Research Article

Performance of Children With Hearing Loss on an Audiovisual Version of a Nonword Repetition Task

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Purpose: The aims of this study were to (a) determine if a high-quality adaptation of an audiovisual nonword repetition task can be completed by children with wide-ranging hearing abilities and to (b) examine whether performance on that task is sensitive to child demographics, hearing status, language, working memory, and executive function abilities.

Method: An audiovisual version of a nonword repetition task was adapted and administered to 100 school-aged children grouped by hearing status: 35 with normal hearing, 22 with mild bilateral hearing loss, 17 with unilateral hearing loss, and 26 cochlear implant users. Participants also completed measures of vocabulary, working memory, and executive function. A generalized linear mixed-effects model was used to analyze performance on the nonword repetition task.

Results: All children were able to complete the nonword repetition task. Children with unilateral hearing loss and children with cochlear implants repeated nonwords with less accuracy than normal-hearing peers. After adjusting for the influence of vocabulary and working memory, main effects were found for syllable length and hearing status, but no interaction effect was observed.

Conclusions: The audiovisual nonword repetition task captured individual differences in the performance of children with wide-ranging hearing abilities. The task could act as a useful tool to aid in identifying children with unilateral or mild bilateral hearing loss who have language impairments beyond those imposed by the hearing loss.

The simple task of repeating made-up words, such as “doichaip,” is highly sensitive to the integrity of certain mechanisms that are critical for spoken word learning. Nonword repetition (NWR) tasks require participants to repeat made-up words that vary in length from single to multiple syllables. Accurate repetition requires phonologic sensitivity, storage, and production. To achieve *phonologic sensitivity*, the listener must be able to correctly perceive unfamiliar phonological information in the speech signal and encode that information into a new representation. That new phonological representation must then be retained in the phonological loop of working memory. This process, known as *phonologic storage*, is overseen by the central executive that serves to allocate attention to the task at hand and manage the movement of information through the working memory system (Alloway, Gathercole, Willis, & Adams, 2004;

Baddeley, 2003). Finally, during *phonologic production*, the representation of the nonword is reassembled and a spoken representation of that nonword is articulated. Knowledge of words in the language is both a reflection of and a contributor to phonologic sensitivity (de Jong, Seveke, & van Veen, 2000; Walley & Metsala, 1990), storage (Gathercole, Willis, & Baddeley, 1991; Metsala, 1999), and production (Edwards, Beckman, & Munson, 2004; Gershkoff-Stowe, 2002).

The use of a number of different sets of nonwords has been reported in the literature, with the most common being the Children’s Test of Nonword Repetition (CNRep; Gathercole, Willis, Baddeley, & Emslie, 1994) and the nonword set created by Dollaghan and Campbell (1998). These, and other, NWR tasks have been used extensively in the assessment of children with specific language impairment (SLI; also known as developmental language disorder), and the poor NWR ability of this population is well documented in the literature (Conti-Ramsden, 2003; Dollaghan & Campbell, 1998; Edwards & Lahey, 1998; Gathercole & Baddeley, 1990). In a meta-analysis comparing children with SLI with typically developing comparison groups, Graf Estes, Evans, and Else-Quest (2007) found that children with SLI performed more than a standard deviation below children with typically developing language on NWR

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tasks. Their difficulty with repetition was apparent at all nonword lengths, but the longest nonwords were the most problematic (Briscoe, Bishop, & Frazier Norbury, 2001; Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1990; Graf Estes et al., 2007). As a result, poor NWR accuracy has been proposed as a clinical marker of SLI (Conti-Ramsden, 2003; Dollaghan & Campbell, 1998), and NWR tasks have shown promise as a clinical tool to identify children with normal hearing (CNH) who are at risk for poor language outcomes (Archibald, 2008).

One population demonstrated to be at a heightened risk for poor language outcomes is children with hearing loss (Ganek, McConkey Robbins, & Niparko, 2012; Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007; Wake, Hughes, Poulakis, Collins, & Rickards, 2004). The audibility and auditory perception problems that children with hearing loss experience limit the quality and quantity of language exposure they can receive. The resulting gap between their language abilities and those of their hearing peers may be evinced as lower scores on standard language assessments. Although there is clinical utility in documenting this gap, such tests rely heavily upon a child's knowledge of the language gained from language input. In contrast, because NWR stimuli are not real words, NWR tasks have the potential to measure the child's processing of language in a manner that is less dependent (although not completely independent) of the child's knowledge of and exposure to the language (Campbell, Dollaghan, Needleman, & Janosky, 1997; Dollaghan & Campbell, 1998; Ellis Weismer et al., 2000). For example, children from underrepresented minorities tend to score lower than White children on standardized language tests (tests typically normed on mainstream speakers), but they perform similarly to White children on NWR and other processing-based measures (Campbell et al., 1997). Thus, both NWR tasks and standardized language tests might be useful for identifying children who have language deficits, but NWR tasks would be better than standardized language tests at avoiding the misclassification of children in regard to language learning problems. Children who present with language differences associated with cultural or socioeconomic variation in language exposure—variation often captured by proxies such as minority status, family income, maternal education, or bilingualism—do not have deficient language learning systems. Hearing loss limits language exposure; therefore, standardized tests might misclassify a child who has a hearing loss in the same way that they misclassify children from low-income families. The NWR task may be particularly useful for prognosis and for the diagnosis of language impairments that may exist over and above the limitations imposed by hearing loss (Gilbertson & Kamhi, 1995; Hawker et al., 2008; Nittrouer, Caldwell-Tarr, Sansom, Twersky, & Lowenstein, 2014). "Disproportionate language impairment" can occur among children with cochlear implants (CCI) who received timely intervention (Geers, Nicholas, Tobey, & Davidson, 2016) and in children with mild-to-moderate degrees of hearing loss (Gilbertson & Kamhi, 1995).

The Performance of Children With Hearing Loss on Traditional NWR Tasks

A number of studies have examined the NWR abilities of children with hearing loss using stimuli presented in a traditional auditory-only format. Briscoe et al. (2001) administered the CNRep to children, ages 5–10 years, with mild-to-moderate sensorineural hearing loss ($n = 19$), SLI ($n = 20$), or typical hearing and language ($n = 35$). The children with hearing loss or SLI performed similarly low and lower overall than the children with typical development. All three groups repeated longer nonwords less accurately than shorter nonwords, but longer nonwords were disproportionately problematic for the children with SLI and the children with hearing loss. Despite the similarity between the SLI and hearing loss groups in the extent of the NWR problem and its presentation, the underlying nature of the problem may be different. In Briscoe et al., for example, the children with SLI exhibited limitations not only in NWR but also in digit span. The children with hearing loss exhibited limitations in NWR only; digit span performance was within normal limits. This finding led the investigators to hypothesize that, for children with hearing loss, deficits in phonologic sensitivity rather than phonologic storage are at play. Also, measures that capture access to the signal, a key requirement for phonologic sensitivity, have been shown to account for a large amount of variance in NWR skills when presented in an auditory-only format. In a study where NWR was administered to children who wore hearing aids, the degree of hearing loss accounted for 57% of the variance in NWR performance, while aided Speech Intelligibility Index, a measure of the audibility of speech provided by hearing aids, accounted for a further 20% (Stiles, Bentler, & McGregor, 2012).

If performance of children with hearing loss on traditional NWR tasks is largely driven by access to the signal, then those with greater degrees of hearing loss should show especially poor performance. Indeed, Carter, Dillon, and Pisoni (2002) reported that children with severe-to-profound hearing loss who used cochlear implants (CIs) could correctly repeat only 5% of a 20-word subset of the CNRep nonwords. When scored at the phoneme level rather than the word level (e.g., percent consonants correct rather than number of words correct), the NWR task is more sensitive to the variability in performance that exists within any given group of CCI. Still, some CCI exhibit very poor performance: Dillon, Pisoni, Cleary, and Carter (2004) found the percentage of consonants repeated correctly to range from 1% to 76% correct across CCI.

Despite considerable evidence that impaired auditory access limits NWR performance among children with hearing loss, deficits in phonologic storage may also contribute to NWR difficulties for children with hearing loss. Ead, Hale, DeAlwis, and Lieu (2013) reported on a group of 9- to 14-year-old children with severe-to-profound unilateral hearing loss who performed significantly worse than their siblings with normal hearing, not only on an NWR task but also on a complex letter span task. In this task of

verbal working memory, participants were presented a series of letters one by one on the screen. Following the presentation of each letter, participants were shown a number of shapes and were asked to count the shapes prior to the presentation of the next letter. At the end, the participant was asked to recall all letters that had appeared. To recall successfully, the participant would need to hold each letter name in phonologic short-term storage while counting. Although the investigators did not examine the relationship between performance on the NWR and complex letter span tasks, the poor performance of the children with unilateral hearing loss (CUHL) on both leaves open the possibility that impaired phonological storage could contribute to the NWR problems that characterize children with hearing loss.

Does the NWR Performance of Children With Hearing Loss Predict Their Spoken Language Ability?

It is clear that, as a group, children with a wide range of degrees of hearing loss have difficulty repeating nonwords on a traditional auditory-only NWR task and that children with the most extreme losses can find the task to be exceptionally difficult. Nevertheless, if the task does not capture variance in language ability, it will be of little clinical use. Is the traditional NWR task a useful tool for identifying language learning problems among children with hearing loss? The answer depends, to some extent, upon degree of loss and device type.

Some studies suggest utility in predicting language variance in CCI. Among fourteen 8- to 9-year-old CCI, NWR accuracy was scored via ratings of global quality collected from naive normal-hearing listeners. The listeners heard the nonword stimulus followed by the child's response for that nonword. Using a 7-point rating scale, the listener judged how similar the response was to the target. The rating of the NWR response was a strong positive predictor of concurrent performance on a comprehensive measure of oral language comprehension (Cleary, Dillon, & Pisoni, 2002). Moreover, the global quality ratings of NWR performance of fifty-two 8- to 10-year-old CCI were predictive of receptive vocabulary and global spoken language skills 8 years later (Casserly & Pisoni, 2013).

In contrast, traditional NWR performance is typically dissociated from language ability in children with less severe hearing loss. In a study testing 6- to 13-year-olds with mild-to-moderate hearing loss and an age-matched control group, children repeated nonwords two to five syllables in length (Halliday & Bishop, 2005). The group with hearing loss performed significantly worse than the normal-hearing group at all syllable levels, despite performing no differently on the tests of vocabulary or grammar. In a comparison to 5- to 12-year-olds with normal hearing, the children with mild-to-severe hearing loss scored significantly lower on a nonword serial recall task, but they did not differ from their normal-hearing peers on receptive vocabulary, expressive vocabulary, or articulation (Klein, Walker,

Kirby, & McCreery, 2017). Finally, among 47 children in Grades 1 and 5 with slight/mild hearing loss and 96 matched normal-hearing peers, the hearing loss group performed significantly poorer on overall repetition of nonwords from the CNRep but equivalently in the developmental, behavioral, and academic domains (Wake et al., 2006). Such findings suggest that, as a group, given appropriate amplification, children with slight-to-severe hearing loss can develop good spoken language despite limitations in access to fine-grained phonologic structure. Of course, these are group-level comparisons. In fact, in Briscoe et al. (2001), the children with mild-to-moderate hearing loss did not differ from their normal-hearing peers in receptive vocabulary on average, but they were a highly variable group, and those with the poorest NWR performance tended to have the lowest vocabulary scores, as would be expected given that both NWR and word learning require phonologic sensitivity and storage.

Potential Advantages of an Audiovisual NWR Task

In summary, the utility of a traditional NWR task administered to children with hearing loss may be limited. In children with slight-to-severe losses, many of whom wear hearing aids, problems with NWR are not indicative of poor language outcomes, at least as measured by standardized tests. It is positive that many children with hearing loss can develop robust oral language given appropriate amplification despite problems with auditory access that interfere with NWR. However, this is a group-level finding, and we need to ensure valid tools for identifying individual children whose risk for poor language outcomes exists over and above any limits imposed by auditory access. In CCI, the utility of a traditional NWR task (at least one with whole-word scoring) may be limited by floor-level performance that obscures individual differences in language learning ability. Finally, in all children with hearing loss, it is difficult to determine whether a poor NWR performance is caused by auditory access and perception problems related to the hearing loss itself or if one of the other mechanisms involved in NWR (i.e., phonologic sensitivity, storage, and reproduction) is at fault (Burkholder-Juhasz, Levi, Dillon, & Pisoni, 2007).

A dual-modality presentation of the NWR task, one that offers both auditory and visual cues, offers several potential advantages. First, such a task offers ecological validity. In typical, everyday interactions, children often have access to visual information and cues along with the speech signal, and this access improves speech perception in children with hearing loss (Jerger, Damian, McAlpine, & Abdi, 2017) and CNH (Lalonde & Holt, 2016). Thus, the ability to process spoken language in the auditory-visual modality may be a better predictor of overall language learning potential. Second, dual-modality presentation will likely eliminate floor-level performance in those with the greatest degrees of hearing loss so that individual differences may be discerned. Third, dual-modality presentation will allow a greater teasing apart of the perceptual constraints due to hearing loss from deficiencies in other abilities, such as

vocabulary, working memory, and executive function, that can impede NWR.

Nittrouer et al. (2014) devised an audiovisual (AV) NWR (AV-NWR) task that lessened the demands of the phonologic sensitivity and reproduction mechanisms of NWR by adding a visual signal and by incorporating nonwords created by Dollaghan and Campbell (1998). These nonwords acted to reduce reliance on extant knowledge of English by excluding highly predictable “word-like” sequences of phonemes, to reduce reliance upon perceptual skills by excluding lax vowels, and to reduce reliance upon articulation skills by excluding the “Late-8” consonants (Shriberg & Kwiatkowski, 1994). CCI were expected to perform better on the Dollaghan and Campbell nonwords, than those from the CNRep (Gathercole et al., 1994) for these reasons.

Nittrouer et al. (2014) administered the AV-NWR to CCI and CNH in second grade. Regardless of hearing status, all of the children were able to repeat back the nonwords. The CCI repeated nonwords with less accuracy than the CNH; for both groups, shorter words were more accurate than longer words and the Syllable Length $\times$ Group interaction was not significant. Thus, the task both avoided floor effects and—given the longer words did not pose relatively greater challenges for the CCI than the CNH—suggested that working memory deficits were not at play among the CI group. With the exception of age of identification of hearing loss and bimodal experience, both of which explained a small amount of variance on NWR performance, other audiological and demographic variables, including age, gender, age at implantation, and preimplant hearing thresholds, were found to exert little influence on the performance of the CCI on the NWR task. This NWR performance was consistent with the results of the vocabulary, reading, and grammar assessments in the study; CCI performed significantly poorer than the CNH on all measures. In fact, performance on the NWR task predicted language skills to some extent. Most children who scored above a given cut-point on the NWR task had good language skills (i.e., the task had good specificity in that a good score reliably ruled out language problems). However, many children who scored below that cut-point also had good language scores; thus, the sensitivity of the NWR task to language deficits in this sample was not high.

Extension of an AV-NWR Task to Children With Mild or Unilateral Hearing Loss

The current study extended the AV-NWR task to CUHL or children with mild bilateral hearing loss (CMBHL). We compared their performance on the AV-NWR task to the performance of CCI and to peers with normal hearing. Our first aim was to replicate the findings of Nittrouer et al. (2014), namely, that CCI can perform above floor on an AV-NWR, and to extend the task to children with a wide array of hearing losses. Additionally, we sought to determine whether performance on the task distinguishes children grouped by hearing status and whether the task

is sensitive to individual differences in vocabulary, working memory, executive function, age, maternal education, and language experience.

Prediction 1

Due to the availability of visual cues on the AV-NWR task, CMBHL and CUHL were expected to perform comparably to the CNH. However, despite the availability of visual cues, CCI were expected to perform poorer than their peers with normal hearing and lesser degrees of hearing loss due to the severely degraded auditory input from the CIs.

Prediction 2

If, as assumed, performance on the AV-NWR task is relatively independent of language experience, then age, maternal education, and language experience should not relate to repetition accuracy.

Prediction 3

If, as assumed, successful AV-NWR performance requires phonologic storage, then individual differences in repetition accuracy should be explained by vocabulary, working memory, and executive function scores, which are expected to support phonologic storage.

Method

Participants

Participants were monolingual English-speaking children aged 6–18 years who underwent clinical evaluation of hearing, nonverbal problem solving, executive function, working memory, language, and speech while enrolled in research studies at Boys Town National Research Hospital. The participants were selected to represent a range of hearing abilities. Of the 100 children who participated, 35 were CNH, 17 were CUHL, 22 were CMBHL, and 26 were CI users (CCI). Children were screened prior to participation, and if parents reported significant cognitive, visual, or motor delays, the child was excluded from this study, as were children who spoke a language other than English or who used American Sign Language or a manual code of English as their primary mode of communication. As is common in research that relies upon volunteer participation, the level of maternal education in our participant sample was higher than that observed in the U.S. population (Ryan & Bauman, 2016). While high levels of maternal education were noted in all of our hearing status groups, the greatest difference was noted between CNH and CUHL. See Table 1 for demographic information.

Procedure and Materials

Data Collection

All clinical measures were obtained during 3–4 hr of testing that occurred over the course of one to two visits within a 6-month period. At one or both visits, or at a visit on a separate day, children also underwent testing on experimental protocols in other research labs. The nonaudiological clinical

Table 1. Demographic and audiological characteristics of the four hearing status groups.

Characteristics	CNH (<i>n</i> = 35)	CUHL (<i>n</i> = 17)	CMBHL (<i>n</i> = 22)	CCI (<i>n</i> = 26)
Sex (%)				
Male	60.00	70.59	45.45	50.00
Female	40.00	29.41	54.55	50.00
Age (years)				
<i>M</i> (<i>SD</i>)	12.23 (3.08)	10.02 (1.72)	10.26 (1.73)	13.08 (3.85)
Range	7.33–18.25	7.92–13.25	8.08–13.08	6.75–18.67
Race (%)				
White	94.29	88.24	95.45	92.31
Asian	0	5.88	4.55	0
More than one	5.71	0	0	3.85
Other	0	5.88	0	0
Declined	0	0	0	3.85
Maternal education (%)				
High school or less	0	5.88	13.64	11.54
Some college	2.86	29.41	18.18	19.23
College graduate	42.86	47.06	27.27	30.77
Graduate education	54.29	17.65	40.91	38.46
Pure-tone average ^a				
<i>M</i> (<i>SD</i>)	5.39 (4.12)	56.40 (32.77)	31.65 (9.83)	
Range	0.00–15.00	12.50–120.00	8.75–45.00	

Note. CNH = children with normal hearing; CUHL = children with unilateral hearing loss; CMBHL = children with mild bilateral hearing loss; CCI = children with cochlear implants.

^aPure-tone average represents the average of audiometric thresholds at 0.5, 1, 2, and 4 kHz of the better ear for CNH and CMBHL and of the ear with hearing loss for CUHL. Audiometric thresholds were not available for CCI.

assessments took place in a quiet room in a research laboratory with the examiner and child seated at a table. Children who were fit with hearing aids or CIs wore them during the testing sessions. The examiners were audiologists or speech-language pathologists with experience testing children with hearing loss. All examiners were trained to follow standardized testing guidelines, and the project coordinator periodically reviewed videotaped assessments to ensure proper adherence to protocols. All assessments were double-scored and double-entered into a repository database to ensure accuracy.

Background Variables

Demographic, medical, and developmental history information was obtained through parent interview or written questionnaire. Medical records of the CCI were reviewed to obtain dates of implantation, etiologies of hearing loss, and device types. Information on the child's hearing history including age of identification and age at first hearing device fitting was obtained through parent report. Age at implantation for the CCI was obtained from the child's medical records, when available, or from parent report.

Hearing

Audiometric thresholds were obtained from medical or research records if an audiogram had been completed within a 6-month period prior to the research visit. If a recent audiogram was not available, thresholds were measured on the day of the research visit for CNH, CUHL, and CMBHL. Thresholds were obtained with insert or supra-aural headphones using conventional audiometry by an

audiologist in a sound-treated, double-walled booth. See Table 1 for pure-tone averages (PTAs). The 35 CNH had air-conducted thresholds at 15 dB HL or better at all octave frequencies of 250–8000 Hz in both ears.

CUHL qualified if they (a) had a four-frequency (0.5, 1, 2, and 4 kHz) PTA greater than 20 dB HL in the ear with hearing loss with thresholds at all octave frequencies less than or equal to 15 dB HL in the better ear or (b) had a high-frequency hearing loss with thresholds greater than 25 dB HL at one or more frequency above 2 kHz in the ear with hearing loss with all thresholds less than or equal to 15 dB HL at all frequencies below 2 kHz in the poorer ear. Of the 17 participants in the CUHL group, seven had a sensorineural loss, six had a conductive loss, two had a mixed loss, and two had a profound loss of undetermined type. Only two of the children in the CUHL group had a high-frequency hearing loss. The CUHL group had hearing loss identified at a mean age of 40.85 months (*SD* = 31.52, range: 1–108 months). Eleven CUHL were fitted with a hearing aid, and six children were unaided. Of the CUHL fitted with hearing aids, the mean age of the initial fitting of hearing aids was 64.18 months (*SD* = 30.17, range: 22–108 months).

A broad definition of mild hearing loss was used in the current study (Walker, Spratford, Ambrose, Holte, & Oleson, 2017). CMBHL qualified if they (a) had a four-frequency (0.5, 1, 2, and 4 kHz) better-ear PTA greater than 20 dB HL and ≤ 45 dB HL with no more than one threshold from 0.25 to 4 kHz greater than 50 dB HL in the better hearing ear or (b) had a high-frequency hearing loss with one or more thresholds greater than 25 dB HL at or above

2 kHz and thresholds less than or equal to 15 dB HL at all frequencies below 2 kHz. The CMBHL group had 22 participants with a mean age of identification of hearing loss of 40.16 months ($SD = 29.55$, range: 1–108 months). At the time of participation, 19 CMBHL had a bilateral sensorineural hearing loss, two had a bilateral conductive hearing loss, and one had a mixed hearing loss. Two of the children in the CMBHL group had a high-frequency hearing loss. Fifteen CMBHL were fitted with hearing devices bilaterally, one was fit unilaterally, one child was fit with a bone-conduction hearing aid, and five children were unaided. Of the 17 CMBHL who wore hearing aids, amplification was first fit at a mean age of 45.03 months ($SD = 36.92$, range: 2–96 months).

The CCI group had 26 participants: 21 implanted bilaterally and five implanted unilaterally. Three of the children implanted unilaterally wore a hearing aid on the nonimplanted ear, and two were unaided on the nonimplanted ear. The CCI group had hearing loss confirmed at a mean age of 6.21 months ($SD = 4.95$, range: 0.5–18 months) and was first implanted at an average age of 21.56 months ($SD = 18.32$, range: 10–95 months).

Measures

Nonverbal problem solving was assessed using the Wechsler Abbreviated Scale of Intelligence–Second Edition (WASI-II; Wechsler, 2011). All children were given the Block Design and Matrix Reasoning subtests to obtain the Perceptual Reasoning Index. In the timed Block Design subtest, children recreate a two-dimensional–design picture using three-dimensional red and white blocks. In Matrix Reasoning, children view a pictured matrix and select the option that best completes the matrix. To qualify for participation, children must have performed within 1.5 SD s below the mean or better (a standard score of 77 or greater) for their chronological age.

The Counting Recall subtest of the computer-based Automated Working Memory Assessment (AWMA; Alloway, 2007) was chosen to assess working memory. Counting Recall tests verbal working memory and requires the child to count the number of red circles in an array of blue and red circles and triangles and then recall the correct number of red circles in an increasing sequence. Raw scores of the memory component of the task were used in all analyses. For reference, to be within 1 SD of the normative mean on the AWMA Counting Recall test, a 10-year-old child would have to have a raw score within the range of 14–23, while a 12-year-old child would require a raw score within the range of 16–25. One CNH was not able to complete this task because of a lack of sensitivity to the color differences of the circles.

Executive function was measured using the Flanker Inhibitory Control and Attention (Flanker) subtest of the NIH Toolbox (Gershon et al., 2013). The Flanker subtest measures attention and inhibitory control by requiring the child to focus on a stimulus while inhibiting attention to surrounding congruent and incongruent stimuli. The task was completed on either a web-based or iPad-based platform

for each participant. Raw scores were converted into standard scores that adjusted for the different administration platforms and were comparable across platforms. The resulting standard scores were used in all analyses. Due to examiner error, this task was not administered to one child with a CI.

Expressive vocabulary was assessed using the Vocabulary subtest of the WASI-II (Wechsler, 2011). The child is presented with a picture or printed word and asked to give a definition of a target word. Raw scores were used in all analyses. For reference, to be within 1 SD of the normative mean on the WASI-II Vocabulary test, a 10-year-old child would have to have a raw score within the range of 21–32, while a 12-year-old child would have to have a raw score within the range of 24–36.

NWR

The NWR task incorporated the instructions and 16 nonwords developed by Dollaghan and Campbell (1998) into an auditory–visual format as described by Nittrouer et al. (2014). We created a high-quality AV recording of a speech-language pathologist saying the nonwords in a sound booth and then programmed the files for random presentation of items within each syllable length group (one-, two-, three-, and four-syllable lengths).

The NWR task was presented to children using a laptop through loudspeakers at 65 dB SPL. Following presentation of the instructions, each child was asked if the presentation level was loud enough, and if not, the level was increased to the most comfortable loudness level and that level was then measured in SPL by a sound-level meter and noted on the score form. Four CCI requested volume be increased to 70 dB SPL. Each child was asked to immediately repeat each nonword after it was presented. Each child's responses were video-recorded for scoring at a later time.

Each nonword was scored on a phoneme-by-phoneme basis following the scoring rules described in Nittrouer et al. (2014) and Ellis Weismer et al. (2000). Two examiners viewed the video recording of each child's responses and came to a consensus on the child's production for each phoneme. If the two scorers were not able to agree on a response, a third scorer was brought in to provide judgment. Phonemes that were scored as substitutions or omissions were counted as incorrect, and phonemes that were counted as distortions were scored as correct. Phonemes added to a nonword response were marked as additions, and in this case, the participant received credit for correct phonemes in that nonword, but the word itself was scored as incorrect. Children were encouraged to attempt every nonword; however, if a child did not attempt a nonword, all phonemes in that nonword were scored as errors (Shriberg et al., 2009). Most nonresponses in the current project were for four-syllable nonwords in the CCI group.

Reliability of the nonword scoring was completed by a third scorer who listened to 20% of the NWR recordings and scored each phoneme as correct/incorrect. Judgments of the third scorer were compared to the initial scoring by the first two scorers to obtain percentage of phonemes judged

the same (i.e., correct/incorrect) by all scorers. Seven of these recordings were from CNH, three were from CUHL, four were from CMBHL, and five were from CCI.

Results

Reliability

Internal

As in Dollaghan and Campbell (1998) and Nittrouer et al. (2014), phoneme-by-phoneme reliability in the current study was estimated by a third scorer for the responses of 20% of the participants in each hearing status group. The mean percentage of phonemes judged the same in each scoring of a sample was 94% (range: 84%–99%), compared to a mean of 94% (range: 91%–99%) reported in Dollaghan and Campbell and a mean of 95% (range: 90%–100%) reported in Nittrouer et al.

External

Total percentage of phonemes correct on the AV-NWR from the current study was compared to results from previous studies using the same nonwords with similar groups of participants. Dollaghan and Campbell presented the nonword stimuli in an auditory-only format to normal-hearing children with typically developing language ages 6–9 years who repeated, on average, 84% ($SD = 7$) of phonemes correct. Normal-hearing second graders in Nittrouer et al. (2014) repeated 83% ($SD = 7$) of phonemes presented in an AV format correctly. In the current study, 94% ($SD = 4$) of phonemes were repeated correctly by the normal-hearing comparison group, ages 7–18 years. In Nittrouer et al., 8-year-old CCI repeated 68% ($SD = 12$) of phonemes correctly, compared to the current study where CCI, ages 6–18 years, repeated 86% ($SD = 7$) of phonemes correctly.

Standardized Assessments

A one-way analysis of variance was conducted to compare performance of each hearing status group on the standardized assessments. Descriptive statistics for these standardized tests of language (WASI-II Vocabulary), verbal working memory (AWMA Counting Recall), and executive function (NIH Toolbox Flanker) are presented for each group in Table 2. A statistically significant difference between

groups was found on WASI-II Vocabulary, $F(3, 96) = 5.731$, $p = .001$, $\eta_p^2 = .152$, and NIH Toolbox Flanker, $F(3, 95) = 5.542$, $p = .002$, $\eta_p^2 = .149$. Tukey post hoc comparisons indicated CNH scored significantly better on WASI-II Vocabulary than CUHL ($p = .009$, $d = 1.04$), CMBHL ($p = .006$, $d = 0.97$), and CCI ($p = .028$, $d = 0.73$). Similarly, CNH scored significantly better on NIH Toolbox Flanker than CUHL ($p = .037$, $d = 0.85$), CMBHL ($p = .003$, $d = 1.00$), and CCI ($p = .026$, $d = 0.69$). No difference in performance between groups was found on AWMA Counting Recall, $F(3, 95) = 1.710$, $p = .170$, $\eta_p^2 = .051$.

NWR Performance

Using SAS Version 9.4 (SAS Institute Inc.), we fit a generalized linear mixed-effects model to the data, using the binomial distribution and logit link. The dependent variable was response on each item, recorded as correct or incorrect. Hearing status (four levels) and number of syllables (1, 2, 3, and 4) were fixed effects. Number of syllables was treated as a categorical factor due to the nonlinearity of the response (four syllables was considerably more difficult than one, two, or three syllables). AWMA Counting Recall, WASI-II Vocabulary, and NIH Toolbox Flanker scores, as well as age in months, were continuous predictors. Maternal education was a categorical predictor (1 = *high school or less*, 2 = *some college*, 3 = *bachelor's degree*, 4 = *advanced degree or coursework beyond bachelor's degree*). A random subject effect was used to account for the correlation due to repeated measures on the same subjects. p values for pairwise comparisons were adjusted with the simulation technique (Westfall, Tobias, & Wolfinger, 2011). AV-NWR scores for each group are presented in Table 3.

There were significant effects of the AWMA Counting Recall score, $F(1, 294) = 6.49$, $p = .01$, $\eta_p^2 = .02$, and of the WASI-II Vocabulary score, $F(1, 294) = 10.33$, $p = .0015$, $\eta_p^2 = .03$, on NWR accuracy. The effect of these variables on NWR accuracy as a function of hearing status group is shown in Figure 1 and as function of syllable length is shown in Figure 2. There were no interactions between hearing status and counting recall or vocabulary. The other numerical factors (NIH Toolbox Flanker scores, maternal education, and age) did not make a significant contribution to the model.

Table 2. Mean and standard deviations of standardized assessments grouped by hearing status.

Assessment	<i>M (SD) score</i>			
	CNH	CUHL	CMBHL	CCI
WASI-II Vocabulary	33.74 (6.92)	26.71 (6.77)	26.95 (7.37)	28.31 (8.36)
AWMA Counting Recall	21.91 (6.06)	18.41 (5.60)	20.27 (5.12)	21.46 (5.02)
NIH Toolbox Flanker	112.53 (21.81)	95.98 (14.55)	92.61 (17.30)	97.14 (24.23)

Note. WASI-II Vocabulary and AWMA Counting Recall are reported as raw scores. NIH Toolbox Flanker is reported as a standard score. CNH = children with normal hearing; CUHL = children with unilateral hearing loss; CMBHL = children with mild bilateral hearing loss; CCI = children with cochlear implants; WASI-II = Wechsler Abbreviated Scale of Intelligence–Second Edition; AWMA = Automated Working Memory Assessment; NIH = National Institutes of Health.

Table 3. Mean and standard deviations for percentage of phonemes repeated correctly for the four nonwords within each syllable length group and on the entire audiovisual nonword repetition (AV-NWR) task grouped by hearing status.

AV-NWR	M (SD) score			
	CNH	CUHL	CMBHL	CCI
One syllable	98.33 (3.94)	95.59 (6.67)	97.35 (3.97)	94.55 (7.80)
Two syllables	98.86 (2.99)	94.71 (6.95)	97.50 (4.01)	95.38 (4.67)
Three syllables	97.76 (2.75)	92.65 (7.20)	93.18 (5.50)	90.39 (7.88)
Four syllables	86.67 (8.28)	76.31 (9.92)	81.57 (11.49)	74.04 (12.64)
Total	93.90 (3.54)	87.32 (6.94)	90.25 (5.93)	85.82 (6.90)

Note. NWR scores are percentage of phonemes repeated correctly within each scoring category. CNH = children with normal hearing; CUHL = children with unilateral hearing loss; CMBHL = children with mild bilateral hearing loss; CCI = children with cochlear implants.

There was a main effect of hearing status, $F(3, 93) = 9.55, p < .0001, \eta_p^2 = .07$. As can be seen in Figure 3, the CNH were more accurate than the CUHL (adjusted $p = .03$) and the CCI (adjusted $p < .001$). The CMBHL were also more accurate than the CCI (adjusted $p = .007$). There were no other significant differences associated with hearing status. There was also a main effect of syllable length, $F(3, 294) = 161.63, p < .0001, \eta_p^2 = .55$. As seen in Figure 4, the accuracy of one- and two-syllable nonwords did not differ, but one-syllable nonwords were more accurate than nonwords with three syllables (adjusted $p = .004$) and four

syllables (adjusted $p < .001$). Two-syllable nonwords were more accurate than three- and four-syllable nonwords (adjusted $p < .001$), and three-syllable nonwords were more accurate than four-syllable nonwords (adjusted $p < .001$). There was no interaction between hearing status and syllables ($p = .24$), so the interaction term was not retained in the model.

Discussion

Hearing Status and AV-NWR

In the current study, children with wide-ranging hearing abilities completed an AV adaptation of an NWR

Figure 1. NWR accuracy estimated by the model for each hearing status group. For purposes of visualization, mean total percentage of phonemes correct on the AV-NWR is plotted at values of the significant covariates chosen to represent the range of the data for low raw scores (AWMA = 15, WASI-II = 20), midrange raw scores (AWMA = 22, WASI-II = 30), and high raw scores (AWMA = 30, WASI-II = 40). Error bars represent the 95% confidence intervals for the means. AV-NWR = audiovisual nonword repetition; WASI-II = Wechsler Abbreviated Scale of Intelligence–Second Edition Vocabulary; AWMA = Automated Working Memory Assessment Counting Recall; CNH = children with normal hearing; CUHL = children with unilateral hearing loss; CMBHL = children with mild bilateral hearing loss; CCI = children with cochlear implants.

Figure 2. NWR accuracy estimated by the model for each nonword syllable length. For purposes of visualization, mean total percentage of phonemes correct on the AV-NWR is plotted at values of the significant covariates chosen to represent the range of the data for low raw scores (AWMA = 15, WASI-II = 20), midrange raw scores (AWMA = 22, WASI-II = 30), and high raw scores (AWMA = 30, WASI-II = 40). Error bars represent the 95% confidence intervals for the means. AV-NWR = audiovisual nonword repetition; WASI-II = Wechsler Abbreviated Scale of Intelligence–Second Edition Vocabulary; AWMA = Automated Working Memory Assessment Counting Recall.

Figure 3. Total percentage of phonemes correct for the CNH, CUHL, CMBHL, and CCI groups on the AV-NWR task. Boxes represent the interquartile range, and whiskers represent the fifth and 95th percentiles. The midline represents the median, and the filled circle represents the mean. Open circles are values that fell outside of the fifth or 95th percentiles. Asterisks indicate a significant difference between groups. AV-NWR = audiovisual nonword repetition; CNH = children with normal hearing; CUHL = children with unilateral hearing loss; CMBHL = children with mild bilateral hearing loss; CCI = children with cochlear implants.

task. Our first aim was a practical one, to replicate a finding of Nitttrouer et al. (2014), namely, that CCI can perform above floor. Indeed they could; they averaged 86% accuracy, and no individual scored lower than 72% accuracy.

Figure 4. Total percentage of phonemes correct for the CNH, CUHL, CMBHL, and CCI groups on the AV-NWR task at each syllable length. Boxes represent the interquartile range, and whiskers represent the fifth and 95th percentiles. The midline represents the median, and the filled circle represents the mean. Open circles are values that fell outside of the fifth or 95th percentiles. AV-NWR = audiovisual nonword repetition; CNH = children with normal hearing; CUHL = children with unilateral hearing loss; CMBHL = children with mild bilateral hearing loss; CCI = children with cochlear implants.

Their performance was numerically higher than the performance reported in Nitttrouer et al., and the difference could be attributed to well-documented variations in the performance of CCI (Niparko, 2010). Differences in the quality of the AV signal of the AV-NWR stimuli could also be at play. We had access to a team of media professionals who recorded and edited the videos of the nonword stimuli. Thus, the high quality of the signal in the videos could have enabled more accurate repetition of the nonwords than the original version. There were also differences in age of the participants, with our sample being older on average; however, this seems unlikely to account for the better performance of our participants given that age was not a significant predictor of NWR accuracy.

The current study extended the AV-NWR task to CUHL or CMBHL. We compared their performance on the AV-NWR task to the performance of peers with severe-to-profound hearing loss who wore CIs and to peers with normal hearing. Given their mild or unilateral hearing loss and the support provided by the visual cues on the AV-NWR task, we predicted that the CMBHL and CUHL would perform better than the CCI and comparably to the CNH. This prediction held only in part. The CUHL performed more poorly than the CNH. Numerically, they fell between the CMBHL and the CCI, and their performance differed significantly from neither. The CMBHL did perform better than the CCI and comparably to the CNH. Because children with mild-to-moderate degrees of hearing loss have consistently demonstrated poor NWR performance on auditory-only versions of the task (Briscoe et al., 2001; Halliday & Bishop, 2005; Wake et al., 2006), we conclude that reduced audibility and auditory perception due to the hearing loss has enough of an effect on phonologic sensitivity to result in poor NWR accuracy when presented in an auditory-only format but, with visual cues, performance is robust. This conclusion holds implications for clinical measurement: A CMBHL who scores poorly on an AV-NWR may have language impairments beyond those imposed by the hearing loss per se.

The addition of visual cues to the NWR task enabled CCI to complete the task and allowed individual differences in NWR accuracy in CCI to be discerned. However, this group of children still struggled to repeat nonwords to a far greater extent than their counterparts with mild degrees of hearing loss and normal hearing. While the degraded auditory input from their CIs likely impeded their phonologic sensitivity, we cannot rule out the potential contribution of phonologic production problems. The CCI in our project were predominantly oral communicators, but we did not test for phonological processes or articulation errors that could have affected the accuracy of the nonword production.

Although we did not expect the poor NWR accuracy observed in CUHL, we suspect it may be related to the unique auditory-linguistic experiences of CUHL. While the hearing losses of the CUHL and CMBHL in our project were identified at similar ages, CUHL were fit with amplification an average of 19 months later than

the CMBHL. Once fit with amplification, CUHL have also been shown to be less consistent users of amplification, at least during the preschool years, compared to children with bilateral hearing loss (Fitzpatrick et al., 2019, 2018). In addition to differences in auditory access and perception, some CUHL may have subtle deficits in the skills that support NWR. Fitzpatrick et al. (2019) reported poorer auditory listening and language skills in early-identified preschool-age CUHL, two thirds of whom were fit with amplification on average within their first year of life, than the study group of CNH. A group of CMBHL was also found to lag behind CNH in auditory skills and language, but to a lesser extent than the group of CUHL. A recent review of studies examining the development of CUHL by Lieu (2018) documents the impact of unilateral hearing loss not only on language but also on cognition and quality of life from early childhood to adolescence. Clearly, a gap exists between the outcomes of CUHL and their peers with normal hearing. Future studies are needed to isolate the mechanisms behind this lag in performance and assessment tools that could identify children who are affected and may need further intervention. AV-NWR could act as one such useful tool to aid in identifying CUHL with disproportionate language learning impairments that require extra attention.

Mechanisms That Support AV-NWR

Our broader aim was to determine the mechanisms that do and do not contribute to AV-NWR performance. We reasoned that if, as intended, performance on the AV-NWR task is relatively independent of amount of language experience, then age and maternal education should not relate to repetition accuracy. This was true. By using nonwords, (AV-)NWR tasks “level the playing field.” They permit assessment of critical skills needed to process language while reducing the threat of confounds due to varying levels of exposure to the language (Campbell et al., 1997; Dollaghan & Campbell, 1998).

What mechanisms do contribute? Because the AV-NWR task minimizes demands on phonologic sensitivity, by including a visual signal, and demands on phonologic reproduction, by excluding the Late-8 consonants among the nonwords, we considered the mechanisms that underlie phonologic storage—executive function, vocabulary, and working memory—to be likely candidates.

As a preliminary step, we compared the children grouped by hearing status on measures of these three domains. The groups did not differ in working memory as measured by the AWMA Counting Recall task, a result that accords with those of Briscoe et al. (2001). Therefore, it is unlikely that deficits in phonologic storage contributed to the poorer NWR performance of the children with hearing loss in the CUHL and CCI groups. The significant effect of syllable length on NWR performance is further evidence in support of this conclusion. While most participants performed at or near ceiling on the one-syllable

nonwords, performance decreased across all hearing status groups as syllable length increased up to four syllables. A critical finding is that there was no interaction between syllable length and hearing status; the performance declined with syllable length in a fairly uniform fashion for the hearing and hearing loss groups. Thus, children with hearing loss were not unusually taxed by the increasing short-term storage demands of the longer words.

We must reconcile the conclusion that the phonologic storage requirements of NWR were not an undue challenge for the children with hearing loss with the finding of weaknesses in vocabulary and executive function, processes thought to contribute to phonologic storage. Compared to the CNH, all groups of children with hearing loss were significantly poorer in vocabulary as measured by the WASI-II Vocabulary subtest, and these were large effects for all groups. At first blush, this finding seems contradictory to those of Briscoe et al. (2001) and Klein et al. (2017) who reported no difference in the vocabulary scores of children with and without hearing loss. However, those investigators used naming and recognition tasks, whereas the WASI-II vocabulary task that we used requires verbal definitions. The ability to correctly define a word is a sign of deep vocabulary knowledge; naming, and especially recognition, requires less depth (McGregor, Oleson, Bahnsen, & Duff, 2013) and, therefore, might be less sensitive to differences associated with hearing status. We also found that, compared to the CNH, all groups of children with hearing loss demonstrated poorer executive function as measured by the NIH Toolbox Flanker task, and these were moderate-to-large effects. Executive function deficits are often characteristic of children with hearing loss (Botting et al., 2017; Ead et al., 2013; Figueras, Edwards, & Langdon, 2008). We conclude that the children with hearing loss, no matter the severity or type, brought weaker vocabulary and executive function skills to the NWR task. That said, those weaknesses in and of themselves are not enough to diminish NWR performance as the CMBHL repeated the nonwords as accurately as their CNH peers.

After preliminary group comparisons, we directly tested the extent to which executive function, vocabulary, and working memory scores accounted for variance in NWR performance. Executive function scores did not predict variance in AV-NWR. This could be because (a) executive function as measured by the NIH Toolbox Flanker task does not contribute to NWR performance or (b) it does contribute to NWR accuracy but no more than already captured by entering hearing status into the model. Further research into the contribution, or lack thereof, of executive function to NWR performance is warranted. Vocabulary and working memory scores accounted for significant variance in the NWR performance of the children. Note that hearing status accounted for variance as well, but there was no interaction between hearing status and vocabulary and working memory. Therefore, we conclude that children—both those with normal hearing and those with hearing loss—who have more limited vocabulary knowledge or poorer working memory are at a greater risk for NWR deficits.

Similar to the use of traditional auditory-only NWR tasks with CNH, the AV-NWR task has potential to serve as a clinical tool to identify children with hearing loss who are at risk for poor language outcomes. Poor AV-NWR accuracy would indicate a need for further support targeting vocabulary and working memory skills. In the current project, the participant responses were recorded and scored at a phoneme level after the assessment session. While the test itself only took a few minutes, this scoring procedure may be burdensome in a busy clinic setting. Further studies should evaluate if online word-level or phoneme-level scoring is equivalent to the current procedure. In addition, future studies should examine if presentation of only the most difficult condition, the four-syllable nonwords, may be sufficient to identify children at risk.

Summary

The AV-NWR task was shown to capture individual differences in the performance of children with wide-ranging hearing abilities and, consistent with Nittrouer et al. (2014), demonstrated that CCI are able to perform far above floor. A deficit in NWR accuracy was identified in CCI and CUHL compared to their normal-hearing counterparts and in CCI compared to CMBHL. Vocabulary and working memory abilities were found to underpin the performance of all groups on NWR. The children who scored the lowest on vocabulary and working memory tasks were at the greatest risk to show weaknesses on NWR. The relationship between NWR and vocabulary knowledge and working memory holds implications for clinical practice: The AV-NWR may be a useful tool for identifying children who struggle with vocabulary and working memory beyond any limitations imposed by their hearing loss per se. Finally, the study uncovers several gaps that require future research including the need to understand the role of executive function in NWR and the particular difficulties faced by children with CUHL.

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