Use of a Digital Hearing Aid with Directional Microphones in School-aged Children

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Abstract
The efficacy of a digital hearing aid with a directional microphone was examined in a school-aged population. Twenty children (9 with a mild-to-moderately-severe hearing loss and 11 with a moderate-to-severe hearing loss) between 7½ and 13½ years of age wore the study hearing aids binaurally for 30 days prior to the evaluation. The testing protocol included speech recognition tests using the CID W-22 word lists presented at 72 dB SPL, 65 dB SPL, and 52 dB SPL (at 0° azimuth) in the presence of a 65 dB SPL party noise (180° azimuth). Subjective rating of hearing aid efficacy in the classroom was examined using the Listening Inventory For Education (LIFE) questionnaire. Parental impression on hearing aid efficacy was also collected at the end of the study. The results showed improved speech recognition in noise with the digital directional hearing aid at all presentation levels. Preference for the digital directional hearing aids over the subjects' own omnidirectional analog hearing aids was also seen on the LIFE questionnaire and parental impression. The degree of hearing loss did not seem to have affected the benefits offered by the digital directional hearing aids. These results were compared to results from other studies on the use of directional microphones in hearing aids.

Key Words: Children, digital, directional, hearing aid, low compression threshold, omnidirectional

Abbreviations: BTE = behind the ear, CT = compression threshold, DI = directivity index, HINT = Hearing In Noise Test, LIFE = Listening Inventory For Education, SNR = signal-to-noise ratio, WDRC = wide dynamic range compression

The use of directional microphones as a means to enhance the signal-to-noise ratio (SNR) of the listening environment can be traced back to the early 1970s (Mueller, 1981). Despite its reported advantages in adults (Nielsen and Ludvigsen, 1978; Mueller, 1981; Madison and Hawkins, 1983; Hawkins, 1984; Hawkins and Yacullo, 1984; Valente et al, 1995; Agnew and Block, 1997; Preves, 1997), the studies on its effectiveness in children are limited (Hawkins, 1984; Gravel et al, 1999).

One reason that may have limited the use of directional hearing aids in children is related to the design rationale of such devices. That is, by reducing the sensitivity of the microphone to sounds from the sides and the back, both desirable (e.g., speech, warning signals) and undesirable sounds (e.g., noise) are attenuated. If the sound that originates from the back is soft speech, a directional microphone may have reduced its sensitivity so much that such is inaudible to the wearer. Indeed, the more effective a directional microphone (i.e., higher directivity index [DI]), the more listening difficulty the wearer may have in situations where the desirable sounds originate from the back (Gravel et al, 1999). For children, such a condition could create a dangerous situation at play as warning signals may not be perceived. Furthermore, this could affect incidental learning and limit the rate...
of proper speech and language development. Thus, despite the known SNR advantage of a directional microphone in children (Hawkins, 1984), its universal recommendation in children is cautioned (Bess et al, 1996).

Recent miniaturization in microphone technology has made possible the use of two omnidirectional microphones to achieve the benefits of a directional microphone. An added advantage is that it allows the wearer to switch conveniently between directional and omnidirectional microphone modes (Kuk, 1996). This could compensate for the loss of audibility in the directional mode. However, it requires that the wearers have the cognitive ability and physical skill to switch between microphone modes. This may be impossible for infants and some young children. Furthermore, the wearers must have the knowledge to know when to switch. Unless they have an a priori knowledge of the demands in the listening environments, they may have left the microphone in the “wrong” position. In a survey of adult wearers of a switchable directional microphone hearing aid, Sommers (1979) reported that only 26 percent of them actively switched between microphones, whereas 41 percent of these wearers left the hearing aid in the directional mode permanently. A potential effect of this practice can be appreciated in the study by Lee et al (1998), who showed an over 20 percent intelligibility decrease between an omnidirectional microphone and a directional microphone when soft speech at 50 dB SPL was presented behind the wearers.

An alternative to switching microphones in order to compensate for the loss of sensitivity is to provide more gain for soft sounds without making conversational sounds any louder. This can be achieved using wide dynamic range compression (WDRC) processing with a very low compression threshold (CT). A lower CT would mean higher gain for sounds below the CT (Kuk, 1998). This means higher intelligibility for sounds presented in the front (Valente et al, 1998) and from the back. Lee et al (1998) tested this hypothesis by comparing the speech recognition scores between a digital directional hearing aid that had a low CT at 20 dB HL and a programmable hearing aid that allowed switching between microphone modes (omnidirectional and directional) and signal processing methods (linear and WDRC with 50-55 dB SPL threshold). On average, when speech was presented to the back of the wearer at 50 dB SPL, the fixed directional hearing aid achieved a higher speech recognition score (44%) than the programmable hearing aid in the directional (11%) and omnidirectional (37%) modes. These authors concluded that a low CT on a directional hearing aid could minimize its limitation on audibility for soft sounds. The same digital directional hearing aid had also been reported by Valente et al (1999) to provide an average of 39 percent increase in speech recognition scores at a SNR of –7 or an estimated SNR improvement of 9 dB. Over 70 percent of the adult subjects in the study preferred the directional hearing aids to their own omnidirectional hearing aids after a 30-day trial of the device. At least for adult subjects, these results suggest that any loss of sensitivity from the fixed directional design may be minimized in real life by the low CT.

If the results of the adult studies on the digital directional hearing aids can be generalized to children, one would hypothesize that children would benefit from the use of directional hearing aids with a low CT in the laboratory and in real-life situations also. Furthermore, one may also speculate few instances of “inaudibility” complaints in real life from such directional hearing aid use. Thus, the purpose of this study was to evaluate the clinical efficacy of a directional hearing aid with a low CT in a school-aged population. Specifically, this study was designed to determine the percentage change in speech recognition score (and an equivalent SNR improvement) offered by the study hearing aids over the subjects’ own hearing aids under typical laboratory conditions. More importantly, the subjective real-world benefit offered by the study hearing aids in the school and in the child’s daily environments was examined. A secondary goal of the study was to evaluate any significant difference in directional advantage (and acceptance) as a function of hearing loss of the child.

**METHOD**

**Subjects**

Twenty children participated in the study. They were recruited from 18 different elementary schools served by the Columbia Regional Program for the Deaf and Hard of Hearing in Portland, OR. These children ranged in age from 7 years, 6 months to 13 years, 8 months, with a mean age of 11 years, 3 months. Their hearing losses were verified to be sensory in nature via immittance measurements (GSI-33). All of the children had been wearing binaural analog moderate-to-high gain behind-the-ear
Table 1  Subjects’ Hearing Aids, Age of Hearing Aids, FM Users, and Purchase Decisions at the End of the Study

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (Mo)</th>
<th>Personal HA</th>
<th>Age of HA (Yr, Mo)</th>
<th>FM Use</th>
<th>Outcome*</th>
</tr>
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<tbody>
<tr>
<td>C19 subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SA</td>
<td>157</td>
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<td>4, 11</td>
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<td>Kept</td>
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<td>113</td>
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<td>5, 8</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
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<td>Kept</td>
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<tr>
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<td>4 yrs</td>
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<td>1, 10</td>
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</tr>
</tbody>
</table>

Kept = purchased directional aids. Own = kept own hearing aids. Exchange = purchased omnidirectional aids.

(BTE) hearing aids since they were 3 or 4 years old. These hearing aids were fitted by the audiologists at the Columbia Regional Program. Children served by the Program returned annually to monitor their hearing sensitivity and to ensure proper functioning of their hearing aids. Electroacoustic tests on the children’s own hearing aids were performed prior to the study. Of these children, three reported that they consistently used FM along with their hearing aids in the classroom. Table 1 identifies the children’s hearing aids, the age of their current hearing aids, the FM users, and the purchase decision at the end of the study.

Subjects were divided into two groups based on their degree of hearing loss. One group (N = 9) had a mild-to-moderately-severe hearing loss and was fit with the moderate-gain model (Senso C9) hearing aid. The other group (N = 11) had a moderate-to-severely-profound hearing loss and was fit with the high gain model (Senso C19) hearing aid. Figure 1 shows the average audiogram of both groups of subjects. These children were mainstreamed and primarily used oral-aural communication. All of the subjects were fit binaurally for the study. To facilitate subject recruitment, participants were promised prior to the study financial compensation or discount on the cost of the hearing aids if they decided to keep the devices after the study. In order to comply with the regulations of the school district on using students for clinical research, all subjects (and their parents) were informed of the nature of the study.

**Hearing aids**

Two directional models of the Widex Senso digital hearing aids were used in this study.

![Figure 1 Mean audiogram for subjects wearing the moderate-gain (C9) hearing aid and the high-gain (C19) hearing aid.](image-url)
The Senso is the only hearing aid currently available with the low CT at 20 dB HL. These two models use the same directional microphone design and differ only in the gain and maximum power output. The C9 is a miniature BTE with 54-dB peak gain and 125 dB SPL peak output. The C19 is the same size as the C9 but has 64-dB peak gain and 130 dB SPL peak output. Both hearing aids use the same single-microphone, two-port, directional design with compensated frontal microphone response and a front-to-back ratio of approximately 15 dB up to 3000 Hz. Figure 2 shows the front-to-back ratio of the directional microphone.

The Senso hearing aid is a three-channel, slow-acting, WDRC hearing aid with a CT at 20 dB HL in all three channels. One feature of the hearing aid that could affect the outcome of the study is the speech enhancement algorithm, which uses the modulation characteristics of the input signal to determine if additional gain reduction should be applied. Valente et al (1999) showed that this mechanism contributed about 2 dB in SNR enhancement. However, this magnitude of SNR enhancement was not statistically significant.

Fitting of the directional Senso hearing aids is identical to fitting any Senso hearing aids (Widex, 1997). This includes selecting the appropriate model, setting the proper crossover frequency (filter set, in Senso terminology), measuring the in-situ threshold in each of the three channels (sensogram in Senso terminology), and completing with a feedback test to limit the maximum gain before feedback.

The appropriate crossover frequencies for the mid-frequency channel were selected based on the child's audiometric configuration. Simply, threshold differences between adjacent frequencies at 500, 750, 1000, 1500, 2000, 3000, and 4000 Hz were first determined. The crossover frequencies were selected at the interval that showed the largest threshold difference. If the threshold differences were similar, the crossover frequencies would be defaulted to 800 and 2500 Hz. Most of the children had crossover frequencies for the mid-frequency channel at 600 to 1800 Hz and 800 to 2500 Hz.

After the filter sets were programmed, the appropriate hearing aids were connected to the child's own earmolds for in-situ threshold measurement (sensogram). Earmolds that were judged to be inappropriate (too loose, too old, etc.) were replaced. The vent size used in the children's own hearing aids was maintained for the study hearing aids. For children who were fit with the C9 hearing aid, the typical vent size on the child's earmold was approximately 2 mm. For the C19 hearing aid, the earmold was typically unvented or used with a pressure vent. The sensogram was determined in each of the three channels (low, mid, and high) following a standard up-down procedure. The merit of the sensogram over direct application of earphone-determined audiogram data is that acoustic modifications of the hearing aid output (e.g., venting, residual volume, etc.) are considered in the sensogram value. Gain of the hearing aid for low, typical, and high input levels was predicted based on the sensogram values.

Finally, a feedback test was performed on the hearing aids while they were placed in the child's ears. During the feedback test, each hearing aid generated a low-level signal in each of the three channels. The gain in each channel was gradually increased until a feedback signal was detected at the hearing aid microphone. The maximum gain of the hearing aid was then leveled automatically at 6 dB below the potential feedback point to provide a "cushion" for real-life use of the hearing aid. When the desired gain was achieved, a feedback value of 0 would be indicated for the specific channel. A negative feedback value (e.g., -5) would indicate that less than the desirable gain was available. The clinician compared the feedback values to a table of "maximum acceptable feedback values" to determine if adequate gain was available. The earmolds were modified (decrease vent size...
or remake) if the feedback values were unacceptably high. All of the fittings had acceptable feedback values (i.e., available gain was adequate). Minor adjustments to the recommended gain settings were made to accommodate individual comments. In general, the majority of the children did not require further adjustment.

**Test Instruments and Conditions**

**Speech Recognition Test**

The recorded W-22 word lists were used as the speech stimulus. The competing noise was a Widex party noise presented at 65 dB SPL 1 meter behind the child. This noise was recorded at the Old Copenhagen Stock Exchange during a party function with over 400 guests in a music background (Valente et al., 1999). The speech material was presented 1 meter in front of the child. This loudspeaker placement facilitated comparison with results from other studies. Three intensity levels of 72 dB SPL, 65 dB SPL, and 58 dB SPL were chosen for the speech stimulus. This corresponded to three SNRs of +7, 0, and −7. Testing at different SNR allowed precise determination of speech recognition scores at each SNR. Furthermore, one can extrapolate from these scores to yield an equivalent SNR improvement offered by the directional microphone (Valente et al., 1999). Speech recognition testing was conducted at the beginning of the study with the child's own hearing aids and then with the study hearing aids after the child had worn them for at least 30 days. All testing was done in the sound field with binaural hearing aids. Presentation order of the W-22 lists was randomized.

**Real-World Questionnaires**

**Listening Inventory For Education (LIFE)**

The effectiveness of the study hearing aids in the child's school environment was evaluated using the Listening Inventory For Education (LIFE) questionnaire (Anderson and Smaldino, 1998). The LIFE is an efficacy tool that is designed to evaluate the changes in the child's perception of listening difficulty (Student Appraisal of Listening Difficulty) and the teachers' perception of the child's school and classroom behaviors (Teacher Appraisal of Listening Difficulty and Teacher Opinion and Observation List) as a consequence of specific intervention (e.g., new amplification system). Pretreatment evaluation and post-treatment evaluation would be necessary.

According to its authors, the LIFE questionnaire is appropriate for students in the elementary grades. The LIFE: Student Inventory includes 15 line drawings, each depicting a listening situation in the classroom or in the school. These situations are selected based on the authors' beliefs that they are valid representations of the listening environments in a modern elementary school. The first 10 items are situations believed to be common in all classrooms. The remaining 5 items are optional and may not be present in some schools. The test is administered in person. During its administration, the clinician shows the student a picture card of a school listening situation, describes its content, and asks the student to rate the amount of difficulty that is experienced in that situation. The student chooses one of five descriptors to indicate the amount of difficulty. These descriptors include “always difficult” (0), “mostly difficult” (2), “sometimes difficult” (5), “mostly easy” (7), and “always easy” (10).

The efficacy of the study hearing aids was estimated by comparing all of the students' ratings on each item and across all 15 items before and after the intervention. Anderson and Smaldino (1998), based on 19 normal-hearing elementary school-aged students (third and fourth grades), reported that the mean ratings fluctuated between 0.03 and 0.7, with a mean of 0.4 after a 3-week interval. These authors judged the test–retest reliability of the questionnaire to be good.

The LIFE: Teacher Appraisal includes 15 questions that are related to specific areas of improvement in the student's behavior or learning. The teachers would be informed of the study at its beginning but are asked to complete the questionnaire only at the end of the study. The teachers indicate how much they agree with the 15 statements. If they fully agree with the statement, a score of +2 is assigned. If they completely disagree with the statement, a score of −2 is assigned. A score of 0 is assigned if no change in the child's behavior is observed at the completion of the study. Additionally, a sixteenth question, which addresses overall impression, is assigned a score of +5 for full agreement and −5 for full disagreement.

The teachers' impression on the efficacy of the intervention is reflected by the total score for all 16 questions. Each child may receive a maximum total score of 35.
**Parent Questionnaire**

The parents of the students were asked to keep a diary of the child's experience with the study hearing aids during the course of the study. They were instructed to record their observations in 12 specific listening situations. At the end of the study, they were asked to transfer their observations from the diary to the Parent Questionnaire that asked them to compare their relative preference between their child's hearing aids and the study hearing aids in the specified situations. The parents were to indicate if “their own hearing aids were better,” “the study hearing aids were better,” or “no difference” to each question. In addition, three overall questions—“improvement in listening,” “better speech understanding,” and “improvement in speech production skills”—were also included in the questionnaire. These questions required the parents to answer with a “yes-no” or “own (better)-study (better)” response.

**Procedure**

All of the testing was performed at the Columbia Regional Program for the Deaf and Hard of Hearing. Typically, each student was seen on three occasions. Subject candidacy for inclusion into the study was determined during the first visit. The adequacy of the child’s own hearing aids and earmolds was also evaluated. Adjustment of the personal hearing aids was made and new earmolds were ordered if such were inadequate.

Speech recognition ability with the child’s own hearing aids and earmolds was evaluated during the second visit. For children whose hearing aids and earmolds were judged to be appropriate, this measure was determined during the first session instead. Testing was done in a double-walled, double-room sound booth using a GSI-16 audiometer. The W-22 word lists were presented at 72 dB SPL, 65 dB SPL, and 58 dB SPL in the presence of the 65 dB SPL Widex party noise. Level of presentation was counterbalanced across subjects. This was followed by fitting the study hearing aids. The pretest LIFE: Student Inventory was also completed during this session.

It was recognized that three of the students used an FM system with their hearing aids in their classroom. The use of FM could bias the results of this study in that it may shadow any positive results from the study hearing aids. However, it was also recognized that the study should not negatively interfere with the child’s learning, especially if they were dependent on the use of FM along with their own hearing aids. Consequently, the pretest LIFE questionnaire was completed based on the child’s typical amplification mode. That is, 17 of the pretest data sets were based on “hearing aid alone” impression, whereas 3 were based on “hearing aid + FM” use.

We were also concerned that learning may be affected if we asked the children not to use their FM with the study hearing aids during the classroom evaluation. As a compromise, we left it to the children to determine if they wanted to use their FM along with the study hearing aids during the evaluation period. They were told that they might use the study hearing aids alone if they experienced no listening difficulty. They were instructed to use their FM with the study hearing aids if they experienced any difficulty with the study hearing aids alone. Interestingly, none of the students used their FM with the study hearing aids for this part of the study. The LIFE: Teacher Appraisal was sent with the itinerant teacher along with a letter of explanation and instruction.

The students returned after using the study hearing aids for about 30 calendar days (30–35 days) during their regular school session. During the follow-up visit, the speech recognition scores with the study hearing aids were obtained again with the W-22 word lists at the same input levels. They also completed the post-test of the LIFE: Student Inventory with the clinicians. Typically, the parents accompanied their children during this session to return the parent questionnaire and to indicate their purchase intent. Parents who did not return with their children were contacted by telephone to solicit their impressions on the parent questionnaire. The teachers returned the LIFE: Teacher Appraisal by mail.

**RESULTS**

**Speech Recognition Scores**

Speech recognition scores were analyzed using a three-way mixed analysis of variance with two within-subject factors (microphone type by SNR) and one between-subject factor (severity of hearing loss). Significant main effects were noted for all three factors, including microphone type ($F = 9.3, p = .003$), SNR ($F = 18.0, p = .000$), and severity of hearing loss ($F = 19.8, p = .000$). None of the interactions
among factors were significant. Post hoc analyses using the Honesty Significant Difference test showed that the mean scores for the study hearing aids were significantly higher than the mean scores for the subjects’ own omnidirectional hearing aids at each of the three SNR conditions at the 0.05 level.

Because the mean W-22 scores at each SNR for the mild-to-moderately-severe subjects (C9 subjects) were significantly higher than that of the moderately-to-severe subjects (C19 subjects), the results for the two groups of subjects were reported separately in Figures 3A and 3B, respectively. The lower speech score for the C19 subjects was presumably due to the increased severity of hearing loss in this group of subjects. We also observed that the difference in speech scores between the study aids and the subjects’ own hearing aids increased as the listening conditions became difficult (i.e., SNR became negative). For example, the difference score for the C9 subjects increased from 8 percent at the SNR = 7 to 18 percent and 19 percent at the SNR = 0 and −7 conditions, respectively. The same was also true with the C19 subjects (difference of 10% at SNR = +7 to difference of 14% at SNR = −7).

The speech recognition scores shown in Figure 3 can be used to calculate the equivalent improvement in SNR ratio (Valente et al, 1999). Briefly, Figure 3, A and B, can be converted into performance-intensity (or signal-to-noise) functions for the study hearing aids and the children’s own omnidirectional hearing aids. For example, Figure 4 illustrates how such calculation can be made using the data from Figure 3A. First, the performance-intensity functions (speech score vs SNR) for the subjects’ own hearing aids (dotted line) and the C9 hearing aid (solid line) were plotted. The SNR corresponding to 50 percent performance can be read off by drawing a horizontal line at the 50 percent performance mark through the two performance-intensity functions. The difference in the required SNR for a 50 percent performance between the two hearing aids represents the equivalent SNR improvement offered by one hearing aid over the other. This approach assumes that the change in speech scores within (and beyond) the range of SNRs is uniform and predictable. With this caveat, the improvement in speech scores was equivalent to a SNR improvement of 5.5 dB for the C9 subjects and 8 dB for the C19 subjects. An average of 6.5 dB was estimated when data from all subjects were included.
Figure 5 Mean ratings on the LIFE: Student Inventory in 10 classroom situations. Dark bars are pretest (or own hearing aids) ratings and light bars are post-test (or study hearing aids) ratings. A, results on C9 subjects; B, results on C19 subjects.

LIFE: Student Inventory

Whereas three of the children completed the LIFE pretest with their hearing aids plus FM, the LIFE post-test was completed by all subjects with the study hearing aids alone. None of the students found it necessary to use FM with the study hearing aids to achieve previous or better than previous performance. Figure 5 compares the average student ratings between the study hearing aids (post-test) and the students’ own hearing aids (pretest). Results on the C9 subjects are summarized in Figure 5A, whereas those of the C19 subjects are summarized in Figure 5B.

Figure 5A shows that 8 of the 10 listening situations were rated at 6 (sometimes difficult) and higher (median rating of 7, mostly easy) with the child’s own hearing aids (one used the FM also). The use of the study hearing aids improved the ratings for all but one situation (teacher moving) where there was no noted difference between the two hearing aids. The median rating was 7.5 for the study hearing aids. A paired t-test revealed significant difference at the 0.1 level in the following situations: “teacher in front,” “teacher’s back,” “answer discussion,” and “projector on.”

The relative improvement of the study hearing aids over the child’s own hearing aids (two had FM also) was also seen in the severe loss group (Fig. 5B) in all but two situations (“projector on” and “teacher moving”). The mean ratings for this group were lower than those of the milder loss group. Six of the 10 listening situations were rated at or below 5 (sometimes difficult) for the child’s own hearing aids. The ratings with the study aids were 6 and higher, with the median at 6.5 (mostly easy). A paired t-test revealed significance at the 0.1 level for the following situations: “teacher in front,” “teacher in transition,” “teacher’s back,” “answer discussion,” and “instruction during test.”

The same comparison between the hearing aids in the remaining five situations on the LIFE: Student Inventory revealed similar improvement. Figure 6 (A and B) shows that the study hearing aids resulted in higher ratings than the subjects’ own hearing aids. Again, paired t-test revealed significance at the 0.1 level between the study hearing aids and the subjects’ own hearing aids for the following situations: “small-group learning,” “gym,” and “lunch break” for the C9 subjects and “gym,” “school assembly,” and “lunch break” for the C19 subjects. Neither group showed a significant difference for the “talking while hanging coats” situation. Both groups, however, reported improvement in the “gym” and “listening during lunch break.”

In summary, the study hearing aids were rated higher than the students’ own hearing aids (some with FM) in many of the listening situations listed in the LIFE questionnaire. The following situations revealed statistically significant improvement for both groups of subjects: teacher in front, teacher’s back, answer discussion, gym, and lunch break. The following situations revealed improvement in only one group of subjects: hallway noise (C9), student noise (C9), projector on (C9), small-group learning (C9), teacher transition (C19), instruction during test (C19), school assembly (C19). Neither group reported significant improvement in these situations: small-large-group discussion, teacher moving, and talking while hanging coats.

LIFE: Teacher Appraisal

Of the 20 teachers, only 10 (seven for students wearing the C19, three for students wearing the C9) returned the questionnaire with assigned ratings and comments. Three returned the questionnaires with no inputs. Only one
teacher of the three students who used their FM in the classroom returned the questionnaire (she did not notice any difference between the student’s “own hearing aids plus FM” and the study hearing aids). Consequently, the following results can be viewed as a direct comparison between the child’s own hearing aids and the study hearing aids.

The total score for each item was computed by adding the scores assigned to each student. Thus, a maximum score of 20 points (totally agree with positive change) and a minimum of –20 points (totally disagree with positive change, or negative change) would be possible on each item (10 teachers returned comments). Scoring on item 16 was adjusted so that the total score range would also conform to the 40-point range. A rating of “0” would indicate no change on the observed behavior. Figure 7 summarizes the total ratings to all 16 items. While the total scores for all the items were positive, some items had a higher score than the others. Items that were rated 10 or higher (agree positive change) included 2 (understood classroom instructions better), 4 (improved attention to listening directions presented in class), 10 (improved understanding of comments and answers from peers during discussion), 11 (improved understanding in noise), 13 (improved attention during group discussions), and 16 (improved overall attention, listening, and learning behaviors). On the other hand, item 6 (followed directions more quickly or less hesitation before work) was only assigned a total rating of 1, suggesting that no overall change was observed on that particular behavior.

The authors of the questionnaire suggested using the total score assigned to each student across the 16 classroom behaviors as the criteria for success of the intervention (i.e., study vs own aids). Of the 10 teachers who replied, only one rated the study hearing aids as “highly successful.” Four teachers (three had students using the power or high gain C19, one had a student using the moderate power C9) rated the study hearing aids as “successful.” However, two teachers rated the intervention with the C19 as “minimally successful” and three teachers rated the intervention (two with the C19 and one with the C9) as showing “no difference” (this included one teacher whose student used the FM consistently). No negative change was reported with the study hearing aids. The distribution of teachers’ ratings is shown in Figure 8.

### Parent Questionnaire

Figure 9 summarizes the parents’ general perception of the study hearing aids over their children’s own hearing aids. Of the parents who responded, 16 of 18 reported that the study hearing aids improved their children’s listening. Fifteen of 17 reported that their children understood speech better with the study hearing aids than their own hearing aids. Seven of 16 reported improvement in the accuracy and consistency of their children’s articulation.

The parents’ favorable impression of the study hearing aids over their children’s own hearing aids was also seen in daily environ-
Highly successful
Successful
Minimal success
No difference

(>26) (15-25) (5-15) (< 4)

Figure 8 Number of students who exhibited significant behavioral change as a result of the use of the study hearing aids in the classroom. The criteria for success were listed on the abscissa.

ments. Figure 10 shows that more parents chose the study hearing aids over their children's own hearing aids in all of the listed situations. Such preference was strongest in situations like “watching TV,” “in a restaurant,” “outdoor,” “large group,” and “small group.”

Although the majority of the parents were pleased with the performance of the study hearing aids, one set of parents (NH) reported that their child did not respond as readily when called from behind with the study hearing aid. Another set of parents (TB) indicated in the diary that their son reported not hearing quite as well with the study hearing aids from the sides and back as compared to his own hearing aids.

Purchase Decision

Figure 11 shows the purchase decision at the end of the study. Of the 20 children who participated, 14 purchased the study hearing aids (8 for the C19, 6 for the C9). Three students exchanged the aids for an omnidirectional model. Two of these students (one C9 and one C19) cited the diminution of sound pressure level from the sides and the back as the main reason for the exchange. One exchanged for a completely-in-the-canal model. Three students returned the hearing aids for financial reasons.

DISCUSSION

The purpose of this study was to compare the laboratory and real-world effectiveness of a digital directional hearing aid over omnidirectional analog hearing aids on school-aged children. A secondary goal was to determine if the degree of hearing loss would diminish the...
amount of benefit and alter its real-world acceptance. The results showed that the SNR advantage offered by the digital directional hearing aids was about 5.5 dB to 8 dB over the students' own omnidirectional analog hearing aids. The benefit was not limited to laboratory findings. Improvement in school listening and in classroom behaviors was reported on the LIFE questionnaire. The preference for the study hearing aids was also noted by the children's parents in their home environments. The small percentage of children/parents (2 or 10%) who reported diminution of loudness for sounds coming from the sides and the back lend indirect support to the efficacy of a low CT in minimizing the loss of sensitivity from a directional microphone. The finding of no significant difference in acceptance and efficacy between the two groups of subjects suggests that children of all degrees of hearing loss (at least up to a severe degree) may benefit from the use of this digital directional hearing aid. Such conclusion was based on the magnitude of the SNR improvement, LIFE questionnaire (students' and teachers') results, parent questionnaire, and purchase decision.

Comparisons among Studies

Recently, Gravel et al (1999) reported on the use of a dual-microphone directional programmable hearing aid in 20 children (4 to 11 years) with a mild-to-severe hearing loss. These authors reported a mean SNR advantage of 4.7 dB offered by the dual-microphone system over its omnidirectional version. The degree of SNR improvement varied with the age of the children and the speech materials used for the evaluation. Specifically, for children between 4 and 6 years, SNR advantage from 0.5 dB to 14 dB was reported when words were used as the stimulus. However, a 2-dB to 9-dB SNR advantage was reported when sentences were used. For the older children (6–11 years), a 0- to 9.5-dB improvement was noted for words and a −2-dB (directional worse than omnidirectional) to 7-dB SNR improvement was noted for sentence materials.

One may be tempted to conclude that the average SNR improvement noted in this study may suggest that the directional microphone used in this digital hearing aid is more effective than that employed in the Gravel et al (1999) study. There are several methodological differences that may confound such comparison. First, the Gravel et al (1999) study compared the SNR difference between the omnidirectional and directional microphones on the same programmable hearing aid. The net effect was that of the directional microphone alone. On the other hand, this study compared the digital directional hearing aids to the students' own hearing aids. The difference in SNR reflected not only the SNR advantage offered by the directional microphone but also the digital processing used in the study hearing aids (including low CT, speech enhancement, steep filter slopes, slow-acting multisegment WDRC). Second, Gravel et al (1999) used the Pediatric Speech Intelligibility test in a speech babble background. This study used the W-22 word lists presented in a party noise background. This could lead to a difference in absolute performance between studies. Third, Gravel et al (1999) manipulated the noise level (fixed speech level) and directly estimated the SNR for 50 percent performance in both microphone modes. This study measured speech recognition scores at three SNRs and extrapolated the SNR benefit of the study hearing aids. Last, Gravel et al (1999) used children who were generally younger than those used in this study.

There is some evidence to suggest that the SNR advantage seen in this study may be comparable to that reported by Gravel et al (1999). Ricketts and Dhar (1999) compared the SNR required for 50 percent correct identification on the Hearing In Noise Test (HINT) among a digital hearing aid with dual microphones, a programmable hearing aid with dual microphones (same as the one used in the Gravel et al [1999] study), and the present study hearing aid. The speech material was presented in the front, whereas the interfering noise (a party noise) was presented at five azimuths to the sides and back of the subjects. Their results showed no difference in SNR requirement for 50 percent HINT identification among the three hearing aids when evaluated in a reverberant room. This suggests that the digital signal processing used in the present hearing aid (low CT, speech enhancement algorithm), along with the single-microphone directional microphone, could provide SNR improvement that is at least comparable to that seen in the Gravel et al (1999) study.

With the exception of the speech materials used, this study was conducted using the same test conditions as the adult study reported by Valente et al (1999) on the same digital directional hearing aid. However, the magnitude of the difference in speech scores between the study hearing aids and the students' own hearing aids, as well as the equivalent improvement
in SNR seen in this study, was smaller than those seen in adult subjects. For example, Valente et al (1999) showed that the speech recognition score improved by 7 percent in the SNR = +7 condition to an average of 39 percent in the SNR = −7 condition. This study showed a difference of 9 percent in the SNR = +7 to 16 percent in the SNR = −7 condition. Such differences probably reflect differences in the speech materials used. This may suggest also that children are less able than adults to achieve the same degree of benefits with directional microphones. They need more improvement in SNR than adults to achieve the same performance increase as adults. Another possibility is that not all children would benefit from the use of directional microphones. This was evidenced in the study where one of the children actually scored higher with the omnidirectional model of the study hearing aid than the directional version. This suggests the need for careful selection of directional candidates.

**Design Considerations**

As in all clinical studies, the extent that one can generalize the conclusion is contingent upon the test conditions used. In this study, the choice of a single noise source at 180° azimuth was made so that the magnitude of the SNR improvement can be compared to previous studies (e.g., Hawkins, 1984; Gravel et al, 1999). The results would be different if the noise source was at a different azimuth. The exact magnitude of SNR improvement is dependent on the interaction between the loudspeaker placement and the polar pattern of the directional microphone. Whereas a directional microphone with a cardioid polar pattern has a null (minimal sensitivity) at 180° in the freefield, directional microphones with hypercardioid and supercardioid (majority of today's directional or dual microphones) polar patterns have nulls to the sides (around 135° and 225°) when measured in a freefield. These polar patterns change substantially when the microphones are worn on the head (as on Knowles Electronic Mannequin for Acoustic Research [KEMAR]). This suggests that placing the loudspeaker (noise) at the 180° azimuth does not guarantee maximum SNR advantage in a directional microphone study.

It is generally accepted that directional microphones improve speech understanding in noise. This conclusion may be less straightforward in the pediatric application. Older children, especially those who were fit with an omnidirectional microphone at a very young age, may not benefit from a directional microphone. In the Gravel et al (1999) study, it was reported that some children received a negative SNR improvement (i.e., omnidirectional microphone better than directional microphone). In this study, one child (NH) who exchanged the directional model (C19) for an omnidirectional model (C18) achieved a higher speech recognition score with the omnidirectional model than the directional model in the same speech-front, noise-back test condition. In this regard, the speech-front, noise-back loudspeaker arrangement may represent a simple clinical set-up to determine potential directional candidates.

Testing directional microphones in multiple loudspeaker arrangement (including the frontal azimuth) has been suggested as a closer approximation to real-life listening situations. However, placement of the noise source in front violates the basic assumption of a directional microphone and would give the appearance that a directional microphone is ineffective. Whereas in real life, if the wearer is properly counseled on the use of a directional microphone, she/he would have reoriented himself/herself so that there is spatial separation between the speech and noise sources. The outcome is that the directional microphone is effective in real life but ineffective in the laboratory. More research/discussions would be necessary in order to determine optimal loudspeaker placement for the sake of predicting “real-world” performance.

An objective of the study was to examine if digital implementation of a directional microphone (i.e., the low CT available in Senso) would minimize the negative impact of a directional microphone in children (not hearing from sides and back, insufficient loudness, etc.). Although one could compare an analog hearing aid with a directional microphone to a digital hearing aid with the same directional microphone, it is not easy to implement in practice for two reasons. First, few children wear analog hearing aids with directional microphones. Second, it would be unethical to conduct a study when one suspects that the analog directional hearing aids could limit audibility and interrupt the children's social and speech and language development. These practical considerations precluded the use of any blinded design. As a compromise, this study used children who were properly fit with analog omnidirectional hearing aids and asked their impressions of the digital directional hearing aids relative to their own hearing.
Digital Hearing Aids in School-aged Children/Kuk et al

It was assumed that if the digital directional hearing aid had overcome the limitation of a directional microphone, SNR improvement would be evidenced but the children would not experience any negative effects related to directional microphones. Furthermore, if the additional processing in the digital hearing aid (flexibility, speech enhancement, etc.) was effective, the children would report higher satisfaction with the digital directional hearing aid. On the contrary, if the digital implementation of the directional microphone had not overcome the negative issues related to directional microphones, one would observe high instances of dissatisfaction albeit the improvement in SNR. In view of the overwhelmingly positive preference for the study hearing aid, it is doubtful if the conclusion would be different even if it were a blinded study.

One may expect a lower magnitude of SNR improvement than that seen in this study in a reverberant environment with multiple noise sources (Studebaker et al, 1980; Hawkins and Yacullo, 1984). Although the exact magnitude of SNR improvement in such an environment was not determined in this study, listening in the two most reverberant environments (“gym” and “listening during lunch break”) was actually rated as “mostly easy” with the study hearing aids. Although it appeared at odds with present research findings, one must remember that the study hearing aids also included digital signal processing algorithms that may improve the listening comfort and ease of communication in some noisy situations. Specifically, the speech enhancement algorithm in this digital hearing aid may have actually minimized the amount of low-frequency noise in the reverberant environments to render the listening condition more tolerable. In addition, the separation between the child and the talker may be within the critical distance to preserve the directional advantage.

This study confirmed the speculation that children in their daily environments can use the digital directional hearing aids successfully. Because of the study design, it is difficult to categorically state that the high real-world acceptance can be solely attributed to the directional microphone, to the digital signal processing (low CT and speech enhancement), to a different type of processing, to different frequency gain characteristics, or to a synergistic action of all of these features. The last hypothesis seems to be the most plausible, although a definitive answer is not possible unless the study was designed to address each one of these features separately. Nonetheless, one may estimate the relative contribution of each feature from Valente et al’s (1999) study. The SNR advantage seen in the laboratory may be primarily the effect of the directional microphone. The contribution of the speech enhancement algorithm to SNR improvement would perhaps be 1 to 2 dB in magnitude. The other reported advantages, such as improved speech production, improved speech clarity in quiet, ease of communication in reverberant environments, and few instances of not hearing from the sides and back, could be attributed to the benefits of the digital signal processing used in the study hearing aids. Although the low CTs have compensated partially for the loss of audibility from the directional microphone, the report of diminished loudness in 2 of the 20 subjects (10%) suggests that compensation may not be complete in all wearers. Clinically, this confirmed the importance of proper counseling and candidate selection prior to the recommendation of hearing aids with a directional microphone (even those with a low CT). Further refinement in directional hearing aid design is necessary to achieve SNR improvement without loss of loudness and audibility.

CONCLUSIONS

The results of this study showed that:

1. Hearing-impaired children of up to a severe degree of hearing loss would benefit from the advantages of a directional microphone.
2. The advantages of a directional microphone are seen in an improvement of:
   - Speech understanding score as evaluated on the W-22 word list when the noise was presented directly to the back (180°) of the student in the laboratory.
   - Ease of listening in the classroom/school as reflected on the LIFE: Student Inventory in the following situations: teacher in front, teacher's back, answer discussion, gym, and lunch break.
   - Attention, listening, and learning behaviors in some students as reflected on the LIFE: Teacher Appraisal. This is especially true in situations where background noise is present.
   - Improved listening at home over the child's own hearing aids in many listening situations. In a number of cases
(7 of 16), improvement in the accuracy and consistency of articulation was observed.

REFERENCES


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