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Original Article

Improving speech-in-noise recognition for children with hearing loss: Potential effects of language abilities, binaural summation, and head shadow

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Abstract

Objective: This study examined speech recognition in noise for children with hearing loss, compared it to recognition for children with normal hearing, and examined mechanisms that might explain variance in children's abilities to recognize speech in noise. *Design:* Word recognition was measured in two levels of noise, both when the speech and noise were co-located in front and when the noise came separately from one side. Four mechanisms were examined as factors possibly explaining variance: vocabulary knowledge, sensitivity to phonological structure, binaural summation, and head shadow. *Study sample:* Participants were 113 eight-year-old children. Forty-eight had normal hearing (NH) and 65 had hearing loss: 18 with hearing aids (HAs), 19 with one cochlear implant (CI), and 28 with two CIs. *Results:* Phonological sensitivity explained a significant amount of between-groups variance in speech-in-noise recognition. Little evidence of binaural summation was found. Head shadow was similar in magnitude for children with NH and with CIs, regardless of whether they wore one or two CIs. Children with HAs showed reduced head shadow effects. *Conclusion:* These outcomes suggest that in order to improve speech-in-noise recognition for children with hearing loss, intervention needs to be comprehensive, focusing on both language abilities and auditory mechanisms.

Key Words: Speech-in-noise recognition; children; hearing loss; spatial release from masking

Children require better signal-to-noise ratios (SNRs) than adults in order to achieve comparable speech recognition scores (e.g. Neuman et al, 2010; Nittrouer & Boothroyd, 1990; Papso & Blood, 1989; Schafer et al, 2012). Paradoxically, children spend much of their lives functioning in environments much noisier than those in which adults live their lives. Picard and Bradley (2001) reviewed studies of noise levels in regular classrooms, and the mean level across studies for elementary schools was found to be 60 dBA, which is 10 dB greater than the average noise level reported for office spaces by Venetjoki et al (2006). SNRs in classrooms have been found to range between −6 and +3 dB (Blair, 1977; Crandell, 1993; Finitzo-Hieber, 1981; Markides, 1986), which are levels known to support word recognition scores of no greater than 60% correct for children (Nittrouer & Boothroyd, 1990; Nittrouer et al, 2011). Add to these challenging acoustic environments the fact that children's goal in the classroom is to acquire new knowledge, which often involves new vocabulary, and it becomes clear that they could be hampered in their efforts to reach that goal.

Evidence supporting this concern comes from a recent study by Valente et al (2012). These authors measured the abilities of adults, 11-, and eight-year-olds to answer comprehension questions after listening to material presented in a simulated classroom. Two conditions were used to present material: one replicating a lecture from a teacher standing in the front and another replicating a discussion among students in the class. In these simulations, the teacher and students were represented by computers placed around the room. Two SNRs and two reverberation times were used. Results showed that the eight-year-old children were generally poorer than older listeners at answering comprehension questions, especially in the condition that simulated classroom discussions where the talker changed often. Across SNRs and reverberation times, eight-year-olds were able to answer only about a third of the questions correctly, supporting claims that the noisy conditions of ordinary classrooms can interfere with learning, even for typical children with normal hearing.

Children with hearing loss are at an even greater disadvantage when it comes to classroom learning. Children with only mild hearing loss (i.e. pure-tone averages for the three speech frequencies between 15 and 30 dB hearing level) who do not use hearing aids (HAs) have been found to have poorer speech-in-noise recognition than children with thresholds better than 15 dB (Crandell, 1993). That outcome was found for sentence-length material, but has been replicated using word lists for children with conductive hearing losses who had auditory thresholds in the same 15 to 30 dB range

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Abbreviations

CI	Cochlear implant
CID	Central Institute for the Deaf
CVC	Consonant-vowel-consonant
HA	Hearing aid
NH	Normal hearing
SE	Standard errors
SNR	Signal-to-noise ratio
SRM	Spatial release from masking

(Keogh et al, 2010). In that latter study, recognition scores obtained at 0 dB SNR were 9 percentage points lower for the children with conductive hearing loss than for children with normal hearing. Children with moderate sensorineural hearing loss (i.e. pure-tone averages for the three speech frequencies between 50 and 80 dB hearing level) who use HAs have similarly been found to experience more interference in their speech recognition from noise than children with normal hearing. Caldwell and Nittrouer (2013) examined the abilities of kindergarten children to recognize consonant-vowel-consonant (CVC) words presented in flat-spectrum noise. At + 3 dB SNR, children with normal hearing were able to recognize, on average, half of the words correctly, which matches what Nittrouer and Boothroyd (1990) found for CVC words presented in speech-shaped noise at the same SNR. Children with moderate sensorineural hearing loss who wore HAs in the Caldwell and Nittrouer study recognized roughly half that number of words correctly. Children with cochlear implants (CIs) in that study showed a further decrease by half of recognition rates, with a mean score of only 12.5% correct.

The current report was concerned with ways to effectively improve the abilities of children with hearing loss to recognize speech in noisy environments. Children with CIs were a special focus, and four potential contributing factors were investigated: vocabulary knowledge, sensitivity to phonological structure, binaural summation, and head shadow.

When considering the relationship of language and speech-in-noise recognition, the fact that listeners with sensorineural hearing loss recognize speech in noise more poorly than listeners with normal hearing is well recognized (e.g. Davidson et al 2011; Fu et al, 1998; Hazrati & Loizou, 2012; Saripella et al, 2011); but at least when it comes to children, Caldwell and Nittrouer (2013) found evidence suggesting that the difference might not just be peripheral in origin. In that study, the effects of noise on speech recognition were found to be largely constant in magnitude across groups of children, such that children with hearing loss performed uniformly more poorly than children with normal hearing, in both quiet and in noise. When potential factors accounting for recognition scores in quiet were examined for children with CIs, it was found that they were primarily associated with language abilities, especially vocabulary knowledge. Thus, language abilities constrained how well these children were able to recognize speech in quiet, and by extension, in noise.

An explanation offered for the observed relationship between language abilities and speech recognition has traditionally been that greater language knowledge allows listeners to make better predictions about what they are hearing based on less robust sensory information (e.g. Ahissar, 2007; Boothroyd, 2010). According to this view, listeners are able to generate hypotheses concerning the speaker's message based on sensory evidence, even if limited, along with their knowledge of all relevant factors, including language. Greater language knowledge permits the positing of better predictions, and allows the listener to make decisions about the message with less sensory evidence.

In addition to vocabulary knowledge, a language-related skill often examined for its effect on speech-in-noise recognition is sensitivity to phonological structure (e.g. Boets et al, 2011; Brady et al, 1983; Lewis et al, 2010; Nittrouer & Burton, 2005; Serniclaes et al, 2005; Vance & Martindale, 2011). This sensitivity is commonly assessed with phonological awareness or speech discrimination tasks. And even though significant correlations are not always found between sensitivity to phonological structure and speech-in-noise recognition within groups (language typical or disordered), listener groups are generally found to differ on both sorts of measures. For example, Caldwell and Nittrouer (2013) found that phonological awareness explained significant amounts of within-group variance for speech-in-noise recognition scores only for kindergarten children with normal hearing. Nonetheless, strong between-groups effects were observed, such that children with CIs were poorer than children with normal hearing at both phonological awareness and speech-in-noise recognition. Consequently, sensitivity to phonological structure appeared to have a limiting effect on speech recognition. These results suggest that early intervention designed to help children with hearing loss develop good language skills (e.g., vocabulary knowledge and sensitivity to phonological structure) is one effective way to improve their capacities to handle the noisy classroom environments they will enter. A goal of the current study was to examine whether similar conclusions would be reached after investigating speech-in-noise recognition for children in second grade: Would language abilities again be found to explain a significant proportion of variance in children's abilities to recognize speech in noise, either within or between groups?

When it comes to listeners with severe-to-profound hearing loss, another way to possibly improve their speech-in-noise recognition is bilateral implantation. There are a number of reasons why two implants may be better than one when it comes to listening in noise, including binaural summation. Strictly speaking, this term refers to the increase in loudness obtained when an identical signal is presented to both ears, rather than to just one (Marks, 1978), but it has been used almost synonymously with the term binaural redundancy to capture the idea that there are benefits beyond increased loudness of listening with two ears. A number of studies have shown that binaural summation, or redundancy, can improve speech recognition both in quiet (e.g. Dunn et al, 2008), and in noise for bilateral cochlear implant users. In the case of noise, that improvement is seen even when the speech and noise come from the same location (e.g. Buss et al, 2008; Litovsky et al, 2006; Müller et al, 2002; Tyler et al, 2002). This binaural summation effect is greater in magnitude for listeners with hearing loss than for those with normal hearing, and the reason is thought to be associated with the errors in transmission that can occur at separate ears for listeners with hearing loss. Each ear may compensate for these errors in the other. For example, holes in the spectrum on one side arising from damage to spiral ganglion cells would be covered by the signal received on the other side (Culling et al, 2012; Dunn et al, 2008).

A second goal of the current study was to see if evidence of binaural summation in children with bilateral CIs could be found. This goal was achieved primarily by comparing the speech recognition scores of children with one and two CIs, in both quiet and in noise. If binaural summation was operating for the children with two CIs, their scores should be higher than those of children with one CI.

Another mechanism thought to facilitate speech-in-noise recognition is head shadow. This effect is generally studied by measuring spatial release from masking (SRM), a phenomenon in which speech is recognized with similar accuracy at poorer SNRs when the noise is spatially separated from the signal than when the signal and noise originate from a common source. Experiments measuring SRM typically present speech material under contrasting noise conditions: (1) with the signal and noise both coming from a single speaker; and (2) with the noise coming from a different speaker, usually on one side of the listener. Using adaptive procedures, speech reception thresholds are then obtained in each condition. SRM is defined as the benefit in having the noise spatially separated from the signal. In experiments involving listeners with normal hearing, SRM on the order of 3 to 5 dB is typically observed (e.g. Litovsky, 2005; Schafer et al, 2012; Van Deun et al, 2010): that is, listeners achieve the same level of accuracy of recognition at 3 to 5 dB poorer SNRs with the noise spatially separated.

An advantage of having speech and noise spatially separated has also been observed for listeners using two CIs, and that advantage is generally equivalent in size to what is reported for listeners with normal hearing (e.g. Culling et al, 2012; Litovsky et al, 2006; Schleich et al, 2004; Van Hoesel & Tyler, 2003). A few investigators have measured SRM for adults with bilateral CIs at only one SNR by calculating the change in percent correct word recognition between the conditions of having speech and noise co-located versus having the noise come from one side (Buss et al, 2008; Mok et al, 2010; Müller et al, 2002; Peters et al, 2007; Tyler et al, 2002). In that case, the magnitude of effect is reported as being a difference in correct word recognition of roughly 10 to 18 percentage points (e.g. Müller et al, 2002; Peters et al, 2007).

In experiments designed to evaluate the contributions to SRM of various binaural effects, head shadow has consistently been found to be the primary contributor (e.g. Litovsky et al, 2006; Schleich et al, 2004; van Deun et al, 2010; van Hoesel & Tyler, 2003). Thus, listeners with one CI would be expected to demonstrate head shadow effects similar in magnitude to those measured for two-CI users, as long as the noise is on the side without a CI, and support for that prediction has been found (e.g. Culling et al, 2012). Nonetheless, having two CIs should help by providing head shadow effects when the noise is on either side, not just the side without a CI. Taken together, binaural summation and more frequent opportunities to benefit from head shadow should help children with two CIs recognize speech in noise better than children with one CI, and these effects should be independent of language abilities.

Several studies by Litovsky and colleagues provide support for this last claim, that the benefits of head shadow should be independent of language abilities. Litovsky (2005), Garadat and Litovsky (2007), and Johnstone and Litovsky (2006) all showed that children with normal hearing generally need more favorable SNRs than adults to achieve equivalent word recognition scores. That outcome can be explained by children's lack of sophisticated language knowledge. However, when SRM was computed, the magnitude of effect was found to be similar for children and adults: again, on the order of 3 to 5 dB across listener groups and conditions. These results were closely replicated by Schafer et al (2012).

Evidence of the head shadow effect has also been observed for children who use bilateral CIs. Misurelli and Litovsky (2012) compared SRM for children with bilateral CIs and age-matched peers with normal hearing in two conditions: with noise on only one side and with noise symmetrically distributed across sides. Although reduced in magnitude, the children with bilateral CIs demonstrated SRM, as long as the noise was on only one side. In a different study, Van Deun et al (2010) observed that children with sequentially implanted bilateral CIs showed the same SRM as children with normal hearing, as long as the noise was on the side of the second CI. Thus, bilateral CIs could offer an effective way of providing better speech-in-noise recognition to children with hearing loss who use CIs, at least under some conditions.

A third goal of the current study was to investigate whether children with CIs show SRM of similar magnitude to that of children with normal hearing. SRM was presumed to rely primarily on the head shadow effect, as demonstrated by others, and evidence to support that claim would be found if SRM was similar in magnitude for children with one and two CIs.

Children who wear HAs were also included in the current study. Ching et al (2011) found no evidence of the head shadow effect for children using HAs, but that result has not yet been replicated.

In summary, the current study investigated speech-in-noise recognition by children with sensorineural hearing loss, and compared their performance to that of children with normal hearing. Most of the children with hearing loss wore CIs, but some used HAs. Of the children with CIs, some wore just one, but most wore two CIs. All children in the study were tested in the summer after they had completed second grade, making them all just about eight years of age.

One hypothesis explored in this study was that children's abilities to recognize speech in noise would be explained in some significant part by their overall language abilities. In the current study, the language abilities examined included vocabulary skills and sensitivity to phonological structure. In particular, expressive vocabulary knowledge was measured, and three phonological awareness tasks were used to assess sensitivity to phonological structure. This variety in tasks was included in this work because without it there is an inherent risk of missing critical differences in skill, both within and between groups. Either a task can be too difficult, even for typical children, or a task can be too easy, so that even children with some delay perform well. In either case, variability is truncated, reducing the likelihood of uncovering significant relationships between sensitivity to phonological structure and performance in other domains, which in this case meant speech-in-noise recognition.

A second hypothesis explored in this study was that children with two CIs would benefit from binaural summation. This hypothesis was examined for recognition scores in both quiet and in noise.

A third hypothesis examined had to do with the head shadow effect. Specifically, speech-in-noise recognition was measured, both when the speech and noise were co-located in front, and when the noise was located on one side. For children with CIs, that meant either the side without a CI (in the case of children with one CI) or the side with the second CI (in the case of children with two CIs). SRM was calculated as the difference in recognition probabilities between these two conditions, and was presumed to arise primarily from head shadow. If other binaural effects contributed to SRM for these children, that would be observed as greater SRM for children with two, rather than just one CI.

Methods

Participants

Children who had just completed second grade participated in the current study (N = 113). All were participants in an ongoing longitudinal study (Nittrouer, 2010). Sixty-five of these children had permanent sensorineural hearing loss with three-frequency pure-tone averages greater than 50 dB hearing level in the better ear.

Of those children, 47 had severe-to-profound hearing loss and wore one or two CIs. Twenty-eight of the children with CIs wore them bilaterally. Of the 19 children with just one CI, six wore a HA on the contralateral ear. Twenty-seven of the 47 children with at least one CI got the first or only CI on the right side, and two children received bilateral CIs simultaneously. Twenty-eight children wore devices by Cochlear Corporation, 18 children wore devices by Advanced Bionics, and two children wore devices by Med-El. These numbers total to 48 because one child wore a Cochlear device on one ear and an Advanced Bionics device on the other ear. Eighteen children had moderate hearing loss and wore bilateral HAs: 11 Phonak, 5 Oticon, 1 Widex, and 1 Unitron. The remaining 48 children had normal hearing (NH), meaning that all thresholds from 0.25 to 8 kHz were better than 15 dB hearing level. That was confirmed with audiometric measurement at the time of testing.

These sample sizes provide greater than 90% power for detecting group differences when those differences are 1 SD (Cohen's $d = 1$), which is roughly the size of group differences found by Caldwell and Nittrouer (2013). For children with NH and those with CIs, the samples used here are also large enough to provide more than 90% power for identifying predictor variables with standardized $\beta > .5$. That was not true for the sample of children with HAs, so regression analysis was not performed alone on data from that group of children.

DEMOGRAPHIC MEASURES

Table 1 presents group means (and SDs) for demographic measures. The top five rows show data for all groups.

Socio-economic status was indexed using a two-factor scale on which both the highest educational level and the occupational status of the primary income earner in the home is considered (Nittrouer & Burton, 2005). Differences between the groups were not statistically significant. These scores suggest that all children came from middle-class families, so had reasonably rich language environments in the home.

A measure of non-verbal cognitive functioning was obtained from all children using the Leiter International Performance Scale – Revised (Roid & Miller, 2002). Four subtests were administered: Figure Ground, Form Completion, Sequential Order, and Repeated Patterns. From these four subtests an estimate of non-verbal intelligence was computed, known as the Brief IQ, which can be represented as standard scores with a population mean of 100 and a SD of 15. Differences in means for these groups were not statistically significant.

Table 1. Means and SDs for demographic variables. Except where noted, numbers in each group are 48 for NH, 18 for HA, and 47 for CI.

	Group					
	NH		HA		CI	
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*
Age at time of testing (months)	101	(4)	99	(5)	103	(5)
Proportion of males	.46	–	.39	–	.51	–
Socio-economic status	35	(13)	32	(13)	33	(12)
Brief IQ (Leiter-R) standard scores	103	(21)	103	(16)	101	(17)
CID percent correct word recognition	95	(3)	71	(20)	69	(16)
Age at identification (months)			8	(9)	7	(7)
Current (HAs)/pre-implant (CIs) PTA			63	(9)	100	(16)
Age at 1st implant (months)					21	(17)
Age at 2nd implant (months); $N = 28$					46	(22)
Mean time, 1st implant (months)					81	(17)
Mean time, 2nd implant (months); $N = 28$					57	(22)

Socio-economic status is a 64 point scale. PTAs are for the three frequencies of .5, 1, and 2 kHz, and are for unaided thresholds.

The CID W-22 word lists were used to obtain a measure of word recognition abilities. These lists are commonly used in clinical settings for this purpose. Each child heard one of the 50-word lists, and lists were randomized across children within each group. Percent correct word scores are shown in Table 1 for children listening with both ears. For the values here, significant group effects were found, $F(2,110) = 52.90$, $p < .001$. In post hoc *t* tests with Bonferroni adjustments, children with NH performed significantly better than children with HAs or CIs ($p < .01$), but there were no differences between children with HAs and those with CIs.

The bottom six rows of Table 1 show information for the children with hearing loss. All children were identified before two years of age, and most before one year. Children with CIs received those implants early, which for 41 of the 47 children meant at or before two years of age. Consequently, these children had considerable experience with their CIs.

Equipment

All testing took place in one of three sound-attenuated rooms: One room was dedicated to use for the phonological awareness tasks, one for obtaining the vocabulary and CID measures, and one for the speech-in-noise testing. The room where the speech-in-noise testing took place was an Acoustic System, double-walled booth. In all cases, stimuli used for testing were presented via computers equipped with Creative Labs Soundblaster digital-to-analog cards using a 44.1-kHz sampling rate and 16-bit digitization. Roland MA-12C powered speakers were used for audio presentation of stimuli. In the case of the speech-in-noise testing, one was positioned one metre in front of where children sat during testing, at 0-degrees azimuth. The other speaker was positioned one metre to one side of where children sat, at 90° azimuth. For the phonological awareness and CID tasks, one speaker was positioned one metre in front of where children sat.

The three phonological awareness tasks used an audio-visual format that included a 1500-kbps data rate and 24-bit digitization in video presentation.

Each test session, other than the one involving phonological awareness, was video and audio recorded using a SONY HDR-XR550V video recorder. Sessions were recorded so scoring could be done at a later time by individuals blind to presentation condition. Children wore SONY FM transmitters in specially designed vests that transmitted speech signals to the receivers, which provided direct line input to the hard drives of the cameras. This procedure ensured good sound quality for all recordings. Scoring for the phonological awareness tasks was done at the time of testing by the experimenter entering responses into the computer.

All children with hearing loss were tested wearing their customary auditory prostheses, which were checked at the start of testing. Although 61 of the 65 children with hearing loss used FM systems in the classroom, no child was tested while wearing a FM system.

General procedures

All testing took place in Columbus, Ohio at the Ohio State University and was approved by the Institutional Review Board. Data were collected during a series of camps that occurred over the summer after these children had completed second grade. Each camp took place over a two-day period and included four to six children. All children were tested in six individual sessions that lasted no longer than an hour each, with a minimum of one hour between test sessions. Measures collected during three of those sessions are described in this report, and include children's abilities to recognize speech in noise, as well as skills that could potentially explain those recognition abilities. The Leiter-R subtests were administered in a separate session during camp.

Stimuli and task-specific procedures

SPEECH-IN-NOISE RECOGNITION

This study used the same stimuli and similar procedures to previous work by Caldwell and Nittrouer (2013), which examined speech-in-noise recognition for kindergarten children. As with that previous research, 18 word lists from Mackersie et al (2001) were used in the current study. Each list consists of ten phonetically balanced CVC words. All words were recorded by a male speaker with a fundamental frequency of roughly 110 Hz. Words were saved to individual files, and RMS amplitude equalized across files. Noise with a flat spectrum was created using a random-noise generator. Two SNRs were selected for use: 0 dB and +3 dB. Both of these SNRs represent typical values found in classrooms, and most children were able to recognize some words correctly at these SNRs during the testing reported by Caldwell and Nittrouer. For the most part, each child was tested at only one of these SNRs in a between-subjects design. For each SNR, nine word lists were heard where the signal (word) and the noise were played from one speaker directly in front of the child (henceforth the *same* condition). For the other nine word lists, the signal (word) was played from the speaker directly in front of the child, but the noise was played from the speaker to the side (henceforth the *separate* condition). For most listeners, speech recognition is comparable when presented on the right and left sides (Findlay & Schuchman, 1976), so there was no reason a priori to select one side over the other for placement of the second speaker. Given the constraints of collecting data in the camp format, it was easiest to keep the speaker on one side for as many listeners as possible, so the noise was presented to the left side for most children. The noise was presented to the right side only for children with one implant on the left and for children with two implants who received them sequentially and the first one was on the left. Accordingly, 18 children had the noise presented on the right side. The order of presentation of the 18 word lists varied randomly across children. Presentation in the *same* and *separate* conditions was alternated, so the set of specific lists heard in each condition varied across children. After testing with all 18 lists in noise was completed, the same word lists were presented in quiet for recognition.

An even split of children in the group that heard words presented at each SNR (0 or +3 dB) was not possible because it was also easiest to use a single SNR at each camp. Nonetheless, care was taken to ensure that a minimum of 20 children with NH and 20 children with CIs heard the lists at each SNR. That was not possible for children with HAs because there were only 18 of them. Still another goal was to ensure that at least 10 children with one CI and at least 10 children with two CIs heard the lists at each SNR. Given all these constraints, the division of SNR across camps resulted in 45 children hearing the 18 word lists at only 0 dB SNR, and 58 children hearing the word lists at only +3 dB SNR.

Ten additional children in the study, six with HAs and 4 with CIs (one with one CI and three with two CIs), heard lists at both 0 dB and +3 dB SNR, but only in the *same* condition. This was done as a check on whether or not recognition scores match what would likely have been obtained if all children had been tested at both SNRs in a repeated-measures design. Children with NH were not included in this check because recognition scores for children of this age with NH for these words have been reported previously (Nittrouer et al, 2011). More children with HAs were included in this repeated-measures group because children with HAs would not be included in regression analyses anyway, given the smaller sample size.

A clown face painted on cardboard was positioned just over the speaker at 0 degrees azimuth. Children were instructed to hold their heads still, while looking at the clown. At the start of testing the examiner checked to make sure that the child's head was positioned symmetrically with respect to that speaker, and then monitored to make sure that the child remained still during testing.

The camera recording children's responses was positioned so that their faces could easily be seen. Responses were scored later. The percentage of words and phonemes recognized correctly served as the dependent measures. A response needed to consist of all three correct phonemes with no additional segments inserted in order for the whole word to be scored as correct. Members of the laboratory staff trained together on responses from "practice" participants who were tested in the spring before camps to ensure that scoring criteria were consistent. One member of the laboratory staff scored all responses, and a second member independently scored 10% of them. No differences between the two scorers were found, so reliability was considered to be high.

HEAD SHADOW: SRM

An important aspect of the current study was to examine how separating the noise from the speech signal influenced children's recognition. To determine this, a measure of SRM was derived by calculating the percent correct words (or phonemes) recognized in the *separate* condition minus the percent correct words (or phonemes) recognized in the *same* condition.

POTENTIAL PREDICTOR VARIABLES

Two kinds of language abilities were examined as potential predictor variables for speech-in-noise recognition. One was vocabulary knowledge and the other was phonological awareness.

VOCABULARY. Expressive vocabulary was measured using the Expressive One-Word Picture Vocabulary Test (Brownell, 2000). The task requires the child to provide the words that label a series of pictured items shown one at a time on separate pages. Children's responses were recorded on camera, and scored at a later time. Standard scores obtained using normative data from the test publishers were used as dependent variables.

PHONOLOGICAL AWARENESS. Phonological awareness was assessed using three tasks that varied in difficulty. Work by Stanovich et al (1984) served as the basis for predictions of difficulty level for the tasks used here, along with a history of performance by children in other studies using these specific tasks (e.g. Nittrouer, 1999; Nittrouer et al, 2011; Nittrouer & Burton, 2005; Nittrouer & Miller, 1999). All three tasks have previously been used with children with hearing loss (Caldwell & Nittrouer, 2013; Nittrouer & Burton, 2002; Nittrouer et al, 2012).

Stimuli in all three phonological awareness tasks were presented in audiovisual format on a computer monitor, which differs from previous methods where stimuli were presented as audio-only signals. However, this method of presentation was chosen over audio-only to maximize the abilities of the children with hearing loss to understand the stimuli. The goal in these tasks was not to measure recognition, but rather to evaluate children's sensitivity to phonological (especially phonemic) structure in the speech signal. That meant that the availability of sensory evidence regarding the stimuli needed to be maximized. All answers were entered directly into the computer by the examiner. Practice was provided before each task. Percent correct scores were used as dependent variables for all three tasks. Consistent articulation errors, such as substitutions, were taken into consideration during scoring.

The first task, the *initial consonant choice* task, was viewed as the easiest. It consisted of 48 items and began with the child getting a target word to repeat. The child was given three opportunities to repeat this target word correctly. If the target was not repeated correctly within three attempts, testing advanced to the next trial and the missed trial was not included in the overall calculations of percent correct. Because of the audiovisual presentation format, this was a low-occurrence event. Following correct repetition of the target word, the child was presented with three more words and had to choose the one that had the same beginning sound as the target word. These items can be found in Supplementary Appendix A. (available in the online version of the journal. Please find this material with the direct link to the article at: http://informahealthcare.com/doi/abs/10.3109/14992027. 2013.792957).

The second task, the *final consonant choice* task, was considered to be intermediate in terms of difficulty for children of this age. This task consisted of 48 items, and was the same as the initial consonant choice task except that children had to choose the word that had the same ending sound as the target word. Items on this task can be found in Supplementary Appendix B. (available in the online version of the journal. Please find this material with the direct link to the article at: http://informahealthcare.com/doi/abs/10.3109/14992027.2013.792957).

The third task, the *phoneme deletion* task, could actually be considered a test of phonological processing, rather than of just awareness. The reason is that children needed to recognize phonemic structure in a non-word, manipulate that non-word structure so that one segment was removed, and then blend the remaining segments. The segment to be removed could occur anywhere within the word (e.g. Say *plig* without the 'l' sound.) The task consisted of 32 items, which are found in Supplementary Appendix C. (available in the online version of the journal. Please find this material with the direct link to the article at: http://informahealthcare.com/doi/abs/10.3109/14992027.2013.792957).

Speech recognition in quiet

The CID W-22 word lists were used to measure word recognition abilities in quiet. Presentation was via a loudspeaker at 0° azimuth. Children with NH and those with one CI heard just one list each, with lists randomized across children. Those with two HAs or CIs heard one of the 50-word lists presented with both devices turned on, and one list with each device turned on by itself. Children were videotaped as they repeated these words. At a later time, the videotapes were viewed and scored on a phoneme-by-phoneme basis, as well as on a whole-word basis. Consistent and obvious errors of articulation were not marked as wrong. All phonemes in a single word needed to be correct, with no intruding segments, for that word to be scored as correct. Both phoneme and whole word scores were used as dependent variables.

Binaural summation in quiet and in noise

For children with bilateral CIs, scores on the CID W-22 word lists obtained for individual ears were compared to results for both ears for the same listeners in order to get an estimate of binaural summation in quiet. The comparison of CID W-22 scores for both ears from the children with bilateral CIs and for one ear from the children with unilateral CIs also provided data regarding the magnitude of binaural summation in quiet. For an estimate of binaural summation in noise, phoneme and word recognition scores for the *same* condition were compared across children with one and two CIs.

Results

Before any analyses were performed, data were screened for normal distributions and homogeneity of variance across groups. In this report, precise values from statistical tests are reported when $p < .10$. Outcomes are reported simply as not significant (NS) when $p > .10$. Bonferroni corrections were used in computing p values for all multiple contrasts.

Reliability

Children tested at both SNRs

The first concern addressed was whether there was evidence of reliability and generalizability for the recognition scores obtained from children in the current study. Accordingly, a series of t tests was conducted examining whether the scores obtained from the ten children tested at both 0 and +3 dB in the *same* condition were similar to the scores obtained for children tested at only one of those SNRs. This was done for 0 and +3 dB separately, and for phoneme and word scores. The six children with HAs were compared to the other children with HAs, and the four children with CIs were compared to other children with CIs. None of the t tests was significant, so it was concluded that scores obtained at each SNR were similar to what would likely have been obtained in a repeated-measures design.

Recognition in quiet of children at each SNR

Recognition of the words used in the speech-in-noise task was examined when they were presented in quiet to see if groups tested at each SNR were comparable in terms of underlying recognition abilities. Figure 1 shows mean recognition probabilities (and SEs) for phonemes and whole words for presentation in quiet for children listening at just one SNR. Two-way ANOVAs were performed on these scores with SNR and listener group as between-subjects factors. Significant group effects were found for both phonemes, $F(2,97) = 44.96$, $p < .001$; and words, $F(2,97) = 68.11$, $p < .001$. However, neither the main effect of SNR nor the SNR × Group interaction was significant. Therefore, children within each group, tested at each SNR, were similar overall in terms of speech recognition in quiet. Post hoc t tests were performed. Significant differences were found in scores between children with NH and both children with HAs and those with CIs ($p < .001$), but no differences were found between children with HAs and CIs. Those findings indicate that children with NH performed better than children with hearing loss, but children with hearing loss performed similarly, regardless of whether they wore a HA or a CI.

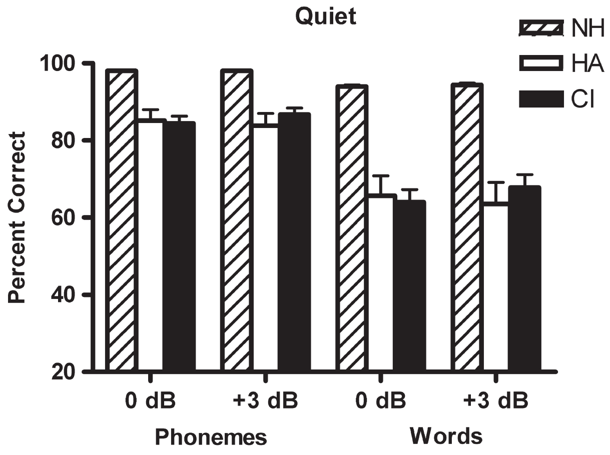

Figure 1. Mean phoneme and word recognition scores in quiet, for each group tested at each SNR. Error bars are standard errors of the means.

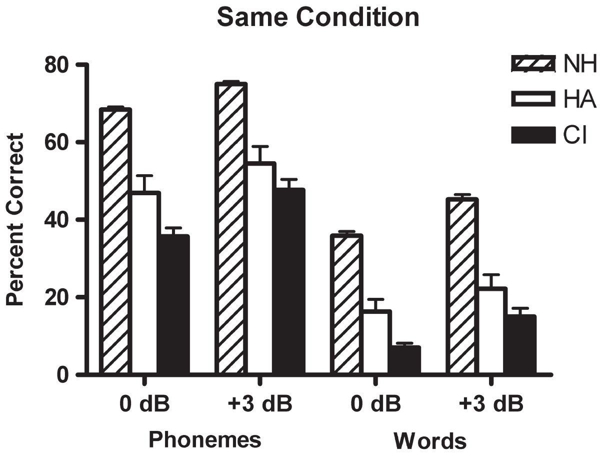

Figure 2. Mean phoneme and word recognition scores in noise for the same condition (i.e. when the speech and noise came from the front) for each group tested at each SNR. Error bars are standard errors of the means.

Caldwell and Nittrouer (2013) tried taking into account children's abilities to recognize speech in quiet by examining group differences for recognition in noise based on whether *absolute* or *conditional* scores were used. *Absolute* scores were those obtained without regard for a child's ability to recognize speech in quiet. *Conditional* scores were those obtained by measuring recognition in noise only for those phonemes and words which had been recognized correctly in quiet. No differences in overall outcomes were found in that study based on whether absolute or conditional scores were examined. Consequently, only absolute scores were examined further in the current study.

Speech-in-noise recognition

Figure 2 shows mean recognition probabilities (and SEs) for each group, at each SNR for the *same* condition. This condition matches that of most studies looking at speech-in-noise recognition. A mixed-effects regression analysis was performed on phoneme and word recognition scores shown in Figure 2, with SNR and listener group as fixed effects and subject as a random effect. This analysis is similar to a traditional ANOVA, but adjusts for repeated measures for some subjects in an otherwise between-subjects design. Looking first at phonemes, significant main effects were observed for both SNR, $F(1,62.53) = 57.03$, $p < .001$, and group, $F(2,109.78) = 107.79$, $p < .001$. Similar trends were observed for word recognition scores, with significant effects observed for SNR, $F(1,70.67) = 43.86$, $p < .001$, and group, $F(2,110.01) = 172.28$, $p < .001$. No significant SNR × Group interaction was found for either score. Post hoc *t* tests revealed significant differences between children with NH and both children with HAs and those with CIs ($p < .001$), for both phoneme and word recognition scores. For both kinds of scores, differences between children with HAs and CIs were also statistically significant ($p < .001$). Thus, unlike scores in quiet, children with CIs performed more poorly in noise than children with HAs.

Predictive value of language measures

Vocabulary scores and scores on the three phonological awareness tasks were examined as potential predictors of children's abilities to recognize speech in noise. First, *t* tests were done separately for each group to see if there was a difference in scores for children who heard the speech-in-noise stimuli at each SNR. None of these tests was significant, so scores were combined across SNR, for each group.

Means (and SDs) for each of these measures are shown in Table 2, and outcomes of one-way ANOVAs performed on each score are shown in Table 3. For all measures, significant group effects were observed. Looking at outcomes for the post hoc *t* tests it is seen that differences in scores between children with NH and those with CIs were significant for all measures. With just two exceptions, children with HAs did not obtain scores that were significantly different from either children with NH or those with CIs. This latter outcome supports the impression gleaned from Table 2 that children with HAs demonstrate vocabulary and phonological awareness skills intermediate to those of children with NH and those with CIs.

These language measures were next used in regression analyses to examine what might account for children's abilities to recognize speech in noise. In the first set of analyses, scores for children in each group were examined separately. Children with HAs were not included in these first analyses because there were not enough of them to provide adequate power. Two analyses were run, one each for phoneme and word recognition. SNR (0 and +3 dB) was entered in a first step to remove the variance in scores explained by differences in noise level. In a second step, the four language measures were entered in a stepwise method, with the criterion *F* to enter set at .05. Looking first at the analysis for phoneme recognition, it was found that SNR accounted for significant proportions of variance for children with NH, standardized $\beta = .690$, and for children with CIs, standardized $\beta = .457$. None of the language measures explained significant proportions of variance for either group. Similar trends were observed when word recognition scores were used as dependent variables: SNR explained significant proportions of variance for children with NH, standardized $\beta = .653$, and for children with CIs, standardized $\beta = .445$, but none of the language measures explained significant amounts of variance for either group. Thus, within groups, no language factors were observed to explain the variance in abilities to recognize speech in noise.

Table 2. Means and SDs for the expressive vocabulary measure and the three phonological awareness measures: Initial consonant choice, final consonant choice, and phoneme deletion. Cohen’s *d* values indicate effect sizes among groups.

	Group						*Cohen’s d*		
	NH 48		*HA* 18		*CI* 47		*NH vs. CI*	*NH vs. HA*	*HA vs. CI*
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*d*	*d*	*d*
Expressive vocabulary	110.4	(13.2)	102.3	(22.2)	95.9	(18.8)	0.89	0.44	0.31
Phonological awareness									
Initial consonant choice	87.3	(13.3)	78.8	(14.4)	64.8	(26.4)	1.08	0.61	0.66
Final consonant choice	69.7	(18.1)	50.6	(25.6)	36.9	(26.2)	1.46	0.86	0.53
Phoneme deletion	71.2	(21.7)	57.3	(29.9)	50.8	(31.4)	0.76	0.53	0.21

Expressive vocabulary is shown as standard scores derived from the test author’s normative sample. All three phonological awareness measures are given as percent correct.

Next, the potential predictive power of these language measures was examined when all children, including those with HAs, were included in the same regression analysis, for each SNR separately. Phoneme and word recognition were examined separately. All four predictor variables were used. Looking at phoneme recognition first, children’s scores on the final consonant choice task were found to explain a significant proportion of variance, at both 0 dB SNR, standardized $\beta = .541$, and $+3$ dB SNR, standardized $\beta = .593$. Similarly, scores on the final consonant choice task were found to explain significant proportions of variance in word recognition scores, again at both 0 dB SNR, standardized $\beta = .520$, and $+3$ dB SNR, standardized $\beta = .606$. Because the language measures were found to have no predictive power when listener groups were examined separately, but had significant power when all children were included, the outcomes suggest that group differences in sensitivity to phonological structure are strongly related to group differences in abilities to recognize speech in noise. To illustrate that point, the relationship between scores on the final consonant choice task and phoneme or word recognition in the *same* condition is shown in Figure 3. It is seen that group membership strongly explains both phonological awareness and speech-in-noise recognition, suggesting a relationship between these factors at the group level. That is, there was a concurrent improvement in performance for both speech-in-noise recognition and final consonant choice across groups, from children with CIs to those with HAs to those with NH.

Table 3. Results of statistical one-way ANOVAs performed on predictor variables. Post hoc comparisons among groups are shown on the right, and represent levels adjusted for multiple comparisons using Bonferroni corrections.

	F	*df*	*p*	*NH vs. CI*	*NH vs. HA*	*HA vs. CI*
Expressive vocabulary	8.22	2,110	< .001	< .001	NS	NS
Phonological awareness						
Initial consonant choice	15.06	2,109	< .001	< .001	NS	.039
Final consonant choice	24.35	2,110	< .001	< .001	.009	NS
Phoneme deletion	6.68	2,108	.002	.001	NS	NS

Binaural summation in quiet and noise

QUIET

The CID W-22 recognition scores were used to examine potential binaural summation effects for the children with CIs in this study. Table 1 listed word scores for the condition in which children were listening with both CIs turned on, if they used two CIs. Figure 4 shows mean recognition scores (and SEs) for children who used one CI and for those who used two CIs, when both were turned on, as well as for the conditions in which only the first or second CI was turned on. Several *t* tests were performed on these data. Looking at only the children with two CIs, *t* tests were done to compare performance with the first CI alone to performance with the two CIs turned on. This difference was significant, both for phonemes, $t(25) = 3.37$, $p = .002$, and words, $t(25) = 3.67$, $p = .001$. This outcome suggests that binaural summation in quiet was present. However, results of the two group *t* tests seem to belie that conclusion. When scores were compared for children with one and two CIs, when both were turned on, neither the *t* test for phonemes nor the one for words revealed a significant group effect. Thus, the children who routinely wore one CI performed as well as the children with two CIs when both devices were on. This outcome suggests that asking a child who typically uses two CIs to turn one off may underestimate what children in general are capable of doing with only one CI.

Of course, based on this study alone the possibility can not be ruled out that there was something different between the groups of children with one and two CIs. It may be that the children with two CIs were given those second devices because they were assessed as being at greater risk of language problems. However, because these children were all part of an ongoing longitudinal study (Nittrouer, 2010), it was possible to examine the language performance of these particular children with two CIs just prior to receiving the second device to see if they were performing differently from children with one CI who never received a second. When that was done, it was found that with one exception, all children with two CIs in this study were performing similarly to other children with one CI (i.e. better than one SD below the group mean) prior to receiving the second CI. Consequently, there is no reason to suspect that these children with two CIs would have performed differently from the children with one CI had they not received a second CI.

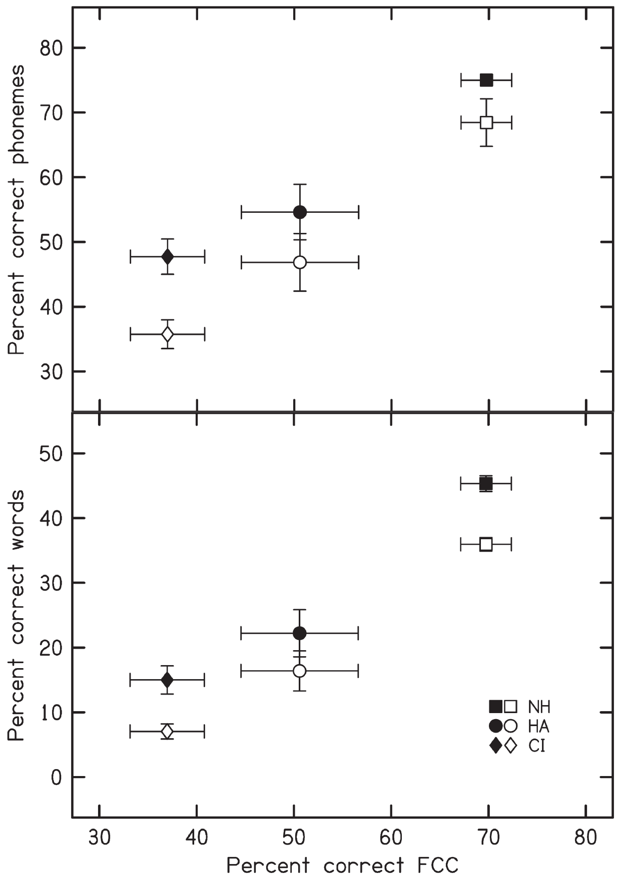

Figure 3. Mean percent correct scores on the final consonant choice task (*x* axis) and mean percent correct phoneme scores (top) and word scores (bottom) in noise when the speech and noise came from the front (*y* axis). Filled symbols are for the +3 dB SNR; open symbols are for 0 dB SNR. Error bars are standard errors of the means.

Noise

The possibility of binaural summation in noise being present for children with two CIs was examined by comparing recognition scores of children with one and two CIs for the *same* condition. Figure 5 shows these scores for phonemes and words. Two-group *t* tests were performed on these scores, and no group effects were observed. Thus, there was no evidence of binaural summation in noise for these children with two CIs.

Head shadow

SRM was examined next to evaluate the presence of head shadow. For this measure, children with CIs were divided into groups depending on whether they wore just one CI (N = 12), wore one CI with a HA on the contralateral ear (N = 6), or wore two CIs (N = 25). These numbers are smaller than those examined for speech-in-noise recognition because four children with CIs were tested at both SNRs, rather than in the *same* and *separate* conditions, so a metric of SRM could not be computed. Two-way ANOVAs were performed on SRM scores, with SNR and group as the main effects. SNR was not significant for either phonemes or words, so SRM was collapsed across the two SNRs. Group means (and SDs) are shown in Table 4.

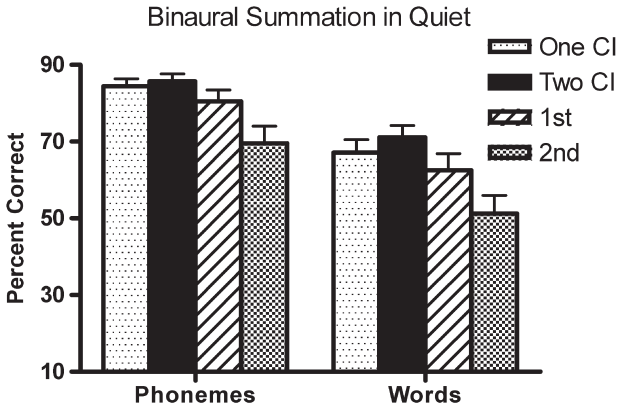

Figure 4. Mean percent correct phoneme and word scores for the CID W-22 lists presented in quiet, illustrating binaural summation by the comparison of scores for children with one CI and children with two CIs when they were using both (two CI), or using just their first or second CI. Error bars are standard errors of the means.

The ANOVAs did reveal significant differences among groups for phonemes, $F(4,93) = 5.39$, $p < .001$, as well as for words, $F(4,93) = 7.29$, $p < .001$, and these effects are apparent in Table 4. Post hoc *t* tests were performed. Children with HAs or with a bimodal configuration performed significantly more poorly than children with NH on both phoneme and word recognition. These results are similar to those of Ching et al (2010), revealing that children with HAs showed less of a spatial advantage than children with NH. The children with HAs in the current study also demonstrated SRM smaller in magnitude than that observed for children with CIs (either one or two). Where children with one or two CIs are concerned, differences in their scores and those of children with NH were not statistically significant for phonemes; for words, only children with two CIs performed more poorly than children with NH. The differences in SRM for children with one and two CIs were not significantly different, even though children with two CIs appear to show slightly smaller SRM than those with one CI.

The possibility was considered that a reason for this slight decrement in SRM for children with two CIs, compared to those with

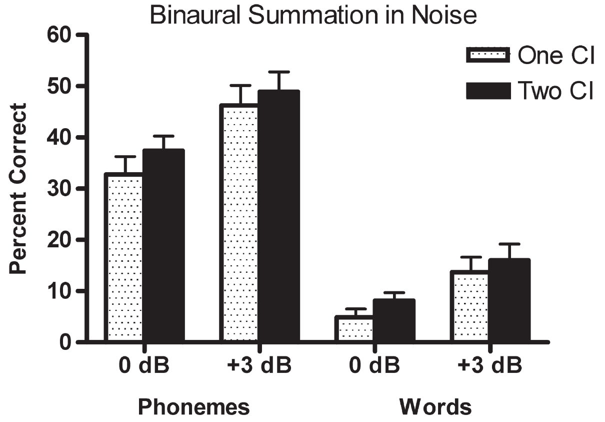

Figure 5. Mean percent correct phoneme and word scores for CVC words presented in noise when both speech and noise came from the front, illustrating binaural summation by the comparison of scores for children with one CI and children with two CIs. Error bars are standard errors of the means.

Table 4. Means and SDs for each group for spatial release from masking (SRM), defined as the differences in recognition for the *same* and *separate* listening conditions.

	Group									
	NH 48		*HA* 12		*CI-HA* 6		*one CI* 12		*two CIs* 25	
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*
Phonemes	9.4	(4.8)	3.4	(6.3)	−0.2	(7.4)	11.6	(6.4)	8.3	(7.3)
Words	15.5	(8.5)	5.6	(7.8)	0.7	(6.2)	10.7	(7.2)	8.4	(7.6)

one CI, might have involved the assumption that the side with the second CI would always be the weaker side in terms of functioning. If in fact the side that received the second CI was stronger in terms of word recognition, placing the noise on that side could have interfered with recognition in the *separate* condition. In order to investigate that possibility, children who showed more than 10% better word recognition for the CID W-22 lists with their second CI were identified. There were only three of these children. One of them did indeed show interference in the *separate* condition, with 9% fewer phonemes and 6% fewer words recognized correctly than in the *same* condition. One of the other children showed no change from the *same* condition, and the third child showed the predicted SRM, with improvements in both phoneme and word recognition in the *separate* condition. Consequently, the slight (and non-significant) diminishment in SRM observed for children with two CIs compared to those with one CI can not be explained by any children inadvertently having the noise placed on the side with better functioning.

Comparison to other studies

Although changes in percent correct recognition were used as dependent measures in this study instead of changes in speech reception thresholds, a comparison between outcomes for this study and earlier ones examining SRM can nonetheless be made. First, the difference of 15.5 percent correct word recognition for the children with NH corresponds to the difference of 10 to 18 percent correct reported by others for adults with CIs (e.g. Müller et al, 2002; Peters et al, 2007). Furthermore, it has been observed that a difference of 10 percentage points in word recognition is typically realized for every 3 dB change in SNR for listeners with NH (e.g. Nittrouer & Boothroyd, 1990). This trend is apparent in Figure 2 where mean word recognition for children with NH is just 10 percentage points higher at +3 dB than at 0 dB SNR (46.3% vs. 35.9% correct). For these same children, SRM was realized as a 15.5 percentage point improvement in word recognition, which corresponds to an effective improvement of roughly 4.5 dB SNR. That is comparable to the 3 to 5 dB improvement in speech reception threshold typically observed for SRM (e.g. Culling et al, 2012; Misurelli & Litovsky, 2012). This provides another indication that the effect sizes observed in this study were comparable to those of other studies.

Explaining variance

Next, several analyses were performed to try to identify the source of the SRM observed here. First, regression analyses were performed to determine if SRM varied as a function of recognition probabilities for phonemes or words in the *same* condition. The question addressed was whether listeners' general abilities to recognize speech in noise explained any of the variance in their abilities to take advantage of the spatial separation of signal and noise. These analyses were done only for children with NH and those with two CIs because samples were too small for the other groups.

In these regression analyses, SNR (0 and +3 dB) was entered first to remove any portion of the variance associated it. Although SRM, the dependent variable in these analyses, was not affected by SNR, speech recognition in the *same* condition, the predictor variable, was affected by SNR. Thus, it was reasonable to use SNR as a first predictor variable. In a second step, recognition scores in the *same* condition were entered as predictor variables. Results of these regression analyses showed that SRM for children with two CIs was not associated with their recognition scores in the *same* condition. However, for children with NH, an effect of speech recognition was observed. Using SRM for phoneme scores, a standardized β of −.605 was obtained when phoneme recognition in the *same* condition served as the predictor variable. Where SRM for word scores is concerned, a standardized β of −.518 was obtained when word recognition in the *same* condition was the predictor measure. Consequently, better speech recognition in the *same* condition was associated with smaller benefits of spatial separation between signal and noise for these children with NH.

Next, potential relationships between language constructs and SRM were examined, again for children with NH, and for those children with two CIs. The one vocabulary and three phonological awareness measures already described were used in regression analyses, with SRM for phonemes and for words as dependent variables. None of these language measures was found to explain any significant proportion of variance in SRM (phonemes or words) for either group of children. Thus, language abilities did not account for the effect, as had been predicted to be the situation.

Finally, the age of receiving a first CI was investigated for children with one or two CIs, and the age of receiving a second CI was investigated for children with two CIs for potential effects on SRM using regression analysis. Neither was found to have a significant effect.

Exploring differences across devices

For children who wore HAs or CIs, the data reported here were collected with those devices on their customary settings. Nonetheless, in order to examine whether specific characteristics of the devices influenced outcomes, *t* tests were performed on phoneme and word recognition scores of children with CIs from Cochlear Corporation and from Advanced Bionics in quiet, in the *same* condition, and in the *separate* condition. Data from children with Med-El devices were not included because there were only two children in that group. None of the results from these comparisons was significant. These analyses do not completely eliminate the possibility that specifics such as microphone settings might be affecting children's abilities to recognize speech in noise. However, they do suggest that whatever variability is due to those factors, it likely does not account for any group effects that were observed.

Discussion

The study reported here was undertaken to examine potential differences among groups of children, with and without hearing loss, in their abilities to recognize speech under noisy conditions, and to explore factors that influence those speech-in-noise recognition abilities. This topic is important when it comes to how we intervene for children with hearing loss because noisy environments are situations they commonly encounter. And not only do children need to listen in noisy settings, they are required to learn new information and novel vocabulary items under conditions of noise in the classroom. Consequently, understanding the factors influencing that performance could help in the design of better treatment options.

In the current study, phoneme and word recognition was measured in two conditions: with the speech and noise both coming from a speaker in front of the child, and with the noise presented separately from one side. Noise was presented at two SNRs in a between-groups design. Measures of vocabulary knowledge and phonological awareness were also obtained and used as predictor variables in regression analyses to see if these language-related abilities can account for any variability in speech-in-noise recognition. The finding of a positive relationship between any of these language skills and speech-in-noise recognition would suggest that early and strong language intervention could help facilitate children's abilities to recognize speech in noise. This experimental design was based on the theoretical perspective that speech recognition is guided by both sensory evidence and the listener's ability to formulate and test hypotheses about the speaker's message based on knowledge of real-world events and language structures.

Binaural summation was also assessed for children with CIs, in both quiet and noise, by comparing speech recognition scores across several conditions. This auditory mechanism depends on children with hearing loss having two prostheses. Thus, if substantial binaural summation were to be observed, it would provide strong support for bilateral implantation in children with severe-to-profound hearing loss.

Finally, the head shadow effect was examined using the SRM paradigm of comparing speech recognition when the noise was co-located with the speech, and when it was off to one side. Although all listeners should be able to benefit from the head shadow effect—at least under some conditions—children with CIs would presumably need two devices in order to take advantage of the effect optimally.

Language abilities and speech-in-noise recognition

The outcomes of regression analyses failed to show any significant effects of language abilities (vocabulary knowledge or sensitivity to phonological structure) on speech-in-noise recognition within separate groups of children. However, when this potential relationship was examined across groups, a strong effect was found. Standardized β coefficients on the order of .5 to .6 were found when scores for the final consonant choice task were used as predictor variables for speech-in-noise recognition in the *same* condition. These results suggest that roughly 30% of the variance in those speech recognition scores can be explained by children's phonological awareness. Although significant regression coefficients were not found for the other two measures of phonological awareness, that outcome was not entirely unpredicted. Three measures tapping into children's sensitivity to phonological structure were used in this experiment, precisely because the sensitivity of these tasks to detect variability among children can differ across tasks with age. In fact, it had been predicted based on earlier studies (e.g. Stanovich et al, 1984) that the final consonant choice task might be the most sensitive of the three tasks used at this age, and that was just what was found. Nonetheless, it is always important to include a range of such tasks so that this variability is not missed.

The combined findings of no significant variability explained within groups, but a strong effect observed when groups are combined, indicates that most of the relationship between factors is at the group level, and that was illustrated in Figure 3. This pattern of results suggests that performance on both measures is strongly explained by group membership, such that performance on one measure may be highly constrained by abilities on the other measure. In this case it is specifically suggested that children with hearing loss have poorer sensitivity to phonological structure in the speech signal than children with NH, and children with CIs have poorer sensitivity than those who use HAs. Although the relationship is likely not completely unidirectional, improvements in phonological awareness would probably improve the abilities of children with hearing loss to recognize speech in noise.

Binaural summation

When speech recognition scores in quiet of children with two CIs are reviewed on their own, it appears as if there was evidence of binaural summation because performance was better with both CIs than with either one alone for these children. However, when speech recognition scores of children with two CIs, either in quiet or in noise, are compared to scores of children with one CI, results suggest that these children do not benefit from having two CIs. Rather, it appears that these children have become accustomed to having two devices, and when one is removed they are hindered in their recognition abilities.

Head shadow

Generally speaking, SRM was found to be of similar magnitude for the children with NH and those with CIs, regardless of whether they wore one or two CIs. This outcome suggests that children with CIs can benefit from the head shadow effect. In this experiment, children were only tested with the noise on the side with no CI or of the second CI. It is likely that the children with two CIs would benefit from having the noise on the other side of the head, as well, but children with just one CI would not. In real-world environments, this increased opportunity to benefit from head shadow could offer an advantage to children with two CIs.

Children with HAs showed head shadow effects of reduced magnitude, compared to children with NH or CIs. That finding matches what Ching et al (2011) observed, although those investigators found no SRM at all for children with HAs. In the current study, a small amount, on average, was measured. Ching et al did not offer a possible reason for the lack of effect, and one can not be proffered from the current data.

The six children using a CI and HA together showed no SRM at all, on average. Again, based on the data strictly from the current study, an explanation can not be offered.

Clinical significance

The current study emphasizes the importance of considering how children function in real-world settings when interventions are designed. Children with hearing loss are tasked with the chore of acquiring language, while they are participating in academic activities. It is not enough to focus only on ways to improve the acoustic environment; their language abilities also must be considered.

Figure 6 illustrates how language and phonological knowledge might be related to children's abilities to recover the sensory evidence needed for speech recognition. Included in this diagram is the term *experience*, because sufficient amounts of appropriate

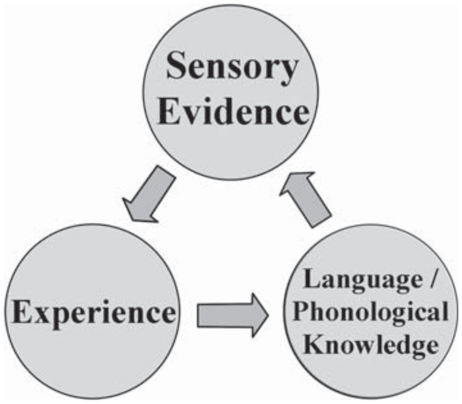

Figure 6. Diagram of the inter-relationship of factors affecting speech-in-noise recognition.

language experience are needed in order for children to acquire the kinds of language and phonological knowledge that should be brought to bear on speech recognition (Nittrouer & Burton, 2005). Although only vocabulary was considered under the rubric of language knowledge in the current study, that largely followed from the fact that words served as stimuli. If sentences had been used, it would have been clear that other sorts of language knowledge, such as syntax, are typically brought to the task of speech recognition, as well. In general, when designing intervention for children with hearing loss it is important to consider all parts of this triangle: (1) Effective noise levels in the environment should be minimized as much as possible in order to enhance the sensory evidence available to the child. (2) Experiences that promote acquisition of language structures and functions overall should be maximized. (3) For children with hearing loss, who typically have diminished opportunity for these experiences, direct instruction should be provided to facilitate the learning of the kinds of language and phonological structures they need to know.

Conclusions

The study reported here investigated speech-in-noise recognition for children with hearing loss, compared abilities of those children to the abilities of children with normal hearing, and examined mechanisms that might explain speech-in-noise recognition for children with hearing loss. Evidence was found to suggest that language abilities (in particular, sensitivity to phonological structure), and auditory mechanisms (in particular, spatial separation of speech and noise) can help explain recognition scores for children with hearing loss. These outcomes suggest that intervention needs to take a multi-pronged approach, focusing on both language skills and auditory mechanisms.

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Supplementary material available online

Supplementary Appendix A to C available online at http://informahealthcare.com/doi/abs/10.3109/14992027.2013.792957