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Cognitive abilities contribute to spectro-temporal discrimination in children who are hard of hearing

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Abstract

Objectives—Spectral ripple discrimination tasks have received considerable interest as potential clinical tools for use with adults and children with hearing loss. Previous results have indicated that performance on ripple tasks is affected by differences in aided audibility (quantified using the Speech Intelligibility Index, or SII) in children who wear hearing aids, and that ripple thresholds tend to improve over time in children with and without hearing loss. Although ripple task performance is thought to depend less on language skills than common speech perception tasks, the extent to which spectral ripple discrimination might depend on other general cognitive abilities such as non-verbal intelligence and working memory is unclear. This is an important consideration for children because age-related changes in ripple test results could be due to developing cognitive ability and could obscure the effect of any changes in unaided or aided hearing over time. The purpose of this study was to establish the relationship between spectral ripple discrimination in a group of children who use hearing aids and general cognitive abilities such as non-verbal intelligence, visual and auditory working memory, and executive function. It was hypothesized that, after controlling for listener age, general cognitive ability would be associated with spectral ripple thresholds and performance on both auditory and visual cognitive tasks would be associated with spectral ripple thresholds.

Design—Children who were full time users of hearing aids for at least one year (N=24, ages 6-13 years) participated in this study. Children completed a spectro-temporal modulated ripple discrimination task in the sound field using their personal hearing aids. Threshold was determined from the average of two repetitions of the task. Participants completed standard measurements of executive function, non-verbal intelligence, and visual and verbal working memory. Real ear verification measures were completed for each child with their personal hearing aids to determine aided SII.

Results—Consistent with past findings, spectro-temporal ripple thresholds improved with greater listener age. Surprisingly, aided SII was not significantly correlated with spectro-temporal ripple thresholds, potentially because this particular group of listeners had overall better hearing and

greater aided SII than participants in previous studies. Partial correlations controlling for listener age revealed that greater non-verbal intelligence and visual working memory were associated with better spectro-temporal ripple discrimination thresholds. Verbal working memory, executive function, and language ability were not significantly correlated with spectro-temporal ripple discrimination thresholds.

Conclusions—These results indicate that greater general cognitive abilities are associated with better spectro-temporal ripple discrimination ability, independent of children's age or aided SII. It is possible that these relationships reflect the cognitive demands of the psychophysical task rather than a direct relationship of cognitive ability to spectro-temporal processing in the auditory system. Further work is needed to determine the relationships of cognitive abilities to ripple discrimination in other populations, such as children with cochlear implants or with a wider range of aided SII.

INTRODUCTION

Spectral resolution, which is the ability to distinguish sounds with contrasting spectral features, is an important auditory skill. Poor spectral resolution may contribute to individual differences in speech perception in quiet and in noise (Henry et al. 2005, Anderson et al. 2011). This is evident in the relationship of psychoacoustic measures of spectral resolution, such as spectral ripple discrimination and detection, to speech perception ability in adults with hearing loss (Henry and Turner, 2003; Won et al. 2007; Davies-Venn et al., 2015). Greater degrees of hearing loss are associated with poorer spectral resolution in adults (Henry et al. 2005). Historically, auditory-specific capacities, such as spectral resolution, have been difficult to measure in children due to the complexity of some psychoacoustic procedures. However, recent research suggests that spectral ripple tasks can be adapted for clinical use with children as non-linguistic measures of signal fidelity in the auditory system (Drennan et al. 2014, 2016; Molis et al. 2014). Ripple tasks typically require the listener to discriminate between broadband noises with contrasting distributions of spectral peaks and valleys, and ripple threshold is expressed as the maximum number of ripples per octave that the listener can reliably differentiate. In the spectral-temporally modulated ripple test (SMRT), the phase of the distribution of spectral peaks and valleys in the ripple stimulus changes dynamically during the stimulus interval to control for several potential confounds on ripple threshold (Aronoff and Landsberger, 2013). Ripple threshold improves between the ages of 6 and 10 years in children with normal hearing, with older children performing equivalently to adults with normal hearing (Allen and Wightman, 1992; Kirby et al. 2015; Landsberger et al. 2017). Greater aided SII was also found to have a modest but statistically significant relationship with better spectro-temporal ripple thresholds when children who are hard of hearing complete the task wearing their personal hearing aids (Kirby et al. 2015). This relationship of aided SII to ripple threshold likely reflects contributions of overall audibility of the ripple noises when listening through personal hearing aids, but also variability in peripheral frequency selectivity of the cochlea. Those children with greater degrees of sensorineural hearing loss likely have both lower aided SII and poorer peripheral frequency selectivity. It is unclear to what extent the developmental gains in ripple discrimination ability of older children reflect improvements in general cognitive abilities such as working memory and executive function versus improvements in spectro-temporal

resolution. This is an important consideration because children's performance on measures of speech perception in noise increases with greater listener age (McCreery and Stelmachowicz, 2011; Johnson, 2000; Scollie, 2008) and in listeners with more developed cognitive abilities (Kronenberger et al. 2014; McCreery et al. 2017). Consequently, the correlation between spectral ripple threshold and speech perception in noise could reflect a shared influence of the listener's age and cognitive abilities on both kinds of tasks rather than a direct relationship of the signal fidelity of the auditory system and speech perception.

One factor that might relate to ripple threshold in adults and children is general intelligence. Previous studies describe a significant association of performance on N-alternative forced choice psychoacoustic pitch and intensity discrimination tasks with standard measures of intelligence in adults and older children with normal hearing (Raz et al. 1987, Deary et al. 2004). Another cognitive factor that could play a role in ripple threshold is working memory. Sheft et al. (2015) reported that higher working memory and visuospatial abilities were associated with better static and dynamic spectral ripple discrimination thresholds in older adults. Similar work describing contributions of working memory, non-verbal intelligence, and executive function to ripple threshold procedures in children have not been reported. Given that adult-like performance on ripple threshold tasks appears to emerge at a later age in comparison to psychoacoustic measures using pure tones (Jensen and Neff, 1993), further research should determine whether or not the observed effects of age on ripple threshold may be related to developmental changes in cognitive abilities or other factors. It could be that greater efficiency in encoding information in memory, holding and manipulating information in working memory, and recalling that information could be advantageous in performing this type of auditory task. Likewise, greater general intelligence and reasoning ability could also contribute positively to listener's success in analyzing and comparing ripple stimuli, independent of peripheral hearing sensitivity. It is also possible that one cognitive ability could mediate the relationship of another cognitive ability to ripple task performance.

One potential concern, however, is the extent to which peripheral hearing status and cognitive abilities are independent of each other in children with hearing loss. Studies suggest that children with cochlear implants have deficits in working memory skills, even when tested in a visuo-spatial modality (AuBuchon et al. 2015). Conversely, children who use hearing aids appear to have working memory abilities equivalent to peers with normal hearing (Stiles et al. 2012). This suggests that the amount of auditory access experienced through hearing loss and hearing devices in early childhood could impact the development of these general cognitive skills. Beyond a direct impact of hearing loss on ripple threshold due to loss of spectral detail in the periphery, it is possible to also experience indirect effects of the hearing loss on the cognitive skills needed to successfully perform the psychophysical task. It could also be the case that normal variability in working memory in children who are hard of hearing accounts for some of the variability in ripple threshold not explained by listener age or hearing variables.

The goal of this study was to identify cognitive factors that contribute to variability in spectro-temporal ripple discrimination performance and speech recognition in children who are hard of hearing who use hearing aids. The main hypotheses were: 1) greater listener age

and aided SII would be associated with higher (better) ripple thresholds, consistent with the results of Kirby et al. (2015); 2) greater working memory, executive function, and non-verbal intelligence would be associated with higher ripple thresholds; and 3) both auditory and visual cognitive assessment scores would be correlated with ripple discrimination ability.

MATERIALS AND METHODS

Participants

Twenty-four children (13 female, 11 male) ages 6 to 13 years with bilateral sensorineural hearing loss participated in the study. All children had worn hearing aids for at least one year. Exclusionary criteria included parent-reported psychiatric or neurological disorder. Written informed consent was obtained following the guidelines of the Boys Town National Research Hospital Institutional Review Board.

Hearing Measures

Hearing thresholds of participants (right ear mean three frequency pure tone average = 39.4 dB HL, left ear mean three frequency pure tone average = 39.9 dB HL) were determined using standard clinical audiometry at octave intervals from 0.5 to 8 kHz in each ear (Figure 1). The aided speech-intelligibility index (SII; ANSI S3.5 1997) for speech (65 dB SPL) was calculated for each participant's personal hearing aids (better ear aided mean=77.7, SD=15.7) using a probe-microphone verification system (Audioscan Verifit II).

Ripple Threshold Procedures

The Spectral-temporally Modulated Ripple Test (SMRT) was used to determine spectro-temporal ripple threshold (Aronoff and Landsberger, 2013). In this three alternative forced-choice procedure the listener discriminates between noises composed of a series of sinusoids (carrier bandwidth 100-6400 Hz) with distributions of spectral peaks and nulls that change dynamically over the duration of the stimulus interval. This iteration of the ripple discrimination task was designed to control for potential confounds such as local loudness cues and differences in upper and lower frequency bounds between target and reference stimuli present in the standard ripple-discrimination task. Threshold is expressed as the number of ripples per octave (RPO) of a target stimulus that a listener can discriminate versus a reference stimulus with 20 RPO. The density of ripples in the target starts at 0.5 RPO and is adapted in steps of 0.2 RPO in a 1-up/1-down procedure to determine threshold, which is calculated as the average of the last six of ten total reversals. Participants were seated with the computer monitor positioned at 0 degrees. Stimuli were presented at 65 dB SPL via a JBL Bi-Amplified Studio Monitor loudspeaker at 45 degrees azimuth at a distance of approximately 1 meter. Participants were familiarized with the task and experimental interface prior to measuring ripple threshold. The mean threshold was calculated from two repetitions of the ripple discrimination threshold procedure.

Cognitive Measures

Executive function, defined as control and coordination of thought processes (Miyake et al. 2000), was evaluated using the Dimensional Change Card Sort (DCCS) executive function

subtest of the National Institutes of Health Toolbox Cognitive Assessment Battery (Zelazo et al. 2013). The DCCS was administered using the online assessment center website. The DCCS subtest measures cognitive flexibility. In this task the subjects were prompted to match the shape or color of a series of target images presented on a computer screen to one of two test images with contrasting shape and color.

Working memory, which is the ability to process, store, and recall new information (Baddeley and Hitch, 1974), was assessed using the odd one out and non-word repetition subtests of the Automated Working Memory Assessment (AWMA; Alloway, 2007). Recorded instructions for each subtest were presented via computer speakers at a level judged by the participant to be audible and comfortable. The odd one out subtest assesses visual working memory. In this task, the subject was presented with a row of three images on a computer screen. One of these images differed from the other two. During each trial, the participant pointed to the image that differed. The subjects were required to recall, after a series of presentations, the location of the odd image from an increasing number of trials in correct serial order by pointing to their locations in a row of empty boxes displayed on the screen. Testing concluded when the participant failed to correctly recall four of six serial position sequences, or when the final set of trial lists was completed. The non-word repetition task assesses verbal working memory. The participant listened to a recording of a woman saying sequences of monosyllabic nonsense words (e.g. 'marg'). The number of non-words in each sequence increased incrementally in successive sets. After each sequence, the subject was prompted to repeat these non-words in serial order. The test concluded when the subject failed to correctly repeat four of six sequences in a set, or when the final set of word lists was completed.

Lastly, non-verbal intelligence was assessed using the matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). In this task, the participant must select one of five images presented on a page to best complete a picture with a missing piece. The complexity of the image to be completed increases with successive trials. The test concluded when the subject either selected incorrect answers during four consecutive trials or four of five successive trials, or when the subject completed a ceiling test item, determined by the subject's age.

Statistical Analyses

Pearson correlations of raw scores on the cognitive measures with spectro-temporal ripple threshold were completed using the R statistical programming language (R Core Team, 2016). Cook's distance was used to identify any outliers (Cook, 1977). Partial correlations of ripple threshold with each predictor were completed while controlling for listener age. Benjamini and Hochberg corrections were used to control for the false discovery rate (Benjamini and Hochberg, 1995). *P* values less than .05 were considered significant. An exploratory mediation analysis (Baron and Kenny, 1986) was completed to establish any indirect effects of one cognitive ability on the relationship between another cognitive ability and ripple threshold. This approach involves a four step process with three simple regression analyses of each univariate predictor to the dependent variable, as well as to each other, followed by a multiple regression analysis including all of the univariate predictors in the

same model. If zero-order relationship exist among the variables, and the mediator and other predictor variable are both significant in the multi-variate model, the conclusion is that mediation is likely. Because raw scores were used for each of the cognitive tasks, age was also included as a predictor in each model. Maximum possible raw scores were as follows: DCCS = 40, odd one out recall = 42, non-word repetition = 36, and matrix reasoning = 28/32/35 (for ages 6-8 years, 9-11 years, and 12-44 years, respectively).

RESULTS

Table 1 shows correlation coefficients amongst the independent variables examined in this study, including subjects' age, aided SII, and raw scores on the cognitive measures. After adjusting p-values for multiple comparisons, there were significant correlations of subject age with non-verbal intelligence ($r(22) = .59, p = .018$) and visual working memory ($r(22) = .52, p = .032$) scores, and these two cognitive measures were correlated with each other ($r(22) = .68, p = .003$). SII was correlated with verbal working memory ($r(22) = .56, p = .024$).

Figure 2 shows scatter plots of ripple threshold and listener age, aided SII, and scores on the four cognitive measures. Following corrections for multiple comparisons, ripple threshold was significantly correlated with listener age ($r(22) = .53, p = .016$), non-verbal intelligence ($r(22) = .64, p = .0021$) and visual working memory ($r(22) = .7, p = .00085$), but not with aided SII ($r(22) = .28, p = .22$), verbal working memory ($r(22) = .4, p = .079$), or executive function ($r(22) = -.22, p = .29$). Inspection of the data revealed a single outlier with relatively poor performance on the executive function test (Cook's D of 1.72) and relatively little variability in raw scores on this test for the other participants. The child in question did not report any problems with the DCCS task and performed within the normal range for the remaining cognitive measures, so it could be the case that the child misunderstood the task instructions or had difficulty entering responses using the computer keyboard.

After correcting for multiple comparisons and controlling for participant age, partial correlations of ripple threshold were significant for both visual working memory ($r(21) = .58, p = .014$) and non-verbal intelligence ($r(21) = .48, p = .04$), but not for executive function ($r(21) = -.22, p = .31$) or verbal working memory ($r(21) = .34, p = .15$). The mediation analysis was completed assuming non-verbal intelligence as a mediator of the relationship between working memory and ripple threshold and simultaneously controlling for listener age in a multivariate model. The multivariate regression model was significant ($r^2 = .55$, $F(3,20)=8.27, p = .00089$), and visual working memory significantly predicted ripple threshold ($\beta = .13, t = 2.18, p = .04$), though neither age ($\beta = .15, t = .77, p = .45$) nor non-verbal intelligence ($\beta = .10, t = 1.12, p = .28$) were significant. This result was inconsistent with an indirect effect of non-verbal intelligence on the relationship of working memory and ripple threshold. A partial correlation of age to ripple threshold, controlling for non-verbal intelligence, was not significant ($r(21) = .24, p = .27$).

DISCUSSION

The goal of this study was to identify cognitive factors that contribute to variability in spectral ripple discrimination performance in children who are hard of hearing. As hypothesized, the observed relationship of greater listener age to better ripple thresholds was consistent with past results showing better performance in older children who are hard of hearing (Kirby et al. 2015). It is unlikely that apparently adult-like ripple thresholds in older children is unique to the SMRT in light of past work showing adult-like ripple discrimination thresholds in children with normal hearing by approximately age ten when using temporally static ripple stimuli (Allen and Wightman, 1992; Horn et al. 2017). Unexpectedly, aided SII was not significantly related to ripple threshold in this group of participants, which was inconsistent with previous results showing greater aided SII was associated with better ripple thresholds (Kirby et al. 2015). One explanation for this discrepancy is that the participants in this study had better hearing and greater aided SII, on average, and less variability in aided SII and/or preservation of cochlear frequency selectivity than the group of listeners who participated in the previous study. That group of child hearing aid users had poorer mean pure tone averages of 55.5 dB HL (SD=15.2 dB) in the right ear and 58.8 dB HL (SD=17.1 dB) in the left and a lower mean better ear aided SII of 61 (SD=20.5). It could be the case, then, that listeners with mild-moderate losses perform similarly to their age-matched peers with normal hearing on this task when provided with appropriate amplification. This is consistent with the fact that several of the participants in this study had thresholds higher than 8 RPO, which is the reported average threshold of normal hearing adults on the SMRT (Aronoff and Landsberger, 2013). Combining the two data sets, including only those individuals from the previous study that did not also participate in the present one, again yielded a modest but statistically significant correlation between SII and SMRT threshold ($r(27) = .375, p < 0.05$).

The significant relationships of ripple threshold with non-verbal intelligence and visual working memory, controlling for listener age, suggest that non-auditory cognitive resources influence performance on the ripple task. The non-significant partial correlation of age to ripple threshold, controlling for non-verbal intelligence, supports the interpretation that it is cognitive ability, not age *per se*, that is predictive of ripple threshold in this population. A significant relationship between general intelligence and working memory has been reported in the cognitive psychology literature (see Conway, Kane, & Engle, 2003 for review). Therefore, it was not surprising that non-verbal intelligence and visual working memory were significantly correlated with each other. An exploratory mediation analysis did not find evidence of an indirect effect of non-verbal intelligence on the relationship of visual working memory to ripple threshold, which suggests that both non-verbal intelligence and visual working memory directly impact ripple discrimination ability. The significant relationship of ripple threshold to general intelligence was consistent with previous findings of significant relationships of intelligence to pure tone pitch and intensity discrimination thresholds in adults and older children with normal hearing (Raz et al. 1987, Deary et al. 2004). A similar relationship, with working memory accounting for approximately 50% of the variance in ripple thresholds, has been reported in older adults (Sheft et al. 2015). These relationships

could reflect the cognitive demands of some three alternative forced choice tasks rather than a direct relationship of spectro-temporal processing to general cognitive ability.

It was unexpected that the verbal working memory measure was not significantly related to ripple threshold in this group of listeners. One shortcoming of the non-word repetition task was that several participants had difficulty repeating back even single non-words with complete accuracy. It could be the case that participants' performance was inhibited by their hearing loss, which contributed to their inability to decode the phonemes accurately, rather than any deficits in recalling information in short term memory. This is supported by the significant correlation of aided SII and performance on the non-word repetition task. This confounding effect of audibility may also explain the comparatively weaker relationship of non-word repetition score to listener age relative to the visual working memory and non-verbal intelligence tests, which are non-auditory tasks that do not rely either on speech perception or production.

The lack of a relationship of performance on the executive function task to ripple threshold was also unexpected. The raw score for the DCCS represents accuracy in the matching task, and most of the participants were close to ceiling performance. The limited variability in DCCS scores could explain the non-significant correlations with listener age, audibility, ripple discrimination, and the other cognitive measures. The DCCS measure may not have been sufficiently sensitive to individual differences in this cohort of participants to show the role that executive function may play in psychophysical tasks like the SMRT.

In addition to the cognitive measures completed in this study, individual demographic variables such as the age when hearing loss was identified, age at first hearing aid fitting, and the number of hours hearing aids are used each day should also be considered as potential sources of variability in spectral-temporal ripple discrimination ability. Recent work has demonstrated the importance of some of these factors in language outcomes in children with hearing loss (Tomblin et al. 2015), and it could also be the case that variability in auditory perception of complex non-speech stimuli is influenced by cumulative auditory experience in children with hearing loss. Data on amplification history was not collected in the present study; these factors should be considered in future work examining the development of spectral-temporal discrimination in this population.

This study found significant relationships of visual working memory and non-verbal intelligence with spectral ripple threshold in children who are hard of hearing, controlling for listener age. This finding suggests that the established relationship of listener age to ripple threshold cannot be attributed entirely to age-related changes in the capacity of the auditory system to represent fine spectral detail. On the contrary, cognitive abilities, which tend to increase across this age range, account for considerable variability in ripple threshold task performance. More study is needed on the effects of cognitive abilities on ripple threshold in children with greater variability in auditory access, including children with a wider range of aided SII, greater degrees of hearing loss, and those who use cochlear implants.

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Figure 1. Mean audiometric thresholds of the study participants for the right (red) and left ears (blue). The shaded area represents the range of thresholds across participants.

Figure 2. Scatter plots with regression lines (blue) for ripple threshold and listener age, aided SII, verbal working memory, visual working memory, executive function, and non-verbal intelligence. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Table 1

Correlation coefficients for subject age, aided audibility, non-verbal intelligence (NVIQ), visual working memory (Visual), verbal working memory (Verbal), and executive function (Exec). P-values were corrected for multiple comparisons.

	SII	NVIQ	Visual	Verbal	Exec
Age	0.31	0.59*	0.52*	0.23	-0.07
SII		0.35	0.15	0.56*	0.13
NVIQ			0.68**	0.43	0.08
Visual				0.43	-0.13
Verbal					0.22

* p<0.05
** p<0.01