The Effects of Digital Signal Processing Features on Children’s Speech Recognition and Loudness Perception

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Purpose: The purpose of this study was to determine the effects of hearing instruments set to Desired Sensation Level version 5 (DSL v5) hearing instrument prescription algorithm targets and equipped with directional microphones and digital noise reduction (DNR) on children’s sentence recognition in noise performance and loudness perception in a classroom environment.

Method: Ten children (ages 8–17 years) with stable, congenital sensorineural hearing losses participated in the study. Participants were fitted bilaterally with behind-the-ear hearing instruments set to DSL v5 prescriptive targets. Sentence recognition in noise was evaluated using the Bamford–Kowal–Bench Speech in Noise Test (Niquette et al., 2003). Loudness perception was evaluated using a modified version of the Contour Test of Loudness Perception (Cox, Alexander, Taylor, & Gray, 1997).

Results: Children’s sentence recognition in noise performance was significantly better when using directional microphones alone or in combination with DNR than when using omnidirectional microphones alone or in combination with DNR. Children’s loudness ratings for sounds above 72 dB SPL were lowest when fitted with the DSL v5 Noise prescription combined with directional microphones. DNR use showed no effect on loudness ratings.

Conclusion: Use of the DSL v5 Noise prescription with a directional microphone improved sentence recognition in noise performance and reduced loudness perception ratings for loud sounds relative to a typical clinical reference fitting with the DSL v5 Quiet prescription with no digital signal processing features enabled. Potential clinical strategies are discussed.

Key Words: speech recognition, amplification or hearing aids, children

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Speech recognition abilities are inversely related to RT, with speech recognition performance decreasing with increasing RT (Nábělek & Nábělek, 1994; Smaldino, Crandell, Brian, Kreisman, & Kreisman, 2008). These acoustic properties have been demonstrated to interact with the individual’s age and hearing status.

In general, children with hearing loss require louder speech signals, higher SNRs, and/or lower RTs than children with normal hearing in order to achieve similar levels of speech recognition performance (Boothroyd, 2008; Elliott, 1979; Fallon et al., 2002; Finitz-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Scollie, 2008; Smaldino et al., 2008). Research has demonstrated that children’s speech recognition performance is more negatively affected by background noise than that of adults and that this impact is age related (McCreery et al., 2010; Stelmachowicz, Pittman, Hoover, & Lewis, 2001). These adult–child differences are well established and are reflected in recently developed evidence-based reviews and practice guidelines related to use of amplification technology for children. Specifically, McCreery, Venediktov, Coleman, and Leech (2012) conducted a systematic review of the literature regarding the efficacy of DNR and directional microphones with pediatric hearing aid users. Because of the relatively small number of pediatric-specific studies, the authors concluded that additional research is needed before conclusions on the impacts of signal processing use with children can be drawn.

It is interesting to note that the American Academy of Audiology (AAA; 2013) also recognized the importance of adult–child differences in the literature by assigning a lower grade of evidence to results gathered with adult participants only, on the basis of the rationale that data gathered directly from children are required to adequately represent children’s reactions to, or benefits from, a specific technology. Therefore, although the current study replicates and confirms much of what has already been demonstrated in the adult literature, it provides pediatric data on a topic for which few such studies are available.

The DSL Prescriptive Algorithm

The DSL prescriptive algorithm has traditionally been a pediatric-focused fitting method that has sought to maximize audibility in the prescription of frequency-gain response in order to account for and accommodate the adult–child differences discussed above (Scollie et al., 2005; Seewald, Ross, & Spiro, 1985). The DSL prescriptive algorithm and its evolution with advances in hearing instrument technology have been detailed by Scollie et al. (2005) and by Crukley and Scollie (2012). In brief, DSL version 3.1 focused on optimizing audibility of average-level speech using linear amplification (Seewald et al., 1985). DSL version 4.1 was developed with the advent of nonlinear amplification in hearing instruments. The goals of the prescription evolved to include targets for a range of inputs above and below average-level speech (Cornelisse, Seewald, & Jamieson, 1995). The most recent version, DSL v5, demonstrates continued evolution of the algorithm by including separate sets of prescriptive targets for congenital and acquired hearing losses as well as separate prescriptions for use in quiet and noisy environments (Scollie et al., 2005). The DSL v5 Noise prescription uses a modified frequency response, which attenuates the low- and high-frequency portions of the frequency response, and a raised compression threshold, compared to the DSL v5 Quiet prescription. The DSL Noise prescription is expected to reduce loudness averisiveness without reducing speech intelligibility when used in noisy environments.

Crukley and Scollie (2012) presented the results of a study that investigated the effects of the DSL v5 Quiet and Noise prescriptions on children’s consonant recognition, sentence recognition in noise, and loudness perception. The data indicated that use of the DSL v5 Noise prescription resulted in significantly lower loudness ratings for high-level inputs; however, there was no difference in sentence recognition in noise performance between the two prescriptions, and consonant recognition performance was poorer at a low input level only with the DSL v5 Noise prescription. These results were in accordance with the goal of the DSL v5 Noise prescription, which is to improve listening comfort in noisy environments more than to improve speech recognition performance (Scollie et al., 2005).

Listening Needs of Children

Maximizing the audibility of speech sounds across input levels is recommended practice in the prescription of hearing instruments for children (AAA, 2013; College of Audiologists and Speech-Language Pathologists of Ontario [CASLPO], 2002; The Pediatric Working Group, 1996). Research has shown that children with hearing loss require more audibility (higher sensation levels) and a larger bandwidth in order to perceive and thus develop language (Pittman & Stelmachowicz, 2000; Stelmachowicz et al., 2001; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000; Stelmachowicz, Lewis, Choi, & Hoover, 2007; Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004).

Although maximizing the audibility of speech sounds in quiet environments is a priority in pediatric hearing instrument prescription, managing children’s listening needs in nonquiet environments is also an important consideration. Crukley, Scollie, and Parsa (2011) demonstrated the diverse range of listening environments experienced by children in their daily lives. They reported large variations in sound levels and RTs across a broad range of listening environments and situations experienced by groups of children over the course of their days at school. Scollie, Ching, Seewald, Dillon, Britton, Steinberg, and King (2010) demonstrated children’s varied listening needs and preferences across the diverse range of listening environments they encountered. Taken together, the data from these studies highlight the need for clinical management of children’s listening needs in nonquiet environments.

Clinical management of children’s nonquiet listening needs has to consider the importance of both maintaining
speech recognition and controlling aversive loudness. One approach to managing nonquiet listening is use of a lower gain prescription. The data regarding the ability of a lower gain prescription to reduce aversive loudness ratings are mixed. Crukle and Scollie (2012) indicated a reduction in loudness ratings for high-level sounds with use of a lower gain prescription; however, companion articles by Ching, Scollie, Dillon, and Seewald (2010) and Scollie, Ching, Seewald, Dillon, Britton, Steinberg, and King (2010) indicated minimal differences in post-acclimatization laboratory ratings of high-level sounds between fittings with DSL version 4.1 and a lower gain prescription (NAL–NL1) yet significant real-world differences in perceived aversiveness of loud sounds for children at the Australian site. Taken together, these results may indicate that real-world experience and acclimatization are factors in a complete evaluation of children’s experiences with high-level sound and hearing aid signal processing. Such evaluations must also consider the role of maintaining good speech recognition across a range of listening environments.

Modern hearing instruments offer strategies in addition to lower gain prescriptions for managing listening in noise. Features such as directional microphones and DNR can be combined with a base frequency-gain response for managing nonquiet listening.

### Directional Microphones

Directional microphones are, by design, less sensitive to sounds originating from certain (nonfrontal) directions relative to omnidirectional microphones (Ricketts, 2000, 2001, 2005). In hearing instruments, directional microphones are used to improve the SNR delivered to a listener’s ear, assuming the signal of interest is in front of the listener and the unwanted noise is not in front of the listener. Therefore, directional microphones, in the aforementioned conditions, enhance adult listeners’ ability to understand speech in noise (e.g., Amlani, 2001; Gnewikow, Ricketts, Bratt, & Mitchler, 2009; Ricketts, 2001, 2005).

A common measure of directional hearing instrument benefit is directional advantage (DA), which is the difference in performance on a speech recognition task (measured with SNR) between omnidirectional and directional hearing aids (DA = omnidirectional SNR – directional SNR). The raw measures of SNR that drive the DA score are typically measured as the SNR at which the listener can correctly understand 50% of sentences, commonly referred to as SNR–50 (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004; Niquette et al., 2003). Clinically available tests are typically designed with a speech signal (the target, which the listener attempts to repeat correctly) and a competing signal, which may be spectrally matched noise or a multitalker babble. This type of test is highly sensitive to DA when the competing signal is placed at nonfrontal locations, in particular when the competing signal is placed to the side (Wu & Bentler, 2012).

Although directional microphones improve performance on controlled, objective measures of speech in noise tests (e.g., Bentler, Egge, Tubbs, Dittberner, & Flamme, 2004; Bentler, Palmer, & Mueller, 2006; Hornsby & Ricketts, 2007; Klemp & Dhar, 2008), the benefit from and listener preference for directional microphones in real-world evaluations has been less clear. Some studies have shown listener preference for directional microphones in real-world listening situations, especially when noise sources were behind the listener and the speech source was in front of the listener (Ricketts, Henry, & Gnewikow, 2003; Ricketts & Mueller, 2000; Walden, Surr, Cord, & Dyrlund, 2004), whereas other studies have reported lack of a distinct difference between directional and omnidirectional microphone configurations in real-world situations (Bentler, 2005; Compton-Conley, Neuman, Killion, & Levitt, 2004; Cord, Surr, Walden, & Dyrlund, 2004; Cord, Surr, Walden, & Olson, 2002; Gnewikow et al., 2009; Walden et al., 2007).

### Children’s Use of Directional Microphones

McCreery et al. (2012) published a systematic review of the literature regarding school-age children’s performance with directional microphone and DNR hearing aids. On the basis of the evidence examined, the authors concluded that although directional microphones may improve speech recognition performance under optimal test conditions, further research is needed to determine the real-world effectiveness of directional microphones for children with hearing loss.

In addition to data demonstrating the benefits of directional microphone use with adults, the literature also includes reports of benefit from directional microphones on measures of speech recognition performance with children (Gravel, Fausel, Liskow, & Chobot, 1999; Hawkins, 1984; Kuk, Kollofski, Brown, Melum, & Rosenthal, 1999; Ng, Meston, Scollie, & Seewald, 2011; Ricketts, Galster, & Tharpe, 2007). Although benefit has been demonstrated in objective laboratory measures of speech recognition performance, this benefit from directional microphones is somewhat dependent on the correct orientation of the listener’s head relative to the talker of interest. Studies have shown that children can correctly orient toward a primary talker, at least some of the time; however, the same studies have indicated that the children are almost as likely to orient incorrectly (Ching et al., 2009; Ricketts & Galster, 2008). Although there appears to be a DA when the signal of interest is in front of the listener, there is also clear directional disadvantage when the listener is not facing the source (Ching et al., 2009; Ricketts et al., 2007; Ricketts & Picou, 2013).

Properties of room acoustics have been shown to interact with directional microphones. Specifically, the DA of directional microphone systems has been shown to decrease with increasing RT (Amlani, 2001; Hawkins & Yacullo, 1984; Leeuw & Dreschler, 1991; Ricketts, 2001; Ricketts & Dahr, 1999; Ricketts & Hornsby, 2003). As Crukle and Scollie (2011) discussed, children experience a wide range of RTs over the course of a school day; this has implications for the efficacy of using directional microphones across the nonquiet environments experienced by children in real-world settings.
Recommendations regarding the use of directional microphones in pediatric hearing instrument fitting are mixed. Some professionals recommend against the use of directional microphones with pediatric hearing instrument fittings because of a lack of sufficient evidence (Foley, Cameron, & Hostler, 2009), others consider directional microphones to be a viable strategy (AAA, 2013; Bagatto, Scollie, Hyde, & Seewald, 2010; CASLPO, 2002), and still others recommend directional microphones for all pediatric hearing instrument fittings because the benefits are thought to outweigh any disadvantages (King, 2010).

DNR in Hearing Instruments

DNR is a hearing instrument processing feature that has been used to address both general categories of nonquiet listening: (a) speech in background noise, with the goal of improving speech recognition, and (b) loud situations, with the goal of improving listening comfort and possibly reducing cognitive demand. Modern DNR algorithms allow for decision making by the processor regarding how noise is defined, which frequency regions are affected, and how much gain reduction to use in the affected regions (Bentler & Chiou, 2006). DNR systems manipulate a variety of processing parameters; for example, the number of channels affected, amount of gain reduction, time constants, and classification schemes can vary between DNR strategies (Chung, 2004). Improving SNR through reduction of competing noise and preservation of the target signal (speech) has proved challenging because of the time variations and spectral overlap of speech and noise signals most often encountered in the real-world listening environments of hearing instrument users. In general, research has shown no improvement in speech recognition performance with the use of DNR (Bentler & Chiou, 2006; Bentler, Wu, Kettel, & Hurtig, 2008; Dillon, 2001; Hu & Loizou, 2007; Nordrum, Erler, Garstecki, & Dhar, 2006; Ricketts & Hornsby, 2005). In addition, previous studies have reported decreased speech recognition performance using DNR with both speech-shaped noise (Van Tasell, Larsen, & Fabry, 1988) and multitalker babble (Jamieson, Brennan, & Cornelisse, 1995; Sarampalis, Kalluri, Edwards, & Hafter, 2009) as competing signals. Although improving speech recognition with DNR has not been successful, the use of DNR in hearing instruments has been shown to provide benefit in terms of listening comfort and preference (Bentler & Chiou, 2006; Bentler et al., 2008; Mueller, Weber, & Hornsby, 2006; Ricketts & Hornsby, 2005). These findings are consistent with the known properties of DNR processing, which affect output level but not overall SNR (Bentler & Chiou, 2006; Dillon, 2001; Levitt, 2001).

Children’s Use of DNR

In the systematic review published by McCreery et al. (2012), the authors concluded that, on the basis of the evidence reviewed, the use of DNR in school-age children’s hearing aids did not improve or degrade speech recognition; however, similar to their conclusions regarding directional microphones, they stated that more research is needed to determine the efficacy and effectiveness of DNR in children’s hearing aids across the broader range of hearing outcomes.

Previous research has demonstrated the potential for DNR to degrade speech perception (Jamieson et al., 1995; Sarampalis et al., 2009; Van Tasell et al., 1988); DNR may degrade speech perception by altering the spectral content of a signal and, more specifically, high-frequency content (Jamieson et al., 1995). Children are less resilient to degraded speech signals than adults and may need more high-frequency audibility than adults in order to perceive speech sounds (Scollie, 2008; Stelmachowicz et al., 2004). For these reasons, some guidelines recommend against provision of DNR processing in pediatric hearing instrument fittings until more data demonstrating benefit without detriment to speech perception become available (Foley et al., 2009), whereas others advise that caution be taken when prescribing DNR in order to avoid degradation of speech recognition ability (AAA, 2013). However, although research examining the effects of DNR on children’s speech perception has demonstrated no effective improvement in speech recognition performance, the use of DNR in children’s hearing instruments does not appear to decrease performance (Pittman, 2011; Stelmachowicz et al., 2010). These results suggest that clinical recommendations against provision of DNR in pediatric fittings could be reconsidered.

Use of Directional Microphones and DNR in Combination

Studies investigating the use of directional microphones in combination with DNR have shown results similar to those of the technologies used independently. In general, performance on objective measures of speech recognition is similar with hearing instruments that incorporate directional microphones alone or in combination with DNR (Nordrum et al., 2006; Peeters, Kuk, Lau, & Keenan, 2009; Ricketts & Hornsby, 2005), and the addition of DNR has resulted in improvements in subjective measures of listening comfort (Peeters et al., 2009; Ricketts & Hornsby, 2005). These results suggest that directional microphones may offer the most improvement in speech recognition, whereas DNR processing may offer more improvement for listening comfort and reduced listening effort in the presence of noise. As discussed previously, children require louder speech signals and larger SNRs than adults to achieve similar levels of speech recognition performance. For children, it is important to consider the potential interaction between directional microphones and DNR because combining these features may affect output bandwidth and frequency-gain response differently than either technology used in isolation. This interaction could thus affect children’s speech recognition performance differently than adults’, for the reasons stated above.

To date, no known studies have investigated the combination of processing features such as directional microphones and DNR with specific frequency-gain responses in
order to achieve the most benefit in terms of both speech recognition and loudness perception.

**Rationale for Current Study**

Most current pediatric hearing instrument fitting guidelines do not offer recommendations for nonquiet environments (Bagatto et al., 2010; CASLPO, 2002; Foley et al., 2009). Although there are no current recommendations for noise management in pediatric hearing instrument fittings, children have demonstrated a desire for amplification options that reduce listening levels in loud, noisy, or reverberant environments (Scollie, Ching, Seewald, Dillon, Britton, Steinberg, & Corcoran, 2010).

Modern hearing instruments offer a number of options to manage nonquiet listening, such as frequency-gain shaping, directional microphones, DNR, and the available combinations of these technologies. Although there is a substantial literature regarding adult use of these strategies alone and in combination, there has been less investigation of their effects in children. For this reason, an evaluation of children’s performance with these available nonquiet management options is warranted, and deemed necessary by AAA (2013), because of the adult–child differences discussed above. Furthermore, children’s listening environments are diverse and different than those experienced by adults. On the basis of the results reported by Crukley et al. (2011), we sought to explore signal-processing strategies that could accommodate the listening environments and situations experienced by children in their daily lives. We chose to evaluate the efficacy of these processing strategies by conducting the current study in real classrooms, using realistic stimuli. Finally, children’s hearing aids are generally fitted with a different prescriptive method (DSL) than what is commonly used in studies with adults (NAL). In the current study, we sought to investigate the effects of pairing available processing strategies with the DSL v5 Quiet and Noise prescriptions because this has not previously been studied. We investigated children’s performance with signal processing in combination with pediatric prescriptions, in a realistic environment. The performance measures used are considered domains of outcome that have emerged as important in other studies of children’s use of hearing aids in real-world environments: loudness and speech recognition in noise. By studying whether hearing aid settings can improve these outcomes in a real classroom, new evidence on important benefits of modern technology may be obtained.

**Research Questions**

We addressed two research questions targeting the two general categories of nonquiet listening. First, does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in better sentence recognition in noise? Second, does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds?

We did not expect use of different prescribed frequency-gain responses to result in sentence recognition in noise score differences based on our previously published data (Crukley & Scollie, 2012). We expected that use of directional microphones alone or in combination with DNR would result in improved speech-in-noise scores relative to scores using omnidirectional microphones, in the classroom environment. We hypothesized that combining directional microphones and DNR might affect speech-in-noise performance relative to directional microphones used alone. We expected differences in comfort ratings for loud sounds between prescribed frequency-gain responses and use of directional microphones and DNR features within the hearing aids.

**Method**

**Participants**

Ten children were recruited to participate in the study. Participants included four children from an elementary school self-contained class for the deaf and hard of hearing and six children from a high school hearing resource class. The average age of the elementary school children was 8.71 years (range = 8.0–9.75 years); the average age of the high school children was 15.18 (range = 13.83–17.58 years). These schools were located in a public school board in Ontario, Canada. All participants were full-time hearing instrument users with stable, bilateral, congenital sensorineural hearing losses. These children also participated in a previously reported study (Crukley & Scollie, 2012).

For sample size estimation, we used data from previous research that evaluated children’s loudness perception with the Contour Test of Loudness Perception (Cox, Alexander, Taylor, & Gray, 1997) with alternate prescribed frequency-gain responses (Scollie, Ching, Seewald, Dillon, Britton, Steinberg, & King, 2010). We used the data from Scollie et al.’s (2010) study to calculate the effect size (f = 0.12) and correlation (r = .8) between repeated measures across level of the independent variable (prescribed frequency-gain response) using G*Power for Windows 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). The results indicated that a total sample size of 10 individuals would be sufficient to detect the hypothesized effect 95% of the time using a .05 alpha level.

**Hearing Threshold Levels**

Hearing threshold levels were measured by the participants’ clinical audiologists within 6 months prior to study enrollment. Hearing losses ranged from moderate to profound degrees; audiometric thresholds for the left and right ears of all participants are shown in Figure 1.

**Hearing Instrument Fitting Procedure**

All participants were fitted with Phonak Versata Art SP behind-the-ear hearing instruments. Earmold venting was provided in accordance with preferred practice guidelines—that is, with larger vents for children with better low-frequency thresholds. For children with steeply sloping losses, the size of the vent was constrained by achieving high-frequency target matching and avoiding feedback. Fitting procedures...
followed recommended protocols and were described in detail in Crukley and Scollie’s (2012) article. In brief, all hearing instruments were fitted using measures of aided speech, in a verification system that allowed simulated real-ear measurement. Hearing instruments were fitted using individual real-ear-to-coupler-difference measurements according to recommended procedures (Bagatto et al., 2005).

DSL v5 Quiet prescription targets were generated by the verification system, and custom software was used to generate targets for the DSL v5 Noise prescriptions using the participants’ audiometric thresholds and real-ear-to-coupler-difference measurements. DSL v5 prescriptive targets for both Quiet and Noise were calculated for input levels of 55, 65, and 70 dB SPL.

Participants wore the hearing instruments for 2 weeks prior to data collection in order to adjust to their new devices. Middle ear status was monitored by immittance testing with a portable tympanometer at the beginning of each session.

**DSP Features**

After the fitting of the omnidirectional programs of each hearing instrument (see Crukley & Scollie, 2012, for details), directional microphones and DNR were enabled by activating the feature within the fitting software with the given base prescription fitting; frequency-gain response was not adjusted further after enabling a given feature. The directional microphone condition used the “Fixed Directional” setting within the fitting software, which put the hearing instruments into a fixed cardioid polar pattern. We verified proper function of the directional microphones using the directional microphone test within the Audioscan Verifit system, prior to behavioral testing. The DNR condition used the “Strong” setting of NoiseBlock processing within the fitting software. NoiseBlock is a channel-based gain-reduction system that reduces gain in channels with lower estimated SNRs. SNR estimates are based on the amount of modulation detected in the input signal per channel. SNR estimates are lower in channels with lower amounts of modulation, which results in higher degrees of gain reduction in those channels. The combined condition had both the Fixed Directional and Strong NoiseBlock settings enabled.

Because of their design, directional microphones result in a reduction of low-frequency output relative to that of an omnidirectional microphone (Ricketts, 2001; Ricketts & Henry, 2002). Figure 2 shows the effects of the DSP features and their combination on frequency response. The figure shows the difference in hearing instrument output, by frequency, for a speech signal at three input levels averaged across all study participants. No manual gain compensation was applied to the directional microphone fittings; however, it is possible that the fitting software imposed adjustments to the frequency response of the hearing instruments when the directional microphone was enabled. The degree of low-frequency output reduction, relative to the omnidirectional microphone setting, appeared to be level dependent and was less than the 6 dB per octave expected on the basis of Ricketts and Henry’s (2002) data. In addition, there appeared to be a level-dependent increase in mid-frequency output when the directional microphone was enabled. The difference in output was less than ± 3 dB across frequencies and input levels. This change was unexpected and was not related to the tuning of the hearing aid to meet prescriptive targets.
The amount of gain reduction applied by DNR depends on characteristics of the input signal and the classification scheme of the DNR algorithm. Most DNR algorithms attempt to maintain audibility of speech and therefore do not typically impose much, if any, gain reduction for speech and speechlike inputs. Figure 3 shows the difference in hearing instrument output between the “Strong” and “Off” NoiseBlock settings for speech and pink noise signals generated by the Audioscan RM500SL at three input levels. The amount of gain reduction ranged from approximately 0 dB for speech and from 5 to 15 dB for pink noise, across frequencies, with more gain reduction applied at the higher input levels tested.

Figure 4 shows the difference in hearing instrument output between the “Strong” and “Off” NoiseBlock settings for Auditec (1971) four-talker babble and pink noise signals, at 75 dB SPL, measured with a Brüel and Kjær measurement system and SpectraPlus software (Pioneer Hill Software, 2008). The amount of gain reduction was approximately 3 dB in the low frequencies for the four-talker babble and ranged from 5 to 10 dB for pink noise across frequencies.

**Equipment**

We used a test system composed of a laptop running custom software and a custom-built external hardware interface to control the presentation of test stimuli and record participant responses for the outcome measures. A detailed description of the experimental setup was presented in Crukley and Scollie’s (2012) article. In brief, target stimuli were presented through a tripod-mounted powered speaker positioned at 0° relative to the test position. The competing stimulus was presented through an Omnipanel speaker system positioned at 180° relative to the test position. As detailed...
by Crukley and Scollie, this speaker system was a distributed mode loudspeaker (DML). DMLs disperse sound in a spherical pattern, which is essentially random and therefore less directional than conventional cone-based loudspeakers (Bai & Huang, 2001). We chose the DML to create a more diffuse noise source behind the listener. The speakers were positioned approximately 6 m apart, with the participant seated between them (approximately 3 m from each speaker).

As detailed by Crukley and Scollie, the test system was set up in a classroom at both the elementary and high school for data collection. The acoustic properties of these rooms were measured prior to data collection using a computerized system equipped with SpectraPlus software. Acoustic testing estimated RTs (RT_{60}) of 200 ms and 550 ms for the elementary and high school rooms, respectively.

**Outcome Measures**

**Sentence recognition in noise.** The Bamford–Kowal–Bench Speech in Noise Test (BKB-SIN; Niquette et al., 2003) was administered through the computer-controlled system according to the test manual’s instructions (Etymotic Research, 2005). In brief, three list pairs were presented for each condition using the split tracks from the BKB-SIN CD. The signal level was calibrated daily to 70 dB SPL for each speaker at the test position, with a tolerance of ± 0.5 dB. The order of prescription was counterbalanced across participants.

**Loudness perception.** The Contour Test of Loudness Perception (Cox et al., 1997; Cox & Gray, 2001) was administered through the computer-controlled system according to the methods of Cox and Gray (2001) as described by Crukley and Scollie (2012). In brief, two conditions were tested: (a) sentences in quiet and (b) sentences in noise. Materials from the BKB-SIN were used for both conditions. In both conditions, stimulus presentation began at 52 dB SPL and ascended in 4-dB steps to a maximum level of 80 dB SPL, then descended in 4-dB steps back down to 52 dB SPL. For the sentences-in-noise condition, the SNR of the sentences relative to the babble was fixed at +10 dB. Loudness perception categories spanned eight levels (0 = did not hear, 1 = very soft, 2 = soft, 3 = comfortable but slightly soft, 4 = comfortable, 5 = comfortable but slightly loud, 6 = loud but okay, 7 = uncomfortably loud). The task automatically
reversed direction after the presentation level reached 80 dB SPL or as soon as “uncomfortably loud” was selected, whichever happened first. The perception categories were displayed as text on a computer monitor, and participants were asked to select their rating by clicking the elected category with a computer mouse. As described by Crukley and Scollie, the youngest participants were given a sheet of paper with pictures representing the perception categories in order to facilitate the task. The order of prescription and loudness perception conditions were counterbalanced across participants.

As detailed by Crukley and Scollie (2012), loudness ratings from the ascending and descending runs were averaged together to create a single loudness rating for each input level for analysis. In instances where the participant selected “uncomfortably loud” before presentation at 80 dB SPL, thus reversing the direction of the task, missing data were replaced with “uncomfortably loud” ratings.

**Test Administration Details**

Children were blinded to conditions. The researcher was not blind to conditions; however, for the computer-administered task (loudness perception), the researcher was not involved in the scoring of the data, and thus the effect of blinding was achieved. For the BKB-SIN, the researcher scored the task, and thus blinding was not achieved. Test order was kept constant, with test order effects addressed by counterbalancing the sequence of hearing instrument conditions across participants.

**Results**

Following the recommendation of Max and Onghena (1999), we used the Greenhouse–Geisser correction to adjust degrees of freedom universally in all repeated measures analyses described below to control for any potential violations of the sphericity assumption. Eta-squared (η²) is reported as a measure of effect size for the statistical analyses presented below.

**Sentence Recognition in Noise**

SNR-50 scores averaged across three list pairs in each prescription and across subject ranged from −4.5 to 16.0 dB. Significant individual differences between conditions relative to the DSL v5 Quiet prescription alone are shown in Table 1. A change in SNR-50 score of ± 2 dB represents a significant difference based on the 95% confidence interval for significant change using three list pairs for the age group of the study participants according to the BKB-SIN manual (Etymotic Research, 2005). In Table 1, a “+” indicates better performance (lower SNR-50), and a “−” indicates poorer performance (higher SNR-50). Individual participant data are presented in order of ascending four-frequency pure-tone average. A high proportion of participants demonstrated improved sentence recognition in noise scores with use of a directional microphone, regardless of base prescription.

Figure 5 shows mean SNR-50 scores for each hearing instrument condition; error bars represent 1 SD above and below the mean. SNR-50 scores were analyzed with a repeated measures analysis of variance with prescription (two levels) and DSP (four levels) as within-subject factors. The results indicated that the main effect of prescription was not significant, $F(1, 9) = 0.22, p = .65, \eta^2 = .02$. The main effect of DSP was significant, $F(1.59, 14.31) = 40.87, p = .001, \eta^2 = .82$. The interaction effect between prescription and DSP was not significant, $F(2.42, 21.73) = 0.97, p = .41, \eta^2 = .10$. Results of Bonferroni post hoc testing indicated that performance was significantly better (lower SNR-50) with a directional microphone alone than with no DSP features enabled, $t(9) = 7.07, p < .001, d = 8.51$, or with DNR alone, $t(9) = 7.76, p < .001, d = 8.52$. Performance was better with a directional microphone and DNR combined than with no DSP features enabled, $t(9) = 6.28, p < .001, d = 6.58$, or with DNR alone, $t(9) = 6.60, p < .001, d = 7.73$. The difference between performance with a directional microphone alone and combined with DNR was not significant, $t(9) = 2.76, p = .02, d = 6.03$. Overall, the best average performance was obtained with directional microphone use.

**Loudness Perception**

Mean loudness perception ratings for the sentences in quiet and sentences in noise loudness perception tasks for each level and hearing instrument condition are shown in Figure 6. Mean loudness perception ratings were subjected to a repeated measures analysis with level (eight levels), prescription (two levels), loudness task condition (two levels), and DSP (four levels) as repeated measures factors. The main effect of level was significant, $F(1.89, 17.00) = 231.99, p < .001, \eta^2 = .96$, indicating higher loudness ratings with higher input levels. The main effect of prescription was significant, $F(1, 9) = 16.09, p = .003, \eta^2 = .64$, indicating lower loudness ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. The main effect of loudness task condition was significant, $F(1, 9) = 31.81, p < .001, \eta^2 = .78$, indicating lower loudness ratings in the sentences in noise condition than in the sentences in quiet condition. The main effect of DSP was not significant, $F(2.339, 21.06) = 1.55, p = .22, \eta^2 = .15$. The interaction effect of Level × Loudness Task was significant, $F(3.49, 31.37) = 3.70, p < .001, \eta^2 = .48$. No other interaction effects were significant.

Mean loudness ratings were averaged across both prescriptions and levels of DSP for each presentation level to investigate the significant interaction effect between level and loudness perception task condition. The results of Bonferroni post hoc testing (see Table 2) indicated significantly lower loudness ratings in the sentences in noise condition at 56, 60, 64, 68, and 72 dB SPL. The difference between ratings was not significant at 52, 76, or 80 dB SPL. The mean loudness ratings collapsed across prescriptions and levels of DSP are shown in Figure 7.

To specifically address the second research question—does the use of a prescribed frequency-gain response,
directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds?—we used the method described by Crukley and Scollie (2012) to create a modified loudness rating. Specifically, loudness ratings for input levels from 68 to 80 dB SPL were averaged together to form a single “loud sounds” rating for each loudness perception task condition. The average rating for loud sounds in both loudness perception conditions and the four DSP conditions for each base prescription are shown in Figure 8.

The loud sounds ratings were subjected to a repeated measures analysis with prescription (two levels), DSP (four levels), and loudness task condition (two levels) as repeated measures factors. The results indicated that the main effect of prescription was significant, $F(1, 9) = 15.65, p = .003$.

Table 1. Sentence-recognition-in-noise performance relative to reference condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Participant number</th>
<th>No. participants with significant change</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSL N</td>
<td>+</td>
<td>3</td>
</tr>
<tr>
<td>DSL Q + DNR</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>DSL N + DNR</td>
<td>+</td>
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</tr>
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<td>+</td>
<td>9</td>
</tr>
<tr>
<td>DSL Q + DNR</td>
<td>+</td>
<td>9</td>
</tr>
<tr>
<td>DSL N + DIR</td>
<td>+</td>
<td>9</td>
</tr>
<tr>
<td>DSL Q + DIR + DNR</td>
<td>+</td>
<td>9</td>
</tr>
<tr>
<td>DSL N + DIR + DNR</td>
<td>+</td>
<td>9</td>
</tr>
</tbody>
</table>

Note. + = change in score exceeded 95% confidence interval in the positive direction; – = change in score exceeded 95% confidence interval in the negative direction. Participants are presented in ascending order of four-frequency pure-tone average hearing threshold level. DSL = Desired Sensation Level version 5; N = Noise prescription; Q = Quiet prescription; DNR = digital noise reduction enabled; DIR = directional microphone enabled.

Figure 5. Mean Bamford–Kowal–Bench Speech in Noise Test signal-to-noise ratio-50 scores by hearing instrument condition. Vertical bars indicate ±1 SD. No DSP = base prescription alone with an omnidirectional microphone.
η² = .64, indicating lower loudness ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. The main effect of DSP was significant, F(2.65, 23.88) = 6.44, p = .003, η² = .42, indicating a difference between loudness ratings when DSP features were enabled. The main effect of loudness task condition was significant, F(1, 9) = 18.53, p = .002, η² = .67, indicating lower loudness ratings in the sentences in noise condition than in the sentences in quiet condition. There were significant interaction effects between prescription and DSP, F(2.48, 22.34) = 3.305, p = .046, η² = .27, and between prescription and loudness perception, F(1, 9) = 5.97, p = .04, η² = .40. The interaction effect between DSP and loudness perception was not significant, F(2.48, 22.35) = 0.495, p = .69, η² = .05.

Two sets of post hoc comparisons were performed to investigate the significant interaction effect between prescription and DSP. In the first set of comparisons, loud sounds ratings were collapsed across loudness perception task.
conditions, and each unique combination of prescription and DSP was compared to a reference condition, which was the DSL v5 Quiet prescription with no DSP features enabled. The results of a Bonferroni post hoc analysis indicated that ratings for loud sounds were significantly lower with the DSL v5 Noise prescription combined with a directional microphone than with the reference condition, \( t(9) = 5.56, p < .001, d = 3.97 \); all other comparisons were not significant.

In the second set of comparisons, each level of DSP was compared between the two base prescriptions, collapsed across loudness perception task conditions. The results of a Bonferroni post hoc analysis indicated that loudness ratings with DSL v5 Noise were significantly lower than with DSL v5 Quiet when both prescriptions were paired with a directional microphone, \( t(9) = 5.84, p < .001, d = 4.42 \); all other comparisons were not significant.

To investigate the significant interaction effect between prescription and loudness perception task condition, loud sounds ratings were collapsed across DSP conditions and post hoc comparisons between each combination of prescription and loudness task condition were performed. The results of a Bonferroni post hoc analysis indicated that loudness ratings with the DSL v5 Noise prescription varied with the loudness perception task condition, with lower ratings in the sentences in noise condition than in the sentences in quiet condition, \( t(9) = 6.39, p < .001, d = 13.33 \). Loudness ratings with the DSL v5 Quiet prescription did not vary with loudness perception task condition, \( t(9) = 2.38, p = .04, d = 3.05 \). In addition, loudness ratings with the DSL v5 Noise prescription were lower than ratings with the DSL v5 Quiet prescription in both the sentences in quiet condition, \( t(9) = 3.49, p = .007, d = 3.47 \), and the sentences in noise condition, \( t(9) = 4.10, p = .003, d = 3.64 \). These results indicate that the between-prescription differences measured in a previous study (Crukley & Scollie, 2012) also were measured in the current study, independent of the DSP feature(s) used in combination with the base prescription.

Discussion

This study provides an evaluation of sentence recognition in noise and loudness perception with a group of children who wore hearing instruments fitted with several strategies for the management of nonquiet listening situations in a classroom environment.

Sentence Recognition in Noise

The results of the sentence recognition in noise task showed significant benefit with the use of directional microphones. This result is consistent with existing literature, which has demonstrated the ability of directional microphones to improve children’s ability to recognize speech in the presence of competing noise (Gravel et al., 1999; Hawkins, 1984; Kuk et al., 1999; Ng et al., 2011). The improvement seen with directional microphone use was expected because DA was likely maximized by the experimental setup, which positioned the signal source at 0° and the noise source at 180° relative to the test position. However, because this study was conducted in real classrooms with moderate reverberation using a diffuse-pattern noise source, these results suggest real-world efficacy of this technology for children. The use of DNR did not have a significant effect on sentence recognition in noise scores. This result is also in agreement with the existing literature, which has demonstrated no

<table>
<thead>
<tr>
<th>Level</th>
<th>Mean sentences-in-quiet loudness rating</th>
<th>Mean sentences-in-noise loudness rating</th>
<th>Difference</th>
<th>( t )</th>
<th>( df )</th>
<th>( p )</th>
<th>( d )</th>
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<td>2.91</td>
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<td>5.78</td>
<td>5.61</td>
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<td>80</td>
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<td>6.28</td>
<td>0.06</td>
<td>1.60</td>
<td>9</td>
<td>.14</td>
<td>2.71</td>
</tr>
</tbody>
</table>
improvement in speech recognition performance with
DNR in adults (Bentler et al., 2008; Bentler & Chiou,
2006; Dillon, 2001; Hu & Loizou, 2007; Nordrum et al.,
2006; Ricketts & Hornsby, 2005) or with children (Pittman,
2011; Stelmachowicz et al., 2010). The differences in output
bandwidth and frequency-gain response resulting from the
combination of directional microphones with DNR, as shown
in Figure 2, could potentially degrade speech recognition in
noise performance for children because they require broader
bandwidth, louder speech, and higher SNRs than do adults.
However, in the current study, the combination of directional
microphones with DNR did not result in any significant
difference in performance relative to use of directional micro-
phones alone, which agrees with previous research con-
ducted with adults (Nordrum et al., 2006; Peeters et al., 2009;
Ricketts & Hornsby, 2005).

The individual data shown in Table 1 indicate that
nearly all participants improved their scores with directional
microphones. Although a small number of participants
showed significant changes in score with DNR, the results are
somewhat equivocal across those participants. Some partici-
pants obtained better scores and others obtained poorer
scores with DNR.

We also evaluated the effects of combining DSP fea-
tures with two different base prescriptions, specifically, the
DSL v5 Quiet and Noise prescriptions. The results of the
sentence recognition in noise task demonstrated that scores
improved with use of a directional microphone regardless
of base prescription and that there was no interaction between
base prescription and the use of DSP features. These group
results suggest that no combination of DSP feature and
base prescription led to decrements in sentence recognition
in noise.

Table 1 also shows individual data for sentence recog-
nition in noise performance with the DSL v5 Noise pre-
scription relative to performance with the DSL v5 Quiet
prescription. The data are similar to the DNR data; individual
performance with the DSL v5 Noise prescription alone was
mixed. Some children had better performance, whereas others
showed poorer performance, with DSL v5 Noise relative to
DSL v5 Quiet. An examination of audiometric trends in
relation to this result suggests that children with steeply
sloping and profound hearing losses may perform more
poorly with the DSL v5 Noise prescription. This result is not
surprising given the reduction of gain and thus audibility in
the low- and high-frequency regions. Children with steeply
sloping losses likely rely more on their residual low-frequency
hearing than their peers with flatter or milder losses.

Together, these results agree with the data presented
by Crukley and Scollie (2012), whose study demonstrated
no significant effect of prescription on sentence recognition
in noise performance between the DSL v5 Quiet and Noise
prescriptions. On the basis of the group data alone, it would appear that any combination of DSP feature and base prescription evaluated in this study could be applied without detriment. However, a closer look at the individual data raises concerns because some children demonstrated poorer performance with the DSL v5 Noise prescription and DNR alone and in combination. Again, these concerns tended to arise for children with steeply sloping and profound hearing loss. Modification of the DSL v5 Noise fitting to increase low-frequency audibility, and/or provision of venting, could be used to potentially improve these outcomes.

**Loudness Perception**

The main effect of prescription on loudness ratings was significant, indicating lower ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. This result shows that lower loudness ratings can be achieved through application of a lower gain prescription. Although this result is consistent with the data reported by Scollie, Ching, Seewald, Dillon, Britton, Steinberg, and King (2010), who compared loudness ratings between DSL v4.1 and lower gain NAL–NL1 fittings, it is in contrast to the data presented by Crukley and Scollie (2012), which indicated no significant main effect of prescription on loudness ratings between DSL v5 Quiet and DSL v5 Noise fittings. A possible explanation for this discrepancy may be the reduction of variance associated with the use of highly correlated repeated measures, which in turn increases statistical power (Portney & Watkins, 2000). The repeated measures analysis in this study subjected the prescriptions to more comparisons than in the previous study.

There was no significant main effect of DSP on loudness ratings over all levels of the loudness perception tasks. The use of directional microphones was not expected to result in a significant change in loudness ratings. Although hearing instrument frequency response was altered with directional microphone use, the change in output appeared to be level dependent and relatively small with low-level inputs (see Figure 2). DNR use was expected to demonstrate an effect based on the literature reporting improved listening comfort with DNR use (Bentler et al., 2008; Bentler & Chiou, 2006; Mueller et al., 2006; Ricketts & Hornsby, 2005); however, most research that has demonstrated improved comfort with use of DNR has used steady-state noise or noise with low modulation rates as the competing signal. The current study demonstrated no effect of DNR use on loudness perception. This lack of effect is likely due to the characteristics of the competing signal used in this study. Recall from Figure 4 that the DNR system of the hearing instruments in the current study demonstrated much more gain reduction with pink noise than with the Auditec four-talker babble used as the competing signal for the sentences in noise loudness perception task. This noise source was chosen in the interest of representing commonly encountered real-world listening situations (Fikret-Pasa, 1993). This choice is consistent with a goal of the current study, which was to identify a fitting strategy for use in the nonquiet environments experienced by children in their daily lives as described by Crukley et al. (2011). Unfortunately, this may indicate that DNR may not be expected to provide significant loudness reduction in high-level multitalker environments, at least for the algorithm, settings, and classroom environments used in this investigation.

There was a significant effect of loudness task condition, which indicated higher loudness ratings when sentences were presented in quiet than when sentences were presented with competing noise. The original purpose of the loudness perception task was to evaluate perceived loudness when competing sound sources were present; we did not expect that the task condition would exert an effect of its own. This significant effect of loudness perception task (sentences alone vs. sentences in noise) was unexpected. A possible explanation for this unexpected result could be attributed to the children rating the intelligibility of the sentences rather than the overall loudness of the sentences and noise combined. The same four-talker babble was used for the sentence recognition and loudness perception tasks, and because BKB sentences from the practice lists of the BKB-SIN test materials were used for the loudness perception task, the sentence structure was the same across tasks and conditions. Although the participants were instructed to pay attention not to the content of the sentences but only to the overall loudness, it is possible that they interpreted “loudness” as referring to the intelligibility of the sentences or the level of the sentences over and above the level of the noise. The SNR of the sentences was fixed at 10 dB for the sentences in noise condition; however, some children required greater than a 10-dB SNR for 50% correct on the BKB-SIN, as shown in Figure 5. This could have led to lower intelligibility and thus lower ratings corresponding to the amount of signal versus the amount of noise, relative to the sentences presented in quiet, even though the overall input levels were matched between conditions. Perhaps it was an interaction between having prior experience and misinterpreting the instructions that led to the unexpected result of lower loudness ratings with competing signals. For this reason, it may be inappropriate to derive clinical implications from comparisons of the loudness ratings between conditions of speech alone and speech in babble. Within each of these conditions, however, the relative changes caused by changes in hearing instrument gain or signal processing are likely valid for that type of listening situation.

Although perplexing, this result has implications for future research regarding loudness judgments with competing signals. Effort should be made to control for task interpretation by young participants in order to avoid confounds and improve the validity of perception ratings. Analysis of the loud sounds ratings indicated that the ratings with the DSL v5 Noise prescription combined with a directional microphone were significantly lower than ratings with any other combination of prescription and DSP. This was likely due to the combined effects of the lower gain DSL v5 Noise prescription and the low-frequency attenuation of the directional microphones at high input levels. Even though the combination of the DSL v5 Noise prescription with a directional microphone resulted in the lowest gain and, thus,
output, it also resulted in the best sentence recognition in noise performance.

Conclusions

In this study, we addressed two research questions regarding fitting strategies for managing the nonquiet listening needs of children who wear hearing instruments. First, does the use of a prescribed frequency-gain response, directional microphone, DNR, or a combination result in better sentence recognition in noise? There was significant improvement in sentence recognition in noise scores with use of a directional microphone, independent of the prescribed frequency-gain response. There was no significant difference between the prescriptions we evaluated, specifically the DSL v5 Quiet and DSL v5 Noise prescriptions. Second, does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds? The perceived loudness of loud sounds was rated lowest with the combination of the DSL v5 Noise prescription and a directional microphone. Overall, use of the DSL v5 Noise prescription with a directional microphone improved sentence recognition in noise performance and reduced loudness perception ratings for loud sounds relative to a typical clinical reference fitting with the DSL v5 Quiet prescription with no DSP features enabled.

If the hearing instrument fitting goals are to improve speech recognition in noise and reduce aversive ratings of loud sounds, the DSL v5 Noise prescription with a directional microphone is a potential strategy. If the goal is instead to provide loudness comfort in high-level environments without risk of directional disadvantages (e.g., when listening from the side), the DSL v5 Noise prescription without directional microphones is a potential strategy. Either strategy could also be combined with DNR, but expectations for outcome should be limited to the known effects of this technology. In addition, further research into the effects of nonquiet fitting strategies with children who have steeply sloping hearing loss may be warranted.

Acknowledgments

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References


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