Efficacy of an Adaptive Directional Microphone and a Noise Reduction System for School-Aged Children

Jane Auriemmo, AuD
Widex USA, Long Island City, New York

Francis Kuk, PhD
Chi Lau, PhD
Widex ORCA, Lisle, Illinois

Briana Kelly Dornan, MS
Stephanie Sweeton, MS
The Learning Center for Deaf Children, Framingham, Massachusetts

Sue Marshall, MA
Margaret Pikora, AuD
Debra Quick, AuD
Natalie Thiele, AuD
Patricia Stenger, MA
The Special School District of St. Louis County, St. Louis, Missouri

A non-randomized, experimental study utilizing double-blinding was implemented to investigate differences in word recognition performance of school-aged children utilizing adaptive directional microphone and noise reduction (NR) features. Children from two educational facilities participated in this study. Signal-to-noise ratio (SNR) benefit of the adaptive directional system was estimated to be 7.6 dB. No SNR benefit was measured for the NR feature; however, no decrease in performance was observed either. Subjective difficulty for desired sounds originating from various azimuths was not significantly greater in either the adaptive directional or NR modes. Results indicate that for the purposes of improving SNR, adaptive directional microphone systems, but not NR systems, are potentially efficacious hearing aid fitting options for school-aged children.

Introduction

The American Academy of Audiology Pediatric Amplification Guidelines suggest that the type of microphone mode should be dictated by the age and abilities of the child (AAA, 2003). The guidelines suggest that efficacy data regarding signal processing schemes utilizing noise reduction (NR) are required before such features can be implemented confidently in children. It is well-documented that children require a more advantageous signal-to-noise ratio (SNR) than adults for equivalent performance on speech recognition tasks (Stelmachowicz, Hoover, Lewis, Kortekaas, and Pittman, 2000; Soli & Sullivan, 1997; Elliot, 1979). The typical method of choice for improving SNR for children is a Frequency Modulated (FM) system because FM SNR benefit is as high as 15-20 dB (Hawkins, 1984; Lewis, Crandell, Valente, & Horn, 2004). However in clinical reality, FM system use cannot always be implemented. Hearing aid (HA) directional microphone systems and NR schemes are both alternative personal technologies with the potential to improve SNR. HA directional microphone systems are known to be less successful than FM systems in this regard (Hawkins, 1984; Lewis, et al., 2004). The reported SNR improvement provided by HA directional schemes varies among studies. For school-aged children, SNR improvement has been reported as 4.7 to 8 dB (Gravel, Fausel, Liskow, & Chobot, 1999; Kuk, Kollofski, Brown, Melum, & Rosenthal, 1999). Noise reduction schemes provide adult listeners subjective benefit (Mueller, Weber, & Hornsby, 2006); however, evidence is lacking to support improvements in SNR (Mueller, et al., 2006). Documentation of efficacy of both of these technologies is limited in regards to use in children. This is due at least in part to the reticence of pediatric clinicians to fit children with these types of features.

The basis for the caution in selecting either of these features, directionality or NR, involves the importance of ensuring audibility and the unknown effects on language acquisition. In terms of traditional directional technology (i.e., fixed directionality with a relatively high compression threshold [CT]), a directional system may not be the ideal choice for young children for two major reasons: safety and potential loss of audibility of speech. Directional systems typically alter the sensitivity of the HA microphone for sounds originating at azimuths other than zero. Some clinicians are wary of fitting directional systems on children, citing concerns for a potential reduced sensitivity of warning sounds originating from the sides or back. Additionally, audibility of speech originating from the sides and back of a child is important because it is known that "over hearing" conversations may be a language-learning opportunity. Similarly, NR systems reduce the gain of the HA, and in so doing, may also reduce the audibility of speech cues. Modern adaptive technology may help alleviate these concerns. Limited evidence exists to support the use of these features in children to date. However, there is evidence supporting both efficacy and preservation of audibility when these features are used in adult HA fittings.

Benefits of an adaptive directional microphone system have been documented for adults (Valente & Mispagel, 2004). In a study investigating performance on the Hearing in Noise Test (HINT) and Abbreviated Profile for HA Benefit (APHAB) using the Widex Diva in-the-canal style HA, Valente and Mispagel (2004) measured SNR improvements by comparing the HINT threshold in omni-directional mode with the HINT threshold in adaptive directional mode. They demonstrated a SNR improvement of 7.2 dB for an uncorrelated noise stimulus presented at 180^0. SNR improvements for more diffuse noise conditions were decreased to 4-5 dB.

Kuk, Keenan, Lau, & Ludvigsen (2005) investigated limitations of an adaptive directional microphone system in adults. The aided soundfield thresholds and word recognition ability were measured at 90^0, 180^0, and 270^0 in omni-directional mode, adaptive directional mode, and in a fixed directional mode for 17 adults in this study. Results indicated equivalent aided thresholds and word recognition performance at azimuths other than zero in omni-directional and adaptive directional mode. The authors attributed this finding to design characteristics of the system. Directionality of the test instrument is not activated in quiet environments; hence, no effect on aided soundfield thresholds was seen. Slow time constants are used to determine activation of the directional system. This provides the listener with an opportunity to turn his head towards desired sounds originating from azimuths other than 0^0. It also allows for a smooth transition among polar patterns. This explained the equivalent word recognition performance at azimuths other than 0^0 in adaptive directional mode. It is likely that similar results would be seen in school-aged children for adaptive microphone technology. This is reasonable to assume since results of studies of basic directional microphone technology in children have been comparable to those for adults (Gravel, et al., 1999; Kuk, et al., 1999).

Noise Reduction systems have been reported to provide a subjective improvement in listening in noise for adults. Ricketts and Hornsby (2005) used a NR enabled/disabled paired-comparison paradigm and determined that listeners preferred listening to speech in noise with NR enabled. However, improvements in speech intelligibility with NR enabled were not measurable (Ricketts and Hornsby, 2005). Mueller, et al. (2006) demonstrated a 4.2 dB improvement in acceptable noise level (ANL) for a group of 22 adults utilizing NR schemes. They did not measure a significant improvement in Hearing in Noise Test (HINT) threshold with NR. However, decrements in performance were not measured either (Mueller, et al., 2006). Nordrum, Erler, Garstecki, & Dhar (2006) studied the combined effect of NR and directionality in 16 adults using the HINT. They found no difference in HINT threshold for the directional alone and directional plus NR conditions.

Efficacy of Directional and Noise Reduction Features for Children

Gravel, et al. (1999) and Kuk, et al. (1999) both used a similar test set-up (speech from 0^0 and noise at 180^0) to examine directional microphone use in school-aged children. Gravel, et al. (1999) examined the word and sentence recognition performance of twenty hearing-impaired children utilizing an analog, single-channel, programmable dual microphone systems. They calculated the SNR at which 50% performance was obtained. A significant average SNR improvement of 4.7 dB was obtained for both words and sentences in directional mode over the omni-directional mode. Furthermore, this study indicated that younger children required a more favorable SNR than older children for equivalent performance.

Kuk, et al. (1999) examined the word recognition performance of school-aged children using digital directional instruments. Efficacy of digital directional instruments was assessed for 20 children using the CID W-22 word lists and Listening Inventory for Education (LIFE) questionnaire (Anderson & Smaldino, 1998). The HA evaluated was a single fixed directional microphone system with a low compression threshold (CT) at 20 dB HL. Testing was performed at three different SNRs: +7, 0, and -7dB. Comparing the performance-intensity function of the directional system to that of the children's own personal HAs, SNR improvements of 5.5 dB and 8.0 dB were extrapolated for the moderate and mini-power directional instruments tested, respectively. Results of subjective inventories demonstrated that children rated the directional systems as higher than their own HAs in the classroom. Teachers saw limited improvement; however, no negative changes were reported. Most parents noted better performance with the directional instruments in various listening environments.

More recently, Ricketts, Galster, and Tharpe (2007) investigated performance of directional microphones in simulated classroom environments. The primary experimental HA utilized by the school-aged children in this study was a two-channel instrument with a CT at 40 dB SPL. The HINT sentences were used to assess speech recognition with the HAs in omni-directional mode, as well as with fixed directional characteristics coupled to unvented earmolds. They observed directional advantages for speech originating from the front of the child and directional disadvantages (i.e., poorer speech recognition performance in directional mode for speech originating from the back of the child).

While studies of HA directionality are limited, those examining the effects of NR in children are even fewer. Marcoux, Yathiraj, Cote, and Logan (2006) studied the effect of NR on language acquisition; however, the sample consisted of adults with normal hearing. In this study, the experimental group listened to speech processed through the digital NR system of a hearing aid. For these adults, "language acquisition," as measured by performance on non-native consonant contrast tasks, was not significantly affected by this NR system. The broader supposition from results of this study was that it is unlikely that NR systems, which operate similarly to the study HA, would contribute to language acquisition problems in a pediatric population.

Language outcomes of children using both automatic directional microphone and NR systems were reported by Auriemmo, Lau, and Kuk (2007). They monitored language progress of a group of 49 children fitted at various ages with HAs utilizing automatic directional microphone and NR systems. The NR system utilized was identical to that studied by Marcoux, et al. (2006). Results indicated that the average language scores of these children progressed at a faster rate than that of their normal-hearing peers. Children fitted with these features earlier (i.e., under the age of five) progressed at faster rates than children fitted over the age of five years. Although this study did not directly look at the effects of automatic directional microphone and NR systems, results indicated that these features did not impede speech and language progress.

Although the information available for performance of children remains limited, recent surveys indicate that the prevalence of directional microphone and NR fittings are increasing (Rigsby, Bradham, Dickinson & Mueller, 2007). Perhaps the design and compensatory features of advanced technology instruments has assuaged some pediatric clinicians. However, efficacy data for children continues to be limited for use of both adaptive directional microphone systems and NR systems. In addition, audibility concerns remain unaddressed.

The present study was undertaken in order to investigate the performance of a fully adaptive directional microphone and NR system for school-aged children. An additional goal was to explore whether or not the use of these features resulted in greater perceived difficulty for children in listening environments where desirable sounds originate from the sides or from directly behind the child rather than in front.

Based on SNR improvements demonstrated for children using single fixed digital microphone technology as those demonstrated in the Kuk, et al. (1999) study, children using an adaptive directional system would be expected to perform at least as well, if not better, on word recognition. Additionally, it is likely that subjective assessments of children and parents would prove more positive with a fully adaptive system, particularly if the limitations associated with directional systems were addressed in the design of the technology (Kuk, et al., 2005).

Efficacy of an adaptive directional system for children has not been reported to date. Such a study would be potentially useful in developing guidelines for fitting directional microphone technology to children. The specific objective of this study was to compare the word recognition performance of a group of children in 3 conditions: (1) adaptive directional mode, (2) omni-directional mode, and (3) omni-directional mode with NR active. Subjective efficacy in each of these three conditions was also assessed using questionnaires. An additional goal was to evaluate performance with the two features working in tangent over time.

Method

Participants

Nineteen hearing-impaired children age 6 years-1 month to age 12 years-9 months (mean age = 10 years) participated in this study. Two sites participated in data collection for this study: The Special School District of St. Louis County, St. Louis, MO (Site 1; N=10) and The Learning Center for Deaf Children in Framingham, MA (Site 2; N=9). All children were proficient English speakers, met developmental milestones, were mainstreamed in their classrooms and primarily used oral-aural communication. Language age of all children was within 1 ½ years of chronological age with good articulation scores. Fifteen children used FM systems along with their HAs in the classroom. All children, with the exception of one, were experienced HA users wearing a variety of digital technology. Children utilized custom-made skeleton-style earmolds with 1mm venting. This amount of venting was chosen based on audiometric thresholds at 500 Hz. This would prevent confounding speech recognition test results, as a result of a decrease in directivity index due to a larger vent size (Kuk, Keenan, & Ludvigsen, 2004; Ricketts, 2000). The average hearing loss of all participants was mild to moderately severe. Hearing losses were sensorineural in nature. Air conduction thresholds were monitored prior to each test session. Experimental assessment was not performed if a significant change in hearing thresholds was determined. The individual and average audiograms of all 19 children are shown in Figures 1a and 1b.

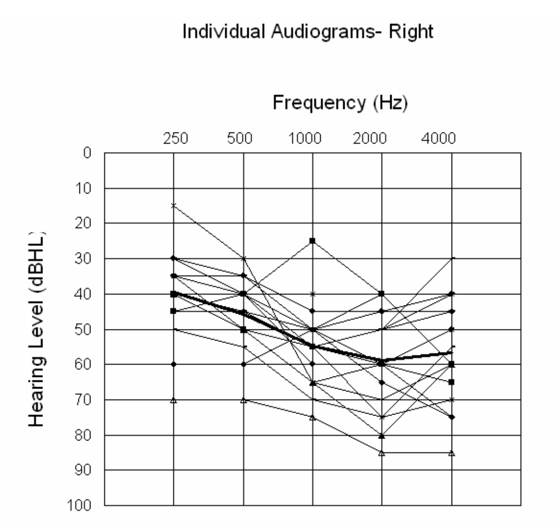
Data were collected from children at each facility with the approval of the protocol by the school boards. Consent was discussed with parent, along with child. In addition, the nature of the study was explained without mentioning specific features. That is, parents and children were informed that three different HA settings would be assessed to determine which resulted in the best performance and highest preference in noise. Additionally, parents and children were informed of the *double-blinding* element. Neither parent/child nor clinician performing fitting and assessment was aware of the specific features being assessed during each six-week-trial period. This involved the participation of two audiologists. One clinician adjusted the HA settings and a second (blinded clinician) performed speech recognition testing and administered and reviewed the surveys. The double-blinded conditions examined were: (1) adaptive directional mode, (2) omni-directional mode, and (3) omni-directional mode with NR active. In addition, after completion of the experimental conditions, the HA default condition (adaptive directionality plus NR) was uniformly adjusted for all children (i.e., not double-blinded), and performance in the default condition was evaluated over time. Families were further informed that they could drop out of the study at any time. No funds were exchanged between Widex and the facilities performing testing. Families were not paid for participation in this study; however, the children received HAs free of charge to keep for their permanent use.

Hearing Aids

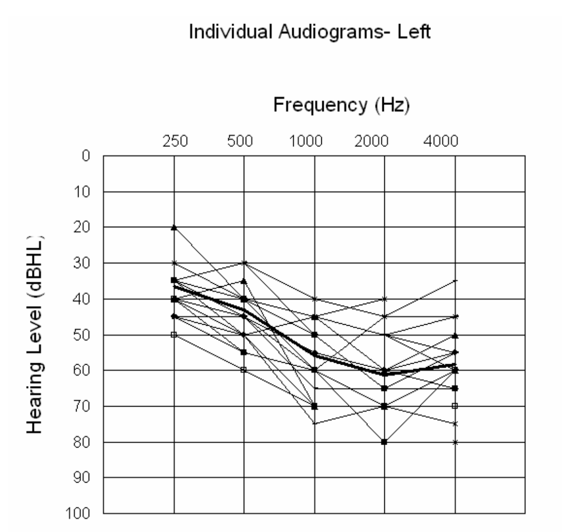
Two models of the Widex Diva digital HA were used in this study: the Widex Diva SD9M and the Widex Diva SD19M. The Diva HA is a fifteen-channel, primarily slow-acting, wide dynamic range compression (WDRC) HA with a CT at 0 dB HL and an active feedback cancellation system. Function and efficacy of the feedback cancellation system is described in Kuk, Ludvigsen, and Kaulberg (2002). The two study models differ only in terms of the receiver component. The SD9M is a miniature BTE with 45 dB peak gain and an Output SPL90 peak of 117 dB SPL. The SD19M utilizes a higher-output receiver, with 52 dB peak gain and an OSPL90 peak of 126 dB. The two study models use the same adaptive directional microphone and NR system design.

The NR system utilizes a level distribution function in order to identify noise signals. The NR system is triggered only above a conversational level (i.e., above approximately 60 dB SPL) in order to preserve important soft level speech and environmental information (Studebaker & Marincovich, 1989). The NR feature operates with long time constants. When NR is triggered, it functions independently in each of the 15 1/3rd octave channels. The design of this NR system incorporates the following ‘safety’ mechanisms, which may preserve audibility. The system is only activated for long duration, un-modulated input signals. The effect of the NR is graded depending upon the level of the noise and SNR of the environment. In addition, a speech intensification system (SIS) operates to reduce a lesser amount of gain in the mid and high frequencies where speech intelligibility cues dominate for the same signal-to-noise ratio (Kuk, Ludvigsen, & Paludan-Muller, 2002).

1a.



1b.



Figures 1a and 1b. Individual audiogram thresholds from 250-4000 Hz for right and left ears respectively. Average audiograms are indicated in bold.

The directional microphone system, fully described by Kuk, et al. (2005), utilizes inputs from two omni-directional microphones separated by 10 mm. It is fully adaptive in that it automatically adjusts to and from omni-directional mode with a potentially infinite number of polar patterns in between omni-directional and bi-directional. The two omni-directional microphones are monitored and adjusted for differences in amplitude and phase characteristics initially and during use. This is a result of a microphone matching algorithm designed to maintain performance even after long-term use of the instrument. The statistical properties of the inputs to each microphone are monitored in order to identify wind noise, circuit noise, or environmental sounds (i.e. speech). The system is not activated for inputs less than approximately 50 dB SPL. The low-frequency sensitivity of the HA is compensated in each directional polar pattern in order to achieve the same frontal frequency response as for the omni-directional microphone pattern. The polar pattern changes require between 5 and 10 seconds for extreme shifts (i.e., omni-directional to bi-directional). Rationale and design of this directional system is detailed in Kuk, Baekgaard, and Ludvigsen (2002).

Hearing Aid Fitting

Fitting of the Diva HAs included measuring the in-situ threshold at four (or more) frequencies and completing a feedback test to limit the maximum gain before feedback. Children wore custom-made, skeleton-style earmolds with 1 mm venting for this procedure. In-situ thresholds were measured at 500, 1000, 2000, and 4000 Hz using frequency modulated sinusoids generated from the hearing instrument. In-situ thresholds were measured at inter-octave frequencies when significant differences (i.e., > 10 dB differences) were obtained for adjacent octaves. Feedback testing was performed in order to determine the maximum amount of available gain in each channel and to estimate the feedback path. This test sets the individual user parameters for active feedback cancellation (FBC). FBC was enabled for all HAs. Active FBC identifies the characteristics of the feedback signal and creates a signal equal in frequency, but opposite in phase, in order to cancel it. This system has been shown to increase available gain before feedback by 10-12 dB (Kuk, Ludvigsen, & Paludan-Muller, 2002).

Clinicians incorporated average, age-based real-ear-to-coupler (RECD) values into the Audioscan Verifit HA analyzer and performed simulated real-ear measurements (S-REM). The goal was to ensure that there was sufficient audibility and appropriate output. Output for soft (55 dB SPL), conversational (65 dB SPL) and loud (75 dB SPL) speech inputs were examined in the default program. Clinicians ensured the average output of soft speech for 500-4000 Hz was 5-10 dB sensation level (SL), the average output of conversational speech was 15-20 dB SL, and the peak output for loud speech and a 90 dB SPL sweep tone was below predicted uncomfortable levels. Generic target-matching was not implemented as, at the time of data collection, corrections for features, such as multiple channels, were not incorporated into the target algorithm (Kuk & Ludvigsen, 1999). Target-matching would have resulted in too high of an output.

The study HAs utilized very low CTs (i.e., as low as 0 dB HL). Therefore audibility of soft sounds was expected. Aided soundfield testing was included in order to confirm audibility of soft sounds was achieved. HA programs were adjusted where necessary to meet the following criteria: 20 dB HL aided thresholds, optimally 500-4000Hz, but at minimum through 2000Hz and no worse than 30-40dB HL thereafter.

Materials

The efficacy of the directional system for speech intelligibility was assessed using mono-syllabic word recognition testing. This was performed using the Central Institute for the Deaf (CID) W-22 word lists at 50 dB HL in quiet and at SNRs of +5, 0 and -10 dB. Half-lists (twenty-five items) were administered. Monitored live voice (MLV) was utilized to present speech materials. Continuous American National Standards Institute (ANSI 2003) speech-shaped noise delivered from an audiometer was used as the noise stimulus. These parameters were selected based on their clinical utility and results of pilot studies at other facilities.

In order to assess the perceived degree of difficulty experienced by each child in various listening environments, the directional subscales developed by Ricketts, Henry, and Gnewikow (2003) were administered to children. These questionnaires were chosen because they included items that assess what percent of the time an individual feels s/he is able to hear desired speech and environmental sounds from azimuths other than 0^{0}, including both near and far field items ("Sound Back" subtest), as well as desired speech from 0^{0} ("Sound Front"). Additionally, the number of items in each of the two subscales is limited to seven, making it easy to administer in survey format. With minor wording changes, we felt these were appropriate for the children participating in this study and would help answer the question as to whether or not children experienced more difficulty in the adaptive directional microphone or NR condition. Parents were asked to complete the parent version of the Abbreviated Profile of Hearing Aid Performance (PA-PHAP) (Kopun & Stelmachowicz, 1998). This questionnaire included various listening environments affording parents an opportunity to observe and report how well their children responded in a broad range of situations. Again, the goal was to identify any situation where the adaptive directional or NR condition resulted in more difficulty for children.

Because both parents and children would be more likely to notice new auditory experiences in the first days following the fitting, we felt that it would not be prudent to wait until the six-week trial period was over for survey completion. Therefore, all questionnaires were completed after one week of HA use. Clinicians made follow-up phone calls to ensure questionnaires were completed. In cases where the written questionnaires presented a problem due to reading or language skills of parents and/or children, clinicians administered the questionnaires in survey format.

Procedures

The audiometers used to present stimuli were a Grason-Stadler Incorporated (GSI) 61 at site 1 and a GSI 16 at site 2. Testing was conducted in a calibrated, double-wall, sound-treated test suite at both facilities. Children were seated one meter from each of two test loudspeakers. One loudspeaker was positioned at 0^0 and the other was positioned at 180^0. We chose this set-up for clinical expediency, as multiple loudspeaker arrays were not available at either test site. Noise was presented for 60 seconds prior to word list presentation. This served to "condition" the hearing instruments in order to ensure that both the adaptive directional mode and NR algorithms were fully activated.

Speech recognition performance was assessed after six weeks of use in each of the three conditions. The HA program button was disabled during trial periods in order to ensure the children only had access to the test condition throughout each trial period. Conditions tested were omni-directional microphone mode, omni-directional microphone mode with NR active, and adaptive directional mode. The order of HA condition was counterbalanced for each facility. Presentation order of each of the four CID W-22 word lists was counterbalanced across participants. The primary goal was to examine the SNR benefit of this adaptive directional system. In order to utilize clinic time most efficiently, the HA default condition - both adaptive directional and NR features concurrently active- was not part of the experimental study (i.e., was not subject to double-blinding). However, the default condition was adjusted uniformly for all participants after completion of the experimental conditions and then evaluated separately.

Each participant attended at least four visits for data collection. The first was an initial fitting and assessment session of the hearing aid default condition. Three assessment sessions followed. Assessments took place after six weeks of use in each trial condition. Implementing these three conditions would allow for later analysis of the effect of NR and adaptive directionality. Again, the default condition was assessed at the initial fitting visit for purposes of collecting baseline data; however, it was not configured for use by children until after completion of the experimental study.

Prior to fitting and test sessions, HAs were tested electroacoustically to ensure they were working properly. ANSI (2003) testing was performed after engaging a HA test mode. In order to prevent confounding test results due to hearing loss fluctuations throughout the trial periods, air conduction retesting was performed at the start of each visit.

Initial fitting and baseline assessment. The initial visit involved fitting and fine-tuning of the instruments and baseline testing, which was performed in the HA default setting. Because no fine-tuning adjustments would be made during the trial periods, audibility and comfort for different input levels needed to be accomplished at the fitting visit. Default setting parameters included adaptive directionality and NR features active.

The baseline testing included word recognition testing in quiet and at various SNRs in the default condition (adaptive directional microphone and NR features active). At the end of this session, HA parameters were adjusted to the first experimental setting. The child and family members were instructed regarding use and care of the HAs and were reminded of the purpose of the study. Specifically, they were asked to pay attention to how well the HAs performed in various environments and questionnaires were distributed. Children and parents were advised that they would later be surveyed with the items contained in the questionnaires after one week of use. Parents were given PA-PHAP questionnaires. They were also given the Ricketts, et al. (2003) directional microphone subtests in order to survey their children. Additionally, children were asked to inform their parents about any new auditory experiences or any problems they encountered throughout the trial period.

Evaluation of experimental conditions. After six weeks of use, children returned to the clinic for assessment of HA Test Setting 1. The speech-to-noise ratio (SNR) levels for speech recognition testing were based on results of pilot testing performed at clinical facilities outside of the test sites. The original test levels chosen were quiet at an input level of 50 dB HL, +5, 0 and -5 dB SNR. However, pilot results indicated a limited range effect. Therefore, test levels were adjusted to include quiet and SNRs of +5, 0 and -10 dB. At the end of the test session, HA parameters were adjusted for Test Setting 2. These steps were later repeated a third time for HA Test Setting 3.

At the conclusion of the third trial period and after word recognition testing, HAs were set with the default parameters active (i.e., adaptive directionality and NR). Testing was then performed after six weeks in the default setting (adaptive directional plus NR). Where possible, retesting was performed once again one year post use with both adaptive directional and NR activated for children. This provided a comparison with baseline performance in order to examine performance over time. Once again, when possible, speech and language of most children were reassessed after one year of use with these features.

Table 1. Results of paired-samples *t*-test. "Locator" is the adaptive directional system, "Omni NR" is omni-directional with noise reduction, and "Omni" is omni-directional alone. Those pairs with significant mean difference are underlined and in bold.

		Paired Differences				
		Mean Difference	SD	t	df	p
Quiet	Locator - Omni NR	0.1	16.0	0.01	18	1.00
	Locator - Omni	0.6	11.9	0.20	16	1.00
	Omni NR - Omni	1.3	14.1	0.38	16	1.00
+5 dBSNR	Locator - Omni NR	3.5	18.0	0.85	18	1.00
	Locator - Omni	5.6	16.1	1.43	16	0.52
	Omni NR - Omni	3.2	16.9	0.79	16	1.00
0 dBSNR	Locator - Omni NR	15.3	20.4	3.26	18	**<u>0.01</u>**
	Locator - Omni	14.6	22.1	2.72	16	**<u>0.05</u>**
	Omni NR - Omni	-0.8	21.6	-0.16	16	1.00
-10 dBSNR	Locator - Omni NR	25.8	22.6	4.97	18	**<u>0.00</u>**
	Locator - Omni	28.1	32.0	3.63	16	**<u>0.01</u>**
	Omni NR - Omni	1.9	32.1	0.25	16	1.00

Results

Speech Recognition

The speech recognition data from the two sites were tested to examine homogeneity (i.e., whether the effect of "Site" was significant). A factorial repeated measures General Linear Model (GLM) was used to examine three factors: within-subjects factor "Hearing Aid Setting" (Adaptive Directional Microphone or "Locator," Omni-directional with NR, and Omni-directional alone), within-subjects factor "Noise Condition" (Quiet, SNR=+5,dB, SNR=0 dB, SNR=-10 dB), and between-subjects factor "Site" (two testing sites). All speech scores were transformed into rationalized arsine units (Studebaker, 1985) before applying statistical analysis. Results indicated "Hearing Aid Setting" ($F(2,30)=5.772$, $p=0.008$, power = 0.8) and "Noise Condition" ($F(3,45)=128.557$, $p<0.001$, power = 1.0) were significant, but "Site" ($F(1,15)=0.094$, $p=0.763$) was not significant. Therefore, combining the data of the two sites as one pooled set of data was determined to be acceptable.

Speech recognition test results are displayed in Figure 2. Using paired-sample t-tests with Bonferroni adjustment for multiple comparisons, the performance of the different HA settings was compared under different noise conditions. Table 1 summarizes the post-hoc results. In quiet and for the +5 dB SNR listening condition, the word recognition scores were the same across the various HA settings. For the 0 dB SNR, speech recognition scores were significantly better ($p<0.05$) for the adaptive directional mode than for the omni-directional with NR (12% improvement) and the omni alone (10% improvement). For the -10 dB SNR, adaptive directional mode resulted in significantly better ($p<0.05$) performance than the other HA settings (27% to 28% improvement).

Speech recognition scores were used to calculate the equivalent improvement in SNR ratio (Valente, Sweetow, Potts & Bingea, 1999). Performance-intensity (PI) functions were plotted in order to calculate SNR differences between performance in adaptive directional mode and performance in omni-directional mode, as well as differences between performance in omni-directional mode with NR active and performance in omni-directional mode alone. These PI functions are displayed in Figures 3 and 4.

The PI function (i.e., the speech score as a function of SNR for results in omni-directional mode [best-fit linear function]) and the PI function in adaptive directional mode (best-fit curvilinear function) were plotted and are displayed in Figure 3. The SNR corresponding to 50% performance can be identified by drawing a horizontal line (dashed horizontal line) at the 50% performance mark through the two PI functions. The difference in SNR between the two conditions represents the equivalent SNR improvement for the adaptive directional condition. This approach assumes a uniform and predictable change in speech scores along the PI function. Using this approach, a SNR improvement of 7.6 dB for the adaptive directional condition was estimated.

The PI functions for results in omni-directional mode with NR active and for omni-directional mode alone are plotted and displayed in Figure 4. These two PI functions essentially overlap, indicating that there is no difference in performance at various

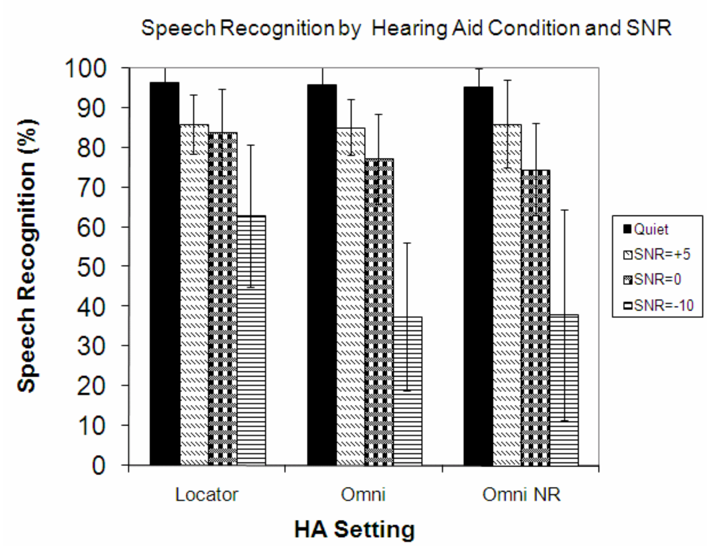


Figure 2. Average speech recognition scores for experimental conditions.

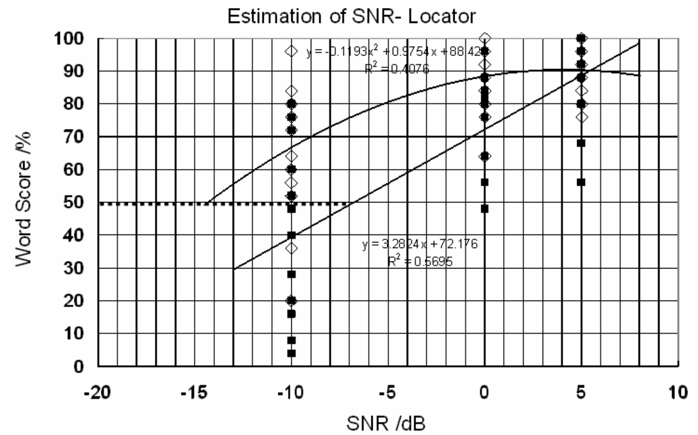


Figure 3. Performance-Intensity (PI) functions for adaptive directional and omni-directional modes.

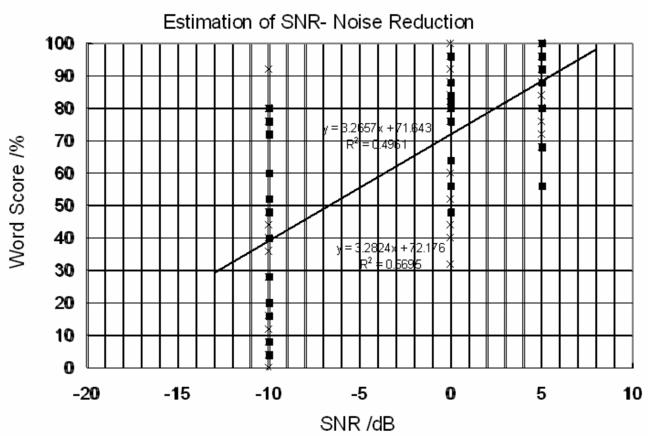


Figure 4. Performance-Intensity (PI) functions for omni-directional and NR modes.

SNRs and consequently no improvement in SNR due to NR.

Finally, an analysis was performed in order to examine the children's performance over time in the default HA condition. The default HA parameters included adaptive directionality plus NR. Performance in this condition was measured at the initial fitting session immediately prior to the first experimental trial period. The default parameters were employed after the conclusion of the study. For 15 children who completed the follow-up testing sessions, the default condition was re-examined after six weeks and after one year of use in quiet and at the three SNRs. Speech recognition results for the three time periods in the default condition are displayed in Figure 5.

Using a repeated measures GLM, two within-subjects factors were tested: 'Time' (i.e., Baseline, six months, one year) and 'Condition' (i.e., Quiet, +5dB, 0dB, -10dB). Again, the speech data were transformed into rationalized arcsine units before applying statistical analysis. Results indicated that the factor 'Time' was significant (F(2,28)=7.939, *p*=0.005, power=0.9). Additionally the factor 'Condition' was significant (F(3,42)=122.224, *p*<0.001, power=1.00). Results of post-hoc testing with Bonferroni adjustment for multiple comparisons indicated that performance at six months and one year was significantly better than baseline (*p*<0.05). Performance at one year was not significantly different from six months (*p*>0.05).

Subjective Assessments

Parent questionnaire. Completed parent and child surveys for each of the three test conditions were available for 13 children. The PA-PHAP questionnaire results provided us with "percent of difficulty" children experienced (in the eyes of their parents) for each HA setting in each environmental condition. Adaptive directionality resulted in less difficulty than other HA settings for all subtests except for the *Aversiveness* (AV) subtest. However, using a repeated measures GLM analysis to study the main within-subjects effect of HA settings and listening categories showed that there was no significant effect of HA setting (own aids, and study aids in omni-directional, omni-directional +NR, and adaptive directional mode) for the PA-PHAP data (F(3,36)=1.621, *p*=0.20). The listening category (EC, BN, RV, AV) was significant (F(3,36)=3.298, *p*=0.03, power=0.71).

Directional microphone subscales- sound front. The average percent of difficulty for the children's own HAs and the study HAs in adaptive directional mode, omni-directional mode with NR, and omni-directional mode alone is shown in the bar graph in Figure 6a. The amount of difficulty experienced with the child's own HAs was the greatest; however, the variance for this condition was the largest. The amount of difficulty experienced by children for desired speech from the front was the least for the adaptive directional and Omni NR conditions, which were similar. A one-way repeated measures GLM indicated no significant difference in

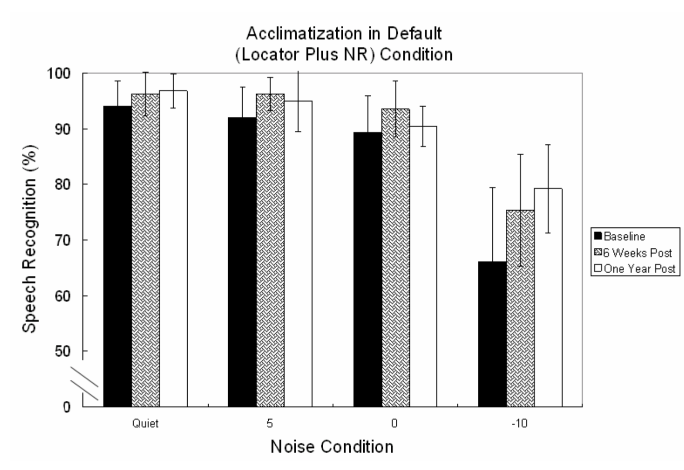


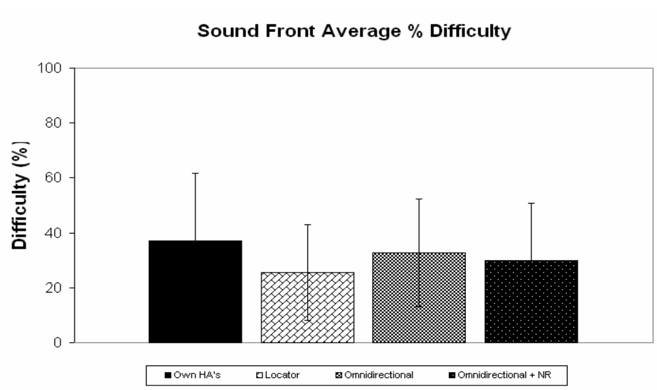
Figure 5. Speech recognition with both adaptive directional and NR active as a function of time.

mean percent of difficulty among HA conditions ($F(3,36)=2.102$, $p=0.117$).

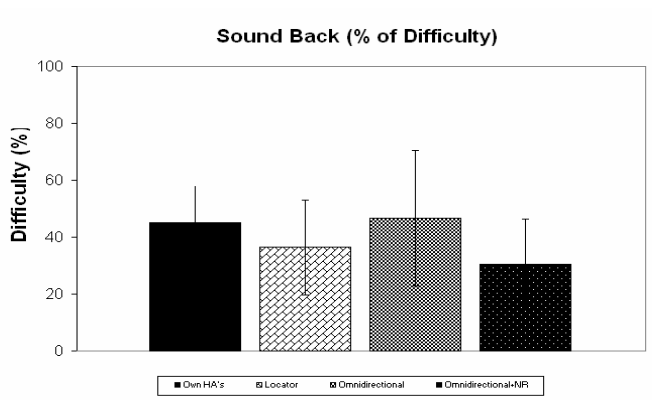
Directional microphone subscales- sound back. Average results of the directional microphone *Sound Back* subscale surveys are displayed in Figure 6b. The amount of difficulty experienced by children for desired speech and environmental sounds at azimuths other than 0^0 was the least for the adaptive directional and Omni NR conditions, which again, were similar. One-way repeated measures GLM indicated a significant difference ($F(3,36)=3.271$, $p=0.03$, power=0.70) in mean percent of difficulty among HA conditions for sounds originating from the sides or back of the child. Post-hoc analysis using paired-sample *t*-tests (with least significant difference) showed significantly less difficulty for the adaptive directional microphone ("Locator") condition than for the "own aids" condition ($t=2.26$, df=12, $p=0.04$, power =0.6) and the omni-directional with NR condition resulted in significantly less difficulty than the omni-directional condition alone ($t=2.51$, df=12, $p=0.03$, power =0.6).

Speech/language progress. Baseline and one-year post total language standard scores were available for 15 children; ten for

6a.



6b.



Figures 6a and 6b.

Results from *Sound Front* Subtest and *Sound Back* Subtest.

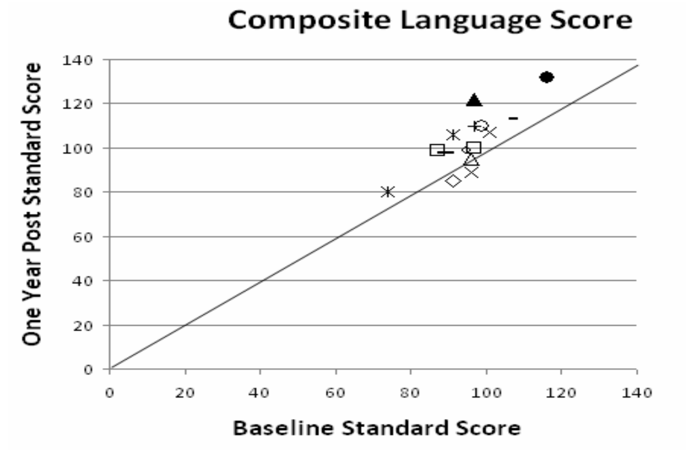


Figure 7. Performance on standard measures of language one year post use of both adaptive directional and NR features as a function of baseline performance.

the Oral and Written Language Scales (OWLS: Woolfolk, 1995) and five for the Comprehensive Assessment of Spoken Language (CASL: Woolfolk, 1999) tools. Individual pre- and post-composite language standard scores are displayed on a scatter-plot in Figure 7. Note that a standard score of 100 represents the average score for a typically developing (i.e., 'normal-hearing'), age-matched peer for both of these measurement tools. One standard deviation is 15 points for both of these measures. Data points on or above the diagonal indicate the same or better composite language scores one year post use of adaptive directional and NR features. This was essentially the case for all children.

Scores for receptive and expressive vocabulary measures were also analyzed. The receptive measure was the Peabody Picture Vocabulary Test- Third Edition (PPVT III; Dunn and Dunn, 1997), which was available for 18 children, and the expressive measure was either the Expressive Vocabulary Test Second Edition (EVT-2; Williams, 1997) or Expressive One Word Picture Vocabulary Test (EOWPVT; Brownell, 2000), which was also available for 18 children. These tools are also standard measures, and as a group, children performed the same or better one year post use of these features.

Discussion

The purpose of this study was to examine the efficacy of an adaptive directional and NR system for school-aged children, as measured by SNR improvement. A secondary goal was to examine whether children experienced more or less difficulty in various environmental situations and for desired sounds originating from azimuths other than 0^0 when using these settings. Results indicated significantly improved speech recognition performance at the poorest SNR in the adaptive directional microphone mode. SNR improvement of the adaptive directional system was estimated to be 7.6 dB compared with performance in omni-directional mode. Results also indicated no significant improvement in SNR for the

NR system alone; however, no decrement in performance was observed for NR either. In other words, objective measurements indicated the adaptive directional system used by the children in this study is clinically efficacious.

Additionally, word recognition was significantly better after six weeks and one year post use of both adaptive directional and NR features. This result may suggest that listening experience with these features improves clinical outcomes, although other factors (i.e., vocabulary development) may also have contributed.

Clinicians' reticence to utilize directional microphones for pediatric HA fitting is typically due to concerns about loss of audibility for desired sounds originating from azimuths other than 0^0. Parent and child surveys did not support this concern for the children in this study. Parents did not report that their children experienced greater difficulty for adaptive directional or NR mode compared to omni-directional mode in various listening environments. Additionally, the amount of difficulty perceived by children for environments where desired sounds originate from the sides or back of the child was not significantly greater in adaptive directional mode or in NR mode. On the contrary, children experienced significantly less difficulty in adaptive directional microphone mode for speech originating from the sides and back than when using their own HAs. We were not surprised by this finding for several reasons. The fully automatic directional microphone system remains omni-directional in quiet environments (i.e., for inputs less than 55 dB SPL). Some questionnaire items may have corresponded to such environments, for example "I can understand my doctor if s/he asks me a question while standing behind me." In quiet environments, soundfield threshold and speech recognition scores have been shown to be equivalent for adults when this instrument is in adaptive directional or omni-directional microphone mode (Kuk, et al., 2005). The instruments evaluated in this study utilized low CTs. Instruments with low CTs have been shown to provide better audibility for soft speech, including for soft speech originating from 180^0 (Lee, Lau, & Sullivan, 1998). Additionally, children experienced significantly less difficulty in the omni-directional with NR condition for speech originating from the sides and back than in the omni-directional condition with no NR active. To the extent that survey responses reflect the real world conditions (Walden, Surr, Cord, & Dyrlund, 2004), these results do not indicate that the adaptive directional and NR feature investigated in the current study presented this group of school-aged children with a disadvantage for desired speech originating from the sides or back.

Comparisons to Past Studies

Valente and Mispagel (2004) used multiple noise source configurations in the test environment in their study of the identical adaptive directional system. Included in their test conditions was a noise condition at 180^0, similar to the test set-up used in our study. However, those investigators utilized an uncorrelated party noise; we used a composite ANSI speech-shaped noise generated from the audiometer. Valente and Mispagel measured an improvement in SNR of 7 dB for adults using the 180^0 loudspeaker configuration for the noise stimuli. The 7.6 dB SNR improvement of the adaptive directional microphone measured in this study is consistent with the SNR improvement measured for adults using this same technology (Valente and Mispagel, 2004).

As previously mentioned, limited research exists that examines the efficacy of directional microphone use for children. In the Gravel, et al. (1999) and Ricketts, et al. (2007) studies, children in a similar age group as those in this study experienced smaller SNR benefits. Differences in findings may be explained by differences in fitting conditions (i.e., venting, test protocol, materials utilized, and hearing instruments and directional technology). The hearing instruments utilized in the Gravel, et al. (1999) study were single-channel, analogue devices with a significantly higher CT and utilizing a switchable directional system, as opposed to the fully adaptive system worn by children in the present study. The primary hearing instruments utilized in the Ricketts, et al. (2007) study were 2-channel digital instruments with higher CTs with fixed directional characteristics. Differences in HA technology could explain better findings for the instruments used in this study compared to those found in both the Gravel, et al. (1999) and Ricketts, et al. (2007) studies.

Kuk, et al. (1999) measured the SNR improvement of a fixed directional system with a low CT for school-aged children. They supplemented word recognition testing with the Listening Inventory for Education (LIFE) tool (Anderson and Smaldino, 1998). The SNR predicted from their study was based on comparing performance to that with the children's own analogue omni-directional instruments. Additionally, a different directional system was evaluated from the one used for this study. Thus, the SNR findings from that study are not readily comparable to our findings. However, the questionnaire results from their study indicated significantly higher ratings for the directional system in various school listening situations, including noisy listening situations. Additionally, student ratings for situations where the teacher was moving around the classroom were no poorer than they were for their omni-directional HAs. This would indicate that the directional system did not create more difficulty for situations where the desired sound originated from the sides or the back of the child. Our findings are consistent with this generalized finding from the Kuk, et al. (1999) study.

Implications of Survey Findings

Results of the parent and child surveys may reassure clinicians who are concerned about audibility loss when considering directional technology or NR systems for children. Indications from survey results indicate children did not experience greater difficulty in their daily environments with the adaptive directional or NR features active. A trend towards less difficulty with the adaptive directional feature for the *Sound Front* subscale items was observed; however an assessment did not indicate significantly less difficulty in adaptive directional microphone mode. The relatively 'weak' support for adaptive directional microphone mode from questionnaire data in the presence of a strong positive finding in terms of SNR improvement may be a reflection of the children's everyday listening environments. If they were very different from the clinical environment, this could explain the lack of correspondence (Cord, Surr, Walden & Olson, 2002; Walden, et al., 2004). However, *Sound Back* subscales, which examined difficulty for desired speech from azimuths other than 0^0, did not reveal a disadvantage with directional or NR features. There are several design considerations of the automatic directional system used in this study that would explain this finding.

The system operates in tangent with several compensatory "safety features" to help ensure audibility, even when directionality is triggered. The automatic directional system is only triggered above a conversational level. When it is activated, it switches polar patterns slowly (potentially as slowly as 5 - 10 seconds) in order to present the wearer with an opportunity to turn his/her head towards the sound source. Finally, the directional system is coupled with a very low CT (i.e., as low as 0 dB HL). Therefore, even if the polar pattern is one where the microphone is least sensitive to sounds from the sides and/or back of the wearer, the gain is higher for those softer input levels. A study investigating the speech recognition of adult wearers utilizing a fixed directional system with a low CT of 20 dB HL showed better speech recognition for speech originating from directly behind the wearer than for omni-directional systems with higher CTs (Lee, et al., 1998). For adults using the identical instruments as those utilized by the children in this study, word recognition in quiet was the same in the adaptive directional mode as it was in omni-directional mode, when presented from the back or sides (Kuk, et al., 2005).

Finally, the PA-PHAP questionnaire results allowed for a third-party assessment of the child's performance. In all PA-PHAP subtests, the adaptive directional microphone mode is perceived by parents as resulting in less difficulty than the child's own HAs. The NR system is perceived by parents as resulting in the same or less difficulty than the child's own HAs. The amount of difficulty is not significantly different in any of the study's HA settings, adaptive directional, omni-directional with NR active, or omni-directional alone. These results are offered as reassurance to pediatric clinicians who are concerned that adaptive directional and NR features may result in children experiencing more difficulty in less than optimal listening situations. The results for this group of school-aged children do not indicate a disadvantage in either adaptive directional microphone or NR mode, at least to the extent that the questionnaire items were sufficiently sensitive to demonstrate an effect.

Impact on Speech/Language Progress

As mentioned previously, pediatric clinicians exercise caution in selecting adaptive directional and NR systems, due to the unknown impact these features may have on speech and language development. We are encouraged by the stability of the language performance of this group of children when compared to the performance of age-matched peers using standard measures. The children participating in this study were not considered "language-delayed." On the contrary, this group of children developed language adequately prior to their participation in this study. For such children, the standardized scores on language measures tend to remain stable over time. For this group of school-aged children, language scores either stayed the same or positive gains were made. These speech and language data hopefully reassure clinicians about the 'safety' of adaptive directional and NR features in terms of longitudinal language performance. For this group of school-aged children (with essentially normal language development) one-year of use of the adaptive directional and NR features utilized in this study did not adversely affect language outcomes. Similar studies are still needed for different technologies, as well as for younger children and children with language delays.

Conclusions

Results of this study of 19 mild to moderately-severe hearing-impaired children showed that:

1. The predicted SNR advantage of the adaptive directional system utilized in this study was approximately 7.6 dB, as measured by monosyllabic word recognition with noise presented at 180^0.
2. No advantage in SNR was measured for the NR feature; however, no decrement in performance was observed either.
3. Performance improvements were observed after six weeks and one year of use with both adaptive directional and NR features.
4. The degree of difficulty experienced by children specifically for desired sounds originating from the sides or back of the child is no greater with adaptive directional or NR features active.
5. The degree of difficulty experienced by children *as perceived by their parents* when their children use either the adaptive directional or NR systems is no different than the amount of difficulty perceived by parents when their children use their own HAs or with the study HAs in an omni-directional mode.
6. Language performance of this group of children is stable one year post use of both adaptive directional and NR systems.

Acknowledgement

Hearing instruments were funded by Widex HA Company, Inc. Neither facilities nor families were paid for their participation in this study. The following facilities participated in pilot studies for this project: Columbia Regional Program, Portland OR, Northshore-LIJ Medical Center, New Hyde Park, NY, Integris Baptist Medical Center, Oklahoma City, OK. The authors would like to thank the clinicians from the facilities involved in this project for providing their ongoing services to children in this study. The preliminary results of this study were originally presented at the American Academy of Audiology Annual Meeting, April 3-5, 2008, Charlotte, NC, USA.

References

American Academy of Audiology (Author). (2003). Pediatric Amplification Protocol [Web Page]. Retrieved September 8, 2009, from http://www.audiology.org/resources/documentlibrary/Documents/pedamp.pdf

American National Standards Institute, Inc. ANSI (R2003). *ANSI S3.22-2003. American National Standard Specification of Hearing Aid Characteristics*. New York.

Anderson, K., & Smaldino, J. (1998). *The Listening Inventories For Education (LIFE).* Tampa, FL: Educational Audiology Association.

Auriemmo, J., Lau, C., & Kuk, F. (2007). Language progress of children using advanced hearing aids. *Hearing Review, 61*(7), 48-54.

Brownell, R. (2000). *Expressive One Word Picture Vocabulary Test.* Los Angeles, CA, Western Psychological Services.

Cord, M. T., Surr, R. K., Walden, B. E., & Olson, L. (2002). Performance of directional microphone hearing aids in everyday life. *Journal of the American Academy of Audiology, 13*(6), 295-307.

Dunn, L. M., & Dunn, L. (1997). *Peabody Picture Vocabulary Test – Third Edition.* Bloomington, MN: Pearson Assessments.

Elliott, L. L. (1979). Performance of children aged 9 to 17 years on a test of speech intelligibility in noise using sentence material with controlled word predictability. *Journal of the Acoustical Society of America, 66*(3), 651-3.

Gravel, J. S., Fausel, N., Liskow, C., & Chobot, J. (1999). Children's speech recognition in noise using omni-directional and dual-microphone hearing aid technology. *Ear and Hearing, 20*(1), 1-11.

Hawkins, D. B. (1984). Comparisons of speech recognition in noise by mildly-to-moderately hearing-impaired children using hearing aids and FM systems. *Journal of Speech and Hearing Disorders, 49*(4), 409-18.

Kopun, J. G., & Stelmachowicz, P. G. (1998). Perceived communication difficulties in children with hearing loss. *American Journal of Audiology, 7*(1), 30-38.

Kuk, F. K., Kollofski, C., Brown, S., Melum, A., & Rosenthal, A. (1999). Use of a digital hearing aid with directional microphones in school-aged children. *Journal of the American Academy of Audiology, 10*(10), 535-548.

Kuk, F. & Ludvigsen, C. (1999). Variables affecting the use of prescriptive formulae to fit modern non-linear hearing aids. *Journal of the American Academy of Audiology,* 10(8), 458-465.

Kuk, F. K., Baekgaard, L., & Ludvigsen, C. (2002). Using digital signal processing to enhance the performance of dual microphones. *Hearing Journal, 55*(1), 35-43.

Kuk, F., Ludvigsen, C., & Kaulberg, T. (2002). Understanding feedback and digital feedback cancellation strategies. *Hearing Review, 9*(2), 36-41, 48.

Kuk, F., Ludvigsen, C., & Paludan-Muller, C. (2002). Improving hearing aid performance in noise: Challenges and Strategies. *Hearing Journal, 55*(4), 34-46.

Kuk, F., Keenan, D., & Ludvigsen C. (2004). Is real-world directional benefit predictable? *Hearing Review, 11*(12), 18-24, 63.

Kuk, F., Keenan, D., Lau, C., Ludvigsen, C. (2005). Performance of a fully adaptive directional microphone to signals presented from various azimuths. *Journal of the American Academy of Audiology,* 16, 333-347.

Lee, L. W., Lau, C., & Sullivan, D. (1998). The advantage of a low compression threshold in directional microphones. *Hearing Review, 5*(8), 30-32.

Lewis, M.S., Crandell, C., Valente, M., & Horn, J. E. (2004). Speech perception in noise: Directional microphones versus frequency modulation (FM) systems. *Journal of the American Academy of Audiology*, 15(6), 426-439.

Marcoux, A. M., Yathiraj, A., Cote, I., & Logan, J. (2006). The effect of a hearing aid NR algorithm on the acquisition of novel speech contrasts. *International Journal of Audiology, 45*(12), 707-714.

Mueller, H. F., Weber, J., & Hornsby, B. W. Y. (2006). The effects of digital NR on the acceptance of background noise. *Trends in Amplification, 10*(2), 83-93.

Nordrum, S., Erler, S., Garstecki, D., & Dhar, S. (2006). Comparison of performance on the hearing in noise test using diectional microphones and digital NR algorithms. *American Journal of Audiology*, 15(1), 81-91.

Ricketts, T. (2000). Directivity quantification in hearing aids: fitting and measurement effects. *Ear and Hearing, 21*(1), 45-58.

Ricketts, T., Henry, P., & Gnewikow, D. (2003). Full time directional versus user selectable microphone modes in hearing aids. *Ear and Hearing, 24*(5), 424-39.

Ricketts, T., & Hornsby, B. (2005). Sound quality measures for speech in noise through a commercial hearing aid implementing digital NR. *Journal of the American Academy of Audiology*, 16(5), 270-277.

Ricketts, T., Galster, J., & Tharpe, A. M. (2007). Directional benefit in simulated classroom environments. *American Journal of Audiology, 16*(2), 130-44.

Rigsby, K., Bradham, T., Dickinson, W., & Mueller, G. (2007, March). Current Practices in Pediatric Amplification and Early Intervention. In: *Perspectives on Hearing and Hearing Disorders in Childhood.* ASHA Division 9 Newsletter, 3-7.

Soli, S., & Sullivan, J. (1997). Factors affecting children's speech communication in classrooms. *Journal of Acoustical Society of America, 101*, S3070.

Stelmachowicz, P. G., Hoover, B. M., Lewis, D. E., Kortekaas, R. W., & Pittman, A. L. (2000). The relation between stimulus context, speech audibility, and perception for normal-hearing and hearing-impaired children. *Journal of Speech, Language, and Hearing Research, 43*(4), 902-14.

Studebaker, G. A. (1985). A "rationalized" arcsine transform. *Journal of Speech and Hearing Research, 28*, 455–462.

Studebaker, G. A., & Marincovich, P. J. (1989). Importance-weighted audibility and the recognition of hearing aid-processed speech. *Ear and Hearing, 10*(2), 101-8.

Valente, M., & Mispagel, K. M. (2004). Performance of an automatic adaptive dual-microphone ITC digital hearing aid. *Hearing Review, 11*(2), 42-46, 71.

Valente, M., Sweetow, R., Potts, L., & Bingea, B. (1999). Comparing the performance between digital signal processing with omni-directional and directional microphones with analog signal processing. *Journal of the American Academy of Audiology* 10:133-150.

Walden, B. E., Surr, R. K., Cord, M. T., & Dyrlund, O. (2004). Predicting Hearing Aid Microphone Preference in Everyday Listening. *Journal of the American Academy of Audiology, 15*(5), 365-396.

Williams, K.T. (1997). *Expressive Vocabulary Test- Second Edition*. Bloomington, MN: Pearson Assessments.

Woolfolk, E.C. (1995). *Oral and Written Language Scales*. Bloomington, MN: Pearson Assessments.

Woolfolk, E.C. (1999). *Comprehensive Assessment of Spoken Language*. Bloomington, MN: Pearson Assessment