($z = 2.4$, $p = 0.02$, two-tailed). Effect sizes for both questionnaires and all conditions were large (Table 2).

3.3.2. Group data and questionnaire items

Individual data on the C.H.I.L.D., shown in Table 3, indicated that all parents perceived improved auditory performance at home of at least 1.1 scale points when the RM technology was used. Also, when examining each listening situation on the questionnaire (Fig. 3), the largest differences (>6 rating numbers) across the participants occurred in quiet, noise, and when the signal of interest was at a distance.

The individual data for the two sections of the SSP (Table 3) revealed greater rating improvements for auditory filtering, with seven of eight children showing score changes, when compared to auditory sensitivity with five of eight children showing score changes. When examining the rating differences (i.e., average RM technology rating − average no-device rating) across the participants, the largest differences (>1 rating number) occurred in the auditory filtering section of the questionnaire for items 22, 23, 26, and 27. These items related to distractibility and function in noise, hearing what was said, responding to name, and auditory attention. On the visual/auditory sensitivity section of the questionnaire, the item with the largest change (change of 1 rating number), related to negative responses to unexpected or loud noises.

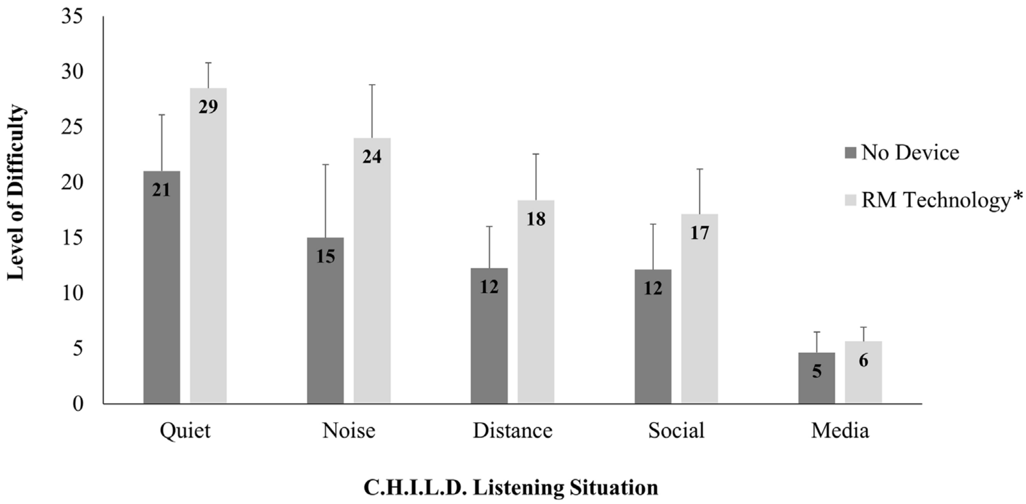

Fig. 3. Average ratings from nine parents on the Children's Home Inventory for Listening Difficulties (C.H.I.L.D.) and. Note. Vertical lines represent one standard deviation; asterisk represents condition(s) with significantly better performance, $p < 0.05$.

3.4. Speech recognition in noise

Individual performance for eight children (Subjects 1, 3, 4–8, 10) who were able to participate in the speech-in-noise measure is provided in Table 4. To determine if a threshold with the RM technology was significantly better (i.e., lower) than a threshold without the technology, the 2.5 dB critical difference level from the test manual was used. The shaded area in Table 4 depicts the six children that had differences greater than 2.5 dB. Overall, two children exhibited no change (−0.25 to 1 dB), whereas six children improved their threshold by 3.75–9.25 dB.

3.5. Acceptable noise levels

Five of the 12 children (Subjects 1, 3, 5, 6, 10) were able to complete the ANL task, which required children to indicate the level of background noise that they were willing to tolerate while listening to a speech signal. The individual data are provided in Table 4. To determine if the ANL improved (i.e., decreased) in the RM-technology condition over the no-device condition, the standard error of measurement (see methods section for details) was used (i.e., difference score of 1 for 95% confidence). As indicated with the shaded regions in Table 4, four of the five participants showed a substantial improvement in the RM-technology condition over the no-device condition. Overall, the ANLs of three participants decreased by about 10 dB, and the ANL of one participant decreased by 14 dB.

3.6. Listening comprehension and auditory memory

Seven of the 12 children were able to complete the two RIPA-P subtests, and raw scores are provided in Table 4. Significant individual improvements were determined using the 95% confidence intervals (0.80–22.9; −0.19 to 26.2) that was estimated based on the mean difference between the conditions (11.8; 13) using *t* distribution. The shaded regions in Table 4 show that only one child improved his or her performance, and the improvement occurred on both subtests (Participant 11).

4. Discussion

The goals of assessing the group and individual benefits of RM technology in children diagnosed with ASD were achieved by addressing the two hypotheses in the study. First, the primary hypothesis of this study was that the 12 children diagnosed with ASD, with higher and lower levels of functioning, would benefit from RM technology on functional questionnaires and behavioral test measures. Although sample sizes varied across the measures, statistical analyses revealed significant average benefit of the RM technology on the functional questionnaires completed by teachers, participants, and parents. These findings suggested significant benefit of the RM technology at school, at home, and in social situations. Similarly, many children experienced significant individual increases in performance on the behavioral measures, particularly on the speech-in-noise measure.

The second hypothesis was related to the individual data with similar patterns of improvement across the functional questionnaires versus the differential patterns across the behavioral measures. This hypothesis was difficult to confirm because of missing data; however, as shown in Tables 3 and 4, a clear pattern of improvement from RM technology emerged from some of the participants. For example, Participants 3, 5, 7, and 11 showed rating changes on at least two functional questionnaires and significant improvements on at least two behavioral measures. Further, Participants 1, 3, 4, 5, 8, 10, and 12 showed rating changes with RM technology on all functional questionnaires that were completed (Table 3), which likely contributed to the significant group differences. One abnormal pattern was seen for Participant 9 where the teacher indicated no RM technology benefit, but the parent and child reported rating changes. The data in Table 4 indicate some differential patterns across the three test measures, but the investigators believe the varied findings relate mostly to the difficulty of the ANL and RIPA-P for many of the children. In particular, on the ANL, children were required to provide perceptual judgements of where speech and noise were most comfortable. The instructions appeared to confuse many of the children, making the ANL a less desirable measure for evaluations. Similarly, the R.I.P.A.-P required children to answer questions that were heard in presence of background noise, which is a much more difficult task than speech recognition, which only requires children to repeat what is heard in background noise. It is possible that some children did, in fact, benefit from the RM technology as measured by the RIPA-P; however the authors of this manuscript chose a conservative approach to analyzing this data (i.e., 95% confidence intervals). The behavioral benefits of the RM technology were also well-supported by the benefit measured in the noise condition on the C.H.A.PS., as well as by questions about functioning in noise on the remaining questionnaires. All of the participants who were able to complete the R.I.P.A.-P were also able to complete the speech recognition task; therefore, when conducing an assistive technology evaluation on children, the R.I.P.A.-P may be considered only after the child successfully completes speech recognition. However, as shown in this study the R.I.P.A.-P may have limited clinical value given its difficulty for some children.

Overall, the first hypothesis of benefit from RM technology was tested and confirmed; however, the second hypothesis of patterns across measures was confirmed only for the functional-questionnaire portion of the study. As a result, the functional questionnaires used in the present study are sensitive to detecting expected benefit from RM systems and are recommended for assistive technology evaluations in the home and at school. Additionally, speech recognition in noise and possibly listening comprehension/working memory testing may be attempted in children who are able to participate in behavioral testing.

4.1. Comparisons to previous studies

Because some aspects of the present study replicate methodology used in previous investigations (Rance et al., 2014; Schafer, Mathews et al., 2014; Schafer, Traber et al., 2014), the group data from between studies can be compared. First, the C. H.A.P.S. was used in a previous investigation of 11 private-school children, ages 9–12 years, with ASD (Schafer et al.). The teacher in the 2014 study reported similar significant improvements in listening abilities across all six listening situations when RM technology was used during instruction relative to the no-device condition. Therefore, similar functional benefits of RM technology have been reported by a private school teacher with similarly-aged, high-functioning children with ASD and by multiple public school teachers who educate children of varying ages and abilities at different schools.

Second, when considering the functional questionnaire data from the nine participants that completed the L.I.F.E.-R., the results in the present study are similar to data reported in two previous investigations (Rance et al., 2014; Schafer, Mathews et al., 2014). For example, in the Rance et al. study, eight children who were high functioning and diagnosed with ASD reported a significant decrease in communication difficulties when listening in quiet and noise with RM technology as compared to a no-device condition. Similarly, in the Schafer et al. study, 10 out of 10 students reported that they liked the system and that it was helpful in class. Nine of the ten students wanted to continue using the system after the study.

Third, results on the parent-completed C.H.I.L.D. in the present and in a previous study (Schafer, Traber et al., 2014) revealed identical findings of significant RM benefit in all listening situations: quiet, noise, speech at a distance, social situations, and when listening to media. Although RM technology is typically recommended for noisy situations because it improves the SNR, it is interesting to note the benefit obtained in quiet on this as well as other questionnaires. As a result, the RM technology may be recommended for multiple listening environments. Additionally, in general, quiet environments in the real world are not completely quiet (e.g., noise from others, heating/air conditioning, computers, dishwasher, and outdoor noise). Additionally, almost all real-world situations require multi-modal processing, so ratings in “quiet” environments may represent situations with low-level noise and multi-sensory inputs.

Fourth, although there are no previous studies that utilized the SSP, the significant improvements with RM technology on this questionnaire are particularly noteworthy given the aforementioned data (Section 1.1) on the SSP from Ashburner et al. (2008). In this previous study, the auditory filtering section of the SSP was the most atypical sensory characteristic identified by parents of children with ASD. Furthermore, the child’s auditory filtering ability was the most significant predictor of his or her educational performance. Given the findings in the present study and Ashburner et al., it is possible that the improved auditory filtering achieved through the use of RM technology could positively impact educational performance in children with ASD. Future research will need to test this hypothesis.

Fifth, when considering the BKB-SIN thresholds of eight children who could complete the task, the RM technology improved average performance by 4.7 dB (SD = 3.7) over the no-device condition. To interpret this finding, previous research indicates that a 1-dB change is equivalent to an approximately 10% change in speech recognition when testing near threshold (Nilsson, Soli, & Sullivan, 1994). As a result, the children in the present study may improve their perception of speech by almost 50% when using the RM technology over no device. However, actual performance in more realistic environments will vary given the dynamic nature of typical classrooms where SNRs could range from −18 to +5 throughout a school day (Larson & Blair, 2008; Sanders, 1965). When compared to a control group of 9- to 12-year-old children in a previous investigation that utilized identical stimuli and loudspeaker arrangement (Schafer, Mathews et al., 2014), the children in the present study have substantially poorer average performance on the order of 9 dB (control group: −10.1 dB; present study: −1.7 dB). This group difference was expected because previous investigations have shown significant performance differences between children with ASD and typical controls (Alcántara et al., 2004; Rance et al., 2014; Schafer, Mathews et al., 2014). With no device, children from the present study also had considerably worse average performance than the group of children with ASD and ADHD in the Schafer et al. study with no device (−4.8). This difference is likely related to the higher functioning and older ages of the children in the previous study as compared to the lower functioning and younger ages of the children in the present study. However, the average benefit achieved with RM technology was similar between the previous (5.9 dB improvement) and present study (4.7 dB improvement).

In the present study, testing was conducted in the soundbooth, and stimuli were presented through loudspeakers located at 0 and 180° azimuth. This arrangement is commonly used to assess the benefits of RM technology because it is standard practice to have two speakers in a soundbooth, and this arrangement simulates the teacher talking in the front of the classroom with noise generated behind the listener (e.g., Rance et al., 2014; Schafer, Mathews et al., 2014). However, the situation was ideal in that the speaker’s voice was at a consistent intensity from the same location (60 dBA), noise was consistently presented from same spatially-separated location, and there was no reverberation in the soundbooth. In a more realistic situation, the talker moves around the room and has varying vocal intensity, the room is reverberant, and noise is dynamic and diffuse. As a result, the children’s speech recognition in this study was likely better than what would be obtained in an actual classroom. At the same time, however, results from the present study will likely generalize to testing done in clinical settings, as the loudspeaker arrangement from the present study is feasible to replicate in an audiology clinic.

Finally, there are no previous studies on children with ASD completing the ANL or the RIPA-P. However, it is interesting to note that the ANL test was difficult for most of the children in this study; only five of the 12 children could complete the task.

The task was difficult because it required the child to provide loudness impressions for speech alone and for speech in the presence of noise. To do this reliably, children had to be able to comprehend multi-step directions. Results for the five children suggested that, on average, they were willing to tolerate significantly higher levels of noise (average noise increase of 8.6 dB; SD = 6.1) when using the RM technology over the no-device condition. As stated in the in the discussion on the SSP results (Section 4.3), these results are noteworthy because, in general, children with ASD have abnormal auditory filtering in the presence of noise. However, when using the RM technology, the children are willing to tolerate higher levels of noise when listening to running speech. Acceptance of higher noise levels likely occurs because the better SNR provided by the RM technology increases the salience of the speech over the noise.

The RIPA-P was also a difficult task that only seven children could complete, which may be related to the +3 SNR used for testing. It is possible that the ability to hear the stimuli was impacted because of the presence of background noise, which was only 3-dB less intense than the speech signal (+3 SNR). However, all seven children were able to provide partial answers to most questions without the RM technology suggesting that at least some of the stimuli were audible. Additionally, even if audibility was somewhat affected in the no-device condition, a +3 dB SNR is better than some SNRs that will be encountered at school (Cruckley et al., 2011; Larsen & Blair, 2008; Sanders, 1965).

4.2. Clinical implications

Average results on the functional questionnaires used in the study suggest that RM technology may be beneficial to children with ASD at home, at school, and in social situations. Despite the average benefit for the children in this study, the variability in the individual data suggests the importance of conducting an individual evaluation on each child to determine potential benefit. If parents are interested in a trial period with RM technology, the investigators suggest contacting a pediatric or educational audiologist in their area. Additionally, when a system is purchased by a school district for a child with ASD, parents or school personnel may want to conduct a trial period with RM technology at home because the system may facilitate progress on IEP goals pertaining to communication and social interaction (see Appendix A). The Appendix A summarizes all email conversations or correspondence from parents or teachers about how the system impacted daily life in and outside of school. Several of the parents purchased or obtained remote-microphone technology through their child's IEP following the study.

In most public-school settings, RM technology is considered as a type of assistive technology. Assistive technology must be considered for all children with a special education eligibility, and most children with ASD are receiving special education services. Therefore, parents and professionals serving children with ASD may recommend and request an assistive technology evaluation to determine the potential benefit that may be achieved by a student. To determine benefit from the RM technology at school, the investigators recommend conducting questionnaires and behavioral measures before and after a six-week trial period with RM technology. In the investigators' clinical experiences, the questionnaires and behavioral measures used in the present study are effective for evaluations (i.e., L.I.F.E.-R., C.H.A.P.S., speech recognition in noise, and listening comprehension in noise). Because the recorded version of the listening comprehension (RIPA-P) test that was used in the present study is not commercially available, an examiner may consider presenting the stimuli via monitored live voice from a loudspeaker at 0° azimuth with fixed intensity noise from the BKB-SIN compact disc playing through a loudspeaker at 180° azimuth. As shown in the present study, use of teacher and parent questionnaires alone and classroom observations (Schafer, Mathews et al., 2014) are effective assessment tools for children who have lower function and are unable to do behavioral testing.

4.3. Study limitations

Limitations associated with this study relate primarily to the participants, study design, questionnaire limitations, and test environment. First, the study included a small sample of children across the ASD spectrum, and as a result, the children had variable speech and language levels. Some children were not able to understand the directions for behavioral testing, participate in traditional hearing testing, or complete the participant questionnaire. The test measure with the smallest sample size was the ANL, which suggests that this measure is likely too difficult for children with ASD to understand and complete. Additionally, a child's overall level of functioning or length of RM-technology use per day may have impacted the ratings on the parent and teacher questionnaires. The examiners asked the children to use the system at least two hours at school and at home per day, but the actual use time was not recorded. Despite the variability, however, the average performance on the questionnaires yielded significant benefit and large effect sizes of the RM technology at school and at home. Another design-related limitation was that the same four examiners conducted all behavioral testing with the participants, which could have introduced bias toward benefit with the RM device. However, the examiners were all trained in research ethics and to work with children with multiple disabilities. Further, the findings in the present study are similar to those reported in Schafer, Mathews et al. (2014) and Rance et al. (2014).

Second, a within-subjects design was used for the present study, which does not contain a control group of neurotypical children. In within-subjects designs, the subject serves as his or her own control because performance at baseline is compared to performance with a treatment (RM technology). Because numerous previous studies have identified and replicated abnormal auditory function and processing (Section 1), our focus was on the treatment of the auditory deficits via RM technology for children across the spectrum. Additionally, the investigators believe that a comparison of our diverse sample to a control group is impossible because, although attempted with every participant, many of the subjects in the present study were unable to do the behavioral testing. As discussed in Section 4.1, average speech recognition of the children in the present study was poor relative to neurotypical peers of a slightly older age in a previous study (Schafer, Mathews et al., 2014). Future research will need to examine how neurotypical children perform on the R.I.P.A.-P to allow for a comparison to children with ASD.

Third, it is possible that certain statements on the questionnaires did not directly apply to situations that the child experienced at home or at school. To minimize this occurrence, we administered two teacher and two parent questionnaire that included different types of statements and listening situations. Additionally, questionnaire ratings were averaged over several questionnaire items to obtain a total score or a score for a particular listening situation (e.g., noise, quiet, ideal). Another potential issue with the questionnaires relates to the fact that only the child's primary academic teacher and the child's primary caregiver completed the questionnaires. It is possible that different ratings could have been obtained from other teachers or from the other parent.

Fourth, behavioral testing was conducted in a sound treated room with stationary speech and noise. This equipment arrangement only simulates one listening situation with the teacher in the front of the room and noise behind. In a real classroom environment, the speech and noise is dynamic and moves around the room. Also, although realistic noise (babble; classroom noise) was used during the behavioral testing, there was no reverberation in the test room. The presence of reverberation is known to degrade speech recognition and comprehension performance in children (Neuman, Wroblewski, Hajicek, & Rubinstein, 2010; Valente, Plevinsky, Franco, Heinrichs-Graham, & Lewis, 2012). As a result, it is likely that the children in this study would perform more poorly in realistic environments than they did in the present study, particularly in situations with a combination of sensory inputs (e.g., visual, auditory, tactile). Also, behavioral performance was not assessed in the present study via direct observations in the classroom as done in a previous investigations (Schafer, Mathews et al., 2014). Single subject behavioral observations would have provided more evidence regarding the individual benefits of using the RM technology.

Finally, it is important to recognize that use of RM technology does not eliminate the multiple sensory and processing issues faced by children with ASD. Use of this technology only improves the SNR and, therefore, makes the signal of interest more salient in the presence of noise. The auditory skill that is most improved with the RM technology is perception of speech. As indicated by the results in this study, use of the RM technology also improves auditory filtering, attention, and communication. However, it should be noted that the device does not cure children of attention deficits, language disorders, and auditory processing issues. These deficits will likely remain. However, future research should consider the possibility that long-term use of RM technology could alter the cortical processing of speech sounds because this phenomenon occurred in children with dyslexia after a year-long trial with RM technology (Hornickel, Zecker, Bradlow, & Kraus, 2012).

5. Conclusions

The results of this study on the potential benefits of RM technology for 12 children with ASD suggested that most children with ASD receive significant functional benefit and some children receive behavioral benefits of the technology over a no-device condition. When using the RM technology, teacher, participant, and parent questionnaires revealed significantly improved auditory filtering, auditory attention, auditory memory, and listening abilities across a wide variety of listening situations at home, school, and social environments. For the children that were able to complete the behavioral measures, use of the RM technology significantly improved perception of speech, tolerance of noise in the presence of speech, and comprehension of auditory instructions, respectively. Overall, use of the RM technology substantially improved auditory performance in children with ASD. As a result, RM technology may be considered in the school-based and home-based treatment and management of the frequent auditory disorders in children with ASD.

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Appendix A. Parent and Teacher Communication Regarding the Remote-Microphone Technology During the Study.

Parent of Participant #1	"After much deliberation with his school, they have decided not to participate in the study. I was very much under the impression that their participation would be indisputable, but after obtaining the equipment and asking for teacher input, I started to receive resistance. I don't think there is anything else I can do. I am so sorry for the inconvenience and interruption to your study. I truly think it is a worthwhile endeavor!"
Parent of Participant #2	"I've just finished using the devices for the first time today, and my daughter and I just had a 3-min conversation about cocoa. She made eye-contact consistently while we talked back-and-fourth, and she responded quickly as I've never seen her do before. Afterwards, we continued with our conversation some more. Usually, a conversation with her requires a lot of work with

	repeated requests, questions, etc. (as many as ten times) to get her to respond, and keeping her engaged in having an ongoing conversation with her is taxing. However, the conversation that I had with her just now was super easy. Because of that, I'm so amazed and excited!!" "She continues to be helped by the device every day. Without it, she will be unable to participate in gymnastics each week. We're so very glad that she participated in the study."
Portions of an Individual Education Plan that mentioned FM system for Participant #2	"She is happy and cooperative but may require several verbal prompts/redirections to keep her on task in all schools settings daily. She does not initiate conversations with peers or adults familiar to her, but will answer when spoken to. When having a conversation with her, she must be reminded to look towards the speaker and prompted to listen. She has been observed to be much more attentive during conversations with the use of an FM system. Without the use of an FM system, she requires prompts before and several during the conversation and the speaker must frequently check for her understanding to know if she is still listening. When using the FM system, one prompt prior to the conversation was sufficient and she would voluntarily participate on topic during the conversation which indicated that she was attentive and focused thus negating the need to frequently check for her understanding or if she was actively listening. She was also observed noticing what the other children were doing In the classroom when wearing the FM system and even initiated a few conversations with peers by inquiring what they were doing. During center time or unstructured time such as recess, typically she has been observed either playing on her own and appeared to not have any interest in what the other students were doing or engaged in parallel play when prompted to join a group of students. However, with the use of the FM system, she became actively involved in what the group was doing. When her general education teacher allowed another student to use the FM system, she engaged in an on-topic conversation with the student and required no prompting." "She is a cooperative student and will follow directions given by the teacher but will require several verbal and visual prompts/directives daily in all academic settings without the use of an FM system. Her disability of ASD impacts her behavior in the general education classroom, and at times, her inattentiveness could be confused with non-compliant behaviors to those not familiar with her. These things hinder her ability to access the curriculum without support from Special Education. She requires specific attention and line of sight vision during all transition activities as she frequently has not listened to the teacher's directions and has been observed attempting to leave her immediate area. When using an FM system, she will stop and return to her assigned area given one to two verbal prompts. Without the FM system she typically will not stop and keep walking out of the classroom requiring physical redirection from the teacher to return to her assigned area in all school settings daily. During times that she has been observed off task, not following teacher directions and/or not participating with class activities, she was engaged in what appeared to be delayed echolalic behavior, mouthing the words of a TV show or movie she has seen, which causes her to tune out all other auditory input. When she uses an FM system this behavior was observed to be significantly decreased and even non-existent in the classroom."
Parent of Participant #5	"The hearing aid is working wonders for him! I was wondering if we could receive information or if the UNT hearing clinic can provide us resources for us to know the steps we need to take to possibly find a hearing aid that fits his needs."
Parent of Participant #7	"I love the system. I'm looking forward to hearing more from his teachers. He's wearing it in 3 classes each day. Language Arts, Science and Math. He never needs a reminder to take it to school which I find interesting because he will forget other things."
Parent of Participant #8 and #9	"They are doing so well with them. The teachers are giving some great feedback. We actually tried them Sunday when we went grocery shopping at Target, and it literally brought me to tears cause it's the first time in years we've all been able to go and they listened. I would talk to them and remind them how we behave while we were in there, and having my voice talk them throughout, they actually helped put things in the cart. I'm just very thankful we are able to be a part of this study."
Parent of Participant #10 and #11	"Is there a chance we could buy the FM device, and what is the price? Their audiologist said they have normal hearing, but if I can get a diagnosis of auditory processing disorder then she will use it to try to get an approval for a device through Medicaid."

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