Purpose: To determine the effect of hearing loss (HL) on children’s performance for an auditory task under demanding listening conditions and to determine the effect of digital noise reduction (DNR) on that performance.

Method: Fifty children with normal hearing (NH) and 30 children with HL (8–12 years of age) categorized words in the presence of auditory or visual competitors, or both. Stimuli were presented at 50 dB SPL at a 0-dB signal-to-noise ratio. Children with HL were fitted with behind-the-ear hearing aids that had DNR technology. When DNR was activated, output decreased 4 dB, and signal-to-noise ratio increased 2 dB.

Results: Significant main effects of group and age were observed. Performance for both groups decreased in noise, and the performance of the children with HL decreased further with the addition of the visual task. However, performance was unaffected by DNR. For the children with HL, stimulus audibility and communication skills contributed significantly to performance, whereas their history of hearing aid use did not.

Conclusions: For the children with HL, tasks unrelated to hearing interfered with their ability to participate in the auditory task. Consistent with previous studies, performance in noise was unaffected by DNR.

Key Words: children, hearing aids, hearing loss, digital noise reduction, perception
of the signal detection, analysis, decision rules, and execution of DNR in commercially available hearing aids. Briefly, when noise is detected at the input of the hearing aid, alterations to the output occur over the entire frequency spectrum or in selected frequency bands. These alterations are unique to each make and model of hearing aid and can include both increases and decreases in output (Hoetink, Koroszy, & Dreschler, 2009). DNR algorithms are most effective (with regard to the detection of noise) in the presence of steady-state noises because they are more easily differentiated from a speech signal (Bentler & Chiou, 2006; Ricketts & Hornsby, 2005).

Unfortunately, studies examining the benefits of DNR in adults have generally revealed equivocal results. Differences in overall speech perception in noise or the change in speech reception threshold with and without DNR are small and often not significant (Bentler, Wu, Kettel, & Hurtig, 2008; Nordrum, Erler, Garstecki, & Dhar, 2006; Peeters, Kuk, Lau, & Keenan, 2009; Ricketts & Hornsby, 2005). Similar results were reported in the only study conducted in children to date. Stelmachowicz et al. (2010) examined speech perception in 16 children with mild to moderately severe HL; the children ranged in age from 5 to 10 years. Each child was fitted with Starkey Destiny 1200 behind-the-ear hearing aids modified to deactivate the parameters that automatically control the noise reduction feature. The hearing aids were programmed for each child to desired sensation level targets (Scollie et al., 2005; Seewald, Moodie, Scollie, & Bagatto, 2005) using manufacturer software and then were verified using real-ear measures. The effects of age and DNR (on vs. off) on the perception of nonsense syllables, monosyllabic words, and sentences were examined. The stimuli were presented at 65 dB SPL in speech-shaped noise at 0-, 5-, and 10-dB signal-to-noise ratios (SNRs). Main effects of age and stimulus type were found; however, no effect of noise reduction was observed. Stelmachowicz et al. concluded that the negligible effects of DNR reported in adults occur in children as well. They also noted that although no improvements in performance were found, DNR was not detrimental to the children’s speech recognition.

Assuming that the DNR used in these studies substantially altered the amplified signal, the results suggest that perhaps the effects of this technology on performance are not apparent using traditional measures of speech perception. It is well established that the redundancy of speech makes it robust against distortion due to signal processing or hearing loss. For example, Walden, Prosek, and Worthington (1975) reported similarly good speech perception in quiet for adults having a wide range of hearing losses. Remez, Pardo, Piorkowski, and Rubin (2001) reported good perception of severely distorted sentences in adults with NH after minimal training. Finally, cochlear implant users, who represent the combined effects of HL and signal distortion, are able to use the limited signal provided by the implant after a period of use (Beadle et al., 2005). Given the robust nature of speech perception, it is no surprise that the relatively small changes to the speech signal via DNR yield equivocal results. Even so, hearing aid users have reported a significant preference for DNR, suggesting that they perceive some benefit from this type of signal processing (see Bentler et al., 2008).

Perhaps the benefits of DNR may be apparent for tasks that depend more heavily on the additional acoustic information provided by the improvement in SNR. If so, then this technology may be particularly important to children as they engage in complex listening situations in the classroom. In addition to noise, children in the classroom must coordinate simultaneous inputs that include both auditory and visual stimuli. They are often required to respond to congruent, and sometimes conflicting, information via multiple modalities. Whereas noise competes with the speech signal by reducing the availability of redundant acoustic elements, competing tasks may reduce the cognitive resources directed toward comprehension of the signal and the message that it contains. Even small improvements in SNR may increase the acoustic information contained in the speech signal and reduce the cognitive resources needed to process the signal.

Recently, attention has been directed toward the effects of multitasking on performance for auditory tasks in adults and children (Choi, Lotto, Lewis, Hoover, & Stelmachowicz, 2008; Downs, 1982; Hicks & Tharpe, 2002; McFadden & Pittman, 2008; Rakerd, Seitz, & Whearty, 1996; Rossiter, Stevens, & Walker, 2006; Sarampalis, Kalluri, Edwards, & Hafter, 2009; Stelmachowicz, Lewis, Choi, & Hoover, 2007). This work involves dual-task paradigms in which the children are asked to attend to an auditory task and a task unrelated to listening at the same time. To date, three studies of dual-task performance have been conducted in children with HL. Hicks and Tharpe (2002) asked children to participate in a standard clinical word recognition test while monitoring a light. The children were instructed to push a button during the test when the light turned on. Their performance on the word recognition test and their reaction time to the light were examined as a function of SNR. In a study by McFadden and Pittman (2008), children indicated the category to which common words belonged (e.g., person, food, animal) while playing a series of dot-to-dot games. Their performance for the word categorization task and the speed with which they proceeded through the dot-to-dot games was also examined as a function of SNR. Finally, Stelmachowicz et al. (2007) asked children to remember five digits while participating in a word recognition test. After the test, they were...
asked to recall the five digits. Performance for both tasks was evaluated as a function of the bandwidth of the acoustic signal.

For each of these studies, the children’s performance for the auditory task decreased as the SNR or bandwidth of the signal decreased, as expected. Performance for the nonauditory task (reaction time, digit recall) was also expected to decrease but instead remained unchanged in each listening condition. These results suggest that the increased difficulty of the auditory tasks in these studies did not affect children’s performance for nonauditory tasks. Presently, the converse (effect of nonauditory tasks on performance for auditory tasks) is unknown.

The purpose of the present study was twofold. First, the effect of progressively demanding listening conditions on performance for an auditory task was examined for children with NH and for children with HL. Second, the effect of DNR technology on the performance of children with HL was also examined. For this study, children were asked to perform an auditory task (categorizing common words) while the complexity of the task was increased through the addition of auditory and visual competitors (noise and dot-to-dot games). It was hypothesized that, compared with the children with NH, the children with HL would demonstrate poorer performance on the auditory task as the overall demands of the task increased. It was also hypothesized that the use of DNR would improve the performance of the children with HL.

Method

Participants

Two groups of children were recruited for this study. The control group consisted of 52 children with NH who were between the ages of 8 and 12 years. Two children were excluded due to procedural errors during testing, resulting in a total of 50 children. Equal numbers of children (10) were recruited at each year of age (8, 9, 10, 11, and 12 years) as well as approximately equal numbers of boys and girls (26 boys, 24 girls). On the day of testing, all children had hearing thresholds ≤ 20 dB HL bilaterally at octave frequencies between 0.25 and 8 kHz, with the exception of one child having a threshold of 25 dB HL at 0.25 kHz in one ear. Tympanometric measures were also obtained at that time and were within normal limits.

The experimental group consisted of 34 children with mild to moderately severe HL who were between the ages of 8 and 12 years. Children for whom monaural or binaural amplification was appropriate were enrolled in the study. Four children were excluded for the following reasons: The first child had a mild HL that did not require amplification; the second child had bilateral, severe HL that was beyond the range of the amplification provided in the study; the third child had malformed pinna that could not accommodate the hearing aid; and the last child failed to cooperate fully during testing. After exclusion of these children, a total of 30 children remained. There were roughly equal numbers of children at each year of age (seven 8-year-olds, nine 9-year-olds, three 10-year-olds, seven 11-year-olds, and six 12-year-olds) and approximately equal numbers of boys and girls (14 boys, 16 girls).

On the day of testing, the children with HL received a full diagnostic hearing evaluation that included otoscopy, acoustic immittance, and pure-tone air and bone conduction audiometry. Children for whom hearing thresholds were unchanged since their last hearing evaluation did not receive bone conduction audiometry. Figure 1 shows the hearing thresholds of each child as a function of frequency for the right and left ears in the upper and lower panels, respectively. Average hearing levels (±1 SD)

Figure 1. Hearing threshold levels (in dB HL) as a function of frequency (kHz) for the right (upper panel) and left (lower panel) ears of the children with hearing loss (dashed lines). The solid lines represent the average hearing thresholds in each ear (filled circles).
are shown in each panel (filled symbols). Note that three children had unilateral HLs (thresholds \( \leq 25\) dB HL at each frequency in the better ear), and two children had monaural hearing (profound HL in the right ear and moderate HL in the left). Monaural amplification was provided to each of these children, whereas all other children received binaural amplification. Acoustic immittance measures were also obtained for each child. Four children had permanent conductive HLs (air-bone gap \( \geq 25\) dB), three children had mixed HLs, and the remaining 23 children had sensorineural HLs. All of the children (NH and HL) were enrolled in the grade level appropriate for their age in public elementary school or through home schooling.

Average age of identification was 3.1 years, with a range of 0 (birth) to 6 years of age. All but one of the children wore personal hearing aids. Average age of amplification was 4.0 years, ranging from 6 months to 8 years of age. Length of amplification for these children ranged from 18 months to 11 years for an average of 5.5 years. The one child who did not use amplification had been diagnosed several years earlier with enlarged vestibular aqueduct syndrome and was evaluated regularly for several years. He was scheduled for a hearing aid consultation shortly after the date of testing. Finally, only one of the children had experience with DNR. The DNR feature was enabled in a dedicated program that could be accessed by the child as necessary.

Prior to testing, the receptive vocabulary of each child was determined using the Peabody Picture Vocabulary Test (PPVT)—Form IIIB (Dunn & Dunn, 2006). Measures of receptive vocabulary (raw score, standard score, vocabulary age) provide an estimate of the long-term effects of HL on children’s ability to hear and learn new words. Previous research has shown that, on average, the vocabulary age of children with HL is \( \geq 2\) years behind that of children with NH (Pittman, 2008). Additionally, significant correlations have been found between children’s performance on tests of receptive vocabulary and on tests of nonverbal intelligence (Moeller, 2000) and cognition (Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998).

**Amplification**

During the test session, the children were fitted with Siemens Explorer 500 behind-the-ear hearing aids. This hearing aid was chosen because it is designed for children, the quality of the amplified signal is good, and all advanced features can be manually disabled. The hearing aids were fitted to each child using their personal earmolds. Four children did not have their personal earmolds with them at the time of testing, so temporary molds (Comply) were used. The hearing aid manufacturer’s software was used to program and fine tune the devices on the basis of the simulated real-ear measures (SREM) provided by the Audioscan Verifit (VF-1) hearing aid test system. Individual real-ear-to-coupler differences were obtained and entered into the Verifit along with the child’s hearing thresholds. The output of the hearing aid was adjusted to within \( \pm 5\) dB of the targets prescribed for average (65 dB SPL) and soft (50 dB SPL) conversational speech by the DSL ([i/o] 5.0) fitting algorithm (Scollie et al., 2005; Seewald et al., 2005). Real-ear measures were obtained for the first five children to confirm that the SREM procedure provided an accurate estimate of real-ear amplification. Thereafter, all hearing aids were programmed using the SREM function only to maximize the time allotted for testing (\( \leq 2\) hr).

The hearing aids were set to have two active programs. In Program 1, all advanced signal processing features offered in the hearing aid were disabled, including Speech and Noise Management (DNR), Sound Smoothing (reduction of impulse noise), eWind Screen (reduction of wind noise), and Feedback Blocker (feedback management). In Program 2, all advanced signal processing features remained disabled with the exception of the Speech and Noise Management, which was set to maximum. The Speech-in-Noise-Only option, which activates the noise reduction feature only when speech is present in noise, was disabled. This adjustment caused the hearing aid to engage the DNR feature any time noise was detected, regardless of the presence of speech. Also, the frequency response and compression parameters were equated across the two programs.

The user controls for this hearing aid included a program button and a volume control. The hearing aid was set to indicate when it was in Program 1 or Program 2 by generating one or two beeps, respectively. The beeps were set to occur at a frequency and output level that was audible to the child. The range of the volume control was set to zero so that the output of the hearing aid could be closely controlled. This caused the volume control to function as an on/off switch only.

Prior to testing, each child was familiarized with the hearing aids and was trained to select the required program when directed to do so. Because all but one of the children were experienced hearing aid users, they required minimal orientation to the device. This experience allowed them to focus their attention on the program button, which was new to many of them. The children were required to indicate the number of beeps they heard when the hearing aids were changed from one program to the other. The Siemens hearing aid includes a feature that synchronizes binaural aids (E2E Wireless 2.0) so that changing the program in one hearing aid also changes the program in the other. A few children were unable to count the correct number of beeps generated by the hearing aid (e.g., “three!”; “six!”). For these
children, the examiner adjusted the hearing aids during testing.

Auditory Task

Stimuli were three sets of 50 words each drawn from three categories (people, food, animals) for a total of 150 words. All the words were nouns selected from an extensive list of words spoken by first graders (Moe, Hopkins, & Rush, 1982) and were used in a previous study examining divided attention in children (McFadden & Pittman, 2008). All of the words were nouns in the singular form that varied in length from one to four syllables. The 150 words were sorted into five lists of 30 words each and contained 10 words from each category (see the Appendix). The words within each list were randomized, and the lists were counterbalanced across experimental conditions to distribute any affects of lexical competition that may occur.

The stimuli were recorded at a sampling rate of 22.05 kHz using a microphone with a flat frequency response to 10 kHz. The words were spoken by a female talker having a standard American English dialect. The stimuli were digitized and edited using Adobe Audition (Version 1.5). Individual audio files of each word were created and equated for root-mean-square (RMS) level. A period of silence was added at the beginning and end of each word so that the duration of each file was 2,000 ms. The stimuli were presented in quiet or mixed with a steady-state broadband noise with a flat frequency spectrum at an overall level of 50 dB SPL and an SNR of 0 dB. In a sound-treated room, 50 dB SPL is equivalent to average conversational speech. All auditory stimuli were delivered through a single loudspeaker housed in a sound-treated booth meeting American National Standards Institute (ANSI) specifications for ambient noise (ANSI, 1990). Due to the rapid onset of DNR in the Siemens hearing aid (~2 s), it was not necessary to present the noise for any length of time prior to testing to allow the DNR to activate. Equipment calibration was performed at the beginning of each test session.

Effective SNR

The effective SNR with and without DNR was determined for each child using an inversion technique described by Souza, Jenstad, and Boike (2006). With this technique, the speech and noise components of an audio file are separated to determine the relative level of each before and after amplification. The first file contains the speech and noise stimuli as they are used in the study (original speech + original noise). In the second file, the noise is inverted and mixed with the original speech (original speech + inverted noise). In the third file, the speech is inverted and mixed with the original noise (inverted speech + original noise). When the first file is mixed with (added to) one of the other two files, the inverted and original component is cancelled, leaving the other component intact. It is necessary to reduce the amplitude of the remaining component by 6 dB as it is doubled when the files are mixed together. The effects of amplification may then be determined.

The output of the hearing aid was captured in a hearing aid test chamber (Verifit) via a 2-cm³ coupler (Frye, HA-2) with an adaptor appropriate for a probe microphone (Etymotic, ER-7C). The output of the probe microphone was routed to the input of a SoundDelux soundcard in a desktop computer. Custom software was used to play the stimuli and record the output simultaneously. The recorded audio files were imported to an audio editor program (Adobe Audition, Version 1.5), and the first file (original speech + original noise) was mixed with each of the other two files (original speech + inverted noise, inverted speech + original noise). The overall level of the long-term average spectrum of the isolated speech and noise component was then calculated. Figure 2 shows an example of the amplified stimuli in noise without DNR (upper panel) and in noise with the DNR feature activated (lower panel). The overall

Figure 2. Waveforms showing five words embedded in broadband noise at 0 dB SNR. The upper panel shows the stimuli amplified without DNR, and the lower panel shows the same stimuli amplified with DNR.
level of the signal decreased 3.91 dB when the DNR feature was engaged, with SNRs of \(-0.03\) and \(-1.97\) dB with and without noise reduction, respectively. This resulted in an average SNR improvement of 1.94 dB. The onset of DNR was approximately 2 s (not shown).

**Speech Intelligibility**

The same audio files were used to calculate the speech intelligibility index (SII) of the stimuli as they were presented to each child. SII values were calculated from the amplified stimuli in the quiet, noise, and noise reduction conditions according to ANSI (1997) standards using the following formula:

\[
SII = \frac{1}{30} \sum_{i=1}^{18} \left| SNR_i + 15 \right| W_i, \quad (1)
\]

where \(i\) is the center frequency of each third-octave band (TOB) and \(SNR_i\) is the SNR within the \(i\)th TOB plus 15 dB, which represents the peak level of speech across frequency. SNR was calculated as the RMS level of the speech (+15 dB) relative to the RMS level of the noise within each band. All measures were referenced to the same 2-cm\(^3\) coupler. These values were multiplied by the importance of each band \((W)\) and summed. The frequency importance function for NU-6 words provided in the ANSI standard was used. The SNR was restricted to a range of 0–30 dB by the 1/30 multiplier. The SII values for the left and right ears of each child were averaged to provide a single estimate of binaural speech intelligibility.

**Complex Visual Task**

Dot-to-dot games were used as a competing task that did not require auditory input. Although this task involves visual, motor, mathematic, and linguistic skills, it is referred to as a complex visual task hereafter. Booklets containing 25 dot-to-dot games were created for this study. The games were adapted from dot-to-dot games found on children’s websites or scanned from children’s books. The original numbers on each game were replaced digitally with numbers having the same font size (18 pt.) and progressing in increments of 3 (e.g., 3, 6, 9, 12). Only the dots and numbers were shown in each game, and all other lines and drawings were removed to reduce shape recognition. This approach required the child to count in increments of three to complete each game rather than use the additional lines as a guide. The completed game was displayed on the back of each page. An example of one dot-to-dot game and the completed picture are shown in Figure 3. The games were printed on light blue paper to prevent the image on the back of the page from being visible to the child during the tests. The number of dots contained in each puzzle ranged from as few as 20 to as many as 47. A box was placed around the number 3 in each game to reduce the time taken for the child to find the starting point. The games were assembled in a booklet having three sections that contained (a) one practice game, (b) three games for a baseline measure, and (c) 21 games for the experimental conditions (up to seven games for each condition). The games were systematically rotated through the sections of each booklet so that each game would occur in each section an equal number of times.

*Figure 3.* Example of a dot-to-dot game. The left panel shows the game as it was presented to the child with only the dots and their numbers. The right panel shows the finished game with additional art but no numbers. The completed picture was displayed on the back of the page of the corresponding dot-to-dot game.
Procedure

For the auditory task, one list of 30 words each was presented in isolation as well as with the visual and/or noise competitors. The children were instructed to listen to each word and verbally indicate the category to which the word belonged (e.g., “person,” “food,” “animal”). If they could not assign a category, then they were encouraged to guess or to say “I don’t know.” No feedback regarding accuracy was provided. Illustrations of each response category were provided as a reference during testing. Each child was seated at a small table in a sound-treated room approximately 1 meter from a loudspeaker at 0° azimuth. The auditory stimuli were presented through the loudspeaker using custom software on a standard desktop computer. Although the temporal parameters of the experiment were controlled by the laboratory software, the children’s responses were self-paced. That is, a stimulus file was presented (2,000-ms duration), the children responded at their own pace (15-s response window), the examiner entered the response immediately, and the next stimulus was presented after a short delay (1,000 ms). The examiner entered the children’s responses on a computer monitor that displayed buttons with labels for each category as well as a button labeled I don’t know.

Each child was asked to perform the auditory task under four listening conditions: (a) auditory task alone, (b) auditory task + visual task, (c) auditory task + noise, and (d) auditory task + visual task + noise. The children with HL participated in an additional condition in which the auditory task + visual task + noise condition was performed with DNR. The order of listening conditions was randomized for each child.

For the complex visual task, the children were given the booklet of dot-to-dot games and instructed when to play the games. To establish baseline performance and to familiarize the children with the task, the speed with which they completed three games was timed in the absence of the auditory task or noise competitor. The children then played the games in the presence of the auditory task and noise as instructed. They were not told to direct their attention to one task or the other. Previous research has shown that children may acknowledge instructions to give priority to one task over another but show no signs of actually doing so (Choi et al., 2008). Performance on the dot-to-dot games was calculated as the number of dots correctly completed per minute. For a dot to be counted as correct, the previous and preceding dots had to be sequenced correctly. One dot was deducted from the total number of completed dots each time a child did not follow the correct numerical sequence. The total number of dots was then divided by the time required to complete the categorization task (approximately 3–5 min). Generally, the children were able to complete two to five dot-to-dot games in each condition.

Results

Receptive Vocabulary

Figure 4 shows the vocabulary age calculated from the PPVT as a function of chronological age for the children with NH (filled symbols) and the children with HL (open symbols). Although the average chronological age of the children in each group differed by only 1 month (NH 10;6 [years;months], HL 10;5), the groups differed in vocabulary age by 3 years (NH 13;4, HL 10;0). The difference was largely due to six children with NH who scored more than two standard deviations above the norm and six children with HL who score more than one standard deviation below the norm. These results are consistent with several studies showing a ≥ 2-year difference in receptive vocabulary between children with NH and children with HL (Blamey et al., 2001; Briscoe, Bishop, & Norbury, 2001; Pittman, 2008).

Speech Intelligibility

Recall that the overall output of the hearing aids was reduced by 4 dB and the SNR increased by 2 dB when DNR was activated. Such alterations should decrease and increase the SII, respectively. On average, the SII was 0.58 (SD = 0.26) in quiet, 0.35 (SD = 0.15) in noise, and 0.36 (SD = 0.17) in noise with DNR, indicating that SII was maintained when DNR was activated. The relation between SII and the performance of the children with HL is shown in Figure 5. Recall that word categorization was conducted in isolation (quiet and
noise) and while performing the visual task (quiet, noise, noise reduction). The single-task conditions are shown in the figure as filled symbols, and the dual-task conditions are shown as open symbols. The lower SII values correspond to the speech intelligibility in noise and in noise with DNR, whereas the higher values correspond to speech intelligibility in quiet. The results show that performance increased with increasing SII and that performance was poorer overall in the dual-task conditions across all levels of SII.

Complex Visual Task Performance

Figure 6 shows the average dot rate (+1 SD) in dots per minute as a function of task difficulty for the children with NH (filled bars) and the children with HL (open bars). Also shown is the performance for the visual + auditory task condition in noise with the use of DNR for comparison, but this condition was not included in the following statistical analyses. Both groups achieved a dot rate of approximately 40 dots per minute in the visual-only condition. Dot rate decreased to approximately 30 dots per minute for each of the remaining conditions, including the condition in which the DNR feature was engaged. A repeated measures analysis of covariance (ANCOVA) was performed to detect differences between groups as a function of task independent of the effects of age, which are known to be significant (McFadden & Pittman, 2008). Group (NH, HL) and gender1 (male, female) were entered as the between-subjects factor, and listening condition (visual only, visual + auditory, visual + auditory + noise) was entered as the within-subjects factor. The covariate of age was found to be significant, $F(1, 74) = 20.235, p < .001, \eta^2 = .215, \beta = 0.993$, showing that age accounted for 21.5% of the variance. However, the analysis revealed no significant main effect of condition, $F(2, 148) = 1.050, p = .352$; group, $F(1, 74) = .000, p = .983$; or gender, $F(1, 74) = 0.461, p = .499$. Subsequent analysis showed that dot rate increased with age from an average of 26 dots per minute in the 8-year-olds to 39 dots per minute in the 12-year-olds. These results suggest that when the effects of age are taken into account, dot rate was not affected by gender or hearing status. Also, dot rate was not influenced by the addition of the auditory task or the competing noise.

Auditory Task Performance

For statistical analyses, data for the auditory task (in percentage correct) were arcsine transformed to normalize the nonlinear distribution of scores (Studebaker, 1985). Values displayed in the figures are in percentage correct, whereas values given in the statistical analyses are based on the arcsine transform. Figure 7 shows average performance (+1 SD) for the auditory task as a function of listening condition. The conditions are arranged in order of decreasing performance, which reflects the increasing difficulty of the tasks. Results are shown for

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1 The variable “gender” was added to the analysis on the basis of the results of studies showing that boys in this age group respond more rapidly than do girls to some time-sensitive visual tasks (Brocki & Bohlin, 2004).
both the children with NH (filled bars) and the children with HL (open bars). The lowest value on the ordinate reflects chance performance for this task (33%). Performance for the auditory + visual + noise condition with the use of DNR is also shown. Overall, the children with NH performed well, and only small decrements in performance were observed as the listening conditions increased in complexity. The performance of the children with HL, however, showed a more pronounced decrease as the complexity of the listening conditions increased. Specifically, performance was highest for the auditory task alone but decreased when noise and the complex visual task were added. The average performance of the children with NH decreased 10% as a function of listening condition, whereas the average performance of the children with HL decreased 21%.

Because the intermediate listening conditions (auditory + visual; auditory + noise) may have increased the demands of the task unequally, two separate analyses were performed to better capture the effects of the systematic increase in task demand. For the first analysis, the effects of adding the complex visual task and then the noise were evaluated using a repeated measures ANCOVA, with age as the covariate to detect differences between listening condition independent of the effects of age. Group (NH, HL) was entered as the between-subjects factor, and listening condition (auditory, auditory + visual, auditory + visual + noise) was entered as the within-subjects factor. The covariate of age was found to be significant, $F(1, 77) = 16.614, p < .001, \eta^2 = .177, \beta = .961$, showing that age accounted for 17.7% of the variance. Significant main effects of group, $F(1, 77) = 64.084, p < .001, \eta^2 = .454, \beta = 1$, and listening condition, $F(2, 154) = 12.968, p < .001, \eta^2 = .144, \beta = .997$, were revealed as well as a significant Group × Listening Condition interaction, $F(2, 154) = 3.462, p = .034, \eta^2 = .043, \beta = .641$. These results indicate that the overall performance of the children with HL was poorer than that of the children with NH and that the performance of both groups decreased as the demands of the listening conditions increased. Also, the effects of group and condition accounted for 45.4% and 14.4% of the variability in the data, respectively. Post hoc analyses revealed a significant difference between the auditory-only and the auditory + visual listening conditions, $F(1, 77) = 7.797, p = .007, \eta^2 = .092, \beta = .787$, and between the auditory + visual and auditory + visual + noise listening conditions, $F(1, 77) = 19.541, p < .001, \eta^2 = .202, \beta = .992$. These results indicate that performance decreased significantly with the addition of the visual task and again with the addition of noise. The Group × Listening Condition interaction indicates that the effects were greater for the children with HL than for the children with NH.

The second analysis was similar to the first, but the effects of adding the noise and then the complex visual task were evaluated. Age was again entered as the covariate, group (NH, HL) was the between-subjects factor, and listening condition (auditory, auditory + noise, auditory + visual + noise) was the within-subjects factor. The covariate of age was again found to be significant, $F(1, 77) = 19.821, p < .001, \eta^2 = .205, \beta = .993$, showing that age accounted for 20.5% of the variance. The results also revealed significant effects of group, $F(1, 77) = 61.368, p < .001, \eta^2 = .444, \beta = 1$, and listening condition, $F(2, 154) = 15.864, p < .001, \eta^2 = .171, \beta = .999$, but no Group × Listening Condition interaction, $F(2, 154) = 2.563, p = .080$. Post hoc analyses revealed a significant difference between the auditory-only and the auditory + noise listening conditions, $F(1, 77) = 19.115, p < .001, \eta^2 = .199, \beta = .991$, and between the auditory + noise and auditory + visual + noise listening conditions, $F(1, 77) = 11.832, p = .001, \eta^2 = .133, \beta = .925$. As in the previous analysis, performance for the auditory task decreased significantly with the addition of noise and again with the addition of the visual task. The lack of a significant Group × Listening Condition interaction indicates that the effect of noise on performance was similar for both groups.

For both analyses, the covariate of age was found to be significant and indicates that the demands of the task had a greater impact on the younger children. Figure 8 shows average (+1 SD) performance as a function of task difficulty for the children with NH in the upper panel and the children with HL in the lower panel. The
parameter within each level of difficulty is age group proceeding from 8-year-olds on the left (open bars) to 12-year-olds on the right (filled bars). This figure illustrates the relationship between age and listening condition and that the effect of age is more pronounced as the demands of the task increased, particularly for the children with HL.

Figures 6, 7, and 8 also show performance with DNR. In general, no improvement in performance was noted relative to the same condition without DNR (auditory + visual + noise) in any age group. To confirm this observation, t tests were performed comparing performance in the auditory + visual + noise condition without noise reduction with that of the same condition with noise reduction. No significant differences were found for either the auditory task, t(29) = 1.089, p = .285, or the visual task, t(29) = −1.661, p = .108. These results are consistent with the similar SII values measured in each condition.

**Factor Analysis**

Recall that the children with HL varied considerably in degree of HL and hearing history. Further analyses were conducted to examine the manner in which these and other factors interacted with the increasing demand of the task. A factor analysis was conducted using 11 variables representing relevant aspects of HL in children: three measures of receptive vocabulary (PPVT age, raw score, and standard score), three measures of hearing history (age at identification of HL, age at amplification, and years of hearing aid use), three measures of audibility (SII in quiet, in noise, and in noise reduction), one measure of HL (three-frequency pure-tone average), and the variable of age. SII and pure-tone average values were averaged across left and right ears. A Varimax rotation with Kaiser Normalization was performed yielding a three-factor solution having eigenvalues greater than 1. Within each solution, factor loadings greater than 0.80 were considered salient to the interpretation of each principal component. The first principal component was characterized by factors associated with audibility, including SII and pure-tone average HLs. Communication stage characterized the second component, which included variables associated with the children’s chronological and vocabulary age. Finally, factors associated with the children’s hearing history made up the third component, including the age of identification and amplification. Table 1 lists each principal component in order of the variance accounted for as well as the variables identified in those components.

Factor scores associated with these principal components were assigned to each child, and correlation coefficients were calculated to determine whether any of these components were related to the children’s performance for each level of task difficulty. The correlation coefficients (Pearson’s r) for each principal component and level of task difficulty are listed in Table 2. Asterisks denote cases in which statistical significance was reached (p < .05). These results show that audibility of the signal and communication stage were significantly correlated with performance in every listening condition, whereas hearing history (i.e., age at amplification and years of hearing aid use) did not significantly impact performance in any listening condition.

**Discussion**

The purpose of the present study was twofold. First, the effect of progressively demanding listening conditions
on performance for an auditory task was determined in children with NH and in children with HL. Children were asked to categorize common words in quiet and in the presence of an auditory (noise) and/or a complex visual (dot-to-dot game) competitor. The stimuli were counterbalanced across conditions, and the listening conditions were randomized for each child. All other test parameters were held constant throughout testing. That is, presentation level of the auditory stimuli was always 50 dB SPL, the SNR was always 0 dB, the dot-to-dot games were all numbered in increments of three, and the children used the same personalized amplification in each condition. This ensured that significant changes in performance across conditions were due strictly to the auditory and complex visual competitors.

Performance decreased with the addition of noise for both groups. For the children with NH, performance was not affected by the addition of the visual task, which is consistent with previous studies that showed the converse: Auditory tasks do not affect performance for visual tasks (Hicks & Tharpe, 2002; McFadden & Pittman, 2008). For the children with HL, however, word categorization was affected by the addition of the visual task. Although the impact of the noise on word categorization was the same across groups, the complex visual task further interfered with the performance of the children with HL. However, the degree of interference observed does not indicate how other competitors might affect children’s performance. The individual and combined impact of auditory and visual competitors is a question for further research and likely depends on the level and complexity of each. That is, a more difficult visual task may interfere to a greater degree than an auditory competitor that does not mask the stimuli as much as that of the present study.

Overall, word categorization was found to improve as a function of signal audibility in every listening condition. Similarly strong relationships between performance and audibility have been reported for a number of other auditory skills in children (Davidson & Skinner, 2006; Pittman & Stelmachowicz, 2000; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000). It is interesting to note that word categorization at every level of audibility (SII) was poorer in the presence of the visual task (see Figure 5). Although the SII may be used to predict performance for auditory tasks, the relation between SII and performance changes somewhat when children are engaged in other tasks while listening. The results of the present study suggest that increasing audibility may improve performance in complex environments, particularly for younger children. Unfortunately, hearing aids cannot detect visual competitors in the environment in the same way that they detect noise and adjust the amplification appropriately. Even if they could, it may cause more problems for the child than provide benefits. Another option is the continued development of effective DNR algorithms that improve, rather than maintain, audibility in noise. That is not to say that devices that

Table 1. Description of the three principal components explaining the variance across children with hearing loss and the percentage of variance accounted for by each.

<table>
<thead>
<tr>
<th>Principal component</th>
<th>Category</th>
<th>Variable</th>
<th>% of variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Audibility</td>
<td>SII in quiet, noise and DNR; PTA</td>
<td>35.3%</td>
</tr>
<tr>
<td>2</td>
<td>Communication stage</td>
<td>PPVT age/raw score; chronological age</td>
<td>30.8%</td>
</tr>
<tr>
<td>3</td>
<td>Hearing history</td>
<td>Age at ID and amplification</td>
<td>20.8%</td>
</tr>
<tr>
<td>Total variance accounted for</td>
<td></td>
<td></td>
<td>86.89%</td>
</tr>
</tbody>
</table>

Note. SII = speech intelligibility index; DNR = digital noise reduction; PTA = pure-tone average; PPVT = Peabody Picture Vocabulary Test; ID = identification.

Table 2. Correlation coefficients (Pearson’s r) between the principal component and performance in each listening condition.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Audibility</td>
<td>0.52*</td>
<td>0.40*</td>
<td>0.40*</td>
<td>0.41*</td>
<td>0.53*</td>
</tr>
<tr>
<td>2. Communication stage</td>
<td>0.40*</td>
<td>0.42*</td>
<td>0.58*</td>
<td>0.55*</td>
<td>0.48*</td>
</tr>
<tr>
<td>3. Hearing history</td>
<td>0.06</td>
<td>0.03</td>
<td>0.09</td>
<td>0.02</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*p < .05.
maintain audibility in noise are not beneficial to the user; rather, children would benefit more from improved audibility in noise for complex listening situations. Additional investigation is necessary to determine the degree to which audibility would need to be improved in noise to maintain performance in complex listening environments and the degree to which hearing aids provide DNR of that quality.

Also, the performance of children with HI was governed largely by their age and communication skills, which is consistent with a number of studies regarding the auditory perceptual skills of children with NH (Allen & Wightman, 1992; Elliott, 1979; Hnath-Chisolm, Laipply, & Boothroyd, 1998; Neuman & Hochberg, 1983). The results of the present study suggest that age plays a significant role in children’s ability to manage complex listening environments. Recall that performance in every level of task difficulty correlated significantly with communication development. These results suggest that perhaps the relation between communication skills (age and receptive vocabulary) and performance in the dual-task conditions was also related to the children’s intelligence. This idea is supported by the significant relationship that exists between young children’s receptive vocabulary and their nonverbal intelligence (Moeller, 2000) and cognition (Yoshinaga-Itano et al., 1998). It stands to reason that a child with higher cognitive aptitude would be able to manage multiple tasks better than a child with lower aptitude; however, a full understanding of this relationship is a question for further research.

Finally, no relation was observed between the children’s performance and their history of hearing aid use, which is consistent with a number of previous studies (Pittman, Lewis, Hoover, & Stelmachowicz, 2005; Stelmachowicz, Pittman, Hoover, & Lewis, 2002, 2004) but inconsistent with others (Moeller, 2000; Sininger, Grimes, & Christensen, 2010; Wake, Poulakis, Hughes, Carey-Sargeant, & Rickards, 2005; Yoshinaga-Itano et al., 1998). The most notable difference among these studies is the age of the children involved. Specifically, a significant relationship between early amplification and communication outcomes was observed for children < 8 years of age, whereas no such relationship has been reported for children > 8 years of age. It is possible that parents are not able to report the hearing aid history of their children as accurately after a period of time. They may also be unaware of how consistently their children wear their hearing aids, as parents and children may spend less time together after the children begin grade school. Another possibility is that early amplification is important for early communication development but less essential once children have acquired a vocabulary sufficient to allow them to use contextual cues to perceive speech rather than rely as heavily on the acoustic signal. This possibility is supported by Moeller et al. (2010), who reported that the communication delays of three out of four late-identified children resolved by the age of 7 years after receiving appropriate intervention. This does not suggest that amplification is unnecessary after the age of 8 years but that the benefits of amplification to older children may be more apparent for complex tasks, like multitasking, that include auditory perception.

**DNR**

The results showed that performance did not increase or decrease with the use of DNR. Recall that the overall level of the signal was reduced approximately 4 dB, and the SNR improved approximately 2 dB. At high presentation levels, these alterations should improve speech perception in listeners with NH (Hornsby & Ricketts, 2001; Studebaker, Sherbecoe, McDaniel, & Gwaltney, 1999), but for listeners with HL, performance is related more closely to the audibility of the signal than to overall level (Dubno, Dirks, & Schaefer, 1989). The same alterations that improve performance for listeners with NH may decrease the performance of listeners with HI if the overall amplitude reduction is not offset by an increase in SNR. For the present study, SII was approximately the same with and without DNR, which is consistent with the equivalent performance in each condition. Hearing aid users may prefer DNR because listening comfort is increased while speech perception is maintained. It could be argued that children with HL may benefit from DNR as well if it increases listening comfort without sacrificing their ability to participate in classroom activities.

The lack of relationship between performance and history of hearing aid use also supports the use of DNR by children. The results showed that, on average, the children were able to perform as well with DNR as they were with standard amplification (no noise reduction) and that their performance was not related to their history of amplification. Although it could be argued that children, like adults, require a period of adjustment to a new hearing aid to perform at their best, these data suggest that their performance is initially maintained and a period of acclimatization may serve to increase the benefits they received.

It should be noted that the results reported here represent only one type of noise reduction in one listening condition. The paradigm taxed the noise reduction feature of the Siemens hearing aid maximally through a fairly severe SNR (0 dB) and a broadband noise competitor. The effects of DNR may differ for more favorable SNRs and for steady-state noises that better represent those of a typical classroom (e.g., traffic noise, heating/air conditioning ventilation systems, computers). The DNR technology offered by other hearing aid manufacturers may also yield different results. However, clinical...
and laboratory research comparing different hearing aid features may be slow in coming until reporting standards and verification procedures are in place to provide audiologists with a way to confirm the reported performance of advanced hearing aid technologies.

**Implications of the Present Study**

The limited evidence regarding the benefits of advanced signal processing like DNR poses unique problems for the pediatric audiologist. Unlike adults, infants and young children are not able to provide input during the hearing-aid selection, fitting, or adjustment process. Nor are they able to indicate which form of advanced signal processing best meets their communication needs. Older children present similar problems because they have little or no experience with NH to serve as a reference during the fitting process. Their situation persists throughout childhood and may affect their ability to determine whether a particular signal processing feature is optimal for a given listening environment. Despite these obstacles, hearing aids with advanced signal processing are regularly prescribed to children. Rigsby, Bradham, Dickinson, and Mueller (2007) surveyed pediatric audiologists in the Southeast United States who routinely fit hearing aids to young children. Of the audiologists who responded (n = 99), 35% prescribed directional microphones, 74% prescribed adaptive feedback suppression, and 54% prescribed DNR to more than half their patients between the ages of birth and 5 years. Because each of these advanced features has the potential to substantially alter the amplified signal that children receive, their impact on communication development and learning in the classroom is an important piece of information that audiologists need in order to make decisions on behalf of the children they serve. As for DNR, there are presently no data to suggest that this technology is detrimental to elementary school children (or adults). The results of Stelmachowicz et al. (2010) indicate that DNR does not decrease children’s ability to perceive speech in noise, and the results of the present study suggest that DNR does not interfere with their ability to respond to speech while attending to another task. The impact of DNR on infants and young children, however, is unknown and should be prescribed with caution.

**Acknowledgments**

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**References**


### Stimuli for the Word Categorization Task

<table>
<thead>
<tr>
<th>Category</th>
<th>List</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Animals</strong></td>
<td>Beaver, Dog, Cow, Bird, Duck</td>
</tr>
<tr>
<td></td>
<td>Goat, Monkey, Donkey, Walrus, Penguin</td>
</tr>
<tr>
<td></td>
<td>Skunk, Frog, Giraffe, Fox, Bear</td>
</tr>
<tr>
<td></td>
<td>Dolphin, Owl, Goose, Rabbit, Lion</td>
</tr>
<tr>
<td></td>
<td>Kitten, Horse, Alligator, Chipmunk, Bat</td>
</tr>
<tr>
<td></td>
<td>Camel, Tiger, Lizard, Deer, Raccoon</td>
</tr>
<tr>
<td></td>
<td>Goldfish, Turtle, Panther, Gorilla, Wolf</td>
</tr>
<tr>
<td></td>
<td>Leopard, Elephant, Shark, Hamster, Crocodile</td>
</tr>
<tr>
<td></td>
<td>Rat, Octopus, Toad, Mouse, Seal</td>
</tr>
<tr>
<td></td>
<td>Zebra, Porcupine, Whale, Snake, Weasel</td>
</tr>
<tr>
<td><strong>Food</strong></td>
<td>Cheese, Fudge, Bacon, Jelly, Bread</td>
</tr>
<tr>
<td></td>
<td>Toast, Pizza, Peanut, Mushroom, Donut</td>
</tr>
<tr>
<td></td>
<td>Candy, Popcorn, Tomato, Brownie, Sandwich</td>
</tr>
<tr>
<td></td>
<td>Potato, Cake, Hotdog, Pancake, Carrots</td>
</tr>
<tr>
<td></td>
<td>Cherry, Cracker, Cereal, Apple, Sugar</td>
</tr>
<tr>
<td></td>
<td>Hamburger, Banana, Berries, Lettuce, Jell-O</td>
</tr>
<tr>
<td></td>
<td>Noodle, Cabbage, Cupcake, Bean, Chocolate</td>
</tr>
<tr>
<td></td>
<td>Pear, Oatmeal, Grape, Ham, Lollipop</td>
</tr>
<tr>
<td></td>
<td>Popsicle, Strawberry, Pineapple, Macaroni, Meatloaf</td>
</tr>
<tr>
<td></td>
<td>Corn, Soup, Taco, Waffle, Pretzel</td>
</tr>
<tr>
<td><strong>People</strong></td>
<td>Baby, Cowboy, Boy, Grandma, Captain</td>
</tr>
<tr>
<td></td>
<td>Grandma, Princess, Girlfriend, Brother, Girl</td>
</tr>
<tr>
<td></td>
<td>Dad, Mom, Father, Lady, Neighbor</td>
</tr>
<tr>
<td></td>
<td>Boyfriend, Friend, Burglar, Daughter, Cousin</td>
</tr>
<tr>
<td></td>
<td>Dentist, Sister, Man, Uncle, Husband</td>
</tr>
<tr>
<td></td>
<td>Nurse, Teacher, Astronaut, Butcher, Woman</td>
</tr>
<tr>
<td></td>
<td>Lifeguard, Coach, Fisherman, Farmer, Carpenter</td>
</tr>
<tr>
<td></td>
<td>Prince, Detective, Principal, Mailman, Policeman</td>
</tr>
<tr>
<td></td>
<td>Robber, Doctor, Sailor, Prisoner, Scientist</td>
</tr>
<tr>
<td></td>
<td>Wife, Pilot, King, Queen, Sheriff</td>
</tr>
</tbody>
</table>
Children's Performance in Complex Listening Conditions: Effects of Hearing Loss and Digital Noise Reduction

Andrea Pittman

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