COGNITIVE AND LINGUISTIC INFLUENCES ON SPEECH RECOGNITION IN CHILDREN WITH HEARING LOSS

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ABSTRACT

Speech recognition assessment of children with hearing loss is typically performed in quiet or with an unmodulated masker. Children with hearing loss have high levels of performance on these tasks with hearing aids, even when subjective measures indicate listening difficulties in their everyday listening situations. In the Finding Appropriate Solutions to Treat Reduced Audibility in Kids (FASTRAK) study, we developed speech recognition tasks designed to reflect challenges that children experience in real-world listening environments. Speech recognition thresholds were measured for a group of children with normal hearing and children with mild, bilateral hearing loss using a two-talker masker in three conditions: 1) co-located target and masker without reverberation, 2) co-located target and masker with reverberation, and 3) spatially separated target and masker. Thresholds in these conditions were compared to those found with a conventional speech-shaped noise masker co-located with the target talker. Receptive vocabulary, working memory, and selective attention were measured for each child. Children with better vocabulary and selective attention skills had lower thresholds in the two-talker masker compared to children with poorer attention and language. There was no relationship between working memory and speech recognition thresholds in speech-shaped noise. These results suggest that cognitive effects on masked speech recognition for children with hearing loss depend on masker type and configuration. **Keywords:** *speech recognition, children, masking, language, attention.*

1. INTRODUCTION

Speech recognition assessment is a key component of outcomes validation for children with hearing loss (CHL) after hearing aid fitting or cochlear implantation [1]. Speech recognition tasks for CHL have been developed with stimuli that have linguistic characteristics [2-4] and response options [5-7] that are developmentally appropriate across a wide age range. With recent progress in lowering the age of identification and age of hearing aid fitting for CHL [8-9], CHL often have aided speech recognition scores in quiet that are near ceiling levels with their devices by 4 years of age [10-11]. Children with mild degrees of hearing loss can achieve aided speech recognition scores in steady-state noise that are like hearing peers, despite underlying delays in language skills [12]. High levels of aided speech recognition may limit the utility of pediatric speech recognition tasks for identifying lack of developmental progress or listening difficulties for CHL, even in cases where delays in language or executive function exist.

Current clinical guidelines for aided speech recognition testing for CHL recommend assessment of words or sentences in quiet, with suggestions to test with steady speech-shaped noise or multi-talker babble after CHL reach ceiling levels of performance in quiet [1, 10, 13]. CHL, particularly those with mild bilateral hearing losses (MBHL), can often reach ceiling levels of performance for open-set words or sentences in quiet by 4 years of age [10, 12], even though many children continue to experience delays in language and academic domains as they transition into primary school [14-15]. Children with MBHL with more audibility and device use have better outcomes in academics and related foundational skills for reading than children with MBHL with less dosage [16].

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But professionals who assess auditory skills in CHL currently lack speech recognition tasks that reflect the listening difficulties experienced in everyday listening conditions. Tasks that reflect underlying linguistic and cognitive abilities may be particularly useful in identifying school-age children with MBHL who may be at risk for academic difficulties. The Finding Appropriate Solutions to Treat Reduced Audibility in Kids (FASTRAK) study was undertaken to develop new clinical tools to improve the diagnosis and assessment of children with MBHL. The goal of this analysis was to evaluate novel speech recognition tasks and their cognitive and linguistic correlates in a group of MBHL and a group of normal hearing children.

The speech recognition tasks developed for the FASTRAK study were based on laboratory measures that have shown promise for reflecting underlying linguistic and cognitive skills. The FASTRAK speech recognition battery includes an assessment of speech recognition with a two-talker masker. Two-talker maskers have been shown to have a more protracted developmental timeframe [17-18] and recruit working memory and executive function skills to a greater extent than steady-state, speech-shaped noise maskers [19]. FASTRAK speech recognition also includes a condition with a two-talker masker with reverberation and a condition where the two-talker masker and target speech are spatially separated. Both reverberation [20-21] and spatial separation of target and masker [22] reflect everyday listening conditions that children with MBHL are likely to experience, such as in classrooms.

Our hypotheses were that children with MBHL would have poorer performance and more variability on the FASTRAK speech recognition tasks with a two-talker masker and a two-talker masker with reverberation than a condition with a speech-shaped noise masker. We predicted that children with MBHL would show a release from masking in the spatially separated two-talker masker condition compared to the two-talker masker condition where the target and masker were co-located. We also predicted that language, working memory, and executive function would have stronger relationships with the speech-recognition threshold (SRT) for conditions with a two-talker masker than for conditions with a speech shaped noise masker.

2. METHOD

2.1 Participants

The sample included 47 children with normal hearing and 35 children with MBHL recruited at the University of Iowa and Boys Town National Research Hospital. All children lived in homes where spoken English was the primary language and did not have a history of additional developmental disabilities. Table 1 shows descriptive statistics for the sample. Children were paid $15-$20/hour for their time and were allowed to choose a book or a prize. Parents provided consent and, if age appropriate, children provided assent to participate in the study. The study was approved by the Institutional Review Boards at both institutions.

Table 1 – Participant characteristics. CNH = Children with normal hearing; MBHL = Children with mild bilateral hearing loss; PTA = Pure-tone average; HL = Hearing level; HA = Hearing aid

	CNH (n = 47)	MBHL (n = 35)
Age (years)	M = 7.1	M = 8.4
Sex	Female = 25 Male = 17	Female = 17 Male = 16
Better-ear PTA (dB HL)	M = 5.4	M = 32.3
Parent education	High school = 8 College = 9 Post-grad = 24	High school = 7 College = 14 Post-grad = 11
Age of diagnosis		M = 22.8 mos
Received HA		Yes = 29, No = 6
Age of HA fit		M = 34.1 mos
Hours of HA use		M = 8.3 hours/day

2.2 Materials

The speech recognition task included sentences from the Bamford-Kowal-Bench (BKB) sentences [4]. The speech-shaped noise masker was generated by taking the Fast Fourier Transform (FFT) of the concatenated BKB corpus and convolving a noise signal with the inverse FFT to create an unmodulated masker with the same spectral characteristics as the BKB sentences. The two-talker masker was the same used in a previous study and consisted of one male and one female speaker reading a passage [18]. The reverberation was mixed with target and maskers in MATLAB based on a classroom simulation designed to provide RT60 = 400 ms, which was the modal reverberation time for elementary school classrooms in a previous study [21]. Stimuli and maskers were presented via personal computer with a Focusrite Scarlett 4i4 audio interface (High Wycombe, UK) connected to JBL Audio IRX108BT amplified speakers (Stamford, CT, USA). Hearing aid output was measured, and speech audibility values were calculated using the Audioscan Verifit 2 (Dorchester, ON, Canada). Calibration of the loudspeakers was completed using a Larson Davis 824 sound level meter (Depew, NY, USA).

2.3 Procedures

2.3.1 Informed consent

Parents completed an online questionnaire on a tablet while the children completed the visit. The questionnaire asked parents to report their child's age at hearing loss diagnosis and hearing aid fitting, if applicable.

2.3.2 Audiometric assessment

Pure-tone audiometric testing was completed via air conduction using a GSI-61 diagnostic audiometer for all participants who did not have a diagnostic audiogram completed in the previous 6 months. Thresholds were measured at octave frequencies from 250 Hz – 8000 Hz in each ear using ER-3A insert earphones with foam tips. The better-ear pure-tone average (BEPTA) was calculated as the lowest mean of the octave thresholds from 500 Hz – 4000 Hz between each participant's ears. Tympanometry was completed using a Madsen OTOflex 100 with a 226 Hz probe tone in each ear to measure middle ear status on the day of the visit.

2.3.3 Masked speech recognition task

Children were seated in a chair at a calibrated position with one speaker at 0 degrees azimuth and the other speaker at 90 degrees azimuth. Custom software was used to randomize conditions and sentence lists for each participant. Speech recognition thresholds (SRT) for each condition were calculated based on scoring by the examiner. Two adaptive, interleaved tracks generated an SRT based on if the participant got more than half of the sentence keywords correct or if fewer than half of the keywords correct on a trial. Both tracks increased the noise level after a correct response and decreased the noise level after an incorrect response. The target presentation level was fixed at 60 dB SPL, and the starting signal-to-noise ratio (SNR) was +10 dB. The SRT for each condition was the average of the SRTs for the two tracks. Children completed four masking conditions: 1) speech-shaped noise, 2) two-talker masker co-located with the target, 3) two-talker masker co-located with the target with reverberation, 4) two-talker masker at 90 degrees with the target at 0 degrees.

2.3.4 Audibility calculations

Speech audibility was calculated using the Audioscan Verifit2 for children with MBHL. The Speech Intelligibility Index (SII) [23] was calculated for unaided conditions by entering the audiometric thresholds into the Verifit2 for each ear of each participant for soft (55 dB SPL) and average (65 dB SPL) input levels. Better-ear unaided SII (BEUSII) values were estimated as the highest unaided SII between ears for each participant.

2.3.5 Language and cognitive assessments

Receptive vocabulary was measured using the Peabody Picture Vocabulary Test – 5th edition (PPVT) [24]. Verbal and visuospatial working memory were measured using the running digit span and running location span subtests, respectively, of the Comprehensive Assessment Battery for Children-Working Memory (CABC-WM) [25]. Inhibition of attention was measured using the Psychological Experiment Building Language (PEBL) [26] Flanker task, and cognitive flexibility was measured using the

PEBL Switcher task. PEBL tasks provide accuracy and response time (ms). Response time measures were standardized and mean-centered.

2.3.6 Statistical approach

Statistical analyses were conducted using the R Language for Statistical Computing [27]. Linear mixed effects models with random intercepts for each subject were used to test within-subjects effects across conditions. Pearson correlations were used to test the bivariate relationships between individual differences in audiological variables, and language, cognitive, and masked speech recognition abilities.

3. RESULTS

3.1 Masked speech recognition

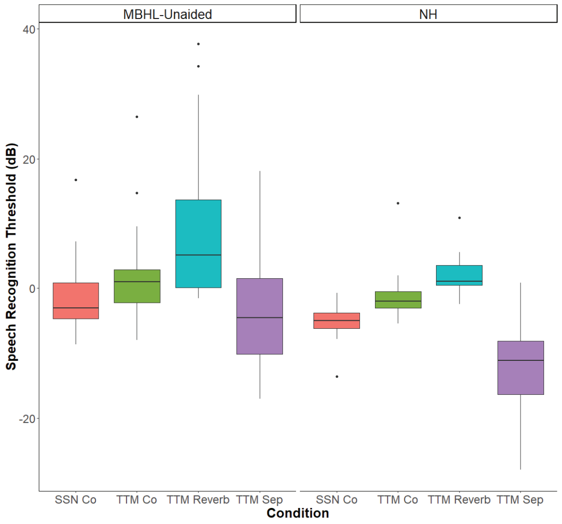

Figure 1. SRT by condition (red, speech-shaped noise co-located [SSN Co]; green, two-talker masker co-located [TTM Co]; blue, two-talker masker with reverberation [TTM Reverb]; purple, two-talker masker spatially separated [TTM Sep] for children with MBHL (left) and children with normal hearing (NH; right).

A linear mixed effects model comparing the SRT for children with MBHL and CNH showed significant main effects of hearing group [F(1,153) = 5.7, *p=0.02*], condition [F(3,200) = 45.3, *p<0.001*], and a significant interaction of hearing group by condition [F(3,200) = 6.2, *p<0.001*]. Post-hoc comparisons were adjusted using the False Discovery Rate method [28]. SRTs were lowest for TTM spatially separated (-3.3 dB, *p<0.001*), followed by SSN co-located (-1.4 dB *p=0.17*), TTM co-located (1.8 dB, *p=0.003*), and TTM with reverberation conditions (9.3 dB, *p<0.001*). SRT for CNH was 3.6 dB lower (*p=0.02*) than for children with MBHL across conditions. The difference between CNH and children with MBHL for the TTM-co-located condition was not significant (0.24 dB, *p=0.86*), but the hearing group differences between SSN co-located (2.1 dB lower for CNH, *p=0.04*), TTM with reverberation (3.7 dB lower for CNH, *p=0.01*), and TTM spatially separated (4.9 dB lower for CNH, *p<0.001*) were all significant.

3.2 Masked speech recognition associations with hearing, language, and cognition

Pearson correlations between language and cognition predictors and masked speech recognition were calculated for all participants and are shown in Table 2.

Table 2. Pearson correlations for masked speech recognition and language and cognitive variables. SSN = Speech-shaped noise; TTM-Co = Two-talker masker co-located; TTM-R = TTM with reverberation; TTM-S = TTM spatially separated; Digit = Digit Span; Location = Location Span; RT = Response Time; **Bold*** correlations represent p < 0.05.

	SSN	TTM-Co	TTM-R	TTM-S
Age	0.09	-0.16	0.08	0.09
PPVT	**-0.25***	-0.15	-0.13	0.03
Digit	-0.03	-0.03	-0.04	-0.04
Location	-0.05	-0.05	0.05	0.02
Flanker RT	**0.36***	**0.39***	0.03	**0.16***
Switcher RT	0.02	**0.18***	**0.19***	0.03

Table 3. Pearson correlations for masked speech recognition and audiological variables for children with MBHL. SSN = Speech-shaped noise; TTM-Co = Two-talker masker co-located; TTM-R = TTM with reverberation; TTM-S = TTM spatially separated; BETPA = Better-ear pure-tone average; dx = diagnosis; BEUSII = Better-ear unaided SII; **Bold*** correlations represent p < 0.05.

	SSN	TTM-Co	TTM-R	TTM-S
BEPTA	**0.65***	**0.41***	0.11	**0.58***
Age dx	**-0.33***	**-0.25***	0.17	-0.13
Age of fit	**-0.48***	**-0.43***	-0.02	-0.19
BEUSII	**-0.61***	**-0.33***	-0.18	**-0.45***

Correlations varied by condition. Longer Flanker response time (RT) was associated with higher SRT for SSN, TTM co-located, and TTM spatially separated. Longer Switcher RT was associated with higher SRT for TTM co-located and TTM with reverberation. Higher receptive vocabulary was associated with lower SRT in the SSN condition. Working memory was not associated with SRT for any condition.

Pearson correlations between audiological variables and masked speech recognition were calculated only for children with MBHL and are shown in Table 3. For SSN and TTM co-located conditions, higher BEPTA (worse hearing thresholds), earlier age of diagnosis and fitting, and lower better-ear unaided SII were associated with higher SRT. Only BEPTA and better-ear unaided SII were associated with SRT in the TTM spatially separated condition. None of the audiological variables were associated with the TTM with reverberation condition.

4. DISCUSSION

In this study, we developed novel speech recognition tools to improve the assessment of masked speech recognition in children with hearing loss. Specifically, we examined masked speech recognition for children with MBHL who may experience listening difficulties even when they have ceiling levels of performance on current clinical speech recognition tasks. We found that SRT for masked BKB sentence recognition were higher for conditions that used a TTM compared to a SSN masker, except when the target and masker were spatially separated. Children with MBHL performed more poorly than CNH in all masked speech recognition tasks, but the deficit for children with MBHL was larger in TTM conditions than for SSN. As in previous studies of masked speech recognition in children with normal hearing, the relationships between language, cognitive factors, and speech recognition depended on the masker [19]. Audiological variables were associated with masked speech recognition for all masking conditions except the TTM with reverberation condition. These results suggest that using an adaptive masked sentence recognition task can help to differentiate listening difficulties experienced by children with MBHL from CNH and that performance on some conditions was associated with underlying audiological, cognitive, and linguistic factors.

The pattern of SRT across masking conditions was consistent with previous research studies that have examined the effects of TTM [17-20], reverberation [20-21], and spatial separation [22] on masked speech recognition in CNH and children with mild to severe hearing losses. For conditions where the target and masker were co-located, children performed best in a SSN masker. The TTM co-located and TTM reverberation conditions produced significantly poorer SRT than the SSN masker. The TTM co-located and the TTM with reverberation conditions produced SRT that were approximately 3 dB and 7 dB poorer, respectively, than the SSN condition. The average reverberation effect was 9.3 dB for children with MBHL and 6.2 dB for CNH. The effect sizes are consistent with the previous literature. The TTM spatially separated condition produced the lowest (best) SRT, as observed in previous studies [22] with an average spatial separation benefit of 1.9 dB. Children with MBHL experienced larger decrements in performance for TTM with reverberation (3.7 dB worse) and lower spatial separation benefit (4.9 dB less benefit) than CNH. These masking conditions differentiated children with MBHL from CNH to a greater extent than current clinical speech recognition tasks for children with hearing loss, which often result in equivocal performance for these groups [10-12].

Masked speech recognition showed variable relationships with vocabulary and measures of attention, whereas working memory was not associated with masked speech recognition in any condition. Previous studies have shown that conditions with TTM are more likely to be associated with measures of attention than SSN maskers [20], but in this study, children with longer response times on the Flanker Task, which measures inhibition of attention. had higher (poorer) SRT for the SSN, TTM co-located and TTM spatially separated conditions than peers with faster Flanker response times. Vocabulary was only associated with SRT for the SSN condition. The vocabulary measure used in this study has shown consistent associations with degraded speech recognition tasks, including those with a two-talker masker in previous studies [19-20], so it is unclear why there was no relationship with other conditions in this sample. Children with higher SRT in the TTM with reverberation condition had longer response times on the Switcher task, which measures cognitive flexibility. Thresholds for the TTM condition did not show an association with any other language or cognitive measures. The lack of a relationship with working memory and masked speech recognition in any condition may seem surprising given that this has been observed previously [20]. However, the relationship between working memory and masked speech recognition has not consistently been observed across studies [29] and may be dependent on the working memory task [30].

Audiological variables were associated with masked speech recognition performance for children with MBHL in the SSN, TTM co-located, and TTM spatially separated condition. Greater degree of hearing loss was associated with higher SRT across these masking conditions, whether indexed by audiometric BEPTA or better-ear unaided SII. There were also significant associations between age of identification of hearing loss and age of hearing aid fitting and masked speech recognition, where it appeared that earlier ages of identification and fitting were associated with poorer masked speech recognition. However, this is likely due to the relationship between degree of hearing loss and age of identification and fitting, where children with greater degrees of loss were identified and fitted with hearing aids at younger ages than peers with milder degrees of hearing loss. The lack of a relationship between any audiological variables and the TTM with reverberation condition was unexpected, but many children with MBHL required a signal-to-noise ratio in that condition where the level of the target was higher than the masker such that no energetic masking was possible. This result highlights that the negative effects of reverberation on children's speech recognition may have other underlying mechanisms that differ from masked speech recognition tasks [20-21].

The current study provides several directions for future research on masked speech recognition for children with hearing loss and assessment of speech recognition tests. All the children with MBHL in this study were tested without amplification, and future analyses should incorporate measures of aided speech recognition to determine whether these measures are sensitive to improvements in masked speech recognition with hearing aids. The current study was restricted to children with MBHL in order to test a population where current clinical outcome measures may not illuminate differences in performance with CNH. However, these measures may also have utility for children with moderate or greater degrees of hearing loss who use hearing aids or cochlear implants. These measures should be validated with children with greater degrees of hearing loss to confirm that these measures can be applied to the broader population of children with hearing loss.

5. ACKNOWLEDGMENTS

This work was supported by grants from the National Institutes of Health National Institute on Deafness and Other Communication Disorders under awards numbers R01DC018330, R01DC013591, and R01DC019081.

6. REFERENCES

[1] Uhler, K., Warner-Czyz, A., Gifford, R., & PMSTB Working Group. "Pediatric minimum speech test battery." *Journal American Academy of Audiology*, 28(03), 232-247, 2017.

[2] Kirk, K. I., Eisenberg, L. S., Martinez, A. S., & Hay-McCutcheon, M. "Lexical neighborhood test: Test-retest reliability and interlist equivalency". *Journal of the American Academy of Audiology*, 10(03), 113-123. 1999.

[3] Haskins H. "A phonetically balanced test of speech discrimination for children". Unpublished master's thesis, Northwestern University, Evanston, IL. 1949.

[4] Bench, J., Kowal, A., & Bamford, J. "The BKB (Bamford-Kowal-Bench) Sentence Lists for Partially-Hearing Children," *British Journal of Audiology*, 13:3, 108-112, 1979.

[5] Cienkowski, K. M., Ross, M., & Lerman, J. "The word intelligibility by picture identification (WIPI) test Revisited". *Journal of Educational Audiology*, 15, 39-43. 2009.

[6] Uhler, K. M., Gifford, R. H., Forster, J. E., Anderson, M., Tierney, E., Claycomb, S. D., & Werner, L. A. "Refining stimulus parameters in assessing infant

speech perception using visual reinforcement infant speech discrimination in infants with and without hearing loss: Presentation level". *Journal of the American Academy of Audiology*, 29(09), 847-854. 2019.

[7] Clopper, C. G., Pisoni, D. B., & Tierney, A. T. "Effects of open-set and closed-set task demands on spoken word recognition". *Journal of the American Academy of Audiology*, 17(05), 331-349. 2006.

[8] Holte, L., Walker, E., Oleson, J., Spratford, M., Moeller, M. P., Roush, P., ... & Tomblin, J. B. "Factors influencing follow-up to newborn hearing screening for infants who are hard of hearing." *American journal of audiology*, 21(2), 163-174. 2012.

[9] Ching, T. Y., & Dillon, H. "Major findings of the LOCHI study on children at 3 years of age and implications for audiological management." *International Journal of Audiology*, 52(sup2), S65-S68. 2013.

[10] McCreery, R. W., Walker, E. A., Spratford, M., Oleson, J., Bentler, R., Holte, L., & Roush, P. "Speech Recognition and Parent Ratings From Auditory Development Questionnaires in Children Who Are Hard of Hearing". *Ear and hearing*, 36(0 1), 60S-75S. 2015.

[11] Wolfe, J., Duke, M., Miller, S., Schafer, E., Jones, C., Rakita, L., ... & Manning, J. "Low-Level Speech Recognition of Children with Hearing Aids." *Journal of the American Academy of Audiology*, 33(04), 196-205. 2022.

[12] Walker, E. A., Holte, L., McCreery, R. W., Spratford, M., Page, T., & Moeller, M. P. "The influence of hearing aid use on outcomes of children with mild hearing loss." *Journal of Speech, Language, and Hearing Research*, 58(5), 1611-1625. 2015.

[13] Ching, T.Y.C., Hou, S.Y.L, & Zhang, V.W. "Measuring outcomes of infants and children with hearing loss" In "Comprehensive Handbook of Pediatric Audiology" Eds A.M. Tharpe & R. Seewald. pp. 713-38. Plural Publishing: San Diego, CA. 2017.

[14] Tomblin, J. B., Oleson, J., Ambrose, S. E., Walker, E. A., McCreery, R. W., & Moeller, M. P. "Aided hearing moderates the academic outcomes of children with mild to severe hearing loss". *Ear and hearing*, 41(4), 775, 2020.

[15] Tomblin, J. B., Oleson, J., Ambrose, S. E., Walker, E. A., & Moeller, M. P. "Early Literacy Predictors and Second-Grade Outcomes in Children Who Are Hard of Hearing". *Child development*, 91(1), e179-e197. 2020.

[16] Walker, E. A., Sapp, C., Dallapiazza, M., Spratford, M., McCreery, R. W., & Oleson, J. J. "Language and reading outcomes in fourth-grade children with mild hearing loss compared to age-matched hearing peers." *Language, Speech, and Hearing Services in Schools*, 51(1), 17-28. 2020.

[17] Leibold, L. J., & Buss, E. "Children's identification of consonants in a speech-shaped noise or a two-talker masker." *J Speech Lang Hear Res*, 56(4), 1144-1155. 2013.

[18] Buss, E., Leibold, L. J., Porter, H. L., & Grose, J. H. "Speech recognition in one-and two-talker maskers in school-age children and adults: Development of perceptual masking and glimpsing." *The Journal of the Acoustical Society of America*, 141(4), 2650-2660. 2017.

[19] McCreery, R. W., Miller, M. K., Buss, E., & Leibold, L. J. "Cognitive and linguistic contributions to masked speech recognition in children". *Journal of Speech, Language, and Hearing Research,* 63(10), 3525-3538. 2020.

[20] McCreery, R. W., Walker, E. A., Spratford, M., Lewis, D., & Brennan, M. "Auditory, Cognitive, and Linguistic Factors Predict Speech Recognition in Adverse Listening Conditions for Children With Hearing Loss." *Frontiers in Neuroscience*, 1093. 2019.

[21] Lewis, D., Spratford, M., Stecker, G. C., & McCreery, R. W. "Remote-Microphone Benefit in Noise and Reverberation for Children Who are Hard of Hearing." *Journal of the American Academy of Audiology*. ePub ahead of print.

[22] Ching, T. Y., Van Wanrooy, E., Dillon, H., & Carter, L. "Spatial release from masking in normal-hearing children and children who use hearing aids." *The Journal of the Acoustical Society of America*, 129(1), 368-375. 2011.

[23] American National Standard Institute. "S3.5-1997 Methods for calculating the speech intelligibility index" *American National Standards Institute*, New York, NY.

[24] Dunn, D.M. “Peabody Picture Vocabulary Test – Fifth Edition.” Pearson Assessments, London, UK.

[25] Cabbage, K., Brinkley, S., Gray, S., Alt, M., Cowan, N., Green, S., ... & Hogan, T. P. “Assessing working memory in children: the comprehensive assessment battery for children–working memory (CABC-WM).” *JoVE (Journal of Visualized Experiments)*, (124), e55121. 2017.

[26] Mueller, S. T. The Psychology Experiment Building Language, Version 0.13. Retrieved from http://pebl.sourceforge.net. 2012.

[27] R Core Team “R: A language and environment for statistical computing.” R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/. 2023.

[28] Benjamini, Y. “Discovering the false discovery rate.” Journal of the Royal Statistical Society: series B (statistical methodology), 72(4), 405-416. 2010.

[29] Magimairaj, B. M., Nagaraj, N. K., & Benafield, N. J. “Children's speech perception in noise: Evidence for dissociation from language and working memory.” *Journal of Speech, Language, and Hearing Research*, 61(5), 1294-1305. (2018).

[30] Füllgrabe, C., & Rosen, S. “On the (un) importance of working memory in speech-in-noise processing for listeners with normal hearing thresholds”. *Frontiers in psychology*, 7, 1268. 2016.