This is the accepted version of Gustafson, S. J., Ricketts, T. A., & Picou, E. M. (2021). Individual Differences Offer Insight Into Clinical Recommendations for Directional and Remote Microphone Technology Use in Children. *Journal of Speech, Language, and Hearing Research*, 1-16. A full, published version is available at https://pubs.asha.org/doi/abs/10.1044/2020_JSLHR-20-00281

Individual differences offer insight into clinical recommendations for directional and remote microphone technology use in children

Samantha J. Gustafson[a]

Todd A. Ricketts[b]

Erin M. Picou[b]

[a] Department of Communication Sciences and Disorders, University of Utah, Salt Lake City, Utah
[b] Department of Hearing and Speech Sciences, Vanderbilt University Medical Center, Nashville TN

Address correspondence to:
Samantha Gustafson
390 South 1530 East, BEHS 1204
Salt Lake City, UT 84112
801-213-3638 (office)
Samantha.Gustafson@utah.edu

Conflict of Interest Statement: The authors declare no current or prior competing interests.

Funding Statement: Support for this work was provided by Sonova AG (hearing aids, remote microphone systems, participant compensation) and the Dan and Margaret Maddox Charitable Fund (to Samantha Gustafson).

Abstract

Purpose: This study sought to evaluate the effects of common hearing aid microphone technologies on speech recognition and listening effort, and to evaluate potential predictive factors related to microphone benefits for school-age children with hearing loss in a realistic listening situation. Method: Children (n=17, ages 10-17 years) with bilateral, sensorineural hearing loss were fitted with hearing aids set to include three programs: omnidirectional, adaptive directional, and omnidirectional + remote microphone. Children completed a dual-task paradigm in a moderately reverberant room. The primary task included monosyllabic word recognition, with target speech presented at 60 dB A from 0° (front) or 180° (back) azimuth. The secondary task was a "go/no-go," visual shape-recognition task. Multitalker babble noise created a +5 dB signal-to-noise ratio. Children were evaluated in both speaker conditions (front, back) using all three hearing aid programs. The remote microphone transmitter remained at the front speaker throughout testing. Speech recognition performance was calculated from the primary task while listening effort was measured as response time during the secondary task. Results: Speech presented from the back significantly increased listening effort and caused a reduction in speech perception when directional and remote microphones were used. Considerable variability was found in pattern of benefit across microphones and source location. Clinical measures did not predict benefit patterns with directional or remote microphones; however, child age and performance with omnidirectional microphones did. Conclusion: When compared to a traditional omnidirectional setting, the directional and remote microphone configurations evaluated in this study have the potential to provide benefit for some children and increase difficulty for others when used in dynamic environments. A child's performance with omnidirectional hearing aids could be used to better inform clinical recommendations for these technologies.

Children with hearing loss are often tasked with learning in classroom environments that routinely exceed recommended noise limits (American National Standards Institute, 2010; Bess et al., 1984; Hétu et al., 1990; Shield & Dockrell, 2004; Spratford et al., 2019). Excessive noise in the classroom creates an environment with a poor signal-to-noise ratio (SNR) that can significantly reduce speech understanding for children (Neuman et al., 2010; Valente et al., 2012). These poor SNRs are particularly problematic for children with hearing loss, who require more favorable listening environments for equivalent speech recognition performance when compared to children with normal hearing (Crandell & Smaldino, 2000; Gravel et al., 1999; Pittman, 2011).

Technology such as directional microphones and remote microphone systems are intended to mitigate challenges created by poor SNRs. As such, they are expected to provide a microphone-based benefit in some listening situations, when compared to hearing aids using omnidirectional microphones. Directional microphones have reduced sensitivity to sounds arriving at the hearing aid microphones from certain azimuths - typically from the back and/or to the side of the listener (Ricketts, 2001). This differential sensitivity can result in small but significant improvements in SNR, resulting in improved speech recognition in noise for adults (Ricketts & Hornsby, 2003, 2006) and children (Gravel et al., 1999; Hawkins, 1984; McCreery et al., 2012; Pittman, 2011; Ricketts et al., 2007). Remote microphone systems place a microphone close to one sound source of interest (i.e., the teacher), potentially providing significant improvements in SNR and thus, speech recognition performance (Boothroyd, 2004; Hawkins, 1984; Larsen & Blair, 2008; Pittman et al., 1999; Thibodeau, 2010). This potential for significantly improved communication in noisy classrooms has led to the recommendation that remote microphone technology be used with school-age children who have hearing loss (American Academy of Audiology, 2011).

These recommendations are primarily based on previous research demonstrating significant improvements in speech recognition with directional and remote microphones when testing is conducted in ideal listening conditions – where the talker of interest is stationary within the front hemifield and unwanted noise sources are located to the side of or behind the listener (e.g., Anderson & Goldstein, 2004; Auriemmo et al., 2009; Wolfe et al., 2013; Wouters et al., 1999). It is important to consider that dynamic classroom environments often require children to listen to talkers who are not necessarily teachers located in the front hemifield. For example, a child could turn around to face another classmate, placing the teacher in their rear hemifield where directional microphones would attenuate the teacher's speech. Alternatively, if that child's teacher is wearing a remote microphone, the child could encounter difficulty understanding the classmate behind, even after turning to face them, due to the superior SNR of the teacher's voice provided by the remote microphone. Thus, benefits of microphone technologies are expected to be limited to specific listening situations. Indeed, early work demonstrated that a remote microphone worn by the teacher in front can impair a child's ability to understand the speech of a classmate who is located to their side (Pittman et al., 1999). Directional microphone technologies also have the potential to impair speech recognition when the talker of interest is behind the child (Ricketts et al., 2007; Wolfe et al., 2017), leading to the recommendation for use only if the child can appropriately orient themselves toward the talker of interest (McCreery et al., 2012). While a general consideration of varying listening environments (e.g., teacher lecture vs student-to-student interaction) is recommended (American Academy of Audiology, 2011), no evidence-based recommendations have been made outlining specific listening configurations and remote microphone use.

Given the lack of clear recommendations and the potential disadvantage of directional microphones, audiologists do not generally provide directional microphone settings for school-age children. In a survey of 66 pediatric audiologists throughout North America, Moodie and colleagues (2016) found that the decision to prescribe directional microphones was reportedly dependent upon the age of the child, the degree and configuration of hearing loss, and the child's listening needs. These motivations appear to be inconsistent with research, as lower-grade classrooms are known to have higher levels of noise than higher-grade classrooms (Crukley et al., 2011; Picard & Bradley, 2001) and benefit from directional microphones is independent from a child's degree of hearing loss (Kuk et al., 1999). Furthermore, the lack of an age-related change in ability of school-age children to adequately orient towards a talker of interest (Ricketts & Galster, 2008) suggests that age of the child will likely not influence benefit from a directional microphone once the child begins school. Additional research is needed to understand if other child-specific factors can predict directional benefit in realistic listening environments. This information would better arm audiologists with evidence supporting their decisions regarding the implementation of directional microphone technology.

Despite the expected improvement in speech perception with the use of remote microphone technologies, a significant portion of children with hearing loss do not appear to be using remote microphone systems in classrooms (Brackett & Maxon, 1986; Gustafson et al., 2017). The rational for this limited remote microphone use is likely multidimensional – including but not limited to psychosocial factors (Elkayam & English, 2003; Keilmann et al., 2007), a shortage of educational audiologists (Richburg & Smiley, 2009), financial resource limitations, and use of other assistive listening technology (e.g., classroom audio distribution systems; Boswell, 2018). One unexplored factor contributing to underuse of remote microphone systems is the benefit realized with these systems in realistic classroom environments. As described above, both traditional directional microphones and remote microphone systems can be limited in the benefits they provide, or even lead to speech recognition decrements in non-optimal listening configurations (e.g., Wolfe et al., 2017). In turn, children with hearing loss may choose not to use remote microphone technology because they do not perceive a significant benefit from the device. Although not the focus of their study, individual data reported by Fitzpatrick and colleagues (2009) for adults with cochlear implants shows limited remote-microphone benefit for listeners with adequate baseline (i.e., cochlear implant alone) performance and a greater benefit for those with poor baseline performance. It is currently unknown if children who perform satisfactorily with the use of hearing aids alone are any less likely to enjoy benefits of remote microphone technology.

While speech recognition benefits are clearly paramount, the cognitive resources or "listening effort" that children must exert can also greatly affect learning (Peelle, 2018; Rudner et al., 2018). Referring to the specific form of mental effort required when the task involves listening, listening effort has long been a topic of interest for adults and children with hearing loss (Downs, 1982; Hicks & Tharpe, 2002; McGarrigle et al., 2019; Ohlenforst et al., 2017). A recent adaptation of the Capacity Model of Attention (Kahneman, 1973) has been applied to the concept of listening effort – the Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al., 2016). FUEL proposes that attention-related responses are based on the complex relationship between factors related to the listener (e.g., hearing loss), signal (e.g., background noise), and limitations on available cognitive capacity that can vary with the listener's arousal level. This framework is consistent with findings of increased listening effort when background noise is present and for listeners with hearing loss when compared to listeners with normal hearing in ideal environments (Ohlenforst et al., 2017; Sarampalis et al., 2009).

For adults, directional microphones in hearing aids have been shown to reduce listening effort in moderately reverberant laboratory environments (Bernarding et al., 2017; Desjardins, 2016; Picou, Moore, et al., 2017). Although it has not yet been directly assessed, it is expected that directional microphones will also reduce listening effort for children with hearing loss, as decreases in listening effort have been shown in children with and without hearing loss with small improvements in SNR (Gustafson et al., 2014; McGarrigle et al., 2019).

There is a similar dearth of research examining the effect of remote microphone systems on listening effort in children; only one study reports measured listening effort with and without the use of a remote microphone. Cruz and colleagues (2020) used a dual-task paradigm to compare listening effort when children (12-17 years old) were using hearing aids alone or hearing aids and remote microphone technology. The dual-task paradigm is a measure of divided attention based on the assumption that the pool of cognitive resources is limited. When the primary task becomes more difficult (e.g., background noise is introduced), fewer resources are available to maintain optimal performance on the secondary task. In Cruz (2020), the primary task consisted of speech-in-noise recognition and the secondary tasks required the listener to memorize and reproduce a four-color sequence. Although the authors did not report whether the use of a remote microphone system improved speech recognition, no improvements in listening effort were measured for these children with hearing loss. Importantly, their study of listening effort and remote microphone use had several limitations. Most notably, they used an adaptive primary task that allowed for performance to remain at 50%-correct with and without use of the remote microphone system. By adjusting the SNR to maintain performance in the hearing-aid-only and remote-microphone conditions, the cognitive demand required to complete the task was held constant, effectively leveling any potential difference in listening effort between conditions. Additionally, research using the dual-task paradigm with adult listeners has shown that listening effort recorded at low levels of primary-task performance (30-50%) can be reflective of cognitive overload and potential disengagement from the task (Wu et al., 2016). It is possible that more favorable listening conditions (resulting in primary-task performance above 50%) that are stable across conditions of interest might show reductions in listening effort with the use of remote microphone technology.

The primary purpose of this study was to evaluate the effects of hearing aid microphone setting (directional microphones, remote microphones) on speech recognition and listening effort benefit (relative to an omnidirectional hearing aid microphone), as measured by dual-task paradigm, in a realistic listening situation where the talker is either directly in front of (teacher/primary talker) or behind (classmate/secondary talker) the listener. Based on existing work in the adult population in moderately-reverberant environments (Desjardins, 2016; Picou, Moore, et al., 2017; Picou & Ricketts, 2018), we hypothesized that the use of directional and remote microphones would reduce listening effort for children, but only for speech originating in the front. A secondary purpose of this study was to evaluate potential predictive factors related to microphone benefits for speech recognition and listening effort. Specifically, we evaluated if child-specific factors available to a clinical audiologist (age, pure-tone-average, unaided word recognition score) would predict benefits with directional and remote microphones. Finally, to examine if benefit from microphone technology is related to performance without this technology, we included performance without microphone technology (e.g., baseline performance with omnidirectional microphones) as an additional child-specific factor when predicting directional and remote microphone benefit.

Materials and Methods

Participants

Nineteen children (ages 9 – 17 years, M = 13.46, σ = 2.74) with bilateral, permanent, sensorineural hearing loss agreed to participate. However, the youngest two participants (both 9 years old), were withdrawn from the study due to their inability to perform the dual-task paradigm reliably during the practice trials. Thus, the following is based on 17 participants (ages 10-17 years, M = 14.00, σ = 2.37). Power analysis using the **powerSim** and **powerCurve** functions of the **simR** package (Green & MacLeod, 2016) in R (R Core Team, 2014) using estimates of effect size and variability from previous work (Picou et al., 2019; Picou, Moore, et al., 2017) revealed a sample size of 15 participants would be sufficient to detect differences between hearing aid conditions with 80% power. Audiometric test results, displayed in Figure 1, indicated bilateral, symmetrical sensorineural hearing loss, as defined for this study by normal immittance findings on the day of testing, air-bone gaps <20 dB from 0.5 – 4.0 kHz, and interaural differences <15 dB at three consecutive audiometric frequencies or <30 dB at any single audiometric frequency (0.25 – 6.0 kHz). Table 1 displays demographic and hearing health history for the 17 participants whose data are included. Most participants had been fitted with bilateral, behind-the-ear hearing aids. The exceptions were participants 11 and 16 who were never fitted with hearing aids and participant 8 who was fitted with in-the-ear hearing aids. Most participants had experience with remote microphone systems in classrooms, although nearly half of the participants had discontinued remote microphone system use at the time of testing.

Participants did not exhibit neurological, cognitive, or language disorders unrelated to their hearing loss, as evidenced by review of medical record and parental report. All testing was conducted with approval from Vanderbilt University's Institutional Review Board (#151136). Participants were compensated monetarily for their time.

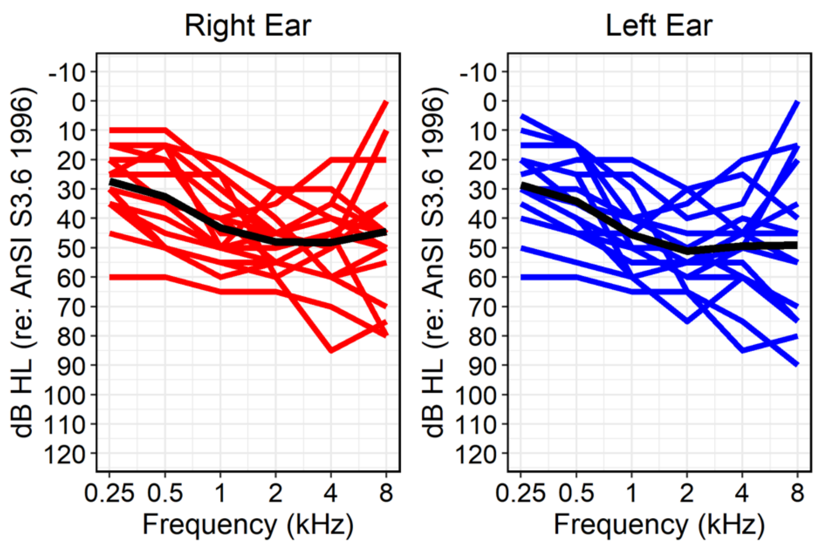


Figure 1. Individual (colored lines) and mean (black line) air conduction, pure tone audiometric thresholds for study participants' right (panel A) and left (panel B) ears.

Table 1. Demographic and hearing health history for study participants

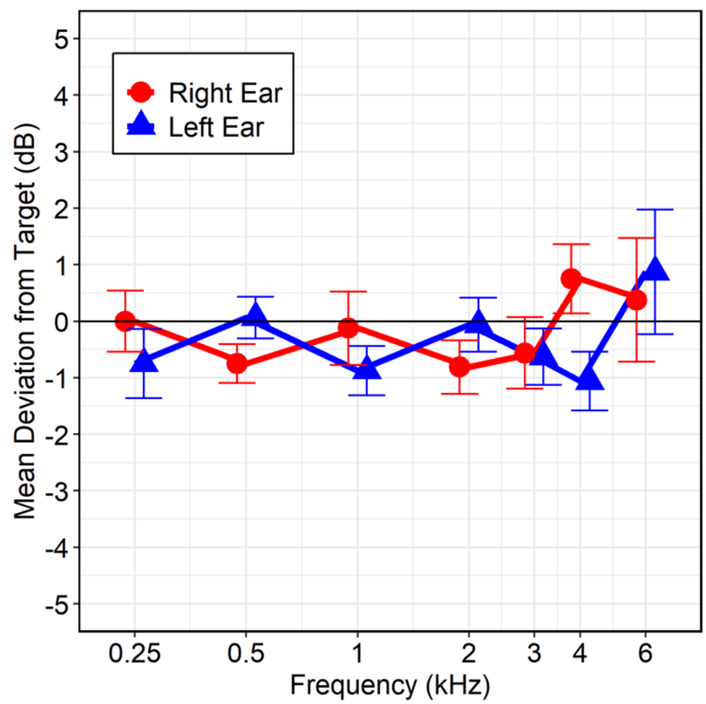
ID	Gender	Age (years)	Age at Diagnosis (years)	Suspected Etiology	History of Chronic Otitis Media	Age at Hearing Aid Fitting (years)	Reported Hearing Aid Use at Time of Study	Other Interventions in Classrooms	WR (rau) in Omni-directional	RT (ms) in Omni-directional
1	M	12	5.5	Unknown	No	6.5	All the time	Personal RM	51.8	1722
2	F	12	9.5	Unknown	No	9.75	All the time	Soundfield RM	68.9	1346
3	M	17	4	Chemotherapy	No	4	All the time	Discontinued RM	96.4	792
4	M	14	8.5	Unknown	Yes	11.5	Sometimes	Personal RM	85.4	1290
5	F	16	3.25	Unknown	No	3.75	Sometimes	Discontinued RM	71.0	1196
6	F	16	2.5	Unknown	No	8.9	Never	Preferential seating	90.0	1227
7	M	17	8	Unknown	No	11	Sometimes	Personal RM	71.8	1197
8	M	16	6	Unknown	Yes	7	All the time	None	90.0	735
9	M	15	8.5	Unknown	No	8.5	Never	Soundfield RM	77.6	1439
10	F	11	5	Prenatal drug exposure	Yes	5	All the time	Discontinued RM	63.9	1475
11	F	11	10.5	Unknown	Yes	NA	Never	Discontinued RM	63.1	1562
12	F	10	6	Chemotherapy	No	7	Sometimes	Personal RM	52.1	1376
13	M	14	9	Familial	No	10.5	All the time	None	84.6	1402
14	F	16	Unknown	Familial	Yes	Unknown	All the time	None	81.9	1287
15	F	14	11.5	Unknown	Yes	11.5	All the time	Discontinued RM	89.6	968
16	F	16	8	EVA	No	NA	Never	Discontinued RM	103.3	1184
17	F	11	5	Unknown	Yes	5	All the time	Discontinued RM	69.1	1179

Note: ID = participant identification code, M = male, F = female, EVA = enlarged vestibular aqueduct, NA = not applicable, RM = remote microphone system

Hearing Aids

For the purpose of the study, participants were fit with bilateral hearing aids that were used only for laboratory testing. The hearing aids were commercially available, behind-the-ear hearing aids (Phonak Sky Q90 M13) paired via integrated receivers with a remote microphone in conference mode (Phonak Roger Pen Version 1™). The hearing aids were coupled to the participant's own, custom earmolds with clinically appropriate venting. Participants 8, 11, and 16, who did not have personal earmolds, were fitted with temporary earmolds (Comply™ Canal Tips). The hearing aids were programmed with three manually accessible programs, which varied only by microphone setting. The microphone settings were: 1) omnidirectional, 2) adaptive directional, and 3) remote microphone + omnidirectional. The remote microphone + omnidirectional program was chosen to be consistent with the American Academy of Audiology guidelines, which state that remote microphone technology should provide the child with full audibility of themselves and others around them (American Academy of Audiology, 2011). This setting allows for the child to monitor their environment via the hearing aid microphone while still providing an improved SNR of the teacher's voice via the remote microphone. Adaptive directionality refers to UltraZoom, Phonak's unilateral, adaptive beamformer technology. The directional properties of the omnidirectional and directional microphone settings were verified on each instrument prior to study commencement for each participant by measuring the relative hearing aid output for signals presented from the front and back using the directional testing function of the Audioscan® Verifit 1 test box.

All three hearing aid programs were otherwise identical, with advanced features deactivated, including digital noise reduction, frequency lowering, wind noise reduction, and reverberation reduction. Feedback reduction was set to 'weak' for all fittings and modeled for each participant’s individual ears. The frequency response of all three programs was also identical; they were all programmed to match prescriptive targets (Desired Sensation Level v5 adult; Scollie et al., 2005). Match to prescriptive target for a 65 dB SPL input was verified using on-ear, probe microphone measures and recorded speech stimuli with the Audioscan Verifit (Cole, 2005). Figure 2 shows the average deviation of measured real-ear sound pressure level (SPL) from prescriptive target (Target SPL– Measured SPL). In the remote microphone setting, microphone transparency was ensured by comparing the signal output of the hearing aid when



coupled and when not coupled to remote microphone technology. The remote microphone advantage was programmed to be +10 dB SNR, in accordance with the recommendations of the American Academy of Audiology (2011). Relative to the hearing aid output in response to a 65 dB input signal, the remote microphone system output in response to a 75 dB input was 8.61 dB ($\sigma_{\bar{x}}$ = 0.37), 9.94 dB ($\sigma_{\bar{x}}$ = 0.37), and 9.25 dB ($\sigma_{\bar{x}}$ = 0.60) at 750 Hz, 1000 Hz, and 2000 Hz, respectively. These data indicate the remote microphone system was relatively successful in providing the recommended +10 dB SNR advantage.

Figure 2. Mean deviation from prescriptive targets (Target SPL – Measured SPL) across frequency in each ear. Error bars represent one standard error of the mean.

Listening Effort Task

Listening effort was evaluated using a dual-task paradigm that has been used in other studies of listening effort in children with normal hearing (Picou, Charles, et al., 2017; Picou et al., 2019). The primary task was word recognition; spoken by an adult female talker, words were monosyllabic and described concrete nouns (e.g., bead, case). Words were presented from a loudspeaker located 1.2 m directly in front of or behind the participant. The level of the words measured at 65 dBA at the position of the child's head. There were 200 words arranged into 8 lists of 25 words each. Based on pilot testing, words were arranged so lists would be approximately equal in difficulty. Details of stimuli development are outlined elsewhere (Picou, Charles, et al., 2017; Picou & Ricketts, 2014).

The secondary task was a "go/no-go," visual shape recognition task. During 19 of the 25 words in a list, a colored shape was presented 500 ms after stimulus onset. The colored shape varied by color (blue/yellow) and shape (circle/triangle). A participant's task was to press the location of the shape on a touchscreen monitor (Dell S2240T) located on a desk directly in front of them. They were instructed to make their response as quickly as possible (i.e., "go"), but only if the shape was the correct color and shape combination (blue circle, yellow triangle). If the shape was the incorrect color and shape combination (blue triangle, yellow circle), the participant's task was to refrain from touching the monitor (i.e., "no go"). Nine of the shapes were incorrect and ten were correct. During the other six words, a small fixation cross was presented. All shapes were presented on a black background. The fixation cross was 1 x 1 cm; the colored shapes were 6.5 x 6.5 cm. Time to respond to the correct color/combination shape was recorded by the experimental program and was taken as an indication of listening effort.

All testing was conducted in background noise. The noise was a four-talker babble, where each talker was a recording of a different female reading passages from the Connected Speech Test (Cox et al., 1987, 1988). The talkers in the babble were different from the primary-task talker. Recordings were edited so the level of each sentence in each passage from each talker were matched (see Picou et al., 2011). The recordings were routed to four loudspeakers, one talker to each loudspeaker. The noise loudspeakers were 3.5 meters from the participant and located at 45, 135, 225, and 315 degrees. The location of the talkers switched throughout testing; recordings of the same talker were not presented from two different loudspeakers at the same time. The overall level of the background noise was 60 dBA at the level of the child's head, creating a +5 dB SNR. This SNR was chosen based on pilot data to approximate 80% word-recognition performance for children with hearing loss. Furthermore, it is broadly consistent with some estimates of classroom listening scenarios; teachers' voices in occupied classrooms are estimated to be between 57 and 70 dBA (Picard & Bradley, 2001; Spratford et al., 2019) and SNRs in classrooms to be between +1 and +11 dB (Larsen & Blair, 2008; Sato & Bradley, 2008).

Test Environment

Clinical test battery measurements (i.e., audiometric thresholds and word recognition) were evaluated in a double-walled, sound attenuating audiometric test booth using standard clinical procedures with a GSI-61 (Grason-Stadler) and insert earphones (EAR-3, Etymotic

Research). Assent, consent, and tympanometry (Tympstar, Grason-Stadler) were completed in a quiet, clinic-like environment. Listening effort testing was completed in a dedicated, moderately reverberant laboratory space (5.5 x 6.5 x 2.25 m). All surfaces of the room are hard (concrete floor, hollow, painted walls); however, acoustic blankets (Sound Stopper 124) hung on the walls (n=4; 4' X 8') and ceiling (n=4; 4' X 4') to limit the reflections. With the reflective treatment, the reverberation time in the room was approximately T30 = 475 ms, which is within the recommended reverberation times for classrooms (Bistafa & Bradley, 2000; Finitzo-Hieber & Tillman, 1978). Additional details of this testing environment were reported previously (Picou et al., 2016). Speech was presented from a computer (Dell) with custom experimental programming (Neurobehavioral Systems v 12.0) and then routed to an auditory-visual switch (Extron), an attenuator (Tucker Davis Technologies PA5), and finally to a powered loudspeaker (Tannoy System 6A). The noise was presented from the same computer (Dell) with Adobe Audition CSS v 5 and was routed to a multichannel amplifier (Crown CTS 8200) and to unpowered loudspeakers (Tannoy System 6).

Procedures

Testing was completed over two or three visits to the laboratory. The first and last research visits were separated by a median of 14 days. The initial visit began with participants providing assent to participate and their parent or guardian providing informed consent. Participants then completed the clinical test battery (audiometric testing, tympanometry, and word recognition assessment) and hearing aid fitting. Audiometric testing included pure-tone air- and bone-conduction threshold testing in each ear. Unaided word recognition scores were evaluated using prerecorded NU-6 monosyllabic, 25-word lists (Auditec, St. Louis, MO) presented bilaterally at 63 dB SPL. This presentation level was chosen to be representative of conversational speech levels and provided a measure of audibility-related constraints on speech recognition when not using hearing aids. Finally, immittance testing was completed (GSI Tympstar) to ensure normal middle ear pressure and compliance.

Subsequent visit(s) to the laboratory including listening effort testing described in this study as well as additional aided testing using similar complex listening tasks for another study. Listening effort testing reported here always occurred prior to additional aided testing and lasted approximately 25 minutes per visit. Prior to experimental listening effort testing, participants completed a series of practice tests to ensure they understood the task instructions. Practice testing was completed with hearing aids set to omnidirectional and used four 25-word lists that were comprised of words that were not included in lists presented during experimental testing. Four conditions were completed as practice: (1) secondary task only in quiet, (2) dual-task paradigm in quiet, (3) dual-task paradigm in +5 dB SNR, and (4) secondary task only in +5 dB SNR. The fourth condition served as the baseline measure of response time to the secondary task. Participants were required to achieve >80% correct in the dual-task paradigm in quiet in order to be included in the study. Experimental listening effort testing included two 25-word lists presented in each of the six conditions, which varied by loudspeaker location (front, back) and hearing aid microphone setting (omnidirectional, directional, remote microphone + omnidirectional). Response time data are not available for the second repetition of all conditions due to experimenter error (participant 1). In addition, participant 16 only completed the first repetition in all conditions.

The remote microphone was placed with a horizontal orientation (i.e. “conference mode”) so the top end of the Roger Pen™ was ~17.8 cm from the cone of the front loudspeaker.

The first-generation Roger Pen used in this experiment activates an omnidirectional microphone setting when placed in this horizontal orientation. The remote microphone remained near the front loudspeaker for both the “front” and “back” test conditions. Conditions were counterbalanced across participants, but blocked such that testing with one speech loudspeaker location (e.g., front) was completed before testing commenced with the second location (e.g., back). Word list was randomized within each participant.

Data Analysis

Prior to analysis, word recognition scores were converted to rationalized arcsine units (rau) according to the equations by Studebaker (1985). Median response times were calculated in each condition. Response times were excluded if the response time was more than three standard deviations from the median of that condition. For both word recognition and response times, the average across the two repetitions was analyzed.

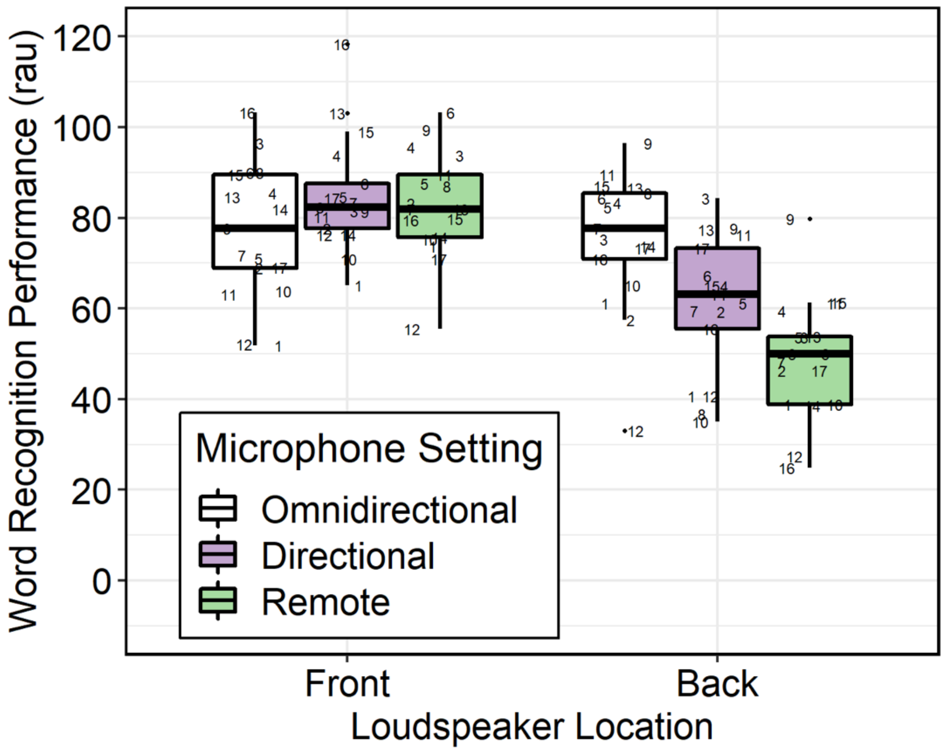
All analyses were conducted in R (v 3.6.1; R Core Team, 2014). To analyze the effects of microphone mode on speech recognition and listening effort measured in the dual-task paradigm, word recognition and response time data were analyzed separately, each using linear mixed effects models with two fixed factors, Hearing Aid Setting (omnidirectional, directional, remote microphone + omnidirectional) and Loudspeaker Location (front, back). Participant was included as a random factor. Models were constructed using the **lmer** function of the **lme4** package (Bates et al., 2014). Significant main effects or interactions were analyzed using pairwise comparisons of the estimated marginal means with Satterthwaite degrees of freedom using the **emmeans** package (Russell, 2019).

To explore the potential predictors of microphone mode benefits, calculated directional and remote microphone benefits were analyzed using multiple linear regressions using the **lm** function of the **stats** package in base R. Eight regression analyses were conducted, one for each combination of outcome (word recognition, response time), microphone (directional, remote) and loudspeaker location (front, back) combination. The dependent variables for all analyses were benefit scores. Benefits were calculated relative to performance in the omnidirectional condition such that a positive score indicates more benefit. Thus, for word recognition scores, the performance in the omnidirectional condition was subtracted from the performance in the directional or remote microphone conditions, but the reverse was true for response times, where lower scores indicate more favorable performance. For all eight analyses, potential predictor variables were entered in a stepwise fashion in the following order: 1) age, 2) better ear pure tone average (0.5, 1.0, 2.0, 4.0 kHz), 3) unaided NU-6 word recognition score, and 4) performance in the omnidirectional condition (either word recognition [rau] or response time [ms], depending on the benefit score). For the experimental omnidirectional conditions, the loudspeaker-specific score was used for the regression model (front or back).

Results

Word Recognition

Word recognition scores are displayed in Figure 3. Analysis revealed significant main effects of Loudspeaker Location ($X^2(1) = 78.8$, $p < 0.0001$) and Microphone ($X^2(1) = 19.3$, $p < 0.0001$), in addition to a significant Location x Microphone interaction ($X^2(2) = 57.5$, $p < 0.0001$). Results of pairwise comparison testing, displayed in Table 2, demonstrate the effects of hearing aid microphone varied based on loudspeaker location. Specifically, compared to performance with the omnidirectional microphones, the directional and remote microphones provided a benefit for word recognition performance for speech originating from the front loudspeaker, but a detriment to word recognition for speech originating from the back loudspeaker. There were no additional benefits of the remote microphone compared to



directional microphones for speech from the front loudspeaker, whereas performance with the remote microphone was worse than with the directional microphone when speech was from behind.

Figure 3. Median word recognition performance (rau) for each loudspeaker location and microphone setting. The boxes indicate the first through third quartile. Participant numbers from Table 1 are overlaid on top of the boxplots.

Table 2. Results of pairwise comparison testing of the estimated marginal means of the Loudspeaker x Hearing Aid interaction for word recognition performance. For all comparisons, the standard error of the estimate is 2.95 and degrees of freedom are 181.2. Estimates are provided in rau. Significant comparisons are indicated by bold type face.

Loudspeaker	Contrast	Estimate	95% CI (lower)	95% CI (upper)	t ratio	p value
Front	**Omnidirectional - Directional**	**-8.64**	**-14.5**	**-2.83**	**-2.93**	**0.004**
Front	**Omnidirectional - Remote**	**-6.10**	**-11.9**	**-0.29**	**-2.07**	**0.040**
Front	Directional - Remote	2.54	-3.28	8.35	0.86	0.39
Back	**Omnidirectional - Directional**	**14.4**	**8.57**	**20.2**	**4.88**	**<0.001**
Back	**Omnidirectional - Remote**	**27.4**	**21.6**	**33.2**	**9.30**	**<0.001**
Back	**Directional - Remote**	**13.0**	**7.19**	**18.8**	**4.42**	**<0.001**

The results of multiple linear regression analyses examining the relationship between child-specific variables (age, pure-tone average, unaided word recognition scores, and omnidirectional performance) and microphone benefits are displayed in Table 3. In general, clinically-obtained variables were not statistically related to microphone benefits. The exception was a small effect of age (R^2 $\Delta = 0.022$) on remote microphone benefit for speech from the front loudspeaker such that younger children enjoyed more benefit from the remote microphone than older children. Performance in the omnidirectional condition, however, was related to benefit in more than one condition. The relationships between directional and remote microphone benefits and word recognition performance in the omnidirectional condition are displayed in Figure 4. Specifically, those with better performance in omnidirectional were more likely to demonstrate a detriment in performance with the directional microphones when listening to the speaker behind and were less likely to demonstrate benefits from the remote microphone when listening to the speaker in front.

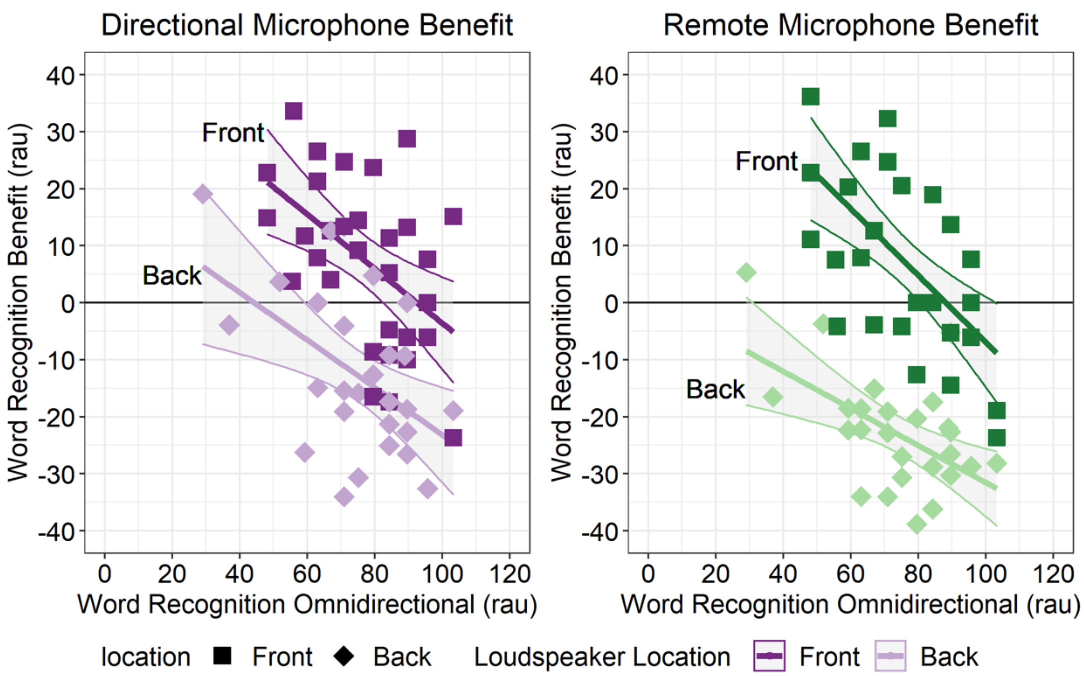


Figure 4. Relationship between directional microphone benefit (panel A) and remote microphone benefit (panel B) for word recognition for front (dark color) and back (light color) loudspeakers as a function of performance in the omnidirectional condition (rau). Linear regression lines and 95% confidence intervals are also displayed.

Table 3. Results of multiple regression analysis of word recognition benefit scores for directional microphones (left panels) and remote microphone (right panels) for speech originating from the front loudspeaker (top panels) and back loudspeaker (bottom panels).

Word Recognition Directional Benefit Front						Word Recognition Remote Benefit Front					
	Est.	Std Error	t ratio	*p*	R^2 Δ		Est.	Std Error	t ratio	*p*	R^2 Δ
(Int.)	87.9	26.1	3.36	0.002		(Int.)	23.3	21.2	1.10	0.28	
Age	-2.08	1.20	-1.73	0.094	0.24	**Age**	**2.31**	**0.97**	**2.37**	**0.025**	**0.022**
PTA	-0.55	0.39	-1.43	0.16	0.024	PTA	0.24	0.31	0.76	0.46	0.026
WRS	-0.12	0.14	-0.89	0.38	0.026	WRS	0.048	0.11	0.43	0.67	<0.001
Omni	-0.28	0.20	-1.42	0.17	0.048	**Omni**	**-0.80**	**0.16**	**-5.01**	**<0.001**	**0.45**

Word Recognition Directional Benefit Back						Word Recognition Remote Benefit Back					
	Est.	Std Error	t ratio	*p*	R^2 Δ		Est.	Std Error	t ratio	*p*	R^2 Δ
(Int.)	32.2	28.0	1.15	0.26		(Int.)	11.0	20.8	0.53	0.60	
Age	-0.30	1.20	-0.25	0.81	0.070	Age	-0.40	0.90	-0.45	0.66	0.046
PTA	-0.16	0.41	-0.40	0.70	0.045	PTA	-0.33	0.31	-1.08	0.29	-0.067
WRS	0.11	0.15	0.74	0.46	0.007	WRS	-0.006	0.11	-0.059	0.95	<0.001
Omni	**-0.55**	**0.18**	**-3.01**	**0.005**	**0.22**	Omni	-0.25	0.14	-1.82	0.079	-0.094

Note: Int. = intercept, Est. = estimate, Std Error = standard error, R^2 Δ = R squared change, WRS = unaided word recognition scores, Omni = experimental word recognition scores in the omnidirectional condition

Response Times

Average baseline response times to the secondary task in noise were 1078.6 ms (σ = 204.5 ms). Secondary task accuracy was high and consistent across conditions, ranging from 96.2 to 98.8% correct identification of the color/shape combination. Experimental response times are displayed in Figure 5. Analysis revealed a significant main effect of Loudspeaker Location ($X^2(1) = 16.3$, $p < 0.0001$), no significant main effect of Microphone ($X^2(2) = 1.21$, $p = 0.55$), and no significant Microphone x Loudspeaker interaction ($X^2(2) = 2.29$, $p = 0.318$). Pairwise comparisons reveal the response times during speech presentation from the front loudspeaker were significantly faster than response times during speech presentations from the back loudspeaker (t ratio = 4.59, $p < 0.0001$, *M* difference = 97.5 ms, $\sigma_{\bar{x}} = 21.3$, 95% CI: 55.6 to 139 ms). These data indicate that hearing aid microphone mode did not affect response times, but the presentation of speech behind the listener slowed response times.

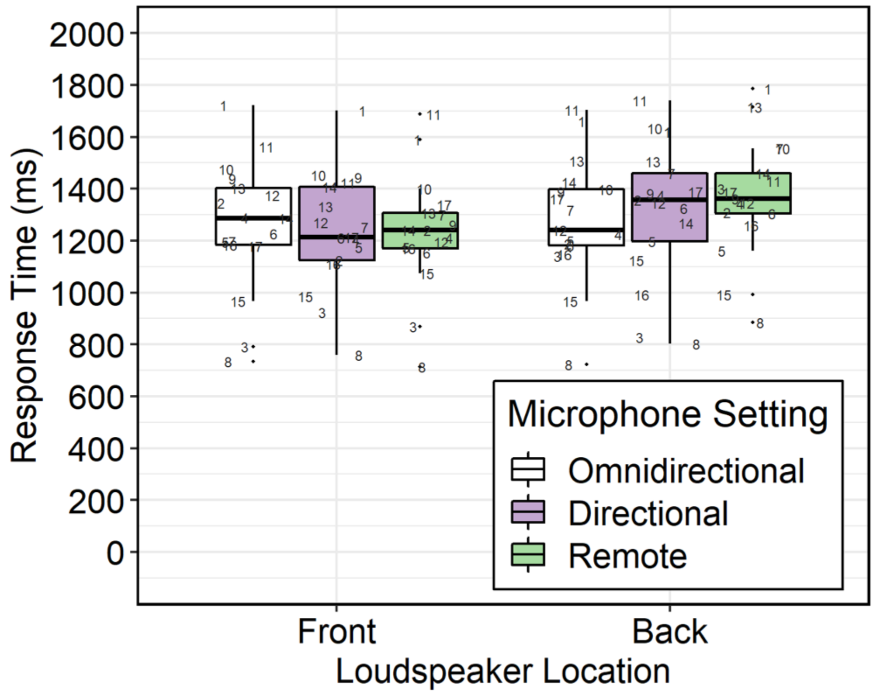


Figure 5. Median response times (ms) for each loudspeaker location and microphone setting. The boxes indicate the first through third quartile. Participant numbers from Table 1 are overlaid on top of the boxplots

Although there were no main effects of microphone, it was of interest to explore the potential child-specific predictor variables related to differences between microphone settings. The results of multiple linear regression analyses are displayed in Table 4. The only clinically-obtained variable that significantly related to microphone benefits was child age, which showed a moderately-sized effect of age (R^2 $\Delta = 0.11$) on directional benefit when speech was behind the child. Response times in the omnidirectional condition were related to microphone benefit; the relationships between microphone benefits and response times in the omnidirectional condition are displayed in Figure 6. These data indicate that, for speech presented from the front, those with slower response times were more likely to benefit from both directional and remote microphones. For speech presented from the back, those with faster response times were more likely to demonstrate detriments (negative benefit) associated with directional and remote microphone use.

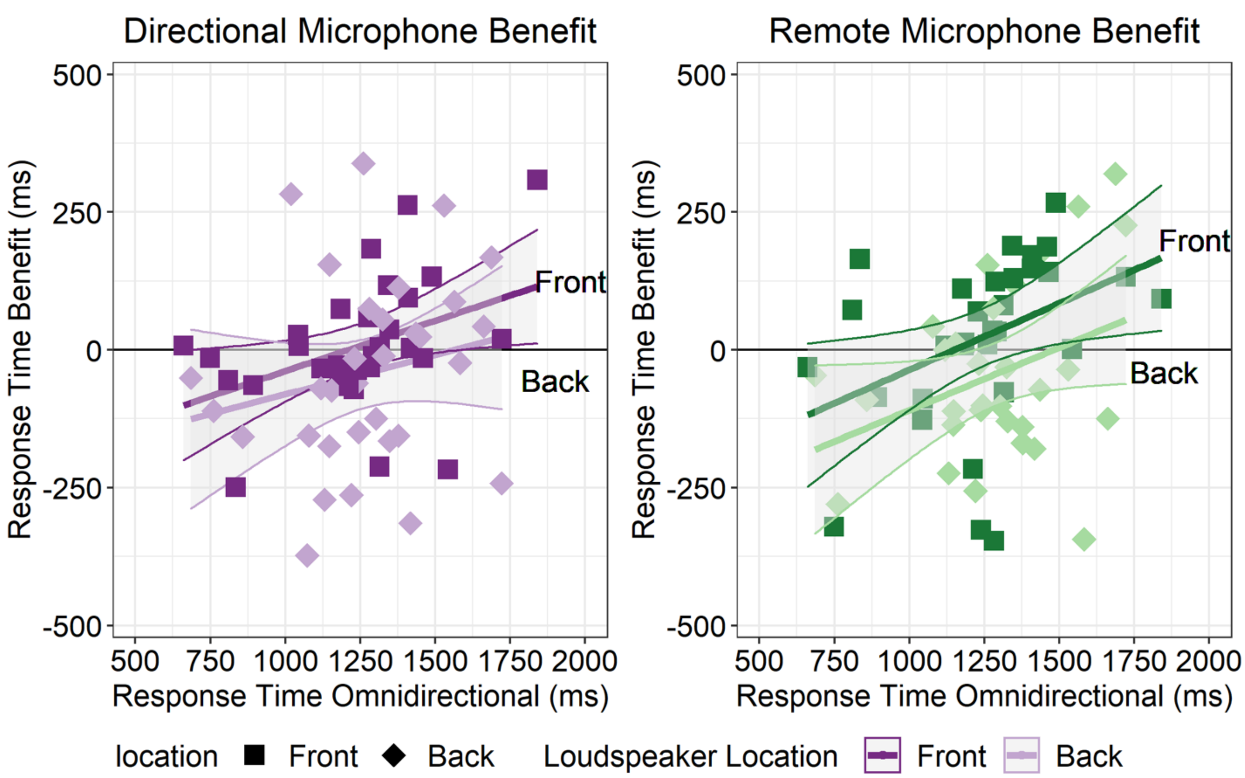


Figure 6. Relationship between directional microphone benefit (panel A) and remote microphone benefit (panel B) for response times for front (dark color) and back (light color) loudspeakers as a function of performance in the omnidirectional condition (ms). Linear regression lines and 95% confidence intervals are also displayed.

Table 4. Results of multiple regression analysis of response time benefit scores for directional microphones (left panels) and remote microphone (right panels) for speech originating from the front loudspeaker (bottom panels) and back loudspeaker (bottom panels).

Response Time Directional Benefit Front						Response Time Remote Benefit Front					
	Est.	Std Error	t ratio	*p*	R^2 Δ		Est.	Std Error	t ratio	*p*	R^2 Δ
(Int.)	-90.7	351	-0.26	0.89		(Int.)	-569	391	-1.46	0.16	
Age	1.75	12.6	0.14	0.89	-0.044	Age	22.9	14.0	1.63	0.11	0.001
PTA	-4.81	4.30	-1.12	0.27	0.016	PTA	-4.58	4.80	-0.96	0.35	0.021
WRS	-1.63	1.59	-1.02	0.32	0.007	WRS	-1.34	1.77	-0.75	0.46	<0.001
Omni	**0.29**	**0.12**	**2.39**	**0.024**	**0.16**	**Omni**	**0.42**	**0.13**	**3.15**	**0.004**	**0.26**
Response Time Directional Benefit Back						Response Time Remote Benefit Back					
	Est.	Std Error	t ratio	*p*	R^2 Δ		Est.	Std Error	t ratio	*p*	R^2 Δ
(Int.)	-814	346	-2.36	0.030		(Int.)	-305	473	-0.65	0.52	
Age	**34.3**	**13.1**	**2.62**	**0.014**	**0.11**	Age	-5.03	17.9	-0.28	0.78	0.090
PTA	-1.61	4.79	-0.34	0.74	0.001	PTA	-3.68	6.55	-0.56	0.58	0.002
WRS	0.025	1.72	0.015	0.99	0.015	WRS	-1.51	2.35	-0.64	0.53	<0.001
Omni	**0.28**	**0.13**	**2.12**	**0.044**	**0.12**	**Omni**	**0.41**	**0.18**	**2.28**	**0.031**	**0.15**

Note: Int. = intercept, Est. = estimate, Std Error = standard error, R^2 Δ = R squared change, WRS = unaided word recognition scores, Omni = response times in the omnidirectional condition.

Discussion

The purpose of this study was to evaluate the effects of hearing aid microphone technology (directional and remote) on speech recognition and listening effort in school-age children, as measured with a dual-task paradigm in a moderately-reverberant environment. A secondary purpose was to evaluate potentially predictive individual variables that are related to microphone benefits. The results demonstrated that the effects of microphones were different for speech recognition and listening effort. Specifically, hearing aid microphone technology improved speech recognition when the speech was in front of the listener but degraded performance when speech came from behind. Although children showed an overall increase in listening effort when speech came from behind, listening effort was not overtly affected by the varying microphone technologies that were assessed in this study. Instead, evaluations of individual variability revealed that child age and performance with an omnidirectional microphone were significant predictors of benefit with microphone technologies.

Speech Recognition and Listening Effort

Consistent with previous work (Ricketts et al., 2007; Wolfe et al., 2017), our results suggest that, while beneficial for recognition of speech in front, directional microphone use in children is detrimental for listening to speech from behind. If the child is able to turn their head to listen to the speaker behind, this is not likely to cause functional problems. However, children with hearing loss are known to accurately look at the talker less than 50% of the time (Lewis et al., 2015; Ricketts & Galster, 2008), creating many opportunities for missed information with the use of directional microphones in dynamic listening environments. To our knowledge, this is the first study to evaluate the effect of directional microphones on listening effort in children. Contrary to our hypothesis, directional microphone use did not reduce listening effort on this task for children with hearing loss who are between 10 and 17 years old. The few studies that have examined the effect of hearing aid technology (e.g., digital noise reduction, extended bandwidth) on listening effort in children with hearing loss have also failed to find reductions in listening effort using different tasks (Brennan et al., 2014; Stelmachowicz et al., 2007). Our findings are consistent with this previous work and support the idea that minor improvements in audibility provided by hearing aid processing appear to have a negligible effect on listening effort in children with hearing loss, on average. Furthermore, our findings are consistent with Cruz et al. (2020), showing no overall effect of remote microphone use on listening effort in children on average. We noted above that non-significant results obtained by Cruz et al. may have been attributed to methodological constraints. Although the present study included reverberation, targeted ~80% speech recognition performance, and assessed children in a listening environment that remained consistent across conditions, we did not reveal effects of microphone technologies on listening effort. This suggests the non-significant effects Cruz et al. noted are not due to these methodological factors.

Despite these nonsignificant main effects of microphone technologies on listening effort as measured with this dual-task paradigm, we found considerable variability in technology-driven changes to speech recognition and listening effort across the children included in this study. Further analysis of child-specific factors predicting these changes (discussed below) suggests that the lack of overall effects of microphone technology on listening effort should not be taken to mean that these technologies are inappropriate for pediatric patients.

Predicting Benefit with Hearing Aid Microphone Technology

One goal of this study was to determine if clinically-derived measures could be used to predict which children might benefit from directional or remote microphone technology. Results showed that degree of hearing loss (PTA) and unaided word recognition could not be used to determine which children will enjoy benefits of this technology under these test conditions. Instead, child age and performance with omnidirectional hearing aids were found to be useful in predicting desired and undesirable changes to speech recognition and listening effort with directional and remote microphones.

A small effect of age was found for benefits in speech recognition with the remote microphone when the speaker was in the front of the listener such that younger children enjoyed more benefit from the remote microphone than older children. Although this suggests that younger children may benefit from remote microphone use more than older children, it is important to note that older children in this study were performing near ceiling in the omnidirectional condition and thus, had little opportunity for improved speech recognition when the remote microphone was introduced. While strong conclusions should not be drawn from the effect of age on speech recognition benefits, we also found a moderately-sized effect of age on changes in response times with the use of directional microphones when speech was behind the child. The direction of this effect indicates that younger children were more likely to show larger changes in response times than older children when using directional microphones. This suggests that the use of directional microphone technology when speech is in the rear hemifield has the potential to increase listening effort for younger children more so than for older children. This pattern of age-related increases in listening effort replicates the age-related effect of listening effort reported by Lewis and colleagues (2016) and is consistent with FUEL. Recall that FUEL allows for listener-related factors – such as hearing loss and cognitive capacity to influence the remaining resources available after the allocation of attention to any given primary task. Because cognitive capacity increases throughout childhood (Casey et al., 2005; Fry & Hale, 1996), it is plausible that the amount of available resources would increase with child age and thus, allow older children to use those remaining resources to successfully complete the secondary task.

Performance (speech recognition and listening effort) in the omnidirectional condition was related to benefits obtained with directional and remote microphone technologies. Considering that typical classroom environments require children to listen to speakers located in the front and rear hemifields, prediction of speaker-location benefits (and decrements) with microphone technology should be considered together. Children with better performance in omnidirectional were more likely to demonstrate impaired speech recognition and increased listening effort with the directional microphones when listening to the speaker behind and were less likely to demonstrate benefits (i.e., improved speech recognition and reduced listening effort) from the remote microphone when listening to the speaker in front. The diminishing benefit of the remote microphone on front-speaker word recognition is not surprising, as word recognition in omnidirectional was already near 100% for the good performers, leaving no room for additional remote microphone benefit. However, when considered with other findings, this pattern of results suggests that children who are performing adequately without this technology are less likely to receive benefit from a remote microphone in ideal listening conditions and are more likely to experience detriments (e.g., reduced speech recognition and increased listening effort) if using a directional microphone when the speaker is off-axis. In other words, directional and remote microphone technologies have the potential to increase the difficulty in dynamic listening situations for listeners who are not struggling with complex listening using omnidirectional microphones alone.

It is important to note that the effects of omnidirectional performance were significant even when we statistically controlled for the significant effects of age. That is, despite the age of the child, information about their performance with omnidirectional microphones in complex listening environments has the potential to predict whether they are good candidates for directional or remote microphone technology.

Clinical Recommendations

Accounting for the significant improvement in speech recognition with the use of directional microphones when speech was in front of the listener, our results showed no additional benefit of a remote microphone. This finding, coupled with the reduction in speech recognition and increased listening effort experienced with the remote microphone when speech was behind the listener, seems to call into question the utility of remote microphones for children with mild-to-moderate hearing loss in this age range under these test conditions (e.g., +5 dB SNR, multitalker babble, good baseline performance). However, it is important to note that performance changes due to remote microphone use appears to be driven by how well the child was performing without this technology. These findings suggest that, if a child is not struggling to understand the teacher in a classroom with omnidirectional hearing aids alone, a remote microphone is not likely to provide speech recognition benefit and may cause an undesirable increase of listening effort when listening to talkers from the rear hemifield. In this case, a remote microphone system should not be recommended. Conversely, our findings show that children who struggle to communicate in complex environments with omnidirectional hearing aids alone are likely to benefit from directional and remote microphone technologies via improved speech recognition and reduced listening effort, supporting clinical recommendations of either microphone technologies.

In order to make these evidence-based clinical recommendations, audiologists should evaluate a child's communication abilities – including both speech recognition and listening effort – in dynamic listening environments with omnidirectional hearing aids. Because limitations in testing environments, clinical equipment, and appointment time may prohibit audiologists from this type of direct aided assessment, subjective outcome measures – particularly those incorporating response from sources familiar with the child's classroom listening skills – might provide this information. Considering that pediatric audiologists across North American report using a wide variety of hearing aid outcome measures (Moodie et al., 2016), future research should focus on determining which, if any, existing outcome measures could be used for this purpose.

Study Limitations and Future Directions

Children using remote microphone technology in this study showed no additional benefit in speech recognition beyond that obtained with directional microphones for speech arriving from the front, and showed an additional drop in speech recognition performance when speech was behind the listener; however, this finding is limited to the technologies used in this study. Specifically, the research hearing aid system included standard, adaptive directional hearing aid microphones and an omnidirectional remote microphone with omnidirectional hearing aid microphones activated. The use of the remote microphone in an omnidirectional mode likely provided gain to the background noise, reducing the audibility of the target speech. Additionally, the remote microphone configuration used here was somewhat limited, as it is common to activate the microphones in the hearing aids for monitoring in addition to using the remote microphone. Improving the SNR at either microphone location (remote or hearing aid microphones) through the use of directional microphones or beamformers would be expected to greatly increase the magnitude of benefits observed for the front speaker configuration (Norrix et al., 2016). Hearing aids that include directional voice detection are expected to eliminate the decrements we demonstrated for speech arriving from behind the listener. Further, the use of dynamic remote microphone technology would be expected to increase the benefits from the front and decrease the decrements from the back (Thibodeau, 2014). Finally, technologies which exist in some advanced remote microphones steer the direction of focus to the loudest talker and have the potential to improve speech recognition for both talkers from the front and back

(Thibodeau, 2019). Further research is required to understand how children might benefit from other configurations that include advanced directional and remote microphone technology.

Children completed this study using laboratory hearing aids that differed from their personal hearing aids and a remote microphone system that may have been unfamiliar. Because they did not have an opportunity to acclimate to this different technology outside of the lab, it is possible that the effects of directional microphones and remote microphone technology found here might differ following an appropriate acclimatization period. Evidence of acclimatization with hearing technology in children is limited. While Scollie and colleagues (2010) found significant acclimatization effects on children’s loudness ratings when using a new prescriptive fitting algorithm, Glista and colleagues (2012) found that some but not all children benefited from an acclimatization period with frequency lowering technology. Future work is warranted to determine if the effects of directional microphones and remote microphone technology on speech recognition and listening effort change as children acclimate to the technology.

This study was conducted with participants ranging in age from 10 to 17 years. As such, these findings should not be extended to children with hearing loss who are younger than 10 years of age[1]. Because younger children require more favorable SNR and tend to have noisier

[1] It was our goal to include children younger than 10 years of age; however, these younger children experienced difficulty with the dual-task paradigm used here. Recall that our dual-task paradigm required a deeper level of processing than the traditional dual-task paradigm where the listener is instructed to press a button in response to a probe (Hicks & Tharpe, 2002). Previous studies have used similar dual-task paradigms requiring additional processing of the secondary task with children as young as seven-years-old who have normal hearing (Hsu et al., 2017; Picou, Charles, et al., 2017). However, this is the first study that required children with hearing loss to conduct this type of deeper processing of the secondary-task stimulus prior to responding. This type of “go/no-go” task requires inhibitory control, a cognitive process that allows for rapid assessment and cancellation of previously-planned (and sometimes initiated) motor activity (Baddeley, 1996; Rubia et al., 2000). Because children with hearing loss have been found to show reduced inhibition when compared to children with normal hearing (Blank et al., 2020;

classrooms than older children, it is important for future research to evaluate the effect of directional and remote microphone use on speech recognition and listening effort in dynamic environments where speech can come from various locations.

Recall that previous work conducted in a similar listening environment with adult hearing aid users showed increased speech recognition and reduced listening effort when using directional microphone technology (Picou, Moore, et al., 2017). As such, we expected that the combination of SNR and moderate levels of reverberation used here would be sufficient to observe reductions in listening effort due to remote and directional microphone technologies. Recent work by Picou and colleagues (2019) has found that children with normal hearing in this age range do not show increased listening effort due to reverberation time greater than was used here. Whether children with hearing loss are more affected by reverberation compared to children with normal hearing requires further research (Finitzo-Hieber & Tillman, 1978; McCreery et al., 2019); however, children with hearing loss are known to experience greater listening effort than those with normal hearing in listening conditions with noise + reverberation (McCreery et al., 2019; McGarrigle et al., 2019). Whether benefits with directional and remote microphone technology vary with noise and reverberation levels commonly found in classrooms is an important area for future research.

While this study expanded upon previous studies by including the evaluation of performance with hearing aid microphone technologies in a non-ideal listening configuration, it is important to note that we considered only a fraction of the realistic combinations of speaker location and microphone technology that might be found in a typical classroom. Specifically, the

Figueras et al., 2008), it is possible this type of “go/no-go” secondary task is beyond the cognitive abilities of some children with hearing loss who are younger than 10 years of age.

noise used here was four individual talkers separated by a relatively small distance – as might be encountered during a group-work activity where voices from neighboring groups arrive at the listener from varying directions and at a lower level than the voice of a group-member or teacher. Although adult listeners gain additional remote microphone benefits as distance between the listener and the sound source increases (Wagener et al., 2018), similar work has yet to be conducted in children. Results of Wagener and colleagues suggesting that children further away from the teacher might benefit more than those who receive preferential seating that keeps them close to the teacher. Whether we would find different benefits of microphone technology in other listening situations (e.g., alternative amounts of reverberation, poorer SNRs, larger listening environments) remains to be seen. Similarly, directional and remote microphone technology continues to rapidly advance - future studies are needed to determine if effects of hearing aid microphone technology found in this study persist with more advanced features (e.g., beamforming technology) or with alternative microphone configurations that can accurately capture off-axis voices (e.g., pass-around microphones).

Acknowledgements

The authors would like to thank Gabby Buono and Katelyn Schott for their assistance during data collection.

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