CHAPTER TEN

Potential for Directivity-Based Benefit in Actual Classroom Environments

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Introduction

Children with hearing impairments exhibit a variety of difficulties with communication and academic achievement, as well as psychosocial and emotional problems (Carney and Moeller 1998; de Villiers 1992; Marschark 1993; Tharpe and Bess 1999). Most recently, data suggest that children with hearing impairment exhibit greater listening effort than their peers with normal hearing (Hicks and Tharpe 2002). The primary objective of early management for the child with hearing impairment is the fostering of speech and language development through improvements in auditory input. Although prescriptive hearing aid gain and output procedures typically result in appropriate audibility and comfort of the speech signal (i.e., Seewald, Moodie, Sinclair and Scollie 1999; Stelmachowicz, Kalberer and Lewis 1996), ensuring that the intensity level of speech is presented well above that of interfering background noise remains a significant problem (Gravel, Fausel, Liskow and Chobot 1999; Joint Committee on Infant Hearing, 2000).

The degree to which the signal of interest is audible above the interfering noise at any given moment in time is quantified by the signal-to-noise ratio (SNR). Data suggest that 25% of adult hearing aid users, who do not wear their instruments, cite poor performance in background noise as the primary reason for hearing aid rejection (Kirkwood 2000). Classroom noise levels, along with reverberation and large speaker-to-listener distance have been identified as the primary nemeses of children with hearing loss (e.g., Crandell and Smaldino 2000). A SNR of at least +15 to +30 dB has been recommended for educational settings (Berg 1993; Blair 1990; Smaldino and Crandell 1995). Unfortunately, most classrooms have SNRs between – 6 and +6 dB (Crandell and Smaldino 2000). Several studies have shown that poor SNRs, such as those typically found in classroom settings, can significantly reduce speech understanding for children both with and without hearing impairment (e.g., Finitzo-Hieber and Tillman 1978; Crandell 1993). In addition, data suggest that both children (Boothroyd, Eran and Hanin 1996) and adults (e.g., Killion 1997; Schum 1996) with hearing impairment require significantly better SNRs for equivalent speech recognition performance when compared to listeners with normal hearing. Speech understanding in noise appears to be further impacted by the maturity of the auditory system. That is, infants and very young children exhibit difficulties in some slightly noisy and reverberant listening situations that do not appear to significantly impact adult speech understanding (Nabelek and Robinson 1982; Nozza, Rossman, Bond and Miller 1990; Nozza 2000). In fact, several studies have indicated that individuals' ability to understand speech in the presence of background noise is not at its peak until their teen years (Elliott 1979; Nilsson, Soli and Sullivan 1994; Stelmachowicz, Hoover, Lewis, Kortekaas and Pittman 2000).

Improvement of SNR

To date, the only methods that consistently have been shown to improve SNR for listeners with hearing impairment are based on microphone technology. The simplest and most effective approach works by placing the microphone and sound source in close proximity. The popular and effective frequency

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modulated (FM) systems that incorporate a microphone worn by, or placed near, the person speaking and transmits the microphone's input directly to a device (often a hearing aid) through an FM signal are the most obvious example of this approach. FM systems have been shown to improve SNR by as much as 16 to 20 dB in noisy environments (Hawkins 1984). Due, in part, to the large magnitude of SNR advantage, some audiologists have recommended FM systems as the primary, full-time amplification device for children (e.g., Madell 1992). Although there is little doubt that FM systems currently reflect the optimal intervention in many classroom listening environments, the sole use of FM systems for listening has been criticized since it may limit children's ability to monitor both their own speech and that of other talkers (Lewis 1991). Common listening situations in which there are multiple talkers of interest represent one environment that is especially challenging for FM systems.

There is little doubt that FM systems are the preferred treatment option in classroom settings in which only the teacher's voice is of interest (Lewis, Crandell, Valente and Horn 2004). However, FM systems may not be the preferred method when listening to other classmates, "overhearing" other conversations, and/or when ease of portability or cosmetics are a significant concern. Research has shown that, in addition to instruction from the teacher, overhearing the conversation of peers also plays a crucial role in the cognitive, linguistic and social development of children with hearing loss (Flexer 1996). The requirement of vigilant monitoring by an adult, which is likely to be necessary to ensure that the FM system's microphone is in proper position for the specific communication situation, may preclude FM system use in environments with multiple primary talkers (Moeller, Donaghy, Beauchaine, Lewis and Stelmachowicz 1996).

In multi-talker environments in which the child can turn to face each listener in turn, a directivity-based approach (i.e., directional hearing aids or microphone arrays) may be preferred to passing a FM microphone to each talker. Multi-talker environments may include formal learning situations as well as social settings such as lunch, the bus and the playground. Directivity-based approaches are advocated as a potential method for improving SNR in some noisy environments, while providing greater portability (since hardware external to the hearing aid is not needed). Even though the magnitude of the improvement in SNR provided by directional hearing aids is much smaller (on the order of approximately 3–6 dB) than has been reported for FM systems, the potential for improvement is still quite significant (Ricketts 2000c).

Potential Benefits and Limitations of Directional Microphones and Microphone Arrays

Directional hearing aids and microphone arrays can be thought of as "directivity based" systems in that any potential advantage is dependent on, and limited by, spatial separation between undesirable signals and the signal(s) of interest. Directional hearing aids and microphone arrays incorporate two or more microphones (or microphone ports) to allow for improved SNR based on the angle and elevation of arrival of the signal of interest relative to unwanted signals. In contrast, single omnidirectional microphones, commonly used in most hearing aids, are not directionally sensitive to sound in the free field. Hearing aids using single omnidirectional microphones do not generally improve SNR in comparison to the unaided ear, and in some cases, SNR is made worse by this type of amplification (Beck 1983; Ricketts 2000a; Ricketts, Lindley and Henry 2001). The resulting improvement in SNR for directional, in comparison to omnidirectional, hearing aid fittings can lead to an improvement in speech recognition in noisy environments commonly referred to as directional benefit.

Although data supporting directional hearing aid use for adults in a variety of noisy listening situations are plentiful (see Ricketts and Dittberner 2002 for a review), much less is known about the appropriateness of this technology for children (Gravel et al. 1999; Hawkins 1984; Kuk, Kollofski, Brown, Melum and Rosenthal 1999). In addition, much of the data collected thus far have been in non-realistic laboratory environments. The lack of directional hearing aid studies with children may have resulted in the lack of recommendations for directional hearing aid use in this population, despite data supporting the advantage of directional amplification in adult listeners (Bess et al. 1996).

As with FM systems, directivity-based approaches are expected to interact with the hearing aid wearer's environment to create either positive or negative outcomes (e.g., Ricketts 2000b, 2000c;

Ricketts, Henry and Lindley 2001). The pattern of angular attenuation provided by any hearing aid can be visualized three dimensionally by its spatial attenuation pattern or two dimensionally by a directional pattern or "polar plot" (Ricketts and Ditberner 2002). These patterns reflect the specific amount of attenuation provided by the microphone system as a function of angle and elevation of sound arrival. Data from frequency-specific spatial attenuation patterns can be used to calculate directivity index (DI), which quantifies the magnitude of amplification a hearing aid provides for sounds arriving directly from in front of the listener in comparison to sounds arriving from all other angles (Ricketts and Ditberner 2002). After quantifying a hearing aid's directional pattern when fitted to a listener, it is possible to make predictions about how specific "auditory scenes" can interact with a directional pattern to provide either increases or decreases in speech recognition performance. A specific auditory scene is defined by the position and intensity level of primary and competing sound sources in a reverberant, real-world listening environment; that is, the orientation and intensity of sound sources around a listener's head.

Because directivity-based approaches selectively attenuate sounds based on their angle and elevation of arrival, positive directional benefit is only expected when children are able to orient their heads toward the sound of interest. In specific listening situations for which the sound source of interest is behind the child, and the child is unable or unwilling to turn to face the sound source, directivity-based amplification is expected to be detrimental. Alternatively, through head movement, a child 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 child turns around to face another classmate, when the teacher walks to another area of the room, or in more common cases, such as when a child looks down to his or her desk to write. In any of the above cases, the reduction in signal level may reduce the amount of speech information that falls within the child's audibility range. Any reduction in audibility of speech is likely to result in a decrease in speech recognition performance (Seewald et al., 1999).

Past investigations with adult listeners have shown that appropriate head angle is imperative for maximal speech understanding in noise when fitted with directional hearing aids. Ricketts (2000a) revealed that listeners could improve speech intelligibility in noise by slightly (30 degrees or less) angling their heads relative to the sound source. Lee, Lau, and Sullivan (1998) revealed that subjects' speech recognition for sounds arriving directly behind was significantly poorer when fit with a directional hearing aid, than when the sound arrived from in front of the listener.

Directional Hearing in Young Children

Given the importance of appropriate head angle when wearing directional microphones, it is important to consider what we know about directional hearing and orienting in normal hearing infants and young children. For example, even in the newborn period, infants can turn their eyes or heads towards the source of sound in the correct hemifield (Clifton, Morrongiello, Kulig and Dowd 1981; Crassini and Broerse 1980; Muir and Field 1979; Turkewitz, Burch and Cooper 1972; Werthiemer 1961). However, this response is quite fragile, being highly dependent upon the infant's state and posture, and the stimulus conditions (Clarkson 1992). Interestingly, this head turn response, present within hours of birth, disappears at approximately two months of age and reappears at about four months of age. Upon its return, the head turn response is faster (i.e., latency of < 1sec), accompanied by visual search, and appears to be more accurate. This U-shaped developmental function is believed to reflect a shift in locus of control from reflexive, sub-cortical to cortical structures (Muir, Clifton, and Clarkson 1989).

The minimum audible angle (MAA) task, used to measure the smallest detectable change in the position of a sound, is a commonly used method for studying sound localization in infants. There is a significant change in the MAA during infancy ranging from about 20–25° at four months of age to less than 5° at 18 to 24 months of age (Ashmead, Clifton and Perrin 1987; Ashmead, Davis, Whalen and Odom 1991; Morrongiello and Rocca 1990). Although this MAA work is instructive in terms of identifying the limits of spatial acuity in infants and young children, we still do not know much about localization accuracy, or a child's ability to determine exactly where a sound is coming from. Morrongiello and Rocca (1987) employed a head orientation task for studying localization and determined that the accuracy of infant localization continues to improve across the age range of 6 to 18 months. However, methodological limitations of using this type of task with young children limit the usefulness of these results.

Based on these studies of localization development, it appears reasonable to conclude that young children are capable of approximately facing the teacher when the teacher is speaking. However, many questions remain. Do the localization abilities of children with hearing loss differ from those of children with normal hearing? How often *do* children with hearing impairment approximately face the teacher when the teacher is speaking? Do children tend to localize toward speakers with their eyes rather than their heads? Is a lot of instruction given to children in classroom settings when they are not oriented toward the teacher? Do these children turn their heads to listen to talkers at other angles? Furthermore, it is unknown whether children, with or without hearing aids, automatically reposition their heads to improve speech recognition in difficult listening situations.

The purpose of this investigation was to quantify the angle and elevation of children's heads relative to important sound sources in classroom environments. This quantification was completed for children ranging in age to determine if age impacted accuracy of orientation. Furthermore, head orientation was evaluated across children with and without hearing loss to determine if orientation accuracy was similar across these two groups. Data quantifying the angle of children's heads relative to sound sources of interest are necessary for design of future studies examining the impact that these head angles might have on aided speech recognition. These data also have implications for both aural rehabilitation with hearing aids and estimations of maximum real-world performance given that this relationship between head orientation and sound source can result in either improving or reducing speech recognition in noise. Preliminary data representing the first 20 children evaluated as part of this investigation follows.

Methods

Three video cameras were used to assess head position relative to sound sources of interest in classroom listening environments. The head angle of 20 children was investigated as a function of age and presence or absence of hearing loss. Ten of the 20 children were aged 5 to 7 years with a mean age of 5.5 years (younger group) and the remaining ten were aged 8 to 12 years with a mean age of 10.2 years (older group). All children were recruited as part of a classroom pair. Specifically, one child with and one without hearing impairment, of the same gender, were recruited from the same classroom. Videotaping was scheduled to ensure that the same classroom activity occurred for both children in each pair. Children's classrooms included one located in the early intervention program of the Vanderbilt Bill Wilkerson Center (two children), two daycare settings in the metropolitan Nashville area (four children), and seven classrooms in the Metropolitan Nashville Public Schools (14 children), for a total of 10 classroom environments.

The presence or absence of hearing loss was established by record review for the children with hearing loss and parental report for the children with normal hearing. Of the children with hearing impairment, teacher report indicated all ten consistently wore hearing aids bilaterally. All children with hearing aids were evaluated while aided. Eighteen of the 20 children were in inclusionary classroom environments with the remaining two children in a self-contained classroom for the hearing impaired.

Evaluation of Head Angle

Angular position in a three-dimensional space can be assessed using two cameras placed at known, fixed distances from the object in space. Head position and sound source locations were recorded in each of the classrooms through the use of three digital video cameras. One camera (Cannon ZR65MC) was mounted over the child's head and aimed directly down. Data from this camera were primarily used to assess head angle in the horizontal plane. A second camera (Cannon ZR65MC) was placed so that the side of the child's head could be viewed at approximately the elevation of the child's head. Data from this camera were primarily used to assess head angle in the vertical plane. A third camera (Cannon Optura 100 MC) was placed in the rear of the classroom in order to capture teacher movement and the position and movement of other sound sources. Individual children were videotaped for 20 minute sessions. These sessions included a traditional lecture or, whenever possible, a class period that required significant interactions among the children (e.g., a collaborative project).

The specific recording session times were identified in cooperation with the classroom teachers. Prior to videotaping, 3–7 small stickers were placed on the child's head to aid in motion and position tracking. The position of the sound sources of interest (i.e., either the teacher or other classmates) were physically measured before and after the class period and combined with video data in order to increase the accuracy of angular measurements. In addition, field notes relative to the position and movement of the speaker of interest and other sound sources were kept during the recording sessions. In order to reduce the novelty of the video recoding, perhaps biasing the results, actual recording did not begin until at least several minutes after the cameras had been placed. Pilot data indicated that conducting a "practice" recording on the day prior to the actual recording did not aid in reducing the distraction caused by the presence of the cameras. Rather, the children generally ignored the cameras and the investigators within several minutes after they were set up.

Analysis

The output from the digital cameras was transferred to a computer for further analysis. All three video streams were time locked by quickly turning a classroom light off and on. The three time-locked streams were viewed and analyzed frame by frame using a commercial video editing package (Sonic Foundry Vegas Video 4.0) and an on-screen protractor. One frame of each of the three streams was systematically selected and analyzed for every second of video. For example, the 10th frame of 30 was selected from each second of recording. The primary data of interest for analysis included: 1) deviation in head angle from the position of the primary talker; 2) deviation in head elevation from the position of the primary talker; 3) number and position of primary talkers; 4) number and location of brief utterances; 5) attention to brief utterances.

For the purposes of this analysis a "brief utterance" was defined as an instance of a talker who spoke for less than three seconds in isolation (e.g., a child answers a question). Instances of "group utterance" (e.g., students in the classroom responded in unison) were not analyzed. Attention to a brief utterance was defined as an instance when the target child participant turned his or her head in the approximate direction of the speaker during the brief utterance. All segments in which there was not a primary talker, including group utterances and quiet times, were excluded from all analyses. That is, only "active listening times" defined as those times in which there was a discernable primary talker were selected for analysis.

A controlled pilot study was completed to assess the accuracy of the measurement method. Specifically, deviation in angle and elevation data obtained using the experimental method was compared to physical measures of these deviations obtained by a second experimenter for several classroom positions. These pilot data indicated that the measurement method accurately measured the actual angle to within ±3 degrees in the horizontal and vertical planes. In addition, changes in angle were consistent between physical and video measurement methods with a tolerance of approximately one degree.

Results

Analysis across individual video taping sessions indicated that the classroom teacher was the primary talker for between 59% to 100% of the active listening time (mean = 89%). That is, the majority of the 10 classroom environments evaluated were didactic, rather than interactive in nature. Informal discussions with the classroom teachers indicated that this was usual and expected in elementary through middle school classrooms in Metropolitan Nashville Public Schools. The number of brief utterances ranged from 2 to 33 across the 20 participant sessions. A one-way analysis of variance (ANOVA) revealed that participants with normal hearing attended to a significantly ($F_{1,18} = 18.9$, $p < 0.001$) smaller portion of the briefs (18%) than those with impaired hearing (31%). It is of note that the six participants with the highest percentage of attendance to briefs all had impaired hearing.

In order to obtain a measure of accuracy, the root mean squared (RMS) deviation of the child's head angle and elevation relative to the primary sound source position was calculated across the active listening times (one data point per second). As these measures of deviation included instances in which there were brief utterances from secondary talkers as well as (primarily) instances for which only a primary talker was speaking, a subset of these data was also selected for analysis. Specifically, instances in which there was only a primary talker were first selected as a sub-group. This sub-group (referred to herein as "most accurate") was further refined by selecting the instances in which accuracy was best (most accurate

50%). The RMS deviation in angle and elevation for these most accurate head orientations in the presence of a primary talker were then calculated. The overall and most accurate RMS deviations in angle and elevation for both children with normal and impaired hearing are shown in figures 1a and 1b, respectively.

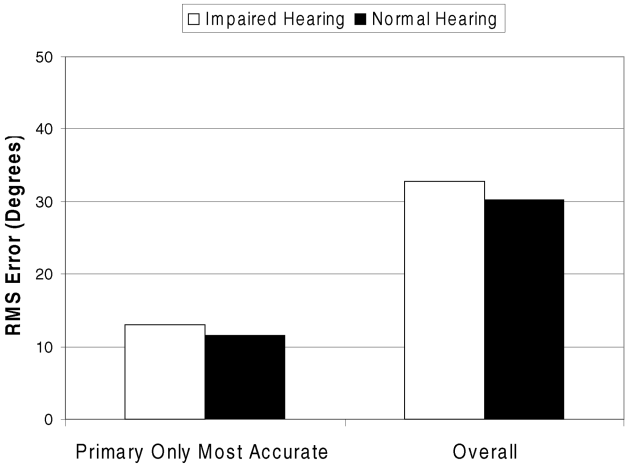

Figure 1a. The overall and most accurate RMS deviations in angle for both children with normal and impaired hearing.

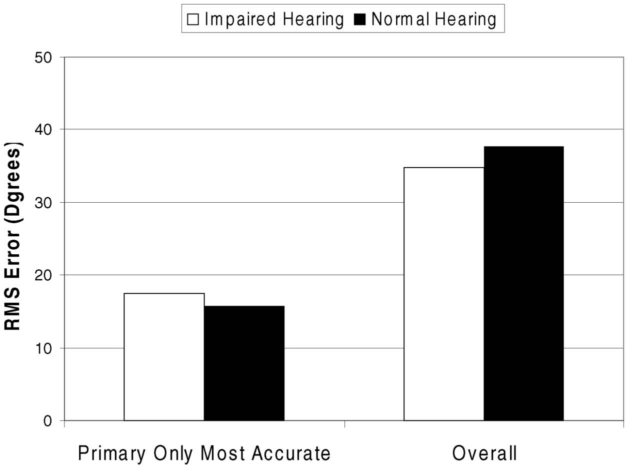

Figure 1b. The overall and most accurate RMS deviations in elevation for both children with normal and impaired hearing.

As expected, the RMS error deviation is much smaller when focusing on only the most accurate sub-set of data. The small data set provided in these preliminary data limit the validity of performing standard statistical analyses. Four separate one-way ANOVA calculations comparing the deviation error for listeners with normal and impaired hearing were completed, however, to identify possible significant differences. Not surprisingly, given both the small number of participants and, most importantly, the similarity in average values, no significant differences were measured across the two groups in either angle or elevation for either the most accurate sub-group or overall.

In order to examine the potential impact of age on head orientation accuracy the most accurate sub-set of angle and elevation data described above were plotted as a function of age (figures 2a and 2b, respectively). These data revealed a non-significant positive correlation (r = 0.34) between age and angle

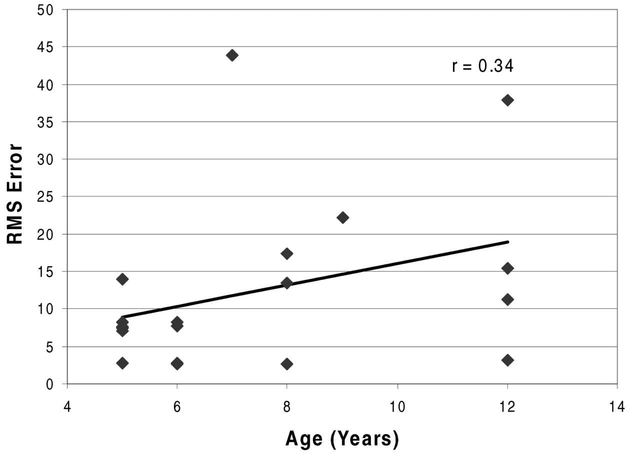

Figure 2a. Correlation between age and angle deviation (r = 0.34) for the most accurate data sub-set.

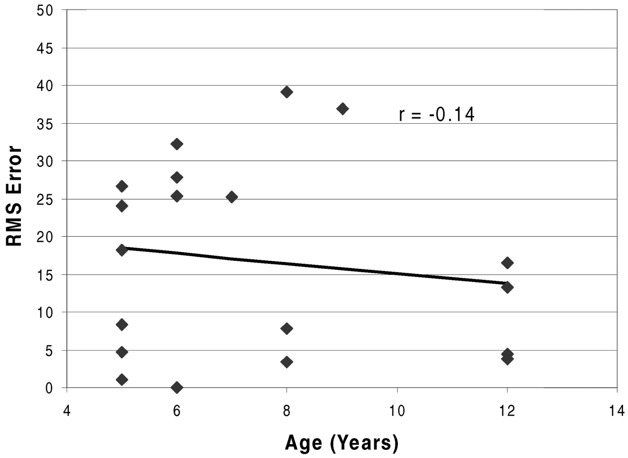

Figure 2b. Correlation between age and elevation deviation (r = – 0.14) for the most accurate data sub-set.

deviation and a non-significant negative correlation between age and elevation deviation (r = – 0.14). That is, no strong relationship between age and head orientation ability was present across the age range evaluated.

Despite the lack of group differences, considerable individual differences in overall RMS error were present for both angle and elevation. Specifically, overall RMS error ranged from 14 degrees to 61 degrees for angle, and from 7 degrees to 66 degrees for elevation.

Discussion

This investigation revealed only one significant difference in the head orientation behavior of children with and without hearing loss. Namely, children with hearing loss were much more likely to attend to brief utterances made by secondary talkers than children with normal hearing. Although the reason for this difference is unclear, it is hypothesized that it may be the result of a need for increased visual information by the children with hearing loss for enhancing speech perception or monitoring the environment in this population.

Although still preliminary given the small number of participants, these data suggest that children can, and do, accurately orient their heads toward sound sources of interest in the real world. In the case of a single principle talker, RMS deviation in head angle was approximately 13 degrees and RMS deviation in elevation was approximately 17 degrees, for the 50% of time that children were attending the best. Although only adult data are available for comparison, previous studies have found no differences in directional hearing aid benefit for deviations in head angle of 15 degrees or less (Ricketts 2000c; Henry and Ricketts 2003). In addition, average hearing aid directivity is not significantly impacted by deviations in elevation of 10 degrees or less (Ricketts and Dittberner 2002).

Interestingly, the data did not reveal any significant impact of age or the presence or absence of hearing loss on orientation accuracy. That is, these data suggest that both hearing aid wearers and children with reportedly normal hearing who are between five and twelve years old are approximately equivalent in their accuracy of orientation toward a primary sound source in classroom settings. It would therefore follow that age, over the range evaluated in this study, does not need to be considered as a factor related to the maximum potential benefit from directivity-based hearing aid processing. This of course does not necessarily indicate that the same directional benefit is expected across this age range. For example, further work is necessary to determine if the same improvement in SNR will lead to the same benefit across children of various ages. The impact of both the ability to switch appropriately between directional and omnidirectional modes and the appropriateness of automatic directional switching modes present in many modern commercial hearing aids in classroom settings also needs to be evaluated, as well as a number of other factors.

Although average data did not reveal any significant differences in orientation accuracy between children with hearing loss and those with normal hearing, it is clear that large individual differences were present. The reason for this variance may not be clear at first glance, but the probable cause is evident when examining the range of classroom tasks. Specifically, it is hypothesized that the specific listening task was most directly responsible for individual differences in accuracy of head orientation. That is, accuracy might be expected to be different when children are listening to a story than when they are required to take notes. It is further proposed that the weak positive correlation between age and RMS error in angle may have been driven by the fact that older children are more likely to be in listening environments requiring desk work. Analysis of the data from a greater number of children is necessary, however, in order to more fully test this hypothesis.

Figures 3a and 3b provide an eight-minute example of one child's individual angle and elevation deviation data. The child in this example was six years old and had a hearing loss. Positive values in these figures correspond to a head angle that is to the right of center and a head elevation that is positive relative to the horizontal plane (the participant's head is pointed up). Each data point corresponds to a one second increment. It may be concluded from these figures that for the majority of time, the child's head is "pointed" directly over the talker's head. That is, the angle is relatively accurate; however, the elevation is consistently greater than expected. The videotape of this classroom revealed that this listening situation was a reading circle with the teacher seated in a chair reading surrounded by children sitting on the floor. The child participant in this case was leaning back on his hands with his head tilted back. He

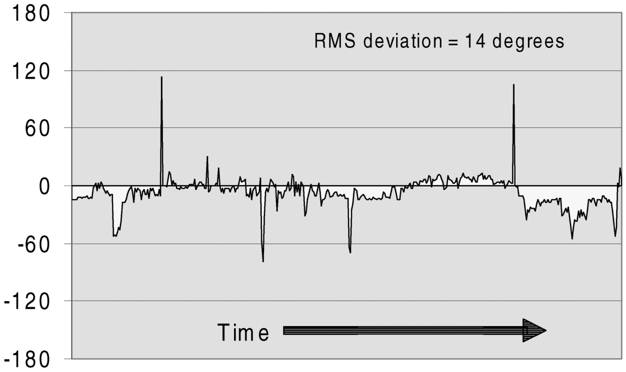

Figure 3a. An-eight minute example of a six-year-old child's individual angle deviation data. Positive values correspond to a head angle that is to the right of center.

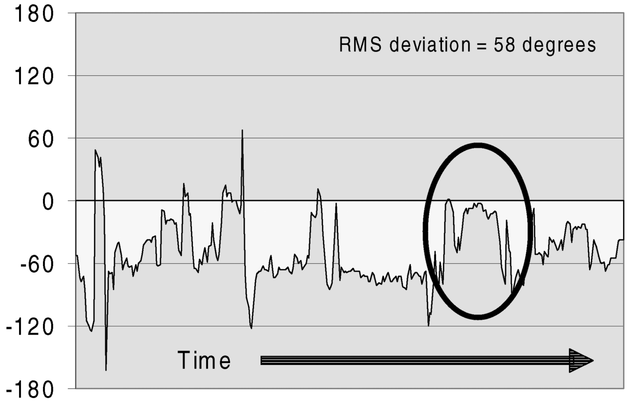

Figure 4a. An eight-minute example of a 12-year-old child's individual angle deviation data. This child's head was to the left of the talker.

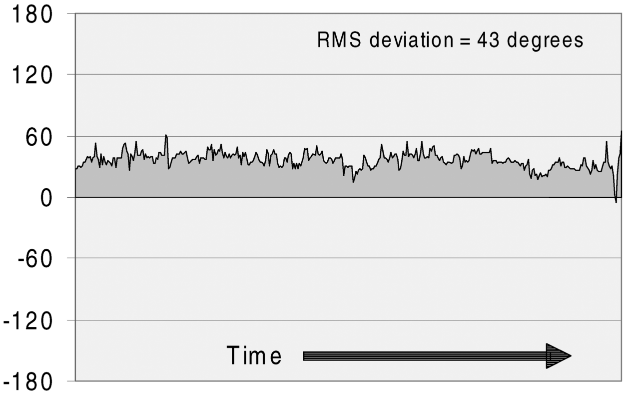

Figure 3b. An eight-minute example of the same six-year-old child's individual elevation deviation data. Positive values correspond to a head elevation that is positive relative to the horizontal plane (the participant's head is pointed up).

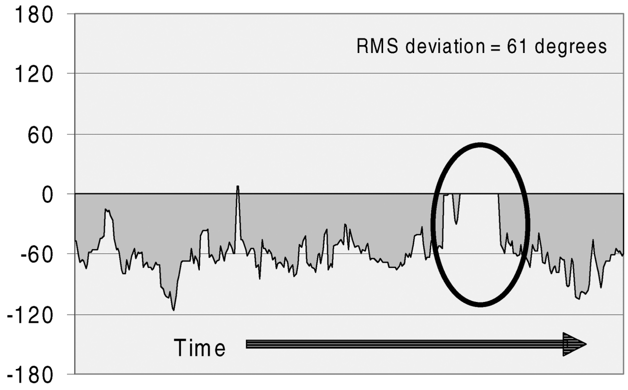

Figure 4b. An eight-minute example of the same child's individual elevation deviation data. This child's head was lowered relative to the horizontal plane.

then lowered his gaze so that he was (usually) directly looking at the teacher. Interestingly, the normal hearing control for this child revealed an almost identical pattern of deviation during the same task.

Another clear example of the impact of listening environment is shown in figures 4a and 4b. In this case, the child was a twelve year old with hearing loss. The data reveal that this student's head was consistently pointed lower and to the left of the talker. Not surprisingly, the video record revealed that these data were collected while this student was taking notes and the teacher was lecturing.

The bias to the left was present because the student was seated on the left-hand side of the classroom and the teacher was standing in the middle. If the time course of the head angle and elevation are followed it is also evident that the student occasionally oriented her head directly toward the teacher. This is most clearly evident during the circled time frame during which the student consistently oriented her head toward the teacher for a period of approximately 30 seconds.

Conclusions

The results of this study support the potential for benefit from directivity-based intervention in some school environments. This potential for benefit does not appear to be limited by age, as similar deviations in head orientation were evident across the age range investigated. Significant individual variations in head angle and elevation (relative to the position of the primary sound source) were also evident. The data are consistent with the hypothesis that variation in head angle accuracy in real classroom environments is highly dependent on the listening task. That is, children appear to be able to orient their heads accurately towards a sound source of interest, but are not always able or willing to do so because of the specific task demands. Tasks such as note taking, drawing, etc. do not allow for accurate head orientation toward the sound source of interest. These data further strengthen the recommendation for FM use in such environments as auditory benefits from FM systems are generally unaffected by head angle (though a loss of visual cues may occur).

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