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Research Note

Remote Microphones Support Speech Recognition in Noise and Reverberation for Children With a Language Disorder

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ABSTRACT

Purpose: Children with typical hearing and various language and cognitive challenges can struggle with processing speech in background noise. Thus, children with a language disorder (LD) are at risk for difficulty with speech recognition in poorer acoustic environments.
Method: The current study compared the effects of background speech-shaped noise (SSN) with and without reverberation on sentence recognition for children with LD (n = 9) and typical language development (TLD; n = 9). We also investigated whether the use of a remote microphone (RM) improved speech recognition for children with LD.
Results: Children with LD demonstrated poorer sentence recognition than peers with TLD in SSN. Both groups had poorer sentence recognition with SSN + reverberation than SSN alone. Notably, using an RM improved speech recognition for children with LD in SSN and SSN + reverberation.
Conclusion: We discuss educational implications and future research questions to identify how to optimally support speech recognition in noisy environments for children with LD.
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Classrooms are complex listening environments with suboptimal acoustic characteristics, which can compromise the student's ability to perceive, comprehend, and learn from the speech stream (Jamieson et al., 2004; Klatte, Lachmann, & Meis, 2010). A student's ability to recognize speech entails a complex interaction between components of the listening environment (i.e., external factors) and the child's language and cognitive abilities (i.e., internal factors). Two external factors that often negatively affect speech recognition in classroom settings are background noise and reverberation (Dockrell & Shield, 2006; Klatte, Hellbrück, et al., 2010; also see Rosenberg, 2010). Background noise generally refers to sounds that interfere with the sounds a listener wants to hear. Reverberation refers to the reflected components of sounds in a room and adds additional masking to speech signals in enclosed spaces (Neuman et al., 2010). Academic performance is negatively related to increased classroom noise levels and reverberation (Brill & Wang, 2021; Klatte, Hellbrück, et al., 2010; Shield & Dockrell, 2008).

Given that background noise and reverberation are ubiquitous to classroom spaces, it is important to identify the children who are most likely to struggle with recognizing speech in background noise. We define *speech recognition* as the listener's ability to correctly identify the words produced by the speaker. The current research note focuses on speech recognition, an essential factor to support language comprehension. Children who are hard of hearing often demonstrate difficulty with speech recognition in complex listening environments (Lewis et al., 2015; McCreery et al., 2019). This is not surprising as these children have reduced auditory access to the speech signal and often have associated deficits in language and working memory abilities (St2iles et al., 2012). Children with

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typical hearing and decreased language knowledge, verbal working memory abilities, and/or attention skills are also likely to struggle with degraded speech recognition (McCreery et al., 2019).

Children with a language disorder[1] (LD) show a larger negative effect of background noise on speech sound recognition than peers with typical language development[2] (TLD; Magimairaj et al., 2021; Ziegler et al., 2005). Currently, there is limited research assessing the ability of children with LD to recognize speech in background noise beyond the sound and word level, such as sentence or discourse level processing. In a notable exception, Torkildsen et al. (2019) found that 5- to 12-year-old children with DLD performed more poorly than TLD peers and performed similarly to children with hearing aids when repeating sentences presented in speech-shaped noise (SSN). SSN has spectral properties that are similar to those of speech but does not include discernable words (American National Standards Institute, 2018). Overall, we need to better understand the differences between children with LD and TLD in their ability to recognize speech in background noise. Of note, research has demonstrated poorer performance in noise plus reverberation versus noise only for children with normal hearing and children with hearing loss (Lewis et al., 2022; McCreery et al., 2019). However, we do not currently understand how adding reverberation to noise affects children with LD.

If children with LD demonstrate more difficulty with sentence recognition in noise and reverberation than children with TLD, as we predict, we need to identify effective interventions. Remote microphones (RMs) are effective interventions to support speech recognition in children who are hard of hearing (Lewis et al., 2022; Thibodeau, 2010, 2014; Wolfe et al., 2016). Recent research demonstrates that children with various language and cognitive challenges and typical hearing can also benefit from RM use (Keller et al., 2021; Rance et al., 2014; Reynolds & Werfel, 2022). The primary goals of the current study are to compare sentence recognition in SSN and SSN + reverberation for children with LD and TLD and to determine if RMs support speech recognition in SSN and SSN + reverberation for children with LD.

How Background Noise and Reverberation Can Affect Sentence Processing

Verbal working memory skills, attention skills, and language knowledge stored in long-term memory work interactively to support sentence processing in complex listening environments (Leibold & Buss, 2019; McCreery et al., 2017; Porto et al., 2023). As each word is spoken the listener must temporarily retain the auditory trace of the word in working memory as they activate related representations from long-term memory to identify the correct word (i.e., speech recognition, Montgomery et al., 2021). As additional words are presented, the listener must temporarily store already presented information, simultaneously process incoming information, and continuously integrate new information with stored information to understand the sentence as a whole (i.e., comprehension; Ronnberg et al., 2013).

Background noise and reverberation can strain verbal working memory and attention abilities during sentence processing as the listener must focus on the target speaker and inhibit attention to the background noise (Leibold & Buss, 2019; McCreery et al., 2016). Notably, background noise can interfere with the listener's ability to keep previously presented information activated and to perceive and process incoming information (Piquado et al., 2010). Language knowledge stored in long-term memory supports the listener's ability to perceptually restore the part of the signal that is obscured by the background noise (i.e., energetic masking, Newman, 2006). Additionally, verbal working memory abilities and language knowledge support the listener's ability to focus on and process the target speech and inhibit attention to the background noise (i.e., informational masking, McCreery et al., 2020).

Recognizing the words the speaker is saying is the first step to support comprehension. As speech recognition tasks are commonly used in the hearing sciences, as a first step we implemented a sentence recognition task with children with LD. A child's receptive vocabulary knowledge and verbal working memory abilities are positively related to the child's speech recognition in noise and in noise plus reverberation (McCreery et al., 2019). This is the case for children with normal hearing and children with hearing loss. Notably, in comparison to children with TLD, children with LD demonstrate limited verbal working memory abilities (Archibald & Gathercole, 2012; Montgomery & Evans, 2009), more attention challenges (Redmond, 2020), and more limited syntactic and semantic knowledge stored in long-term memory (Leonard, 2014). Thus, it is

[1]In this past literature, children with a language disorder are labeled as children with developmental language disorder or language learning impairment. Refer to the individual citations regarding the specific characteristics of the included samples including qualification criteria.

[2]There are various ways to define typical language development. For the current research note, we follow Bishop's CATALISE framework (Bishop et al., 2016, 2017). Children with typical language development are able to produce and understand language comparably to same-age peers. In contrast, children with a language disorder demonstrate difficulty producing or understanding language in a way that affects everyday functioning.

likely that background noise and reverberation will more negatively affect speech recognition in children with LD than children with TLD.

RMs

Improving access to speech in complex listening environments, such as classrooms, has the potential to improve learning outcomes (Johnston et al., 2009; Moeller et al., 1996). RM systems[3] reduce the negative impacts of noise, distance, and reverberation by placing a microphone at the mouth of the talker, providing consistent communication access (Wolfe et al., 2016). One potential advantage of ear-level RM systems over other solutions such as classroom-wide systems is that speech from the primary talker is routed directly to receivers worn at the listener's ear(s) rather than to speakers placed within the listening environment. Children with hearing loss and with normal hearing show greater improvements in speech understanding in noise with personal or desktop RM systems in comparison to sound-field systems (Anderson et al., 2005; Anderson & Goldstein, 2004; Wolfe et al., 2013). Recent research demonstrates that children with typical hearing comorbid with autism or ADHD demonstrate better sentence recognition when using an RM system (Keller et al., 2021; Rance et al., 2014; Reynolds & Werfel, 2022). Given that children with autism, ADHD, and LD often demonstrate reduced verbal working memory abilities, attention abilities and/or language knowledge compared to same age peers (Geurts & Embrechts, 2008), we predict that RM systems will improve sentence recognition in SSN and SSN + reverberation for children with LD.

Current Study

In the current study, we used an adaptive task to identify the signal-to-noise ratio (SNR) at which children with LD and TLD could repeat sentences in SSN and SSN + reverberation. All children completed the task without an RM system. Children with LD also completed the task with an RM system to identify the relative benefit to sentence recognition when using the RM. The current study addressed the following key questions: (a) Do children with LD and TLD demonstrate different sentence recognition abilities in conditions with SSN and SSN + reverberation? and (b) Does use of an RM system improve sentence recognition for children with LD in conditions with SSN and SSN + reverberation?

Method

Participants

This study was approved by the institutional review board of Boys Town National Research Hospital (IRB 12–05 XP). Written assent and parental consent to participate were obtained for each child and they were compensated monetarily for participation. Eighteen children participated including nine males (White: n = 8; biracial: n = 1; non-Hispanic or Latino: n = 9) and nine females (White: n = 8; biracial: n = 1; non-Hispanic or Latino: n = 8; nonreported ethnicity: n = 1) ranging in age from 5 years 5 months to 12 years 2 months.

During the initial qualification visit, all participants achieved a standard score above 70 on the Kaufman Brief Intelligence Test–Second Edition, matrices subtest (KBIT-2; Kaufman & Kaufman, 2004), demonstrating nonverbal IQ in the typical range. Participants also completed the Test of Narrative Language–Second Edition (TNL-2, Gillam & Person, 2004) to assess language abilities (see Supplemental Material S1). Child and family history forms were completed by each parent/guardian. During the second visit, children completed a nonword repetition test (Dollaghan & Campbell, 1998) to assess verbal working memory abilities and the sentence repetition task. At the beginning of this visit, all included participants passed a hearing screening at 15 dB HL for both ears at octave frequencies from 250 to 8000 Hz using ER-3A insert earphones with foam tips. Otoscopy was completed prior to the hearing screening to ensure ear canals were clear. Three additional children were recruited, but their data were excluded from analyses. One participant was excluded due to a standard score below 70 on the KBIT-2 and one participant was excluded because they did not complete all visits. One participant was recruited as a child with LD based on their qualifying score in a previous study. However, their data were later excluded when we reassessed the previous score and determined that it was above the cut point (Supplemental Material S2). One child with LD did not complete the SSN + Reverberation conditions due to computer error (Supplemental Material S2, Participant 9). However, we included their data for the SSN conditions in the analyses.

Participants were classified into two groups, LD (n = 9) or TLD (n = 9). It is recommended that researchers use one qualifying test and a cut score with adequate sensitivity and specificity to determine qualification to a DLD group (Nitido & Plante, 2020). Five of the children qualified as DLD based on these criteria, in that

[3]The term *remote microphone system* describes a variety of hearing assistance technologies using different means of signal transmission that includes frequency modulated systems, digitally modulated systems, and induction loop systems. It also includes both ear-level and sound-field systems (Wolfe et al., 2016).

they demonstrated a current standard score less than 92 on the TNL-2. The other four children included in the LD group demonstrated a TNL-2 score greater than 92, but they fit at least one of the following criteria: (a) The parent indicated that the child had a diagnosis of DLD, LD, or language delay; (b) the child is currently receiving or previously received speech/language services, per parental report; or (c) the child previously qualified as DLD in a past research study (see Supplemental Material S2). Per parental report, children did not have a health history indicating neurologic or other disorders (e.g., autism) that would exclude a diagnosis of DLD. Given that four children did not achieve the cut point on the TNL-2 to qualify within the DLD group at the time of the study, we elected to use the broader category of LD to describe the sample as a whole (Bishop et al., 2016, 2017). Participants in the TLD group demonstrated a standard score greater than 92 on the TNL-2. Per parental report, these children did not have a history of a neurologic or other disorder or a history of speech/language services. On the group level, the participants with TLD were matched to the participants with LD based on age and maternal education (Supplemental Material S1).

Procedure

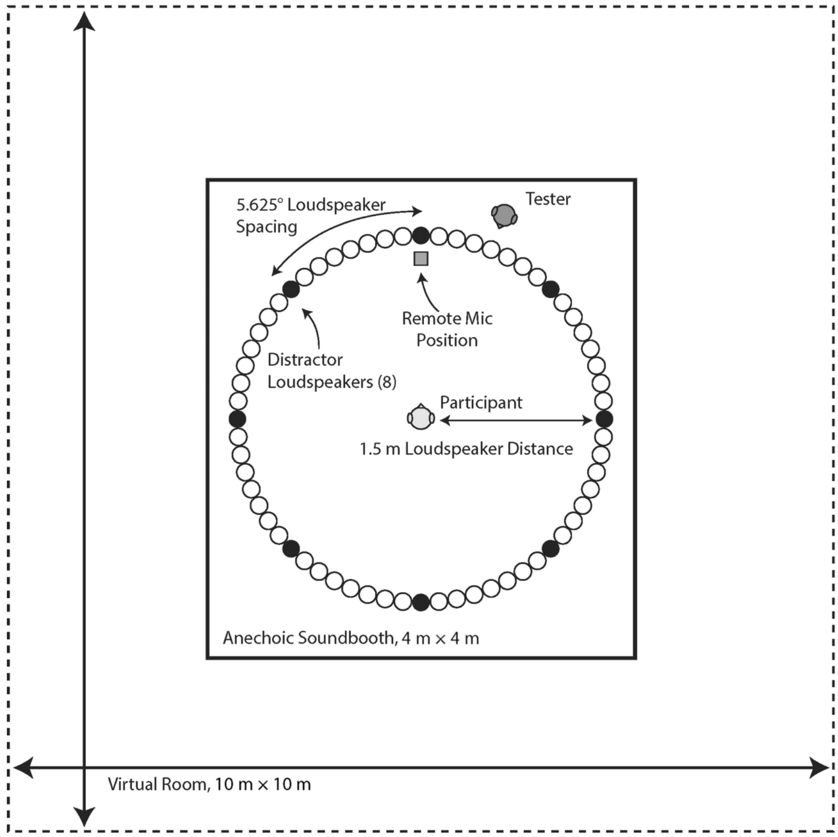
Children with LD were tested in four conditions: without the RM system in SSN, without the RM system in SSN + reverberation, with the RM system in SSN, and with the RM system in SSN + reverberation. Children with TLD were tested without the RM system in SSN and SSN + reverberation. The order of conditions was randomized for both groups. Participants were given verbal encouragement and breaks, as needed, to help them maintain attention to the task. In all conditions, children with LD wore the RM receivers, but the microphone was muted for the non-RM conditions. The receivers were removed and replaced between conditions to make it less likely that children would know when the microphone was being muted. Children with LD were fitted binaurally with Phonak Focus II RM receivers coupled to a Phonak Roger Touchscreen microphone. Children were asked about the comfort and loudness of the RM signal prior to testing so that adjustments to the settings could be made, if needed. All participants reported that the sound level was comfortable (Supplemental Material S3).

The stimuli included 16 lists (20 sentences per list), balanced for level of difficultly, from the Pediatric AZBio Sentence Test which were prerecorded by an adult female talker (Spahr et al., 2014). This test is normed for children 5–12 years of age and is used in pediatric clinical audiology protocols (Uhler et al., 2017). We selected these sentences as a starting place given that this is an established task to assess sentence recognition in the hearing science literature (Colasacco et al., 2024; Lewis et al., 2022; Sheffield et al., 2016; Uhler et al., 2017). The sentence lengths vary from 3 to 11 words (M = 6.91, SD = 1.50). Included words have one to six syllables (M = 1.56, SD = 0.75) and an average age of acquisition of 4.92 (SD = 1.39; Kuperman et al., 2012). For each condition, all participants heard 40 sentences. The starting list and the starting sentence within that list were selected randomly without replacement across conditions to ensure that no participant heard a given sentence more than once across all conditions. SSN, synthesized to spectrally match the average spectrum across all target recordings, served as the masker. Reverberation, when present, simulated that of a 10 m × 10 m room with reverberation time (RT60) of approximately 0.3 s (see Supplemental Material S3)

Testing took place in a large acoustically isolated anechoic chamber (ETS-Lindgren A100, inside dimensions: 4 m × 4 m × 4 m) containing a circular array of 64 ear-height loudspeakers spanning 360° of azimuth (spacing 5.625°). The participant was seated in the center of the loudspeaker array at a distance of 1.5 m (see Figure 1). The target speech signal was presented at 60 dB SPL from the loudspeaker at 0° azimuth. Independent noise maskers were presented from seven loudspeakers positioned to either side, at azimuths ±45°, ±90°, ±135°, and 180° relative to the target location. Masker levels were adjusted on each trial to achieve a desired total SNR. For RM conditions, the microphone/transmitter was placed at the 0° loudspeaker (see Supplemental Material S3).

Participants were instructed to repeat back target sentences and to guess if unsure. The task was adaptive in that the SNR was adjusted trial-by-trial based on participant response (see Lewis et al., 2022 and Supplemental Material S3). Two interleaved independent adaptive tracks were used. For one half of the 40 trials, SNR decreased if the participant repeated at least one word in the sentence correctly and increased if no words were repeated correctly (Track 1). A decrease in SNR indicates that the listening condition is less favorable in that there is less of a difference in intensity between the target and background noise. For the other half of the 40 trials, the SNR decreased if the participant repeated all except one word correctly and increased if more than one word was repeated incorrectly (Track 2). Combined results from the two tracks were used to calculate SNR for 50% correct word recognition (SNR50) for each participant in each condition. There were no restrictions on participants' head movements during testing. An examiner was seated inside the booth and used an iPad to score each word in the sentence as correct or incorrect. During testing, all participants wore a Phonak Touchscreen transmitter/microphone and the examiner wore a Phonak Focus receiver to ensure

Figure 1. Test setup of virtual 10 m × 10 m environment.



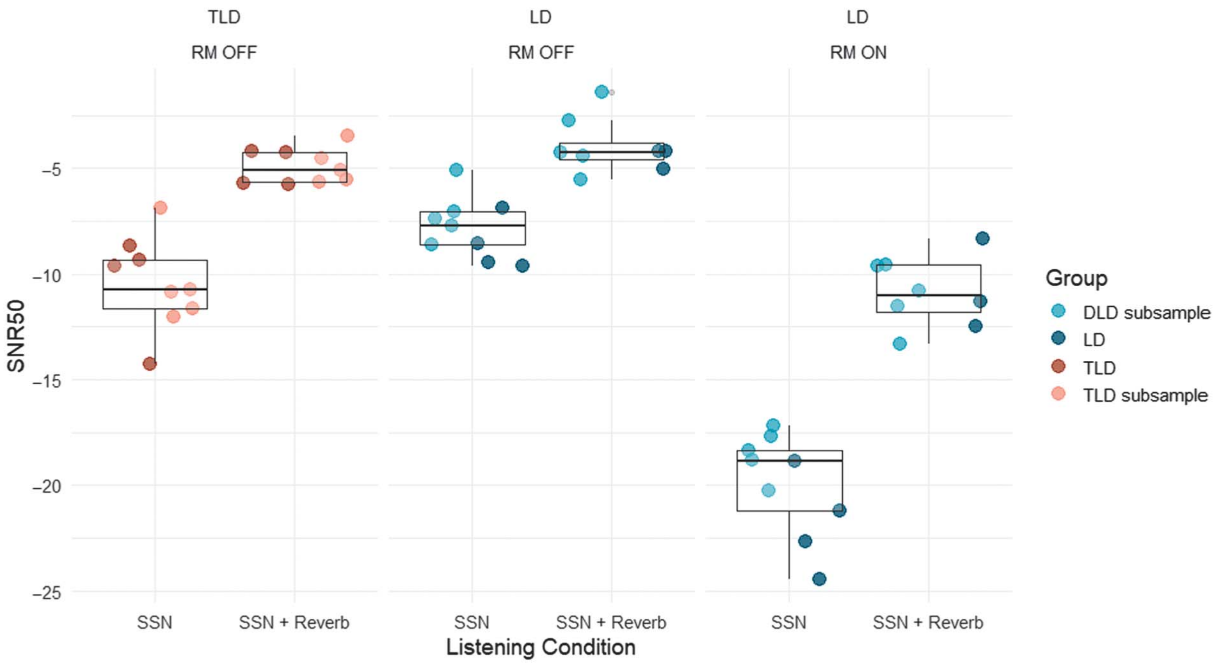
that she would be able to hear the participant's responses clearly and could complete live scoring.

Analyses and Results

To address the primary questions, we conducted a series of linear mixed-effects models in an R environment using the lme4 package (Bates et al., 2015). The outcome variable in all models was the SNR50 performance across all words in the sentences for each condition. All models included a random intercept for participant to account for the correlation structure that occurs with repeated measures from the same participant across conditions. Fixed effects were group (TLD, LD), noise condition (SSN, SSN + reverberation) and RM condition (without RM, with RM – LD group only). Interactions were included between groups and conditions. Each child's age in months and raw KBIT score were included in each model and mean centered. Assumptions of normality were confirmed for each linear mixed-effects model by examining the distribution of residuals. None of the model residual values indicated violations of normality assumptions. We conducted the models with the full sample and conducted the models with children who qualified as DLD based on SPELT score (n = 5) and the children with TLD matched to this subsample, n = 5 (see Supplemental Material S1). Full model results are reported in Supplemental Material S4.

The first question was, without the RM system, do children with LD and TLD demonstrate different sentence recognition abilities in conditions with SSN and SSN + reverberation? A lower SNR50 indicates better performance in that the listener is able to achieve the targeted 50% correct performance at a higher level of background noise relative to the level of the target speech signal. Figure 2 shows the SNR50 for each noise condition for children with LD (blue circles) and children with TLD (red circles) without the RM. The y axis indicates the SNR50. For example, an SNR of −5 indicates that the target speech is 5 dB quieter than the background noise. There was a significant language group by condition interaction (p = .02) where SNR50 for the children with LD and TLD was similar for the SSN + reverberation condition (LD: M = −4.0 dB, SD = 1.31; TLD: M = −4.92 dB, SD = 0.83), but the SNR50 for the children with LD (M = −7.8 dB, SD = 1.44) was poorer than children with TLD (M = −10.5 dB, SD = 2.13) for the SSN condition.

Figure 2. The signal-to-noise ratio (dB) required for 50% correct performance of children with language disorder and typical language development in the various noise conditions (speech-shaped noise [SSN], SSN + Reverberation). TLD = typical language development; LD = language disorder; RM = remote microphone; SNR50 = signal-to-noise ratio (dB) required for 50% correct performance; DLD = developmental language disorder; SSN + Reverb = speech-shaped noise plus reverberation.



After controlling for noise condition and language group, the effect of age in months was not statistically significant (Coefficient = −.004, p = .79). Children with a higher KBIT score achieved a lower SNR50 (Coefficient = −.09, p = .15). The model with the subsample, children with DLD (TNL score < 92) and matched peers, failed to converge likely due to the sample size. Based on descriptive data, differences between the subsample DLD and TLD groups were similar to the pattern found in the analyses with the whole group. Across conditions, children with DLD required a higher SNR50 than the TLD group. Additionally, the differences between groups were smaller in the SSN + reverberation condition (DLD: M = −3.67 dB, SD = 1.60; TLD: M = −4.87 dB, SD = 0.89) than the SSN condition (DLD: M = −7.2 dB, SD = 1.31; TLD: M = −10.45 dB, SD = 2.05).

The second question was, does use of an RM system improve sentence recognition for children with LD in conditions with SSN and in SSN + reverberation?[4] For this model, fixed effects included RM (on, off), condition (SSN, SSN + reverberation), age in months, and KBIT score for the children with LD. Figure 2 (blue circles) shows the SNR50 for children with LD with and without the RM across noise conditions. The noise condition by RM interaction was significant (p < .001) such that children with LD had a larger improvement with the RM in the SSN conditions (no RM: M = −7.8 dB, SD = 1.44; with RM: M = −19.9 dB, SD = 2.42) than in the SSN + reverberation conditions (no RM: M = −4.0 dB, SD = 1.31; with RM: M = −10.9 dB, SD = 1.64). The effect of age on sentence recognition was not statically significant (coefficient = .01, p = .31), but children with a higher KBIT score achieved a lower SSN (coefficient = −.16, p < .01). The model with the subsample of children with DLD (TNL < 92) demonstrated a significant noise condition by RM interaction (p < .01). They demonstrated a larger improvement with the RM in the SSN conditions (no RM: M = −7.2 dB, SD = 1.31; with RM: M = −18.46 dB, SD = 1.18) than in the SSN + reverberation conditions (no RM: M = −3.6 dB, SD = 1.60; with RM: M = −11.0 dB, SD = 1.56).

[4]Although it was not one of our primary questions, we did run models to assess if children with language disorder with the remote microphone (RM) on performed better than children with typical language development with RM off per a reviewer's suggestion. We found evidence that this was the case, results reported in Supplemental Material S5.

Discussion

The goal of this study was to determine whether children with LD demonstrate poorer sentence recognition in SSN and SSN + reverberation than children with TLD.

We also evaluated whether RM systems can minimize speech-in-noise deficits for children with LD. Children with LD had poorer sentence recognition in the SSN condition than children with TLD. Adding reverberation to the SSN led to poorer performance for children with LD and children with TLD. Notably, children with LD experienced significant improvements in sentence recognition in SSN and SSN + reverberation with an RM compared to listening without an RM. This was also the case for the subsample of children with DLD, TNL < 92. These results suggest that an RM may be an effective intervention for children with LD who have difficulties recognizing speech in classrooms and other noisy environments where there is a single talker of interest. It is important to note that this is a preliminary study assessing whether RMs support speech recognition in noise and reverberation for children with LD. The current results should not be interpreted as a clinical recommendation to purchase RMs for children with LD. Instead, this study serves as a foundation for larger future studies through which we can better understand the benefits of RM use for children with LD and gain a nuanced understanding of which children with LD are particularly likely to benefit from RM use in the classroom.

The current preliminary results conform with recent results that RM use can be beneficial to children who have typical hearing but are likely to struggle with recognizing and comprehending speech in noise. These include populations of children who have reduced verbal working memory and attention abilities and more limited vocabulary knowledge compared to same age peers, such as children with autism or ADHD (Keller et al., 2021; Rance et al., 2014; Reynolds & Werfel, 2022). It is well documented via sentence repetition tasks that children with LD have more difficulty processing speech in quiet settings than their peers with TLD (Riches, 2012). Additionally, current and past findings indicate that for children with LD, speech recognition is more likely to be negatively affected by the presence of background noise and reverberation than same age peers at the word level (Magimairaj et al., 2021; Ziegler et al., 2005) and the sentence level (Torkildsen et al., 2019). Thus, when children with LD are processing verbal classroom instruction in background noise and reverberation, they may be at a double disadvantage. They will have more difficulty processing speech in quiet than peers and will show a larger negative effect of adding background noise than same-age TLD peers.

In the current methodology, we asked children to recognize and repeat sentences with familiar words. Even in these circumstances, the use of an RM benefited children with LD and the subsample of children with DLD. Speech processing in noise is a complex interaction between characteristics of the listener, characteristics of the listening environment, and characteristics of the language input. In future research, researchers should systematically vary these components to determine which children with LD are most likely to struggle with processing speech in background noise and reverberation, which classroom environments are particularly likely to lead to listening difficulties for children with LD, and which language content is likely to lead to the most difficulty with processing speech in background noise. Notably, children with LD may demonstrate an even greater benefit from RM use if the content of the speech is more challenging. For example, during classroom instruction, children are asked to learn new academic content, including new words and increasingly more complex syntactic structures, from the teacher's speech. Thus, two clear next steps are to evaluate the relative benefit of RMs for children with LD to support sentence comprehension, in addition to sentence recognition, and to support learning new academic content in noise.

For children who are hard of hearing, regular use of RMs can improve both in-the-moment language processing and long-term outcomes such as language development (Johnston et al., 2009; Moeller et al., 1996). We may see similar benefits for children with LD. By providing better acoustic access to the target speech during classroom instruction, children with LD should be able to encode more linguistic and academic knowledge from that speech. As children are supported in building linguistic and academic knowledge through day-to-day input this should, in turn, support the child's ability to recognize, comprehend, and learn from classroom instruction in the future. Overall, we can optimally support the language development and academic trajectories of children with LD by gaining a better understanding of their ability to recognize and comprehend speech in background noise and reverberation and by gaining a better understanding of the effective use of interventions, such as RMs, to optimally support that language processing.

Data Availability Statement

De-identified data are available from the first author upon request.

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