Evaluation of Speech Recognition with Personal FM and Classroom Audio Distribution Systems

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Speech recognition in quiet and in noise was evaluated for children with normal hearing, children with hearing loss, and adults with normal hearing. Performance was evaluated in a classroom environment without use of wireless radio frequency (RF) hearing assistance technology (HAT) and with two different types of classroom audio distribution (CAD) systems (a fixed-gain multiple loudspeaker system and an adaptive single-tower CAD system). Children's speech recognition was also assessed with an adaptive personal frequency modulation (FM) system coupled to their personal hearing aids as well as with simultaneous use of the personal FM system with the aforementioned CAD systems.

The results of this study indicated that performance in quiet was similar between the condition without RF use and each of the conditions with use of RF HAT. However, speech recognition in noise was significantly better with use of each of the RF HAT. Use of the adaptive single tower CAD system provided better speech recognition in noise than use of the fixed-gain multiple loudspeaker CAD system. The best performance was achieved with the adaptive personal FM system and simultaneous use of the personal FM and adaptive single tower CAD system with no differences between those conditions. Performance with simultaneous use of the personal and adaptive CAD system was considerably better than performance obtained with simultaneous use of the personal and fixed-gain, multiple loudspeaker system. Adults with normal hearing achieved better performance across all conditions when compared to children with normal hearing, while children with normal hearing outperformed children with hearing loss.

Introduction

It is well known that children require a more favorable signal-to-noise ratio (SNR) than adults in order to understand speech in the presence of noise. Specifically, the typical five-year- old child requires an SNR that is around 5 dB higher than an adult in order to recognize words in noise with a similar level of accuracy as adults (Boothroyd, 1997). Research has shown that children with hearing loss are even more likely to experience difficulty understanding speech in noise. For instance, Finitzo-Hieber and Tillman (1978) evaluated speech recognition in noise and showed that children with mild to moderate hearing loss had speech understanding scores that were twenty to thirty percentage points lower than children with normal hearing. Additionally, Crandell (1993) compared speech recognition in noise between children with typical hearing and minimal hearing loss and found that children with minimal hearing loss scored 25 percentage points poorer at a -6 dB SNR.

Numerous studies have shown that children with hearing loss experience a considerable reduction in speech recognition in reverberant environments (Finitzo-Hieber & Tillman, 1978; Nabelek & Nabelek, 1985; Neuman, Wroblewski, Hajicek, & Rubinstein, 2012). For instance, Finitzo-Hieber and Tillman (1978) measured speech recognition at different signal-to-noise ratios and reverberation levels and reported that speech recognition scores typically decreased by about 20 percentage points when reverberation time was increased from 0 to 1.2 seconds. Furthermore, research has shown that persons with hearing loss begin to show deterioration in speech recognition when the reverberation time exceeds 0.4 to 0.5 seconds (Crandell, 1991, 1992; Crandell & Bess, 1986).

Additionally, research has shown that children encounter significant difficulty with understanding speech that originates a great distance from the source (Crandell & Bess, 1986). Specifically, Crandell and Bess (1986) measured speech recognition of 5 to 7 year-old children in a typical classroom environment. The children scored 89% correct on a word recognition task when the words were presented from six feet away, but their performance decreased to 36% correct when the source of the signal of interest was located 24 feet away.

Our national guidelines pertaining to classroom acoustics suggest that the ambient noise level of an unoccupied classroom should not exceed 35 dBA and reverberation times should not exceed .6 seconds (American National Standards Institute, 2010). Furthermore, the SNR should ideally be 15-20 dB, and the reverberation time should be less than 0.4 seconds in order for children with hearing loss to communicate effectively. However, numerous studies have shown that the acoustics of typical classrooms do not meet these criteria. For example, Choi and McPherson (2005) reported that mean ambient noise levels in a group of typical occupied classrooms in Hong Kong were 61 dBA. Likewise, Massie and Dillon (2006) measured noise levels in occupied classrooms in Australia and reported ambient noise levels ranging from 64 to 72 dBA. Similarly, Sanders (1965) measured the SNR in classrooms and noted a mean SNR of -1 dB in 17 kindergarten classes and +5 dB in 24 elementary and high school classes. Other studies have reported classroom SNRs ranging from -7 to +4 when the classroom is occupied (For a review, see Crandell and Smaldino [2000a]). Finally, research has shown that reverberation times in typical classrooms range from .6 to 1.2 seconds (Knecht, Nelson, Whitelaw, & Feth, 2002).

Use of remote microphone hearing assistance technology (HAT) is the most effective method to improve speech recognition in classrooms with challenging acoustics. Remote microphone wireless systems are available in a variety of configurations and include classroom audio distribution (CAD) systems (also known as soundfield amplification systems), personal soundfield systems, or personal radio frequency (RF) systems. Please note that remote microphone wireless assistance technology refers to a system that contains a transmitter that captures a signal of interest (typically via a microphone) and wirelessly transmits that signal to a personal RF receiver coupled to a child's hearing aid or cochlear implant sound processor or to a loudspeaker or multiple loudspeakers. CAD systems are comprised of a microphone coupled to a transmitter which wirelessly delivers the signal captured by the microphone to one or more loudspeakers that are strategically placed in the classroom. Some CAD systems feature one loudspeaker to distribute the sound, while others include multiple loudspeakers (two to four, typically) in an attempt to provide a more uniform distribution of the signal of interest across the classroom. Although there would seem to be a theoretical advantage in using multiple loudspeakers in a CAD system so that the signal of interest may be distributed evenly throughout the classroom, there are currently no known studies comparing performance obtained with multiple loudspeaker and single loudspeaker CAD systems.

In general, the objective of a CAD system is not to amplify the signal of interest to a high level, but instead, to provide an even distribution of the signal throughout the classroom so that each child has consistent access to the primary signal regardless of the position of the teacher or students. The improvement in SNR provided by CAD systems depends upon a number of factors, including the quality and position of the loudspeakers, the position of the students relative to the loudspeakers, and the acoustics of the classroom. Because of these various factors, previous research in classrooms with children with normal hearing has suggested that CAD systems improve the SNR by as little as 2 dB and as much as 11 dB (Larsen & Blair, 2008; Massie & Dillon, 2006). Other studies have also shown that use of CAD systems results in improvements in literacy development, standardized test scores, and classroom behavior, as well as a reduction in teacher absences (Chelius, 2004; Flexer & Long, 2003; Gertel, McCarty & Schoff, 2004; Massie & Dillon, 2006; Massie, Theodoros, McPherson, & Smaldino, 2004).

A personal soundfield system is another form of a remote microphone wireless system designed for classroom use. A personal soundfield system is essentially comprised of the same components as a CAD system, but the loudspeaker is smaller and intended to be placed on the desk of the child with hearing loss. The close proximity of the loudspeaker to the child is intended to provide a more favorable SNR than a CAD system. There is a paucity of research examining the SNR improvement provided by personal soundfield systems. One of the few extant studies, by Crandell, Charlton, Kinder, and Kreisman (2001) found significant speech-perception benefit for a desktop portable soundfield system over unaided listening, but the desktop system was less effective than a body-worn personal frequency modulation (FM) receiver. Iglehart (2004) reported improved speech perception by children using cochlear implants with desktop and soundfield FM systems, but no difference between the two types in a quiet room and an advantage for the desktop system in noisy rooms.

Remote microphone personal radio frequency (RF) systems (historically referred to as personal FM systems) are comprised of a microphone, which is coupled to a transmitter that wirelessly delivers the signal captured by the microphone to RF receivers that are directly coupled to the child's hearing aids or cochlear implants. Personal RF systems provide the most improvement in SNR, ranging from as little as 5-15 dB (when the microphones of the RF system and hearing aid are both active) to as great as approximately 15-25 dB when the RF microphone is active and the hearing aid microphone is disabled (Boothroyd & Iglehart, 1998; Hawkins, 1984). Typically, the microphones of the RF system and the hearing aid are both enabled so the child has access to the signal from the RF systems, his/her own voice, and other speech and environmental sounds throughout the classroom. Personal RF systems can improve speech recognition in noise by as much as 50 to 60 percentage points when compared to performance without a personal RF system (Schafer & Thibodeau, 2004).

For all three types of remote microphone wireless systems, the signal of interest may be delivered from the transmitter to the receiver using a variety of methods. Most personal systems and some CAD systems and personal soundfield systems deliver the signal of interest via a RF transmission. Historically, FM radio frequency transmission has been used to deliver the signal of interest. The advantages and limitations of different types of transmission are provided in Table 1.

Recently, digital RF transmission has been used to deliver the signal of interest from the transmitter to the receiver (Table 1). The specific method of digital RF transmission varies across devices and may include amplitude shift keying, Gaussian frequency shift keying, or phase shift keying. Although there are theoretical advantages and limitations associated with each method, there are no published studies showing one method to be superior to another when used with hearing technology. As mentioned in Table 1, one of the primary advantages of digital RF is that there is a reduced risk of interference (crossover) when two children use digital RF systems in close proximity to one another. In fact, some digital RF systems utilize a protocol in which code is established between the transmitter and receiver during a "grouping" (or "pairing") process, and communication can only occur between the transmitter(s) and receiver(s) that have been grouped together. This type of approach eliminates the potential of signal interference from crossover between devices. Additionally, the digital control of the signal has the potential to allow for a more accurate analysis and delivery of the signal of interest from the transmitter to the receiver. Research has shown that subjects achieve better speech recognition in noise with personal digital RF systems compared to their performance with personal FM systems (Thibodeau, 2012; Wolfe et al., 2013a; Wolfe et al., 2013b).

Many CAD systems use infrared technology to transmit the signal of interest from the transmitter to the receiver. The pros and cons of infrared technology are also provided in Table 1. Specifically, the primary advantage of infrared transmission is the fact that it does not travel through walls, so interference/crossover between classrooms is not a problem. However, infrared technology requires a direct line-of-sight in order to transmit to the receiver, and it is susceptible to signal interruption when the classroom is brightly lit (i.e., by sunshine). Few studies have conducted direct comparisons across transmission types (i.e., infrared vs. conventional FM or digital FM). Furthermore, there are a few studies that have compared speech recognition obtained with CAD systems, personal soundfield systems, and personal RF systems. In one of the few studies to compare personal versus soundfield reception, as well as FM versus infrared transmission, Anderson and Goldstein (2004) measured speech recognition in noise for eight children (9-12 years of age) who had mild to severe hearing loss. Participants in this study used a personal FM system, a personal soundfield system, and an infrared CAD system with multiple loudspeakers located throughout the classroom. Sentences were presented in a classroom with a SNR of

Table 1. Advantages and Disadvantages of Types of Transmission

Infrared Transmission		Frequency Modulation (FM) Transmission		Digital Radio Frequency (RF)Transmission	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Not susceptible to crossover in adjacent classrooms	Requires line of sight between transmitter and receiver	Does not require line of sight between transmitter and receiver	May be susceptible to crossover in adjacent classrooms	Does not require line of sight between transmitter and receiver	None
Unlimited number of carrier frequencies	May be susceptible to interference from bright light sources	Not susceptible to interference from bright light sources	Finite number of transmitting frequencies	Not susceptible to crossover in adjacent classrooms	
			Possible interference from strong FM broadcasters, such as radio stations & police/emergency services	Not susceptible to interference from bright light sources	

+10 dB and a reverberation time of 1.1 seconds. The investigators reported that the infrared CAD system did not provide a significant improvement in speech recognition, but both the personal soundfield and personal FM systems provided a significant improvement in speech recognition in noise. There was no difference in performance between the two.

Anderson, Goldstein, Colodzin, and Inglehart (2005) also compared speech recognition obtained with a personal FM, personal soundfield (desktop FM), and CAD system for 28 children (8-14 years of age) using hearing aids or cochlear implants. Overall, children performed better with the personal FM and personal soundfield when compared to the CAD system and their hearing aids or cochlear implant alone. On average, participants did not show improved performance with the CAD system relative to their hearing aids and cochlear implants alone.

It should be noted that many professionals advocate for the combined, simultaneous use of personal RF and CAD systems (Cole & Flexer, 2007). However, there are no studies suggesting that performance with simultaneous use of personal RF and a CAD system is significantly better than performance with personal RF alone. Additionally, it should be mentioned that recent reports suggest that children with hearing aids and cochlear implants perform better when using personal RF systems featuring adaptive technology (Thibodeau, 2010; Wolfe, Schafer, Heldner, Mulder, Ward, & Vincent, 2009).

Traditionally, personal FM systems have been fixed-gain systems, where the strength of the signal from the FM receiver to the hearing aid is fixed at a pre-determined value. The American Speech-Language Hearing Association (ASHA) clinical practice guideline (2002) suggested that the output of the speech signal delivered from the FM system should be 10 dB higher than the output of the same speech signal at 65 dB SPL delivered to the microphone of the hearing aid. This was referred to as a 10-dB FM advantage and was recognized to be a compromise for what the user might prefer across the broad range of acoustical environments encountered from day to day. However, Lewis and Eiten (2004) showed that FM users preferred a small FM advantage when listening in quiet environments, but a very favorable advantage (+24 dB) when listening in high-level noise environments. As a result, the 10 dB FM advantage was acceptable, but not ideal across all environments.

Adaptive RF technology (also known as Dynamic FM/Digital RF) seeks to address the need for a range of FM advantages across various listening situations. Adaptive RF systems provide no gain from the RF receiver when there is no signal of interest present (i.e., speech) from the RF transmitter. When a signal of interest is present in a quiet environment, the RF gain is set to a default of 10 dB. From that point, the gain from the RF receiver is adaptively increased once the ambient noise level at the RF microphone exceeds 57 dB SPL to a maximum RF setting of +24 dB at an ambient noise level of approximately 80 dB SPL. Research has shown that adaptive RF technology provides substantial improvement in speech recognition in noise when compared to fixed-gain RF systems (Thibodeau, 2010; Wolfe et al., 2009). It should be noted, however, that there are no studies examining the potential benefit of adaptive technology for use with CAD systems. As a result, the purposes of this study were:

(1) To compare speech recognition in quiet and in noise for adults with normal hearing, children with normal hearing, and children with hearing loss in a classroom environment when using a fixed-gain, multiple loudspeaker, infrared CAD system and an adaptive, single-tower loudspeaker array, digital RF CAD system.

(2) To compare, for children with hearing loss, speech recognition in quiet and in noise between (a) a fixed gain, multiple loudspeaker, infrared CAD system, (b) an adaptive, single-tower array digital CAD system, (c) use of personal FM alone, (d) simultaneous use of a personal FM with a fixed gain, multiple loudspeaker, infrared CAD system, and (e) simultaneous use of a personal FM with an adaptive, single-tower array digital CAD system.

Materials and Methods

Participants

Study participants included 10 adults with normal hearing (mean age: 34 years; range: 18-48 years of age), 15 children with normal hearing (mean age: 8 years; range: 5-12 years of age), and 15 children with hearing loss (mean age: 9.5 years; range: 6-13 years of age). The following inclusion criteria were used for selection of participants:

Adults with Normal Hearing

1. At least 18 years old and less than 60 years old.
2. Air-conduction audiometric thresholds of 15 dB HL or better at octave frequencies from 250 to 8000 Hz.
3. No conductive hearing loss (i.e., air-bone gap not to exceed 10 dB at octave frequencies from 500 to 4000 Hz.
4. No history of significant otologic problems.
5. All participants used English as their primary language.

Children with Normal Hearing

1. At least 5 years old and less than 13 years old
2. Air-conduction audiometric thresholds of 15 dB HL or better at octave frequencies from 250 to 8000 Hz.
3. No conductive component (i.e., air-bone gap not to exceed 10 dB at octave frequencies from 500 to 4000 Hz).
4. No history of significant otologic problems.
5. All participants used English as their primary language.
6. No history of language, auditory processing, or attention disorders per parent report.

Children with Hearing Loss

1. Mild to severe sensory hearing loss as defined by a four-frequency pure-tone average between 35 to 75 dB HL for at least the better ear. The mean audiogram for participants with hearing loss is provided in Figure 1.
2. Full-time wearer of bilateral hearing aids.
3. The output of each of the children's hearing aids was matched (+/- 5 dB) to the DSL m[i/o] v 5.0 prescriptive target for standard speech presented at 55, 65, and 75, dB SPL as indicated by probe microphone measures made with the Audioscan Verifit. Furthermore, the output for an 85 dB SPL swept pure tone was within +/- 5 dB of the maximum output targets as indicated by the DSL m[i/o] v 5.0 method.
4. No conductive component (i.e., air-bone gap not to exceed 10 dB at octave frequencies from 500 to 4000 Hz).
5. No history of significant otologic problems, including auditory neuropathy spectrum disorder.
6. All participants used English as their primary language.
7. No history of language delay, auditory processing disorder, or attention disorder per parent report.
8. All participants in this study utilized spoken language as their primary mode of communication. Additionally, an Auditory Verbal therapist who was familiar with the spoken language aptitude of each pediatric subject confirmed that the pediatric subjects were capable of completing open-set Hearing in Noise Test (HINT) sentence testing (Nilsson, Soli, & Sullivan, 1994).

Remote Microphone Wireless Hearing Assistance Technology

In this study, speech recognition in quiet and in noise was evaluated while subjects used several different types of hearing assistance technology (i.e., test conditions):

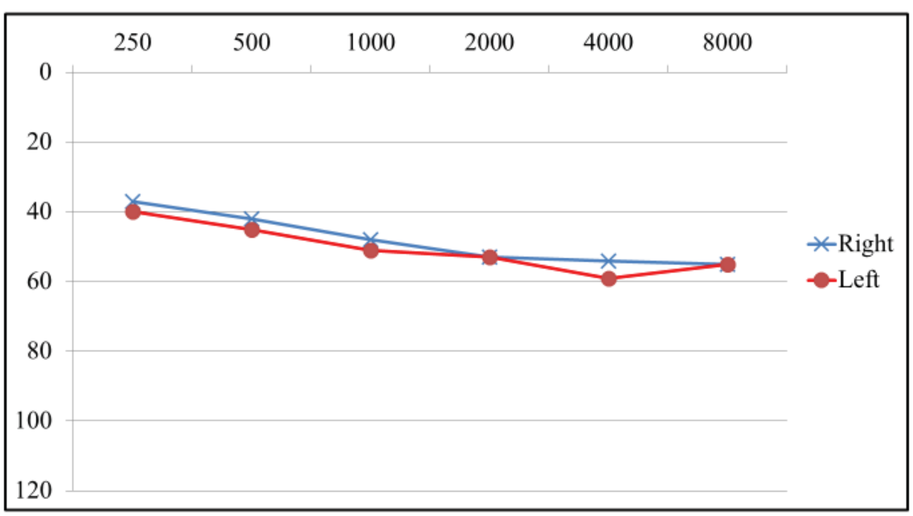

Figure 1. Average audiograms for children with hearing loss

1. No HAT condition: The speech recognition abilities of adults and children with normal hearing were evaluated in the unaided condition. The speech recognition abilities of children with hearing loss were evaluated while the children used their personal hearing aids. The children with hearing loss also used their own hearing aids in all of the remaining conditions.

2. Fixed-gain, multiple-loudspeaker infrared CAD system condition: The Audio Enhancement Elite II utilizes a uni-directional (cardioid polar plot pattern) Audio Enhancement *Tear Drop* microphone, which is designed to be clipped on the shirt or worn on a lanyard around the neck of the talker so that it is about 6-8 inches from the mouth. The *Tear Drop* microphone delivers the signal of interest via infrared (IR) transmission (2.3 megahertz was the IR frequency used in this study) to the infrared dome sensor (IR receiver), which is hard-wired to the Elite II audio receiver/amplifier. The Elite II audio receiver/amplifier features a 30-watt, two-channel amplifier, which is hard-wired to four wall-mounted WS09 monopole loudspeakers strategically placed in the classroom. The Elite II audio receiver/amplifier possesses a gain control to allow for adjustment of the output level of the system. The primary objective is to position the loudspeakers and set the gain control to ensure that an audible and uniform distribution of the signal of interest is provided throughout the classroom. The gain of the system is fixed regardless of the ambient noise level in the classroom.

3. Adaptive single-tower array digital CAD system condition: The Phonak DigiMaster (DM) 5000 is comprised of multiple components including the Phonak inspiro transmitter, which is coupled to a lavaliere-style clip-on directional microphone (hyper-cardioid polar plot response pattern). The Phonak inspiro transmitter is capable of delivering the signal of interest via FM or digital RF transmission. For the DM 5000 system, the signal of interest is captured by the microphone and delivered to the loudspeaker tower via digital RF on the 2.4 gigahertz band (2.4000 to 2.4835 GHz). Audio signals are digitized and packaged in very short (160 µs) digital bursts of codes and broadcast several times each at different channels in the 2.4 GHz band. The frequency-hopping behavior across channels is intended to avoid interference that may exist with traditional FM transmission. The Phonak DigiMaster 5000 loudspeaker tower is actually an array of 12 loudspeakers stacked in a vertical column. The distance between the centers of two adjacent loudspeakers is 54 mm, and the overall design of the system is reported to emit sound primarily within the horizontal plane with very little vertical spread. As a result, the impact of reverberant sound is intended to be reduced. The array of loudspeakers stands on a support pole and is positioned so that the loudspeakers reside at a height ranging from 33 to 63 inches. This height is designed to coincide with head level while students sit at a desk. A "pairing process" is required to couple the Phonak inspiro transmitter to the DigiMaster 5000 system.

The Phonak DigiMaster 5000 is an adaptive CAD system in that it automatically increases the gain of the signal of interest once the ambient noise level exceeds 54 dB SPL. Specifically, for a typical classroom (reverberation time of .9 seconds), when the ambient noise is below 54 dB SPL, the gain is kept at a value of 6 dB. This should result in an SNR of no less than 12 dB in the middle of a typical classroom given a quiet condition. When the ambient noise levels ranges between 54 and 66 dB SPL, the gain of the DigiMaster 5000 is automatically increased with the goal of maintaining an SNR of +10 dB. The maximum gain the system delivers is 20 dB. Further, the frequency response of the system changes automatically. At low gain levels the direct sound of the voice of the teacher is taken into account to attain a flat (transparent) response of the combined direct plus amplified sound. At high gain levels, where the critical bands in the cochlea are wider, some high pass filtering is applied to reduce upward spread of masking. Finally, the Phonak DigiMaster 5000 system possesses an adaptive feedback cancellation system, which is intended to reduce the chances of acoustic feedback when the wearer of the inspiro transmitter/microphone is located in close proximity to the loudspeaker array tower.

4. Personal FM condition: The Phonak Dynamic MLxi personal FM system, only used by children with hearing loss, was directly coupled to the children's personal hearing aids via the appropriate FM receiver adapter and the Phonak inspiro transmitter. The Phonak inspiro transmitter delivered the signal of interest to the Phonak MLxi FM receiver via FM transmission at 216 megahertz (i.e., channel 1). The MLxi receiver was programmed to provide a default FM advantage of 10 dB when speech was present in a quiet environment (ambient noise level of less than 57 dB SPL). Adaptive increases in FM advantage were automatically provided as the ambient noise level exceeded 57 dB SPL. The maximum gain of the MLxi adaptive FM receiver was 24 dB. The Phonak MLxi receiver was coupled to each of the children's personal hearing aids via the appropriate hearing aid/FM receiver adapter.

5. First combined-device condition (fixed-gain infrared CAD system + personal FM): The first combined condition entailed simultaneous use of the Audio Enhancement Elite II classroom audio distribution system along with the Phonak MLxi personal FM system directly coupled to the children's personal hearing aids.

6. Second combined-device condition (adaptive digital RF CAD system + personal FM): The second combined condition entailed simultaneous use of the Phonak DM5000 classroom audio distribution system along with the Phonak MLxi personal FM system directly coupled to the children's personal hearing aids.

In the condition in which the Phonak DigiMaster 5000 CAD system and Phonak MLxi adaptive personal systems were used simultaneously, the Phonak inspiro transmitter was used to simultaneously transmit the signal of interest to the Phonak CAD system and personal FM receiver by way of digital RF and FM transmission, respectively. In the condition in which the Audio Enhancement Elite II CAD system and Phonak MLxi adaptive personal systems were used simultaneously, the Audio Enhancement *Tear Drop* microphone/transmitter was used to deliver the signal of interest by way of IR transmission to the Audio Enhancement Elite II audio receiver/amplifier from where it was delivered to the four Audio Enhancement Elite II WS09 loudspeakers. The Phonak inspiro transmitter was coupled to the audio output port of the Audio Enhancement Elite II receiver, and was used to deliver the signal from the Audio Enhancement receiver to the Phonak MLxi adaptive personal receiver by way of FM transmission. The order of the test conditions was counter-balanced across participants.

Stimuli, Equipment, & Room Arrangement

Testing in this study was completed in a classroom measuring: 22 feet, 4 inches in length; 15 feet, 5 inches in width; 8 feet, 9 inches in height (Figure 2). The ambient noise level of the unoccupied room was 45 dBA. The level of the ambient noise, test sentences, and competing classroom noise was measured with a Quest Technologies Model QC-20 Type 1 sound level meter.

Per the recommendation of the manufacturer, the Phonak DigiMaster 5000 CAD system was placed in the front of the classroom (see Figure 2). Also per the recommendation of the manufacturer, the classroom was divided into quartiles, and the four wall-mounted WS09 loudspeakers of the Audio Enhancement system were mounted at these quartile locations at a height of 40 inches at the center of each loudspeaker (see Figure 2), which corresponded to the estimated head level of the seated subjects.

Speech recognition abilities in quiet and in noise were evaluated in each condition using one list of randomly-selected HINT sentences (10 sentences per list) scored by the percentage of key words repeated correctly. HINT sentences were delivered from a Dell Latitude E6500 laptop computer with an IDT High Definition Audio codec sound card and presented from a Fostex 6301 B single-cone loudspeaker with a built-in amplifier. The loudspeaker used to present the test sentences was positioned in the front and center of the classroom (17 feet from the subject at 0 degrees azimuth), and the microphone of the inspiro FM transmitter was positioned on a microphone stand eight inches directly in front of this loudspeaker, simulating the distance from the transmitter microphone to a teacher's mouth (Figure 2). The calibration signal for the HINT sentences was set to 76 and 70 dBA measured at 50 cm and 100 cm, respectively, from the center of the loudspeaker, which results in a level of about 85 dBA if measured eight inches from the center of the loudspeaker. When an RF system is used according to the manufacturer's settings, the speech of the talker is approximately 85 dBA at the microphone of the transmitter. The calibration measures were made at 50 cm and 100 cm in this study to reduce the possibility of errors associated with a near-field measure made 20 cm from the center of the loudspeaker. The sentences were presented at approximately 85 dBA at the location of the FM transmitter microphone and 64 dBA at the location of the subject. The gain control of the Phonak DM 5000 CAD system was set to the manufacturer's default, which resulted in the signal of interest arriving at the location of the subject at 68 dBA. The gain control of the Audio Enhancement Elite II CAD system was set to also deliver the signal of interest at a level of 68 dBA at the location of the subject. As a result, the level of the target sentences was identical between the two CAD systems in the quiet condition.

Four-classroom noise (Schafer & Thibodeau, 2006), which has a difference of 2.95 dB between the minimum and maximum root-mean-square (RMS) values, served as the competing noise signal. The competing noise signal was generated by a Dell Latitude D-520 notebook with a SigmaTel High Definition Audio CODEC sound card, amplified by a Radio Shack 250 Watt PA amplifier, and presented from four KLH B-Pro6 Titan Series loudspeakers located in the four corners of the room. The loudspeakers used to present the speech and competing noise were positioned at approximately the same height as the typical pediatric subject's head (40 inches at center of loudspeaker). The noise was presented from the two sets of loudspeakers (i.e., the noise from the front two loudspeakers was correlated, and the noise from the back two loudspeakers was correlated; uncorrelated noise refers to a situation in which the temporal characteristics of the noise from two or more loudspeakers are different, whereas correlated noise refers to a situation in which the temporal characteristics of a noise signal from multiple loudspeakers are the same.). The rationale for the aforementioned loudspeaker arrangement was to simulate listening in a noisy environment at a distance from the talker of interest (i.e., typical classroom environments). The competing noise signal was presented at 50, 55, 60, 65, 70, and 75 dBA when measured at the location of the subjects' head and at the position of the transmitter microphone.

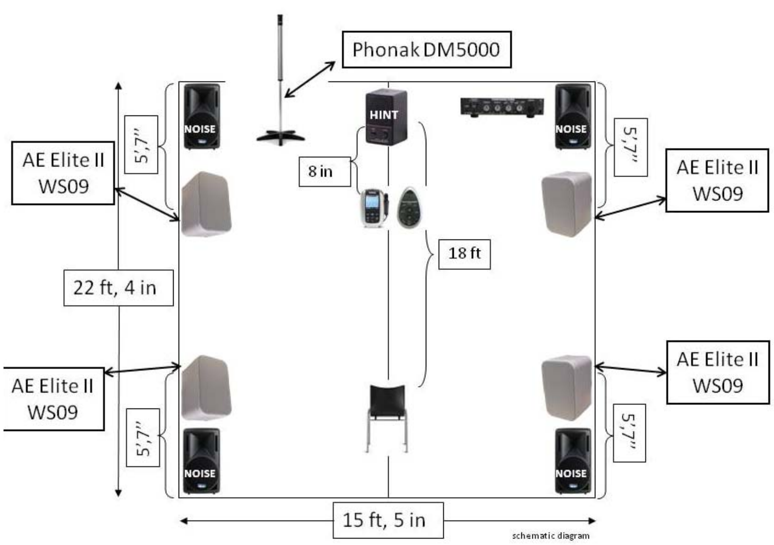

Figure 2. Test environment and equipment. AE Elite II WS09 =Audio Enhancement Elite II WS09 wall-mounted sound field speaker; HINT=Loudspeaker used to present Hearing In Noise Test sentences; Noise=Loudspeaker used to present classroom noise; Phonak DM5000=Phonak Digimaster 5000 classroom audio distribution system.

Procedures

Adults and children with normal hearing were assessed in a total of 21 conditions, while children with hearing loss were assessed in a total of 42 conditions. For all participants, open-set sentence recognition was assessed in quiet and in the presence of noise at multiple levels without FM and with both of the CAD systems. Additionally, speech recognition of the children with hearing loss was assessed in in quiet and in noise with use of the Phonak MLxi adaptive personal FM system and also with simultaneous use of each of the CAD systems and the Phonak MLxi adaptive personal FM system. The participants were instructed to repeat what they heard, and two examiners presented the recorded sentences and documented participant responses to ensure reliable scoring. The order of device conditions and signal levels (i.e., quiet vs. noise at various levels) were randomized. The HINT sentence test possesses 25 sentence lists. These lists were not repeated while assessing the adults and children with normal hearing (as they were assessed across 21 conditions). However, the children with hearing loss were evaluated across 42 conditions, so it was necessary to repeat the presentation of some lists while evaluating children with hearing loss. Care was taken to use lists in which a poor score was obtained during the first time it was used for assessment. This was done to reduce the likelihood that repeating a list would increase performance for a given condition. It is, however, possible that a child may have performed better on a list that was repeated than he/she would have on an original list, because of familiarity with the speech materials. It should be noted that the test conditions were evaluated in a randomized manner, so the repeating of lists should not have resulted in an increase or decrease of a particular condition. Only 13 of the original 15 children with hearing loss were able to complete the conditions with the personal FM system, and as a result, data from only 13 children were analyzed. The two children who dropped out of the study did so because of fatigue. Their results for the completed conditions were similar to the group as a whole, so their exclusion should not affect the final analysis.

Results

The average speech-recognition scores obtained with no FM and with the CAD systems are shown in Figure 3 for the adults with normal hearing, Figure 4 for children with normal hearing, and Figures 5 and 6 for children with hearing loss. The data for the CAD systems were analyzed with a three-way, repeated measures analysis of variance (RMANOVA) with one between-subjects variable of group (i.e., adults with normal hearing, children with normal hearing, children with hearing loss) and two within-subject variables of device condition (no FM; Audio Enhancement Elite II CAD; Phonak DigiMaster 5000 CAD) and signal level (quiet, 50, 55, 60, 65, 70 75). This analysis revealed a significant main effect of group (F [2, 840] = 15.1, p = 0.00002), a significant main effect of device condition (F [2, 840] = 254.4, p < 0.00000), and a significant main effect of signal level (F [6, 840] = 909.2, p < 0.00000). Several interaction effects were also detected and included a significant interaction effect between device condition and signal level (F [12, 840] = 45.3, p < 0.00000) and between signal level and group(F [21, 1184] = 65.6, p < 0.00000). A significant interaction effect was also detected between group and signal level (F [12, 840] = 4.4, p = 0.000003).

Post-hoc analyses were conducted with the Tukey-Kramer Multiple Comparisons Test to examine the significant differences detected for the main and interaction effects. For the main effect of group, the children with hearing loss performed significantly worse (p < .05) than both the groups with normal hearing. The analysis for the main effect of device condition suggested that all CAD systems were significantly better than the no-FM condition (please note the no-FM condition refers to the situation in which no remote microphone technology was used by the subjects; however, the children with hearing loss did use their hearing aids (without the personal FM receiver) during assessment in the no-FM condition) (p < .05), and scores between the CAD systems were significantly different (p < .05). The best performance was obtained with the Phonak DigiMaster 5000. When examining the main effect of signal level, almost all signal level conditions were significantly

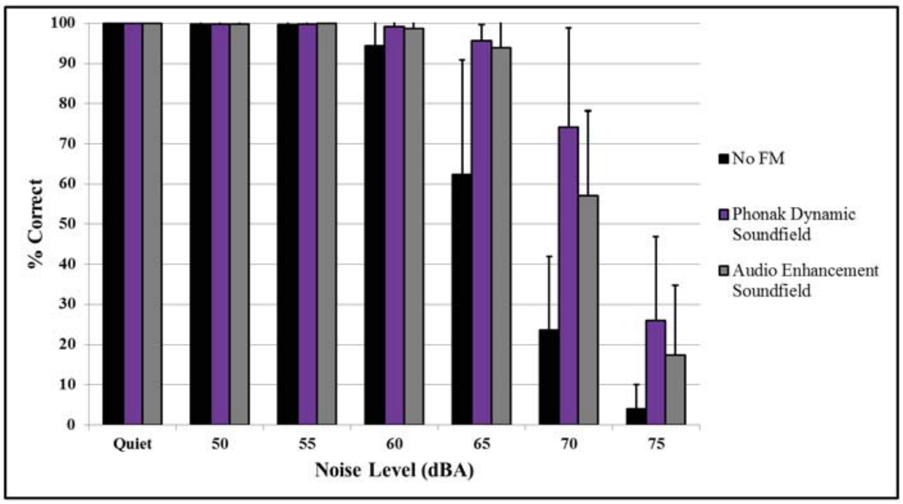

Figure 3. Average speech-recognition scores across the noise conditions for adults with normal hearing without and with the classroom audio distribution (CAD) systems.

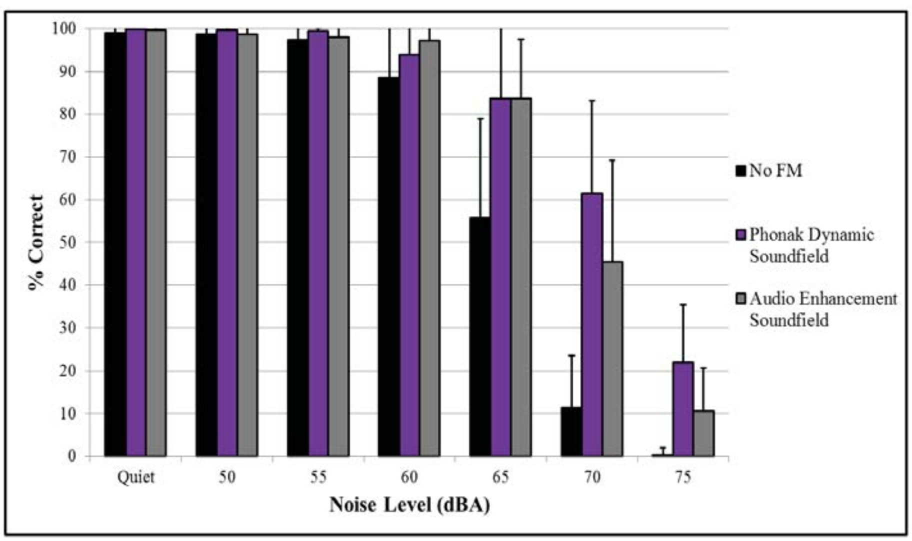

Figure 4. Average speech-recognition scores across the noise conditions for children with normal hearing without and with the classroom audio distribution (CAD) systems.

different ($p < .05$) with the exception of the quiet condition as compared to 50 or 55 dBA noise condition and the 55 dBA noise condition as compared to the 60 dBA noise condition.

Post-hoc analyses were also conducted for the most relevant significant two-way interaction effect, the interaction effect between device condition and signal level, using the Tukey-Kramer Multiple Comparisons Test. This analysis revealed several notable findings. First, the no-FM conditions in quiet and in noise at 50 and 55 dBA were not significantly different ($p > .05$) from performance with the two CAD systems at the same signal levels. However, in all remaining signal level condition, the two CAD systems produced significantly better ($p < .05$) performance than the corresponding no-FM condition. When comparing the two CAD systems, the Phonak system resulted in significantly better ($p < .05$) performance than the Audio Enhancement system in the 70 and 75 dBA noise conditions,

The second RM ANOVA involved data from the 13 children with hearing loss who were able to complete the three extra device conditions. This RM ANOVA included two within-subject variables: signal level (quiet, 50, 55, 60, 65, 70 75) and device condition ([1] no FM; [2] Audio Enhancement Elite II CAD; [3] Phonak DigiMaster 5000 CAD; [4] Phonak MLxi personal FM; [5] Audio Enhancment Elite II CAD and Phonak MLxi personal FM combined; [6] Phonak DigiMaster 5000 CAD and Phonak MLxi personal FM combined). The analysis revealed a significant main effect of signal level (F [6, 546] = 338.6, $p < 0.00001$), significant main effect of device condition (F [5, 546] = 115.7, $p < 0.00001$), and significant interaction effect between signal level and device condition (F [30, 546] = 51.3, $p < 0.00001$).

The Tukey-Kramer Multiple Comparisons Test was used to conduct post-hoc analyses on the significant main effects and interaction effect. Similar to the previous post-hoc analysis of signal level, performance in the quiet condition was not significantly different ($p > .05$) than performance in the 50 or 55 dBA noise conditions; performance in the 55 dBA noise condition was not different ($p > .05$) from performance in the 60 dBA noise condition. Performance at all remaining signal levels was significantly different ($p < .05$) from all other signal levels.

The post-hoc analysis on conditions suggested that all device conditions were significantly better ($p < .05$) than the no-FM condition. The device conditions with the Phonak MLxi personal FM and the MLxi combined with the Phonak DigiMaster 5000 CAD resulted in significantly better ($p < .05$) performance than all remaining device conditions. There were no significant differences in performance across the remaining device conditions (Audio Enhancement Elite II CAD; Phonak DigiMaster 5000 CAD; Audio Enhancment Elite II CAD and Phonak MLxi personal FM combined).

There were several important findings from the post-hoc analysis of the two way interaction effect between signal level and condition. First, the no-FM conditions in quiet and in noise at 50 and 55 dBA were not significantly different

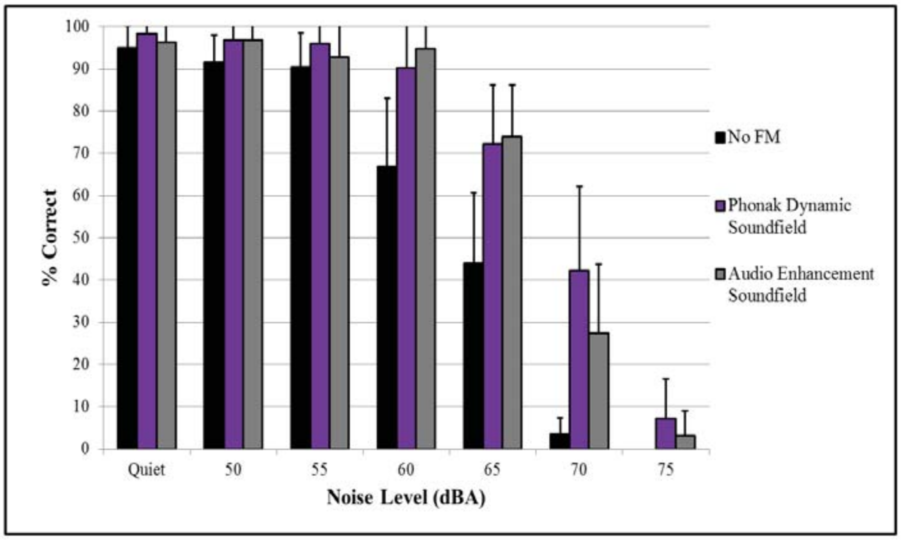

Figure 5. Average speech-recognition scores across the noise conditions for children with hearing loss without and with the classroom audio distribution (CAD) systems.

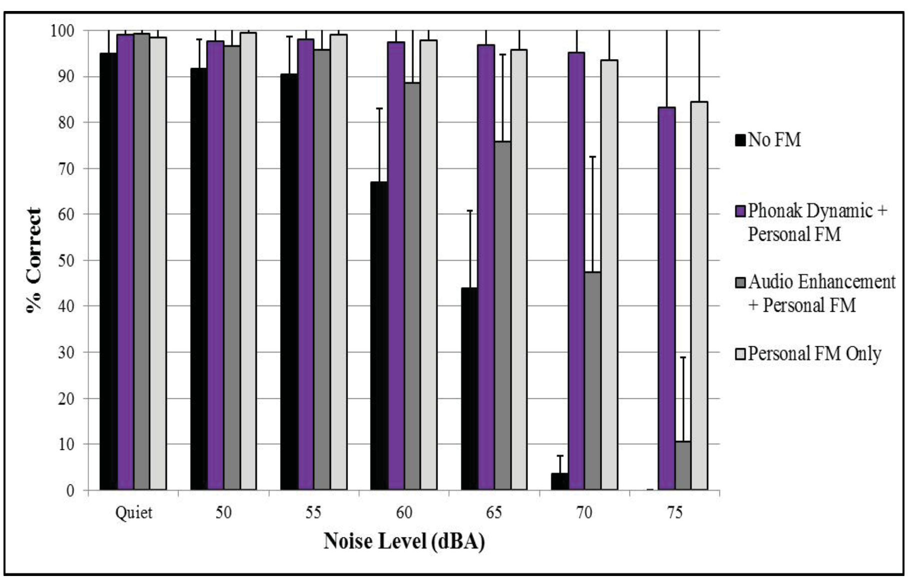

Figure 6. Average speech-recognition scores across the noise conditions for children with hearing loss without and with the classroom audio distribution (CAD) and frequency modulation (FM) systems.

($p > .05$) from performance in any device conditions at the same signal levels. At all remaining signal levels, all devices produced significantly better performance ($p < .05$) than the corresponding no-FM condition. In the 60 dBA noise condition, there were no significant differences ($p > .05$) across the devices. However, at the 65, 70, and 75 dBA noise conditions, performance with the Phonak MLxi receiver alone and MLxi combined with the Phonak DigiMaster 5000 CAD was significantly better ($p < .05$) than all remaining device conditions. There were no other significant differences ($p > .05$) across devices at the 65 and 75 dBA noise levels; however, at the 70 and 75 dBA noise levels, use of the Phonak CAD resulted in significantly better performance ($p < .05$) than use of the Audio Enhancement CAD.

Discussion

The authors identified several objectives for this study. A primary goal was to determine if differences exist in speech recognition performance in quiet and in noise with the use of a fixed-gain, multiple loudspeaker CAD system versus an adaptive gain, single tower loudspeaker array CAD system. A secondary goal was to compare speech recognition in quiet and in the presence of competing noise in a classroom situation for adults with normal hearing, school-aged children with normal hearing, and school-aged children with hearing loss. Finally, speech recognition in quiet and in noise was compared between the use of the CAD systems alone, versus use of a personal FM system alone, versus simultaneous use of each CAD system along with the personal FM system.

Speech Recognition in Quiet

All three groups of subjects approached ceiling-level performance on speech recognition tasks in quiet, even without the use of the HAT. As a result, there were no significant differences in performance in quiet across the three groups of subjects as well as across the different types of HAT. In this study, the speech signal reached the user at a level of 64 dBA, which approximates, or is slightly higher than, average conversational level speech (Pearsons, Bennett, & Fidell, 1977). As a result, performance likely reached asymptotic levels even without the HAT. Indeed, previous research has indicated that children with moderate hearing loss typically achieve ceiling-level performance on tests of speech recognition in quiet when using contemporary hearing aid technology (Wolfe, John, Schafer, Nyffeler, Boretzki, & Caraway, 2010). Of course, anecdotal experience would suggest that persons with normal hearing would be likely to experience few or no problems with understanding sentences presented in quiet.

Speech Recognition in Noise

In contrast to the results in quiet, significant differences in sentence recognition in noise did exist across the three subject groups and the various HAT conditions. Additionally, all three subject groups experienced substantial difficulty understanding speech in the presence of moderate-level noise, particularly without the use of HAT. For instance, at a competing noise level of 60 dBA (SNR = +4 dB), children with normal hearing began to show a reduction in their ability to understand sentences through audition alone without the use of HAT. Even greater difficulty was observed for children with hearing loss for whom a 30 percentage point reduction in speech recognition was observed between performance measured in quiet and their performance at a competing noise level of 60 dBA (+4 dB SNR without the use of HAT).

The results from these data are concerning for several reasons. First, they underscore the well-known fact that children with hearing loss are likely to have substantially greater difficulty hearing in noise than adults and children with normal hearing. Second, the difference in speech recognition in noise between children with hearing loss and children with normal hearing is actually greater than the difference observed between children and adults with normal hearing. In other words, the presence of moderate hearing loss has a greater effect on hearing performance in noise than the maturation of the auditory nervous system associated with age. Additionally, these data are alarming because previous research has suggested that typical classroom SNR range from 0 to + 5 dB (Sanders, 1965). As such, the results of this study suggest that children with hearing loss are quite likely to struggle understanding speech in academic settings.

The data further indicate that children and adults with normal hearing also experience difficulty understanding speech in noise when the SNR is unfavorable (competing noise level = 65 dBA resulting in an SNR of -1 dB without HAT). Again, this is a disturbing finding when one considers the fact that previous research has suggested that the SNR in a typical kindergarten classroom is approximately -1 dB (Sanders, 1965). Young children do not have the same command of linguistics as adults, and consequently, they are less able to “fill in the gaps” when they are unable to capture all of the signal of interest via audition alone. Furthermore, students are often unable to look at the teacher’s face when she is talking. For instance, they may have to focus on a lesson being demonstrated on a “smart board,” while the teacher provides verbal instruction. These data suggest that even young children with normal hearing are likely to experience some difficulty following a teacher’s instructions through audition alone in the typical classroom setting. Considering these data, it should come as no surprise that children with normal hearing achieve better levels of academic success and demonstrate better behavior in classrooms with CAD systems, which likely improve the SNR of the environment (Berg, Bateman, & Viehweg, 1989; Bitner, Prelock, Ellis, & Tzanis, 1996; Langlan, Sockalingam, Caissie, & Kreisman, 2009).

Fortunately, performance in noise obtained with all of the HAT systems evaluated in this study was significantly better than the no-FM condition, particularly when compared at the moderate to high noise levels. This finding is encouraging for the CAD systems given the lack of benefit from CAD systems in previous investigations (Anderson & Goldstein, 2004; Anderson et al., 2005). For this study, all three groups showed improvements in speech recognition in noise with CAD use beginning at the competing noise level at which they begin to experience difficulty without HAT. For example, adults and children with normal hearing suffered approximately a 35 and 40 percentage point reduction in speech recognition, respectively, when performance without HAT in quiet was compared to performance without HAT at a competing noise level of 65 dBA (-1 dB SNR). However, both groups achieved an approximately 30 percentage point improvement in speech recognition at the 65 dBA competing noise level with the use of the CAD systems. Likewise, children with hearing loss received an approximately 25 percentage point improvement in speech recognition in noise from CAD use at the 60 dBA competing noise level and about a 30 percentage point improvement in speech recognition in noise with CAD use at 65 dBA. These noise levels and unaided SNR are common in academic settings. The present findings support the idea that CAD use would be beneficial in typical classroom environments.

One important finding of this study was the fact that use of the Phonak DigiMaster 5000 single-tower loudspeaker array, adaptive CAD system resulted in equivalent performance at moderate noise levels (with an SNR ranging from +4 to -1 dB without the use of remote microphone CAD technology, which are quite common for typical classrooms) when compared to the Audio Enhancement Elite II multiple-loudspeaker, fixed-gain CAD system. Additionally, performance with the adaptive, single-tower loudspeaker array CAD system was actually better at the higher competing noise levels of 70 and 75 dBA (with an SNR ranging from -6 and -11 dB SNR without the use of remote microphone CAD technology, and although such unfavorable SNR are uncommon during classroom instruction, they are likely to occur occasionally when classroom noise levels are high and the teacher is standing across the classroom from a student or group of students) for all three groups when compared to performance obtained with the Audio Enhancement Elite II multiple-loudspeaker, fixed-gain CAD system. This finding has potential clinical relevance for a number of reasons. First, the primary difference between the two systems that is most likely to explain the better performance obtained with the Phonak DigiMaster 5000 system is the fact that the Phonak system possesses the adaptive increases in CAD gain with increases in ambient noise level. Each system was matched in output level (68 dBA) for speech in quiet. It is unlikely that it would be appropriate to increase the gain setting for quiet environments as doing so would result in a speech level that would approach a psychophysical percept associated with loud speech. However, at higher noise levels, it is appropriate to increase the level of the speech signal (Pearsons et al., 1977). It appears as though the automatic increases of the Phonak DigiMaster 5000 system provided an improvement in the SNR and a subsequent improvement in speech recognition at the higher competing noise levels. Additionally, the single-tower loudspeaker array is comprised of an array of 12 single-cone loudspeakers arranged in a vertical column in order to provide an even distribution of the audio signal throughout the classroom with minimal vertical spread. This feature may have also contributed to the relatively favorable results obtained with the adaptive, single-tower CAD system, even though the position of the single-tower loudspeaker array was much further from the subject (approximately 18 feet) than the distance between the subject and the rear loudspeakers of the multiple-loudspeaker, fixed-gain CAD system (approximately six feet).

Further examination of the data indicates that children with hearing loss continue to experience substantial difficulty understanding speech in noise levels of 65 dBA and greater, even with the use of the CAD systems. In contrast, Figure 6 shows that children with hearing loss perform quite well, even at the highest noise levels, when using a personal FM system coupled to their personal hearing aids. In fact, many of the children continued to perform near ceiling levels at a competing noise level of 70 dBA. This finding is consistent with previous studies showing considerable improvement in performance in noise from use of an adaptive personal RF system (Thibodeau, 2010, 2012). Given the results of this study, audiologists working with children should consider the provision of adaptive personal FM or digital RF technology as mandatory for children with significant, bilateral hearing loss.

Furthermore, installation of the single tower, adaptive CAD system used in this study requires approximately 15 minutes. In contrast, installation of a multiple loudspeaker CAD system, in which the loudspeakers must be mounted to the wall or ceiling and hard-wired to a CAD receiver/amplifier, which in turn is also hard-wired to an infrared receiver, requires a substantially longer amount of time. The installation of the latter system also requires some expertise in order to securely mount the loudspeakers and to run the loudspeaker cables through the ceiling or wall. The findings of this study are important, because they indicate that performance with an adaptive single-tower loudspeaker array CAD system which is relatively simple to install is at least as good, if not better, than performance obtained with a fixed-gain, multiple-loudspeaker CAD system, which does require more time and expertise to install.

Previous research has suggested that audiologists are more likely to recommend multiple loudspeaker CAD systems than a single-tower system (Crandell & Smaldino, 2000b). Specifically, Crandell and Smaldino (2000b) surveyed 241 audiologists regarding their current practices pertaining to the provision of CAD systems in school settings. Five percent of the respondents recommended a one-speaker system, while the overwhelming majority noted that it was ideal to provide a CAD system with at least two to four loudspeakers strategically placed in the classroom. Of course, CAD system technology has changed significantly since the Crandell and Smaldino (2000b) study, so it is possible that audiologists would respond differently if a similar survey were administered today. Indeed, the results of this study suggest that it is possible to obtain speech recognition that is at least as good, if not better, with a single-tower loudspeaker array compared to a multiple loudspeaker system. Clearly, more research is needed to compare different speaker arrays to maximize the benefit that can be provided by CAD systems.

Two additional clinically relevant findings were observed when analyzing the results obtained with simultaneous use of the CAD systems along with the personal FM system. First, speech recognition in noise with combined use of either the CAD system and the personal FM system did not improve when compared to performance obtained with the personal FM system alone. It is possible that the children reached asymptotic levels of performance with use of the adaptive personal FM alone, and there was simply no room for additional improvement from the CAD. This explanation is quite plausible for performance measured at noise levels ranging from 60 to 70 dBA. However, it does not appear as though the children with hearing loss approached ceiling-level performance at a competing noise level of 75 dBA. The fact that use of the CAD system did not provide an improvement in speech recognition at the 75 dBA noise level is most likely explained by the fact that the modest gain provided by a CAD system is not resulting in a tangible improvement in SNR at such a high noise level.

Finally, speech recognition at moderate and high noise levels (60 to 75 dBA) was considerably better with the combined use of the Phonak DigiMaster 5000 CAD system and the Phonak adaptive personal FM system when compared to performance obtained with the Audio Enhancement Elite II CAD system and the Phonak adaptive personal FM system. The difference obtained between CAD systems in the combined use mode ranged from 10 percentage points at a competing noise level of 60 dBA to 75 percentage points at a competing noise level of 75 dBA. When the performance of children with hearing loss using FM in classrooms with the DigiMaster and Audio Enhancement Elite II CAD systems was compared, the performance with the personal FM system plus Phonak DigiMaster 5000 CAD system was equivalent to performance with the personal FM alone. A very disconcerting finding was the fact that performance with the personal FM system plus Audio Enhancement CAD system was poorer than performance with the personal FM system alone (a reduction of 20% or more was observed at the moderate to high noise levels). This reduction in performance with personal FM system alone was not evident in classrooms that had better SNR (+9 - +14). In a noisy classroom, use of the DigiMaster did not decrease performance of use of the personal FM system, but use combined of the Audio Enhancement CAD system and personal FM system in a noisy classroom did result in poorer performance than what was obtained with the personal FM alone.The educational audiologist should administer validation measures of the child's performance with the use of remote microphone technology when a personal FM system is used simultaneously with a CAD system in order to ensure that the CAD system is not causing negative impact to the personal FM. Again, it should be noted that these findings are concerning given the common recommendation that personal FM and CAD systems should be used simultaneously in a classroom environment.

There are several reasons which may explain why performance decreased when the personal FM system was used with the Audio Enhancement CAD system. First, when the Phonak inspiro transmitter was coupled to the audio output port of the Audio Enhancement Elite II CAD system (by way of an auxiliary cable), the adaptive nature of the inspiro system was eliminated. As a result the increases in FM gain that have been shown to improve speech recognition at moderate to high noise levels may have been eliminated (Thibodeaus, 2010; Wolfe et al., 2009; Wolfe et al., 2013a).

Secondly, the Phonak inspiro transmitter possesses multiple forms of pre-processing, including a directional microphone with a hyper-cardioid response and digital noise reduction. It is possible, but not certain, that these noise technologies may provide a more favorable SNR than the directional microphone of the Audio Enhancement *Tear Drop* microphone. Again, these noise technologies are eliminated when the inspiro transmitter is coupled to the receiver of another CAD system. Finally, it is possible that the output signal of the Audio Enhancement Elite II CAD was not sufficient in level to deliver a robust signal via the Phonak inspiro transmitter. If this was indeed the case, there was not a simple method to ameliorate the problem, as there was not a gain control for the audio output port.

There are at least two solutions that may address the insufficient gain problem. First, rather than coupling the Phonak inspiro transmitter directly to the audio output port of a CAD system of another manufacturer, the teacher may simultaneously wear the microphones/ transmitters of both CAD systems (AAA Clinical Practice Guidelines, 2008). This would preserve the adaptive and noise reduction technologies of the adaptive personal RF system and presumably support at least the same level of performance in noise as obtained with use of the personal system alone. Of course, this solution does require the teacher two wear two transmitters/ microphones, which may be awkward and uncomfortable.

Another solution would be to use a special interface device referred to commercially as the Phonak DigiMaster X. The DigiMaster X may be coupled to an existing CAD system by way of an auxiliary audio cable connected to the audio input port of the receiver of the CAD system. The DigiMaster X receives the signal of interest by way of RF transmission from the inspiro transmitter and delivers it to the existing CAD system by way of an auxiliary audio cable connected to the audio input port of the receiver/amplifier. This solution allows for preservation of the adaptive gain feature and noise reduction technologies for the signal delivered from the inspiro transmitter to a Phonak adaptive personal RF receiver, and it also converts the existing CAD system to an adaptive system. The downside of this solution is that it requires a separate piece of equipment (the DigiMaster), so it is more expensive than using two microphones/ transmitters.

Study Limitations

Only two types of CAD systems and one type of adaptive personal FM were evaluated in this study. Numerous differences exist in the design and technology incorporated in existing CAD and personal RF systems. Consequently, the results of this study may not apply to all CAD systems. Furthermore, the results obtained with the adaptive personal FM system are likely to be more favorable than results obtained with a fixed-gain, personal FM system, especially when compared at higher competing noise levels (Thibodeau, 2010; Wolfe et al., 2009). Additionally, performance with an adaptive digital personal RF system is likely to be more favorable than the performance obtained with an adaptive personal FM system. Finally, classroom acoustics vary considerably from school to school, so the results obtained in the classroom used for data collection in this study may not represent what may be observed in every classroom. As such, it is important that educational audiologists validate the performance and benefit a child achieves with remote microphone technology in the classroom.

Conclusions

Based on the data presented in this paper, the authors propose the following conclusions:

(1) Adults with normal hearing understood speech in noise better than children with normal hearing. Adults and children with normal hearing both experienced some difficulty understanding speech in moderate to high level noise (unfavorable SNR; e.g., -1 dB to -6 dB SNR) via audition alone.

(2) Children with normal hearing understood speech in noise better than children with hearing loss. Children with hearing loss experienced difficulty understanding speech at noise levels and SNRs commonly encountered in typical classroom settings.

(3) CAD systems improved speech recognition in noise for children with hearing loss and also for children and adults with normal hearing.

(4) An adaptive, digital CAD system with a single-tower array of loudspeakers has the potential to provide equal or better speech recognition in noise than fixed-gain, infrared CAD system with multiple loudspeakers.

(5) Personal FM provided significantly greater improvement in speech recognition in noise than what is obtained from use of CAD systems.

(6) Combined use of the adaptive, digital single-tower CAD system + Personal FM (each was designed by the same manufacturer) provided better performance in noise than combined use of the fixed-gain, infrared CAD system with multiple loudspeakers + Personal FM (each system designed by a different manufacturer). In other words, it was evident that use of the CAD system negated some of the benefit provided by the personal FM system. It is important for educational audiologists to administer validation measures to evaluate performance and benefit of remote microphone technology when CAD systems and personal FM systems are used simultaneously. This study suggests that this validation is particularly important when combining personal FM and CAD systems manufactured by two different companies.

(7) There was little to no improvement in speech recognition in noise with simultaneous use of a Phonak CAD system and personal FM system compared to performance with a personal FM alone.

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