Potential for Directional Hearing Aid Benefit in Classrooms: Field Data

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Introduction

Several studies have shown that poor signal-to-noise ratios (SNRs) can significantly reduce speech understanding for children both with and without hearing loss (e.g., Crandell and Smaldino 2000; Finitzo et al. 2000). In addition, data suggest that listeners with hearing loss require significantly better SNRs for equivalent speech recognition performance when compared to listeners with normal hearing (Boothroyd, Eran and Hanin 1996; Killion 1997; Schum 1996). Indeed, school-aged children with hearing loss find it much more difficult than children who have normal hearing to learn vocabulary, grammar, word order, idiomatic expressions, and other aspects of verbal communication (Bess, Dodd-Murphy and Parker 1998; Khairi et al. 2010). Furthermore, data have shown that children with hearing loss exhibit a variety of difficulties with communication and academic achievement, increased listening effort, as well as psychosocial and emotional problems (Bess and McConnell 1981; Bess and Tharpe 1984; Davis, Stelmachowicz, Shepard and Gorga 1981; de Villiers, Eavey and Klein 1992; Hicks and Tharpe 2002; Tharpe and Bess 1999).

One of the primary factors limiting students' ability to understand speech in classroom settings is noise. Ensuring that the intensity level of speech is presented well above that of interfering background noise level in a classroom remains a significant problem for school-aged children (Finitzo et al. 2000; Gravel, Fausel, Liskow and Chobot 1999). Due to SNR advantages as large as 12-15 dB, the most common and popular systems for improving listening in noisy classroom environments introduced to date have been based on frequency modulated (FM) technology (e.g., Hawkins 1984; Lewis, Crandell, Valente and Horn 2004; Madell 1992). An FM system includes a microphone worn by the speaker of interest, a transmitter near the listener, and coupling to the listener's ear, typically via connection to the hearing aid. When an FM system is coupled to a hearing aid, the hearing aid microphone may be disabled providing significant SNR benefits in noisy situations. This SNR improvement occurs in large part because the close proximity of the microphone to the sound source of interest allows for delivery of this signal directly to the listener's ear while greatly limiting the intrusion of other competing sounds.

Although there is little doubt that personal FM systems are the preferred intervention in classroom settings in which only the teacher's voice is of interest (Lewis et al. 2004), a number of factors limit recommendation of full- time use of such systems (Lewis, 1991; Madell 1992). These factors include: a) the presence of multiple talkers of interest during which passing a microphone is difficult or not possible (listening to other classmates); b) cosmetic or social concerns (especially among older children); c) portability concerns; and d) "overhearing" other conversations and in playground and lunch room environments. In addition, it is sometimes the case that for financial or other reasons FM systems are not available.

One of the reasons that FM systems may not be ideal is the elimination of a child's ability to "overhear" other conversations when the hearing aid microphone is disabled. In order to limit these possible detriments, activation of the environmental microphone is often advo-

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cated when FM systems are used in school settings. However, activation of the environmental microphone limits the SNR benefits provided by FM systems to approximately 3-5 dB (e.g., Crandell and Smaldino 2000; Fabry 1994; Hawkins 1984; Lewis et al. 2004). A microphone location that is less than optimal due to the presence of multiple primary talkers may also limit FM system benefit.

Another technology that may help improve the SNR is the directional microphone. In contrast to FM systems which use a proximity-based approach, the directional microphone mode in hearing aids incorporates two microphones (or microphone ports) to allow for improved SNR based on the spatial location of the signal of interest relative to unwanted signals. Specifically, a significant directional advantage of approximately 2-5 dB is found in both children and adults for a range of realistic, but difficult, listening environments (Bentler, Tubbs, Egge, Flamme and Dittberner 2004; Gravel et al. 1999; Henry and Ricketts 2003; Kuk, Kollofski, Brown, Melum and Rosenthal 1999; Ricketts 2000a, 2000b; Ricketts, Galster and Tharpe 2007; Ricketts, Lindley and Henry 2001; Walden, Surr, Cord and Dyrlund 2004). Given this potential for SNR advantage, there is continued interest in the application of directional microphone hearing aids in school settings.

Despite these potential advantages, providing both directional and omnidirectional hearing aid modes may be necessary to obtain an optimal aided listening experience throughout the course of the day for both adults and children. Survey and self-report data have shown that listeners prefer the omnidirectional mode for some environments and the directional mode for others, suggesting a lack of support for the full- time use of the directional mode in adult listeners (Cord, Walden, Surr and Dittberner 2007; Ricketts, Henry and Gnewikow 2003). Similarly, work with school- aged children has indicated that, although the directional mode can be quite beneficial in some settings, it may be detrimental in other environments, even in the presence of noise (Ricketts et al. 2007).

A number of environmental factors affect whether the directional or omnidirectional hearing aid mode leads to the best speech recognition in a particular environment. Environmental factors can also affect the magnitude of any directional advantage measured. The presence and position of any competing noise sources comprise one key environmental factor (Hornsby and Ricketts 2007; Ricketts 2000a; Ricketts and Henry 2002). Importantly, for directional benefit, competing signals must either arrive from behind or surround the listener. No benefit will be present if the noise arrives only from the front hemisphere where the microphones are maximally sensitive.

The location and distance of the sound source of interest are also key factors. For optimal performance in noisy environments, it has been shown that directivity-based systems require that the users accurately orient their head toward the sound source of interest (Lee, Lau and Sullivan 1998; Ricketts 2000a; Ricketts et al. 2001; Walden et al. 2004). The directional microphone mode can lead to reduced performance (in comparison to the omnidirectional mode) when the listener is not facing the sound source of interest (Ricketts et al. 2007). Data indicate that children as young as 4 years of age in school environments (Ricketts and Tharpe 2004) and infants and toddlers in home environments (Ching et al. 2009) can orient their heads accurately toward sounds of interest approximately 33-40% of the time. While these data provide further support for potential directional benefit in real classroom environments, they also suggest that 60 to 67% of the time children may not be oriented for maximal directional benefit.

In specific listening situations for which the sound source of interest is behind the listener and the listener is unable or unwilling to turn to face it, the directional hearing aid mode will be detrimental (Ricketts et al. 2007). For example, through head movement a student could place a signal of interest (such as the teacher's voice) at a position for which the directional microphone provides significant attenuation. This might occur when a student turns around to face another classmate. Alternatively, the teacher could walk to another area of the room, placing themselves behind the child. In any of these cases, the reduction in signal level may reduce the amount of speech information that falls within the child's audible range and above the level of the background noise. Any reduction in audibility of speech is likely to result in a decrease in speech recognition performance.

In addition to location of signals of interest and location of competing signals, another factor that influences directional benefit is proximity of the sound source of interest. That is, the sound source of interest must also be relatively near the listener, particularly if the listening environment is reverberant (Ricketts et al. 2007; Ricketts et al. 2003). If reverberation is high and the sound source of interest is far away, the potential for directional benefit is greatly reduced.

Together these data indicate the directional benefit is typically present when listeners are generally facing the sound source of interest, when the sound source of interest is relatively near, when the reverberation is moderate or less, and when the competing noise is either behind or surrounds the listener. Given the interaction between microphone mode and listening environment, it is clear that optimal use of directional hearing aids by students in a school environment is dependent on whether the optimal microphone mode is active in every listening situation. The acoustic and physical characteristics of each specific classroom listening environment can in turn be used to make judgments regarding the optimal microphone mode. Hearing aid systems which automatically switch between microphone modes do so based on the acoustic input. Importantly, information which allows the hearing aid to estimate the environmental factors that lead to the directional or omnidirectional mode being optimal may or may not be present in the acoustic signal. This requires manufacturers to make decisions which are aimed at improving microphone switching. One factor that is often considered is sound level. Specifically, it is often assumed that a relatively high overall sound level is present in most noisy environments. Therefore most systems are designed to remain in omnidirectioanl mode when the overall signal level is low.

The purpose of this descriptive study was to quantify the optimal microphone mode (directional or omnidirectional) for the specific listening environments experienced throughout the school day and to quantify the amount of time these situations occur. Since both formal and social listening situations were of interest, observers attempted to quantify listening activities for the entire school day, including interactions in the hallways between classes, during gym and/or recess, during lunch and during special classes such as music. This information is expected to be useful for future studies aimed at quantification of switching accuracy via manual and automatic modes, as well as establishing the listening situations where directional microphone mode may be of use. In addition, this information may provide insight regarding how microphone switching based on acoustic factors might be optimized for school listening environments.

Method

Participants

Although we were primarily interested in children with hearing loss, the signals of interest are expected to be the same for children with normal and hearing loss. Therefore, we tracked specific listening situations for 13 children with normal hearing and 18 children with impaired hearing for a total of 31 participants. Children ranged in ages from 5 to 17 years (mean = 12 years). A wide range of ages was selected because it was expected that younger and older children will be in listening environments that differ at least slightly in their demands. For example, our previous experience suggested that the younger children would experience more group play situations, whereas older children were expected to be involved in more classroom lectures (Ricketts and Galster 2008).

Procedures

To quantify the listening situations encountered by school children, trained observers followed participants during a typical school day and made notes about the listening environment. The observer's task was to enter a general note about the listening situation (e.g., taking a math test in a quiet room) and quantify a variety of factors including: 1) the type of listening setting (classroom, lunch, hallway, recess/gym, or special); 2) the primary source position (front, back, side, or multiple positions); 3) the range of estimated main source distance in feet; 4) the general noise position (front, back, side, surround); 5) the dominant noise position in cases where noise was judged to surround the listener (if applicable; front, back, or side); 6) estimated noise level (1-quiet, 2-low [approximately 55 dB SPL], 3-moderate [approximately 65 dB SPL], 4-high [approximately 75 dB SPL], or 5-very high [approximately 85 dB SPL or higher]); 7) the estimated reverberation time (1-low [less than approximately 500 ms], 2-moderate [500 to 1500 ms], or 3-high [greater than 1500 ms]); 8) the optimal microphone mode (directional [D], omnidirectional [O], or No Talker Present [NT]); and 9) the degree of confidence in optimal microphone mode recommendation (not confident to very confident on a five point scale).

Importantly, observers were trained to focus on what the student appeared to actually be listening to rather than what might be judged to be the most important information. For example, if the student was only partially paying attention to the instructor and at the same time whispering to a friend, both sources (the friend and teacher) were deemed to be primary sound sources.

Each of these factors was coded with the time of day. Each time there was a change in any of the factors, observers entered a new time of day and made notes about all the relevant factors. For example, if a child was in the lunchroom talking to a classmate in front of him, but then started to listen to a child behind him instead, the observer would note the time of the change and make notes about all nine factors of interest listed above. All factors and times were logged on a coded check sheet to facilitate data collection. These data were then entered into a spreadsheet for analyses after the day of observation was over.

In order to ensure consistency and reliability across observers, all observers were thoroughly trained. Training consisted of a brief lecture followed by hands on training and practice. During the lecture, the observers were instructed about the purpose of the project, factors of interest, and tips for observing students in busy classrooms. During the lecture, observers were also instructed about use of the checklist for data collection and subsequent data entry. Following the lecture, observers went with the instructor(s) to practice making notes and observing. During this hands-on training, observations were checked and all questions were answered. Specific examples of signal and noise position, noise level and reverberation were provided. Observers minimally completed one training session, but often attended several sessions to refresh their training. The first time observer was always accompanied by an experienced observer who was available to answer questions.

In order to determine consistency of ratings, two trained observers completed ratings for the first five participants. At the end of the school day, the ratings from these two observers were compared and any discrepancies in ratings were resolved. These comparisons revealed only a single instance of disagreement, which was related to a judgment of whether a noise originating from the side of the participant was in the front or rear quadrant. Further training was completed, but because of the lack of discrepancies, all further observational data were collected by single observers.

Results

A series of mixed model Analyses of Variances (ANOVAs) were completed to determine if there were any significant differences between observations based on participants with normal (n = 13) or impaired hearing (n = 18), or younger (4–10 years; n = 16) and older (11–17 years; n = 15) age groups, for any of the factors evaluated. For these analyses, the between-group factors were age group (older or younger) and hearing status (normal or impaired), whereas the within-group factor was each specific environmental condition (e.g., position of the noise). These analyses revealed no significant main effect of group; consequently, all the results and discussion reflect data which were collapsed across all participants (a total of 31). For various technical and logistical reasons it was not always possible to observe every child for the entire school day. On average, students were observed for 5.2 hours. This average reflects the fact that approximately half the students were observed for an entire school day (approximately 6.5 hours), while the remaining students were only observed for approximately one-half the school day (approximately four hours). Of the total time observed during the day, 66% was classified as traditional classroom, 14% was classified as "special" classroom (consisting primarily of music or art classes), 9% was classified as lunch time, 7% was classified as hallway time, and 4% was classified as recess.

On average, the observer reported that no talker was present for approximately 30% of the recorded school day. These data reflect conditions including studying, taking tests in classrooms, walking between classes, playing alone, etc. The average percentage of the school day that the observer reported that the directional or omnidirectional microphone modes were expected to be optimal (based on the constraints highlighted in training) were 24% and 46% respectively.

Because the choice of microphone mode arguably is only important when there is a talker of interest, for all subsequent analyses only those results where there was a talker of interest were analyzed. When examining only those times when a talker was present, the observer reported the percentage of time the directional and omnidirectional modes were optimal. This is shown in Figure 1. In addition to the total time in each microphone mode, the number of switches per hour required to maintain the microphone mode judged to be optimal was also calculated. The actual activity greatly influenced the optimal microphone mode. In one case a single microphone mode was rated as appropriate for nearly two continuous hours (small group activities). At the other extreme, there was a case for which 22 changes between directional and omnidirectional modes were deemed necessary to maintain the optimal microphone mode during a single 50 minute class period (music class). On average, observational data suggested that 3.4 switches per hour between microphone modes were necessary.

As discussed in the introduction, there are several environmental factors that may lead to the recommendation of one microphone mode over another, including: relative position of the source and competing noise sig-

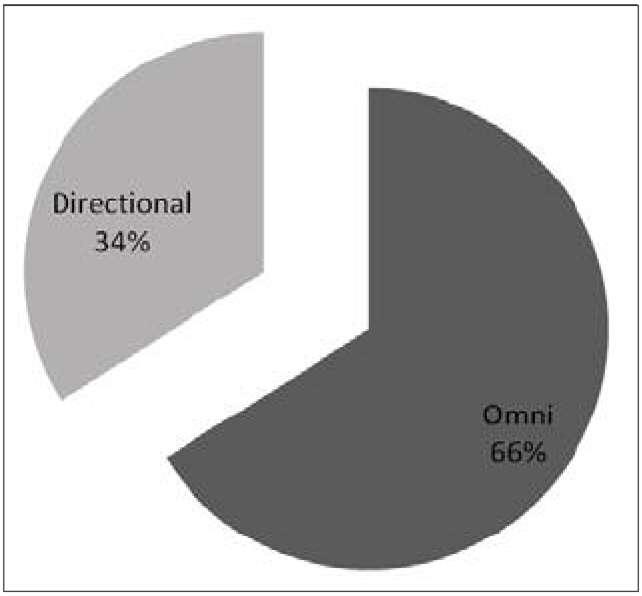

Figure 1. The average proportion of the active listening time (when a talker was present) that the observers reported that the directional or omnidirectional microphone modes were expected to be optimal.

nals, distance to the sound source, reverberation time and the overall noise level. Each of these environmental factors was analyzed using a separate Analysis of Variance (ANOVA). For these analyses the within-subjects factors (independent variable) were the microphone mode rated optimal (directional or omnidirectional) and the specific environmental factor (e.g., main speaker position). Statistical significance was defined at = 0.05 level, and Tukey honest and significant difference (HSD) testing was used, when necessary, for post-hoc analyses of the data.

Of the factors evaluated, it is of interest to note that the estimated average reverberation time for listening environments for which the directional and omnidirectional modes were rated optimal were not significantly different and were essentially identical. Ratings of reverberation were 1.94 and 1.97 for directional and omnidirectional modes, respectively, indicating approximately moderate reverberation on the three point rating scale used by the observers. While not significantly different, a trend was found when comparing estimated noise levels. Specifically, on a five point scale, the estimated noise level was 2.8 (slightly less than 65 dB SPL) for the directional environments, compared to a rating of 2.2 (slightly more than 55 dB SPL) for the omnidirectional environments. The average distance of the listener from the source was significantly different for the two microphone modes ($F1, 30 = 23.02$, $p < 0.0001$). On the average, the source was significantly farther away (mean = 2.4 M) for the omnidirectional environments than for the directional environments (mean = 1.1M).

The average proportion of the total observation time for each of five possible primary sound source (main talker) locations reported by the observers for the two microphone modes is shown in Figure 2. As expected, when the directional mode was judged as optimal, the source position was nearly always (94% of listening time) in front of the listener. For the remaining 6% the source was either to the side (but still in the front hemisphere), or there were multiple sources that were in the front hemisphere. In contrast, when the omnidirectional mode was judged as optimal, the primary sound source was either in multiple locations both in the front and rear hemisphere, or was mainly in the rear hemisphere a total of 67% of the time.

The average proportion of the total observation time for each of five possible competing noise locations reported by the observers for the two microphone modes is shown in Figure 3. Interestingly, it is evident that noise was present in the majority of school environments regardless of the rated microphone mode. As expected, noise was either surrounding or behind the listener for 96% of the directional environments. Somewhat surprisingly however, background noise was also located in these positions in 86% of the omnidirectional environments. The similarity of the noise position across the microphone modes was supported by the statistical analysis, which revealed a significant effect of noise position ($F_{4, 120} = 181.30$, $p < 0.0001$), but no significant effect of microphone mode or significant interaction between microphone mode and noise position.

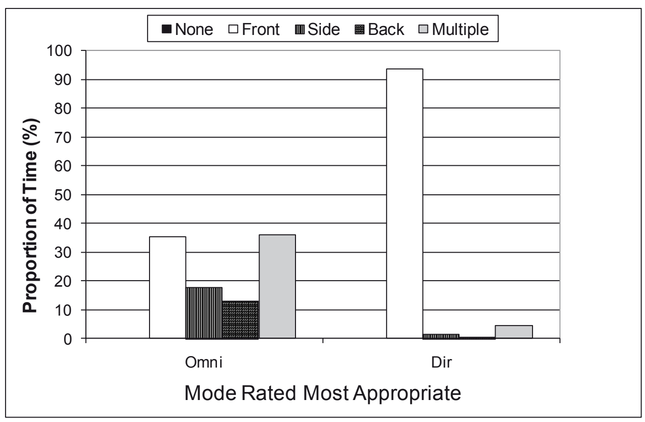

Figure 2. The average proportion of the total observation time for each of five possible primary sound source (main talker) locations reported by the observers for the two microphone modes.

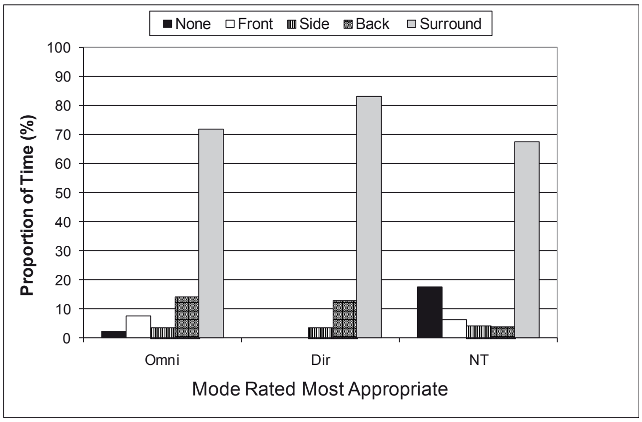

Figure 3. The average proportion of the total observation time for each of five possible competing noise locations reported by the observers for the omnidirectional (Omni), directional (Dir) and No Talker (NT) environments.

Post-hoc analysis revealed that the percentage of time the noise surrounded the listener was significantly greater than all other noise positions ($p < 0.0001$). In addition, the noise was located behind the listener significantly more often than it was located to the side ($p < 0.03$), front ($p < 0.03$), or when no noise was present ($p < 0.003$). Given how common it was that noise surrounded the listener, the presence and location of a dominant noise within the environment of noise surrounding the listener was examined (Figure 4). Interestingly, these data revealed that there was rarely a single dominant noise that was rated as clearly louder than the general noise levels surrounding the listener.

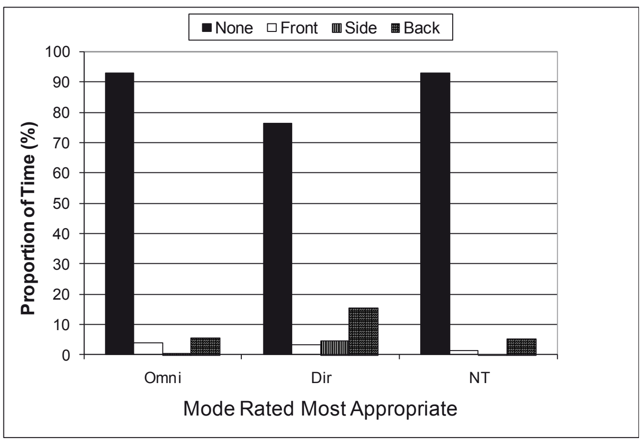

Figure 4. The average proportion of the total observation time for each of four possible dominant noise positions reported by the observers for the omnidirectional (Omni), directional (Dir) and No Talker (NT) environments. These data reflect only the proportion within the general environmental situations in which the noise surrounded the listener.

Specifically, the dominant noise position was rated as "none" for 93% of the omnidirectional environments and 77% of the directional noise environments.

In order to examine microphone mode as a function of specific school listening environments, the microphone mode judged to be optimal was plotted against the general category of listening environment (Figure 5). These data clearly show that the relative proportion of time each of the two microphone modes was judged optimal depended greatly on the general type of listening environment. Specifically, the directional mode was judged as optimal for only 10% of the active listening time during recess, but it was judged as optimal 83% of the time when in lunch environments. The large effect that environment had on the optimal microphone mode was supported by the statistical analysis which revealed a significant effect of listening environment ($F_{4, 120} = 62.97$, $p < 0.0001$). Post-hoc analysis revealed that the percentage of time the directional mode was optimal was significantly greater for the lunch environment than all other environments ($p < 0.0001$). In addition, the percentage of time the directional mode was optimal was significantly less for the recess environment than the special classroom ($p < 0.005$) or classroom ($p < 0.046$) environments.

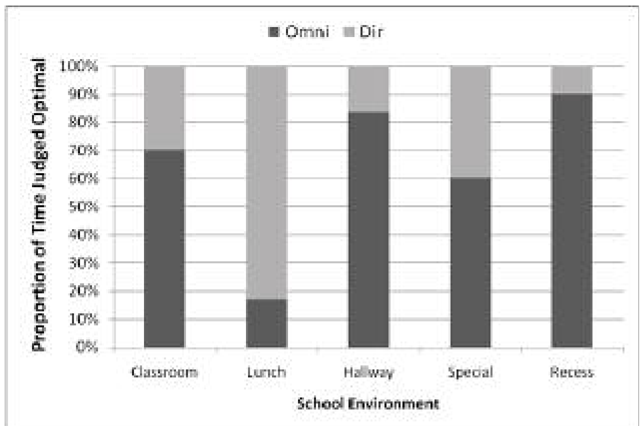

Figure 5: The average proportion of the active listening time the directional and omnidirectional microphone modes were judged to be optimal for each of five general categories of listening environment.

Discussion

The primary findings of this study support the potential for benefit from directional hearing aids in 34% of active listening environments. These data are in excellent agreement with previous results suggesting that the directional mode is appropriate for about a third of active listening situations experienced by adult listeners (Cord et al. 2007). These data provide further evidence of the potential for directional benefit in at least some school settings. However, it is also clear that the omnidirectional mode is most appropriate for the majority of the school day. As discussed in the introduction, a non-optimal microphone mode can reduce speech recognition performance. For example, it is expected that when students are surrounded by noise and facing a talker who is near, the directional mode may result in speech recognition performance that is 20-35% greater than when in the omnidirectional mode (Ricketts et al. 2007). However, it is also clear that in some listening situations, including those for which the talker is behind the listener, the directional mode will result in an approximately 20–25% decrement in speech recognition when compared to the omnidirectional mode.

Consequently, it is critically important that the optimal microphone mode is maintained as often as possible throughout the school day, presumably through either automatic or manual switching. It might be argued that the manual mode could be a reasonable method for maintaining the appropriate microphone mode when a small number of switches are required. However, the manual mode does not seem particularly feasible if indeed up to 22 switches are required in less than an hour in some situations. Switching so often might be bothersome even in an automatic system; however, even the average of 3.4 switches in an hour would require considerable vigilance when switching manually. These data are therefore interpreted as providing some support for use of an automatic, rather than manual switching method. However, more work is needed to evaluate the accuracy of directional switching algorithms to examine which method actually results in maintenance of the optimal microphone mode the greatest percentage of the time.

In addition to a small but significant difference in estimated noise level, these data demonstrated that the distance and angle of the sound source (figure 3) were the primary factors that affected whether the directional or omnidirectional modes were judged to be optimal. While it was expected that the location of the source would be important, it was somewhat surprising that the presence and location of the noise sources did not play a larger role. These data suggest that competing signals are present in the vast majority of school environments. Specifically, for the environments in which the directional mode was rated optimal, the competing signals (often times other talkers) typically surrounded the listener and the talker of interest was in front and close. For the environments in which the omnidirectional mode was rated optimal, competing signals again were typically present and surrounded the listener, albeit at a slightly lower level, and the talker of interest was in front or in other locations and slightly further away.

The similarities between the listening environments for the two microphone conditions may present a considerable challenge for automatic microphone switching programs. This is due to the fact that, in order to be most accurate, switching decisions would need to consider small differences in competing signal level, as well as the distance and location of the primary talker, often times present in a background of other talkers at various angles. Unfortunately in many cases, therefore, there may be little acoustic information to distinguish when each of the two microphone modes may be optimal. Instead, it appears that knowing what the listener actually wants to listen to (listening intent) is important. That is, a talker at a specific level, angle and distance might be a primary source or a competing noise, depending on the communication situation. The importance of the listener's intent suggests that manual input may be necessary to maintain the optimal microphone mode in some environments.

Another interesting implication relates to the finding that the competing noise, when present, typically surrounded the listener or was behind the listener. Adaptive directional microphones have been advocated as beneficial over fixed systems because they are able to modify their directional sensitivity pattern to provide greater attenuation when noise arrives from specific angles. Compared to fixed systems which are optimized for noise surrounding the listener, adaptive systems have been shown to primarily provide additional benefit when noise sources arrive from the side (Bentler et al. 2004; Ricketts and Henry 2002). The current data suggest that noise arrived from the side in only approximately 4% of the environments where the directional mode was judged to be optimal (figure 3). In addition, the dominant noise source was from the side in approximately 5% of the environments in which noise surrounded the listeners and the directional mode was judged to be optimal (figure 4). Together, these data reveal that a relatively small portion of school environments are expected to lead to additional benefit from adaptive directional systems. This is consistent with previous research which suggests that the number of real world environments for which additional adaptive directional benefit occurs may be limited (Woods, Merks, Zhang, Fitz and Edwards 2010). However, it may be the case that these few situations are quite important to the listener. Further, it should be noted that adaptive directional systems are never expected to provide less directional benefit than their fixed counterparts.

The overall noise level in directional environments was judged to be less than 65 dB SPL on the average, and in 20% of cases, was judged to be around 55 dB SPL. If these estimates are accurate, they also have important implications for automatic directional systems. Specifically, the noise levels may be relatively low in some environments for which a directional advantage may still be expected. Consequently, automatic systems that switch into directional mode at lower overall input levels than is currently typical may be warranted in order to maintain the optimal microphone mode in some school environments.

The data shown in figure 5 clearly demonstrated that the relative proportion of time each of the two microphone modes is appropriate is greatly affected by the specific type of listening environment. In the lunch environment the listener was typically facing the talker who was near, and there was moderately high level noise surrounding the listener. This was in contrast to the recess and hallway environments, for which the listener rarely faced the talker even though there were high levels of noise. In these environments, it is proposed that logistical constraints (watching where you are walking, climbing or running, etc.) limit a listener's ability to optimally orient their head to obtain directional benefit.

Somewhat surprisingly, despite the finding that low to moderate noise levels were commonly present, the directional mode was rated as optimal in only 30% of classroom environments. The omnidirectional mode was rated as optimal much more often primarily because the sound source was located in a position other than in front of the listener in 47% of classroom environments. In addition, the noise and speech sources were both rated as being in front of the listener in 4% of classroom environments. We believe these findings support two separate recommendations. First, for children who are wearing directional microphones in school environments, it seems prudent to provide at least minimal instruction to face the sound source of interest. However, it is recognized that this may be logistically difficult in many situations. Secondly, given the fact the talkers are commonly not in front of the listener, it is proposed that an FM system with an active environmental (hearing aid) microphone may provide more consistent speech recognition benefit in a classroom setting than a directional microphone for a primary talker of interest.

Conclusions

The results of this study support the potential for benefit from directional hearing aids in some school environments. The data also demonstrate that the optimal microphone mode is highly dependent on the specific type of listening environment and the specific listening task. The fact that environments for which the directional and omnidirectional modes were rated as having similar acoustic properties on the average, suggests that some manual interaction may be necessary to maintain the optimal microphone mode, which may shift based only on the listeners interest. Finally, these data further strengthen the recommendation for FM use when a single talker of interest is present as auditory benefits from FM systems are generally unaffected by head angle (though a loss of visual cues may occur).

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References

Bentler, R. A., Tubbs, J. L., Egge, J. L. M., Flamme, G. A., and Dittberner, A. B. 2004. Evaluation of an adaptive directional system in a DSP hearing aid. *American Journal of Audiology* 13(1): 73–79.

Bess, F.H., Dodd-Murphy, J., and Parker, R.A. 1998. Children with minimal sensorineural hearing loss: Prevalence, educational performance, and functional status. *Ear and Hearing* 19(5): 339–54.

Bess, F. H., and McConnell, F. E. 1981. *Audiology, education, and the hearing impaired child.* St. Louis, MO: CV Mosby.

Bess, F. H., and Tharpe, A. M. 1984. Unilateral hearing impairment in children. *Pediatrics* 74(2): 206–216.

Boothroyd, A., Eran, O., and Hanin, L. 1996. Speech perception and production in children with hearing impairment. In F. H. Bess, J. Gravel and A. M. Tharpe (eds.), *Amplification for children with auditory deficits* (pp. 55–74). Nashville, TN: Bill Wilkerson Center Press.

Ching, T. Y. C., O'Brien, A., Dillon, H., Chalupper, J., Hartley, L., Hartley, D., et al. 2009. Directional effects on infants and young children in real life: Implications for amplification. *Journal of Speech, Language, and Hearing Research* 52(5): 1241–1254.

Cord, M. T., Walden, B. E., Surr, R. K., and Dittberner, A. B. 2007. Field evaluation of an asymmetric directional microphone fitting. *Journal of the American Academy of Audiology* 18(3), 245–256.

Crandell, C., and Smaldino, J. 2000. Classroom acoustics and amplification. In M. Valente, R. Roeser and H. Hosford-Dunn (eds.), Audiology *volume II: Treatment* (pp. 382–410). New York: Thieme Medical Publishers.

Davis, J. M., Stelmachowicz, P. G., Shepard, N. T., and Gorga, M. P. 1981. Characteristics of hearing-impaired children in the public schools: Part II–Psychoeducational data. *Journal of Speech and Hearing Disorders* 46(2): 130–137.

de Villiers, P., Eavey, R. D. I., and Klein, J. 1992. *Educational implications of deafness: Language and literacy.* Paper presented at the 102nd Ross Conference on Pediatric Research, Columbus, OH.

Fabry, D. A. 1994. Noise Reduction with FM Systems in FM/EM Mode. *Ear and Hearing* 15(1): 82–86.

Finitzo, T., Sininger, Y., Brookhouser, P., Epstein, S., Erenberg, A., Roizen, N., et al. 2000. Year 2000 position statement: Principles and guidelines for early hearing detection and intervention programs. *Pediatrics* 106(4): 798–817.

Gravel, J. S., Fausel, N., Liskow, C., and Chobot, J. 1999. Children's speech recognition in noise using omnidirectional 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): 409–418.

Henry, P., and Ricketts, T. 2003. The effect of head angle on auditory and visual input for directional and omnidirectional hearing aids. *American Journal of Audiology* 12(1): 41–51.

Hicks, C. B., and Tharpe, A. M. 2002. Listening effort and fatigue in school-age children with and without hearing loss. *Journal of Speech, Language, and Hearing Research* 45(3): 573–584.

Hornsby, B. W. Y., and Ricketts, T. A. 2007. Directional benefit in the presence of speech and speechlike maskers. *Journal of the American Academy of Audiology* 18(1): 5–16.

Khairi, M., Daud, M., Noor, R.M., Rahman, N.A., Sidek. D.S., and Mohamad. A. 2010. The effect of mild hearing loss on academic performance in primary school children. *International Journal of Pediatric Otorhinolaryngology* 74(1):67–70. Epub 2009 Nov 12.

Killion, M. C. 1997. SNR loss: I can hear what people say, but I can't understand them. *Hearing Review* 4(12): 8, 10, 12, 14.

Kuk, F., Kollofski, C., Brown, S., Melum, A., and 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.

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

Lewis, D. 1991. FM systems and assistive devices: Selection and evaluation. In J. Feigin and P. T. Stelmachowicz (eds.), *Pediatric amplification* (pp. 139–152). Omaha, NE: Boystown National Research Hospital.

Lewis, M. S., Crandell, C. C., Valente, M., and 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.

Madell, J. R. 1992. FM systems as primary amplification for children with profound hearing loss. *Ear and Hearing* 13(2): 102–107.

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

Ricketts, T. 2000b. Impact of noise source configuration on directional hearing aid benefit and performance. *Ear and Hearing* 21(3): 194–205.

Ricketts, T., Galster, J., and Tharpe, A. M. 2007. Directional benefit in simulated classroom environments. *American Journal of Audiology* 16(2):130–144.

Ricketts, T., and Henry, P. 2002. Evaluation of an adaptive, directional-microphone hearing aid: Evaluación de un auxiliar auditivo de micrófono direccional adaptable. *International Journal of Audiology* 41(2): 100–112.

Ricketts, T., Henry, P., and Gnewikow, D. 2003. Full time directional versus user selectable microphone modes in hearing aids. *Ear and Hearing* 24(5): 424-439.

Ricketts, T., Lindley, G., and Henry, P. 2001. Impact of compression and hearing aid style on directional hearing aid benefit and performance. *Ear and Hearing* 22(4): 348–361.

Ricketts, T. A., and Galster, J. 2008. Head angle and elevation in classroom environments: Implications for amplification. *Journal of Speech, Language, and Hearing Research* 51(2): 516–525.

Ricketts, T. A., and Tharpe, A. M. 2004. Potential for directivity-based benefit in actual classroom environments. Paper presented at the A Sound Foundation through Early Amplification Conference, Chicago, IL.

Schum, D. 1996. Speech understanding in background noise. In M. Valente (ed.), *Hearing aids: Standards, options, and limitations* (pp. 368–406). New York: Thieme.

Tharpe, A. M., and Bess, F. H. 1999. Minimal, progressive, and fluctuating hearing losses in children: Characteristics, identification, and management. *Pediatric Clinics of North America* 46(1): 65–78.

Walden, B. E., Surr, R. K., Cord, M. T., and Dyrlund, O. 2004. Predicting hearing aid microphone preference in everyday listening. *Journal of the American Academy of Audiology* 15(5): 365–396.

Woods, W. S., Merks, I., Zhang, T., Fitz, K., and Edwards, B. 2010. Assessing the benefit of adaptive null-steering using real-world signals. *International Journal of Audiology* 49(6): 434–443.