Effects of Voice Priority in FM Systems for Children with Hearing Aids

Erin C. Schafer, Ph.D.
Katie Sanders, B.S.
Danielle Bryant, B.A.
Karin Keeney, B.S.
Nicole Baldus, B.A.

University of North Texas
Denton, TX

Recently introduced frequency modulation (FM) systems provide an adaptive adjustment to the emphasis of the FM system through the user's hearing aid via VoicePriority *i*™ (VP*i*). VP*i* measures the noise level at the listener's hearing aid microphone and adds gain to the FM signal when the background noise increases to a detrimental level. However, the potential benefit of VP*i* technology has yet to be determined. Therefore, the goals of this investigation were to determine behavioral performance and subjective ratings with VP*i* as compared to traditional, fixed-gain FM systems or hearing aids alone. According to speech-recognition performance in noise, VP*i* provided significantly better scores when compared to the traditional FM system in conditions with high levels of noise. Acceptable noise levels were also significantly better with VP*i* over the traditional FM system and the study hearing aids alone. Speech intelligibility ratings with both FM systems were significantly higher than ratings with study aids alone. Parent and child questionnaires yielded similar findings to the behavioral results, with significantly higher ratings for the FM system with VP*i* over the study and personal hearing aids alone. In conclusion, the FM systems with VP*i* provided superior performance and subjective ratings relative to traditional, fixed-gain FM systems or hearing aids alone.

Introduction

Children and adolescents with hearing loss experience significant declines in speech-recognition performance in the presence of background noise when compared to performance in a quiet condition and to peers with normal hearing (Leibold, Hillock-Dunn, Duncan, Roush, & Buss, 2013; Nittrouer et al., 2013; Schafer, Pogue, & Milrany, 2012-b; Schafer et al., 2012-d). These significant declines in performance in noise are concerning given that typical classrooms have high unoccupied noise levels and reverberation times (Knecht, Nelson, Whitelaw, & Feth, 2002; Nelson, Smaldino, Erler, & Garstecki, 2008; Pugh, Miura, & Asahara, 2006), which do not meet recommendations from the American Speech-Language Hearing Association (2005) or the American National Standards Institute (2010).

The most direct approach to improving the speech-recognition deficits in noise of children with hearing loss is the use of remote-microphone technology, such as a frequency modulation (FM) system (Pittman, Lewis, Hoover, Stelmachowicz, 1999; Wolfe et al., 2013). FM systems consist of a microphone and transmitter for the talker and a receiver for the listener. FM systems greatly improve the signal-to-noise ratio (SNR) at a listener's ear by transmitting the primary talker's signal to the listener's ear via soundfield speakers, an electromagnetic receiver (neckloop) worn by the listener, or a personal receiver that is directly connected to the listener's hearing aids or cochlear implants. The more direct signal and improved SNR obtained with the FM system helps to combat poor classroom acoustics.

Children with hearing loss show significantly better speech-recognition performance when using FM systems as compared to their hearing aids or cochlear implants alone in noisy situations (Pittman et al., 1999; Wolfe et al., 2013). Even with the addition of advanced features in hearing aids, such as directional microphones, speech-recognition performance with FM systems is superior to performance with hearing aids alone (Lewis, Crandell, Valente, & Horn, 2004).

The most recent research on children with mild to profound sensorineural hearing loss and hearing aids shows that children perform significantly better with personal soundfield, a single loudspeaker placed on student's desk, or personal FM systems when compared to hearing aids alone or classroom (multiple loudspeakers) soundfield FM systems (Anderson & Goldstein, 2004; Anderson, Goldstein, Colodzin, & Iglehart, 2005). Another study by Boothroyd (2004) further supports the significant benefit of FM systems over performance with hearing instruments alone. In addition, when compared to hearing aid alone, use of personal FM systems by children with moderate to profound hearing loss significantly improves listening comprehension and functional listening skills at home according to ratings from parents and children (Flynn, Flynn, & Gregory, 2005).

The FM systems used in most of the aforementioned 2004 and 2005 studies utilized a fixed FM-gain setting, which is most often set to provide a 10-dB advantage over the microphone input from the hearing aid as recommended by the American Academy of Audiology (AAA, 2008). The exact origin of the +10 dB recommendation is undefined, but recent research suggests that SNRs ranging from 9 to 16 dB are required for children with normal hearing to repeat an average of 95% of words correctly (Bradley & Sato, 2008; Neuman, Wroblewski, Hajicek, & Rubinstein, 2010). Furthermore, children with hearing loss require approximately 4 to 8 dB better SNR to obtain speech-recognition performance similar to normal-hearing peers (Neuman, Wroblewski, Hajicek, & Rubinstein, 2012).

More recent FM systems allow for programmable adjustments of FM gain provided to the listener. When coupled to a hearing aid, the FM gain adjustment controls the relationship between inputs from the FM system and hearing aid, whereby higher programmable FM gain settings would result in greater emphasis for the signal from the FM system. As stated previously, when using a programmable FM system, it is important to achieve an advantage of **at least** +10 dB for the FM signal while still maintaining audibility of other sounds through the hearing aid microphones (AAA, 2008). To our knowledge, there is no published research on the effects of programmable, fixed FM-gain settings on speech-recognition performance of individuals with hearing aids. However, a study with adults using unilateral cochlear implants suggests that higher FM-gain settings result in significantly better speech-recognition performance in noise for some participants (Schafer, Wolfe, Lawless, & Stout, 2009).

More recently, technological improvements to Oticon and Phonak FM systems allow for the automatic adjustment of FM emphasis in an adaptive manner based on the background noise level in the environment. The goal of this approach is to provide substantial FM emphasis in situations with high levels of noise and to provide lower FM emphasis in less noisy situations. Using this adaptive approach, consistent audibility for the primary talker is maintained regardless of the noise level in the environment. In Phonak FM systems with this Dynamic FM feature, the necessary FM emphasis is determined at the location of the teacher's transmitter. When background noise levels are below 57 dB SPL, the FM receivers are set to provide a +10-dB FM advantage. However, when the noise level measured at the FM transmitter exceeds 57 dB SPL, the FM transmitter broadcasts a signal to the FM receivers to systematically increase FM receiver gain until the maximum setting of +24 is achieved. In 2010, Thibodeau reported a significant benefit of Dynamic FM gain at higher noise levels for 10 adults and adolescents with hearing aids. Specifically, when using Dynamic FM, speech-recognition performance was significantly better in 68 and 73 dBA noise conditions when compared to performance with a fixed-gain programmable FM system set to +10-dB FM advantage in the same noise conditions. Participants also preferred the Dynamic over the traditional FM when participating in two classroom activities and six lessons in a public aquarium. Wolfe et al. (2009) reported similar findings of significantly better performance with Dynamic FM versus traditional FM systems for adults and children with cochlear implants.

One potential disadvantage of measuring the noise level at the location of the transmitter is that the noise levels located at the teacher and child may differ to some degree. Background noise may be diffuse or more intense (localized) in a particular area in the classroom. In a larger classroom, noise levels across the room may vary due to the source(s) of the background noise, reverberation time in the classroom, and the presence of reflective or absorbent surfaces in a given area. More localized noise may be generated near the back of a classroom during small group activities or near hallways, windows, computers, or other noise-producing equipment. Even when localized and diffuse noise sources are of equal intensity at the listener's ears, the location or distance of the noise sources from the teacher or listener may impact performance due to more direct versus reflected sound and temporal differences.

The recently released Oticon Sensei hearing aid with the dedicated Amigo R12 FM receiver and Amigo T30 transmitter also allows for automatic and adaptive adjustment of FM emphasis (i.e., VoicePriority *i* [VP*i*]), but the necessary FM input is determined at the location of the hearing aid. When background noise levels are below 57 dBA, the FM receivers coupled to Oticon Sensei hearing aids are set to the +8 dB FM-receiver value. The +8 dB setting is recommended by Oticon because it is the setting necessary to achieve electroacoustic transparency, or equal outputs from the hearing aids and FM system when providing equal inputs to the two devices, which is recommended by AAA (2008). Also, when used in a realistic situation the +8 dB setting is designed to provide a consistent +10 dB FM advantage over the input from the hearing aid microphone. When the noise level measured at the aid exceeds 57 dBA (65 dB SPL), the VP*i* in the hearing aid systematically increases the direct audio input (DAI) signal until the maximum DAI input is achieved (i.e., 13 dB increase in DAI signal). The VP*i* gain changes occur rapidly, with attack and release times of 30 and 600 ms, respectively. The FM gain returns to the default +8 dB setting once the noise level decreases below 57 dBA. As a result, this system will provide the most favorable FM input for each child in a classroom and should account for any variation in acoustics at the location of a particular child relative to his or her peers. At this time, there is no published research examining or comparing the potential benefits of VP*i* and traditional fixed-gain FM system on children with hearing aids. Therefore, the primary goals of the present investigation were to compare behavioral and subjective performance with two types of FM systems. First, speech-recognition performance in noise was compared with two FM-system settings: FM receivers programmed to provide fixed-FM gain and the same FM receivers programmed to provide VP*i* (i.e., adaptive FM emphasis). Second, acceptable noise levels (ANLs) and speech intelligibility ratings (SIRs) of children were compared when children were using (1) bilateral Oticon hearing aids alone, (2) the same hearing aids with the fixed-gain FM, and (3) the aids with the FM and VP*i*. Finally, the listening abilities of children were determined via parent and child questionnaires while using the Oticon hearing aids alone and while using the aids coupled to the FM system with VP*i* during a four-week trial period with the devices. In general, the investigators hypothesized that use of the VP*i* technology would result in significantly improved behavioral performance over traditional, fixed-gain FM, and subjective ratings relating to performance with VP*i* would reveal significant improvements over the hearing aid alone when listening in noisy situations.

Methods

Research Design

A within-subjects, repeated measures design was used for this study. Participants and parents completed subjective scales before and after a trial period. Behavioral measures were completed after the trial period and included speech-recognition performance with the VP*i* and fixed-gain FM as well as ANL and SIRs with the study aid alone and in the two FM system conditions (VP*i* and fixed-gain FM).

Participants

Twenty children, 10 males and 10 females, ages 5;3 years to 18;0 years (M=10;5, SD=3;5) participated in the study. Demographic information about the children is provided in Table 1. Nineteen children had symmetrical moderate to severe mixed (n=1) or sensorineural (n=18) hearing losses; the average pure-tone air-conduction thresholds for these children is provided in Figure 1. One child had a unilateral profound sensorineural hearing loss, but was included in the study given difficulty recognizing speech in the presence of background noise and his bilateral acoustic neuromas. His speech-recognition scores were comparable to other participants. Hearing thresholds were determined prior to the study with recent hearing evaluations (< 6 months old) or with a new hearing evaluation prior to the study. With the exception of the one child with unilateral hearing loss (Subject 11) who was not aided, children were required to have permanent hearing loss, spoken English as their first and primary language, and bilateral hearing aids. One child (Subject 20) had bilateral hearing aids that were used in school, but the child was not a consistent user. As a result, the parent completed the subjective scales in the unaided condition, and these data were not included in the questionnaire analyses.

Procedures and consent/assent forms used in this study were approved by the University of North Texas Institutional Review Board. Parents of children less than 18 years of age and the adolescent who was 18 years completed a consent form prior to the study. In addition, children who were seven years and older completed an assent form prior to the study.

Equipment and Fitting Procedures

An outline of the two test sessions is provided in Table 2.

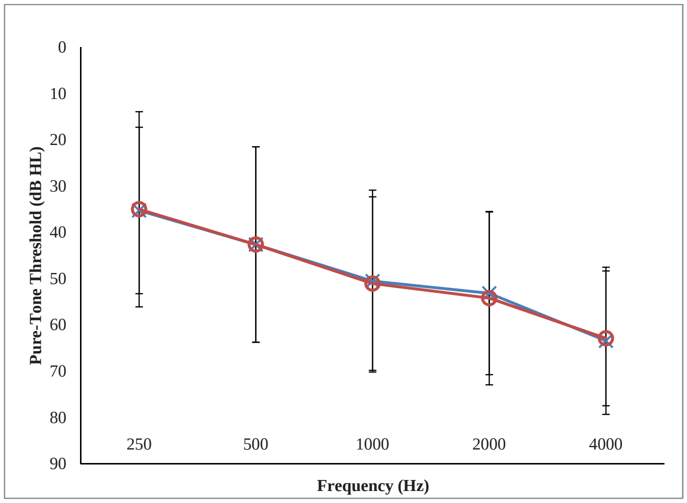

Figure 1. Pure-tone air-conduction thresholds of 19 participants with bilateral sensorineural or mixed hearing loss. *Note.* Vertical lines represent one standard deviation.

During the first test session, children were fit with bilateral Oticon Sensei Pro behind-the-ear (BTE; n=12) or receiver in the ear (RITE; n=8) hearing aids. Children used their personal earmolds or an appropriate-sized dome with the RITE aids. The type of hearing aid used in the study was determined by the type of personal hearing aid currently in use by the child. In other words, the investigators did not want to confound results of the study by changing the type of aids used previously by the child. The aids were programmed with Oticon Genie software to provide Desired Sensation Level (DSL v5; Scollie et al., 2005) prescribed gain for the child's chronological age and hearing loss. Default manufacturer settings on the hearing aids of all children included active directional microphones (Auto Tri-Mode and Opti Omni Surround Mode) and noise management. The investigators chose to activate volume controls for all children to ensure comfort during the trial period with this new hearing aid. All of these settings were active with the hearing aid alone and with both FM-system settings. In addition, all aid and FM signals were subjected to Super Silencer, which aims to provide additional circuit noise reduction when speech from the FM transmitter is absent. Following the fitting, the investigators conducted real ear measures on each ear with the Speechmap function (Std. Speech signal) of the Audioscan® Verfit™ to ensure that the DSL v5 prescriptive targets were met within ± 5 dB at 55, 65, and 75 dB SPL for frequencies between 0.25 to 4 kHz. The investigators also measured real ear maximum power output (MPO) with a 90 dB SPL pure-tone sweep to ensure that output would not exceed the estimated uncomfortable loudness levels (UCLs) for the child's age. If the targets were not met, outputs exceeded the UCLs, or the subject reported discomfort, appropriate adjustments were made using the Genie software.

Once the hearing aids were fit and verified with real ear measures, bilateral Oticon R12 FM receivers were attached, and the Oticon T30 transmitter with omnidirectional lapel microphone was activated. Following a listening check to ensure audible

Table 1. Demographic Information About Study Participants and Answers to General Questions on the Auditory Performance Scale for FM Systems

Subj #	Age (yrs)	Personal Aids	Avg FM Use (hrs)	Where Most Helpful?	Liked Most About FM?	Liked Least About FM?	Interference?	Recommend to Others?
1	8	Phonak Naida V SP BTE	2	At mall & in car	Long range; could hear whispers	Charging	No	Yes
2	11	Unitron Element 8BR RITE	2	Voices far away and didn't carry	Multiple uses, use as headphones	Mic clip not durable, too big	No	Yes
3	9	Unitron Next 4 HP BTE	1-2	Car, getting attention from another room	Automatic frequency connection, small FM	Flashing light, batteries	No	Yes
4	11	Unitron Element 16 BTE	6-10	Coaching, presentations, school	Portable	*	*	*
5	13	Unitron Element 16 BTE	6-10	Coaching, presentations, school	Easy to use, portable, hear clearly at distance and background noise	Feedback	Yes, when out of range and randomly	Yes
6	18	Phonak Solana Micro P BTE	1-2	When person was in different room, TV	Worked well, reliable	Look, size	No	Yes
7	6	Phonak Nios Micro III BTE	8-10	In car, TV	Could hear much better, easy to use	Bulky transmitter, mic detached easily	Not too much	Yes
8	14	Phonak Extra 311 AZ BTE	2	In car, TV	Easier to understand people, TV connection	Feedback	If far from receiver	Yes
9	6	Oticon Safari 900 BTE (Couldn't verify, emailed mom)	8	School, shopping	Very easy to use, small	*	No	Yes
10	9	Phonak Nios Micro V BTE (Couldn't verify, emailed mom)	3	Happy to hear better	Helps a lot, proud of it	Makes some unwanted noise	Yes	Yes
11	10	None	2	Event outside with large group; grocery shopping	Child could hear all words said and didn't ask 'huh?', heard better outside the home	Need more than one transmitter: for each parent	No	Yes
12	9	Starkey Zon 7 RITE	4	Classroom, large noisy rooms	Simplicity, size	*	2-3 times after charging; fixed after battery reinserted	Yes
13	7	Phonak Naida UP BTE	6-7	Noisy places	Small, easy to use	Little buzzing, clip	Yes, like a noisy waterfall	Yes
14	16	Phonak Certena Micros Open BTE	5	Hear better, gets attention more	Music player, mic was sensitive	Yes, when talking or a lot of noise	*	*
15	11	Phonak Audeo RITE	3-4	iTouch, classroom, teacher instructions	Clarity	Static, size	When cord touched another part of the cord	Yes
16	13	Phonak Audeo RITE	4-5	Classroom	Clarity when there was no static	Size	Yes, static many times	Yes
17	12	Oticon Safari 600 Power BTE	1-2	Hear from different room, in noise	Mom doesn't have to yell	*	Static when close to computer speakers	Yes
18	14	Phonak Versata Micro	3	Noise	Distance, directly to ears	Teachers would not mute, interfered with participation in class	Yes, nearly all the time	Not in the classroom setting
19	7	Phonak Nios Micro III	1	Restaurant, another room	Could hear from different room, when it was loud	Transmitter didn't clip well, too heavy on shirt	No	Yes
20	5	None	1	Restaurant, another room	Heard much better without needing to be loud or yell	Transmitter was too heavy to clip on shirts without pockets	No	Yes

Note. The type of personal aid also relates to the type of aid used in the study. BTE=behind the ear hearing aid; FM=FM system; RITE=receiver in the ear; Subj.=subject; *participant did not provide information.

output from the hearing aid and FM system (i.e., FM+M), the transparency (i.e., equal output with equal input) of the FM system to the hearing aid was determined with electroacoustic test procedures recommended by AAA (2008). The Audioscan® Verfit™ was used to measure and compare the output of the hearing aid alone coupled to a 1-cc (RITE) or 2-cc (BTE) coupler and then the hearing aid coupled to the FM receiver with input to the FM transmitter when using a 65 dB SPL speech input (Std. Speech signal). Transparency was achieved for all hearing aids and FM systems with the manufacturer default settings on the FM receiver (+8 dB gain).

After the fitting, children and parents were given an orientation on use, care, and maintenance of the hearing aids and FM system. Written instructions were also provided. Following the fitting session, children were asked to use the equipment over a four-week trial period. Specifically, children were asked to use the FM system for a minimum of two hours a day and to use the Oticon Sensei aids the remainder of their day. The investigators believed two hours per day over a period of four weeks would provide the children and parents with ample experience to rate subjective performance with the devices. Use of the hearing aids during waking hours was confirmed for all children following the study using the Activity Analyzer feature in the manufacturer programming software. The VP*i* feature (automatic adjustments to FM emphasis in hearing aid) was activated for the trial period, and participants were instructed to leave the FM receiver attached to the hearing aids for the entire trial period. When the transmitter was turned on, the FM receiver was automatically activated.

Equipment and Behavioral Testing

After the four-week trial period, children returned for the second test session (Table 2), which included three behavioral test measures: speech recognition, ANLs, and SIRs.

Speech recognition in noise. Speech recognition included 12 listening conditions with randomly-selected sentence lists from the Hearing in Noise Test for Children recorded on a CD (HINT-C; Nilsson, Soli, & Gelnett, 1996) and four-classroom noise (i.e., noise from four classrooms digitally overlapped) from the Phrases in Noise Test (Schafer et al., 2012-a; Schafer & Thibodeau, 2006). Each sentence list consisted of approximately 50 words, and children's responses were scored according to the number of words he or she repeated correctly. In a total of 12 conditions and HINT lists, children were tested in both traditional fixed-gain FM and VP*i* FM conditions in two loudspeaker arrangements described below (diffuse; localized) and at three SNRs measured at the participant's head: (1) speech 65 dBA/ noise 55 dBA: +10 dB SNR, (2) speech 70 dBA/ noise 63 dBA: +7 dB SNR, and (3) speech 74 dBA/ noise 70 dBA: +4 dB SNR. These SNRs were based on the expected increase in speech level with an increase in noise level and were used in a previous investigation on effects of automatic adjustments to FM gain (Wolfe et al., 2009). The intensity of the speech signal across the three SNR conditions at the location of the transmitter microphone was 82, 87, and 91 dBA, respectively. Speech-recognition performance was not assessed with the study aid alone because of the expected fatigue in the children, and there is no speech-recognition test that is appropriate for younger children that also has the necessary number test lists to add six more hearing-aid-alone conditions (i.e., for a total of 18 conditions).

The speech-recognition testing was conducted in a 20 ft. by 13 ft. classroom setting (Figure 2) with an average unoccupied noise level across eight locations of 43.9 dBA, and an average reverberation time of 0.39 seconds across octave frequencies between 500 and 4,000 Hz as measured with a sound level meter (Larson Davis System 824). Speech was presented from a single head-level loudspeaker located at 0-degrees azimuth using a compact disc (CD) player (Sony CD-Radio-Cassette-Corder). Uncorrelated four-classroom noise was presented from four head-level loudspeakers (Bose Companion 2 Series II Multimedia Speaker System) and two portable CD players (INSIGNIA NS-P5113). As shown in Figure 2, two different noise loudspeaker arrangements were used during speech-recognition testing; however, speech was always presented from 0-degrees azimuth. When the FM transmitter was in use, the transmitter microphone was placed on a stand six

Table 2. Overview of Study Sessions and Test Conditions

Session 1	Session 2
1. Informed consent/assent obtained 2. Parents completed case history form 3. Parents and children completed the C.H.I.L.D. and APS scales: performance with his/her personal aids 4. Hearing test conducted, if necessary 5. Study hearing aids programmed and verified using real ear measures 6. FM connected and transparency verified using electroacoustic test measures 7. Verbal and written orientation to devices provided 8. Participants asked to use devices over a 4-week trial period	1. Parents and children completed the C.H.I.L.D. and APS scales for performance with: (a) study aids alone; (b) aids with VP*i* 2. Speech recognition in noise with traditional fixed-gain FM and VP*i* in 2 loudspeaker arrangements (Figure 2) each at 3 SNRs: 65/55; 70/63; 74/70 3. Acceptable Noise Levels with (a) study aids alone; (b) traditional FM; (c) VP*i* 4. Speech Intelligibility Ratings in Noise with (a) study aids alone; (b) traditional FM; (c) VP*i*

Note. APS=Auditory Performance Scale for FM Systems; C.H.I.L.D.=Children's Home Inventory for Listening difficulties; SNRs=signal-to-noise ratios; VP*i*=VoicePriority *i*.

inches from the single-coned loudspeaker. Intensity levels of all stimuli were calibrated with a sound level meter. The examiners were required to re-program the hearing aids between some randomized test conditions using a laptop computer and the Oticon Genie software for the two FM settings: (1) traditional fixed-gain FM at a +8 dB and (2) VP*i* (automatically adjusts FM emphasis based on noise measured by hearing aid). Participants were given a break between the conditions to allow the examiner to reposition and recalibrate the four loudspeakers and/or adjust the FM settings.

Acceptable noise levels. The children's ANLs were determined in three conditions with speech and multi-talker babble noise recorded on a CD (ANL, 2009) from spatially-separated loudspeakers (speech at 0 degrees; noise at 180 degrees). The conditions included (1) the study aid alone, (2) the study aid plus FM system set to traditional fixed-gain (+8 dB) FM, and (3) the study aid plus FM system with VP*i* enabled. Children were given a paper-based loudness rating scale to use during these conditions. To measure ANL, the examiner determined the child's most comfortable listening level (MCL) for running (continuous) male speech at 0-degrees azimuth by adjusting the intensity of the speech stimuli in 5-dB HL steps to a level that was 'too loud' and a level that was 'too soft'. The speech was then adjusted in 1-dB HL steps in between levels that were rated as 'too loud; or 'too soft' to find the child's MCL. After the MCL was determined, the examiner continued to present speech at the MCL while adding background noise at 180-degrees azimuth. The background noise level (BNL) was adjusted in 5-dB HL and then 1-dB HL steps until the child indicated that he or she would be willing to 'put up with' the noise level for a long period of time. The MCL and BNL procedures were conducted twice, and the signal levels in each procedure were averaged before calculating ANL (i.e., ANL= MCL – BNL).

The ANL was conducted in a sound-treated booth with a GSI 61 Clinical Audiometer and two head-level Grason-Stadler loudspeakers. The signal speaker was located at 0-degrees azimuth and the noise loudspeaker was located at 180-degrees azimuth. The ANL stimuli were presented from a CD played on a Dell Latitude E6530 laptop computer. When the FM system was in use, the FM transmitter microphone was placed on a stand six inches in front of the signal speaker. Stimuli intensity levels were calibrated with a sound level meter.

Speech intelligibility ratings. These intelligibility ratings were determined in three conditions with the Revised Speech Intelligibility Ratings (R-SIR) speech and multi-talker babble stimuli (Speaks, Trine, Crain, & Niccum, 1994). Similar to the ANL procedure, running speech was presented at 0-degrees azimuth, and background noise was presented at 180-degrees azimuth. However, for this procedure, the speech stimuli were fixed at 60 dBA, and only the noise levels were adjusted. The SIR procedures began in a study-aid alone condition where the examiner adjusted the noise level in 5-dB HL steps until the child indicated on a paper scale, ranging from 0% (none) to 100% (all) of words heard, that he or she heard approximately 50% of the speech passage. Along with the speech presented at 60 dBA, the noise level determined in the first hearing-aid-only test condition was used for the remaining two conditions, which included (1) the study aid plus FM system set to traditional fixed-gain (+8 dB) and (2) the study aid plus FM system set to VP*i*. In these two conditions, children were also asked to use the paper scale to rate the percentage of the words, ranging from 0% (none) to 100% (all), in the passages that were heard. Two

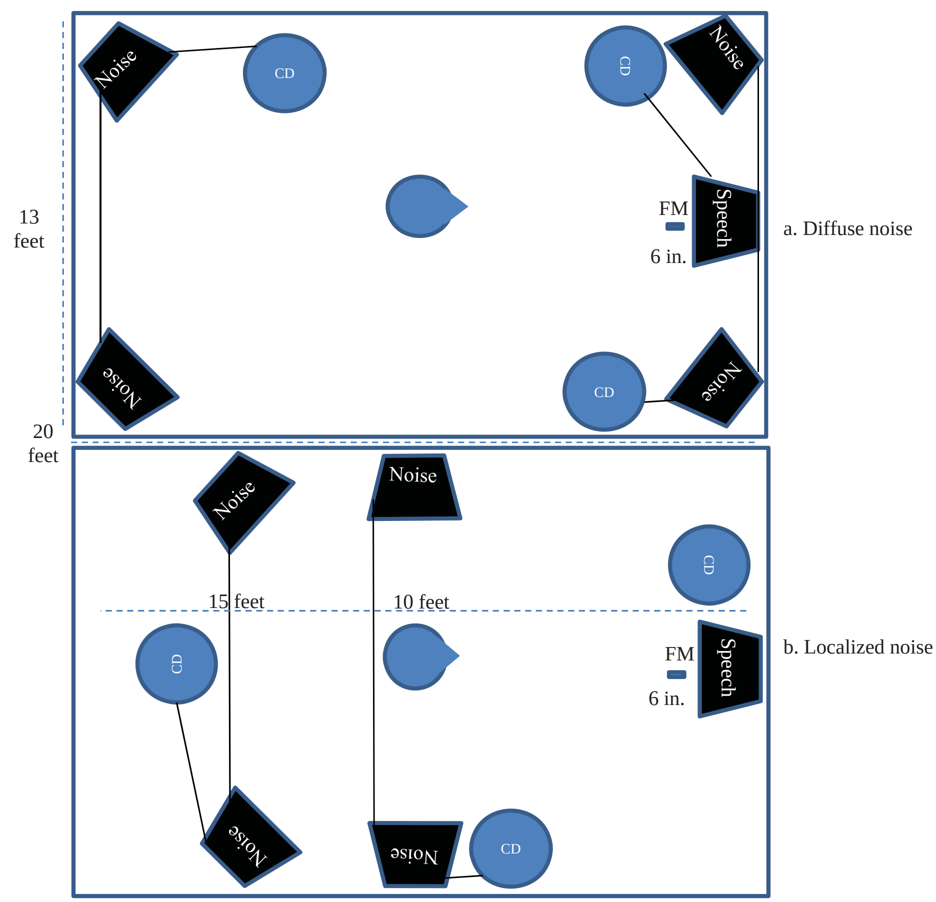

Figure 2. Classroom test arrangement for the (a) diffuse noise loudspeaker arrangement and for the (b) localized noise loudspeaker arrangement.

passages were given in each condition, and the children's ratings within each condition were averaged. For some children, the SIR procedures were slightly adapted (i.e., shortened) from the original version to address the short attention spans of many of the younger participants. When procedures were shortened, participants would listen to two to three sentences per condition rather than an entire passage. The equipment used for the SIR was identical to the equipment for the ANL, but the SIR stimuli were in digital format (.WAV) and were presented using the laptop soundcard.

Subjective Measures

Following consent/assent to participate, all participants and parents completed the same subjective rating scales before and after the four-week trial period with the devices. In the first session, participants and parents completed one set of questionnaires related to hearing performance with the child's current personal hearing aids, with the exception of Subjects 11 and 20 who were not using personal hearing aids and were excluded from the analyses of the questionnaires. In the second session, the participants and parents completed two sets of the same questionnaires to provide ratings for (1) the new hearing aid alone and (2) the new hearing aid plus the FM system with VP*i* enabled. In total, the three administrations of the questionnaires enabled the investigators to determine benefit of the hearing aid alone relative to the personal aid and benefit of the FM system.

The subjective rating scales included the parent and child versions of the Children's Home Inventory for Listening Difficulty (C.H.I.L.D.; Anderson & Smaldino, 2011) and a laboratory-developed questionnaire, the Auditory Performance Scale for FM systems (APS-FM; Schafer, Romine, Musgrave, Momin, Huynh, in press). The family and child versions of the C.H.I.L.D. included 15 items, which can be separated into five categories: hearing in quiet (four questions), media (one question), social situations (three questions), noise (four questions), and at a distance (three questions). For specific information regarding the items associated with each category, the reader is referred to the web link of the questionnaire, which is provided in the Anderson & Smaldino (2011) reference. A rating and modifier was assigned to each item on the scale relating to hearing ability, which ranged from 'Great' (rating of 8) to 'Huh?' (rating of 1). As stated previously, parents and children provided (1) baseline ratings on the C.H.I.L.D. at the beginning of the study for performance with the child's personal hearing aids. Following the four-week trial period, parents and children completed the same C.H.I.L.D. scale for (2) the child's hearing with the study aid alone (Oticon Sensei) and (3) the child's hearing with the study aid plus the FM system with VP*i* enabled (Oticon Sensei; R12 receiver; T30 transmitter). As a result, there were three C.H.I.L.D. scales obtained from the parent and three questionnaires obtained from the participant.

The APS-FM, originally designed to assess performance with FM systems and cochlear implants, was slightly modified from its original version to make it appropriate for hearing aids and to focus on questions related to a primarily home-based trial period (Schafer et al., in press). At baseline, the child completed (1) an APS-FM questionnaire consisting of 17 questions focused on hearing at home (6 questions) and hearing in social situations (11 questions). Each item on the scale was assigned a modifier and rating to indicate the child's level of difficulty hearing in each situation. Ratings ranged from 'Can Do This Well' (rating of 0) to 'Cannot Do This At All' (rating of 6). After the four-week trial period, the children completed the APS-FM for (2) hearing with the study aid alone and (3) hearing with the study aid plus the FM system. In addition to the 17 questions included in the baseline APS-FM, an additional 12 statements were included on the third administration of the APS-FM (during Session 2) to assess the child's opinions about the FM receiver and FM transmitter. Additionally, eight open-ended questions were asked regarding duration of FM system use, where it was most and least helpful, presence of any interference, experience connecting to other devices (i.e., TV, computer, etc.), and whether they would recommend it to others. Examiners and parents provided the children reading assistance on the C.H.I.L.D. and APS-FM scales, if necessary. After each of the two test sessions, participants were paid for their time and effort over the two sessions and four-week trial period, and parents were reimbursed for mileage expenses.

Results

Subjective Ratings Scales

Participant C.H.I.L.D. Average ratings from 18 participants across the three conditions (personal hearing aid; study aid; study aid plus FM with VP*i*) and five listening situations on the C.H.I.L.D. are provided in Figure 3. Participants 11 and 20 were excluded from the analysis because they were not using personal aids at the time of the study. Also, one child (Participant 18) chose to use the FM system only at school rather than at home because he wanted to determine if it would be helpful in the classroom. The remainder of children primarily used the FM system during a home-based trial during the summer.

Data for each listening situation were analyzed in separate one-factor repeated measures analysis of variance (RM ANOVA), and post-hoc analyses on the main and interaction effects were conducted with the Tukey-Kramer Multiple Comparisons Test. Results of these analyses are provided in Table 3 and suggest that children provided significantly higher ratings for the FM system relative to the personal aid and/or study aid.

Family C.H.I.L.D. Ratings were collected from 17 of the 20 parents, and average ratings are provided in Figure 4. One

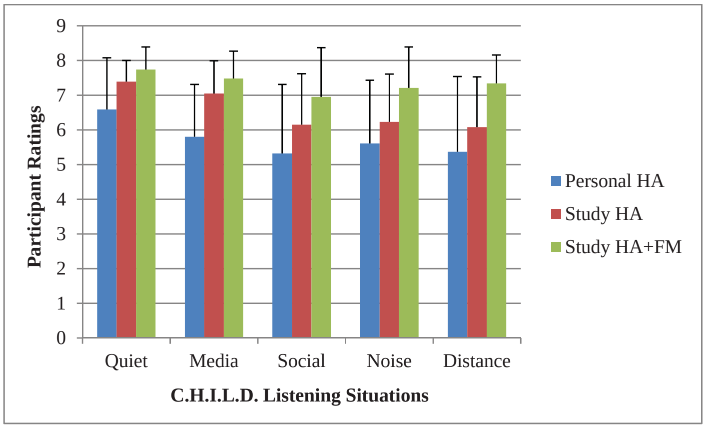

Figure 3. Average participant ratings on the Children's Home Inventory For Listening Difficulties (C.H.I.L.D.) *Note.* On scale, 5=okay but not easy; 6=pretty good, 7=good, 8=great. HA=hearing aid; FM=frequency modulation system. Vertical lines represent one standard deviation.

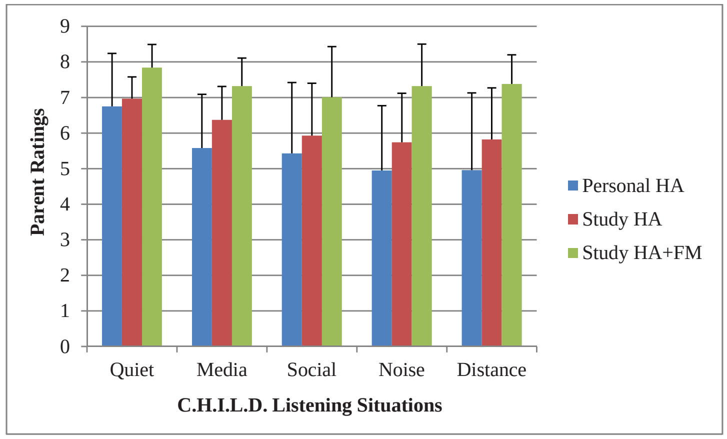

Figure 4. Average parent ratings on the Children's Home Inventory for Listening Difficulties (C.H.I.L.D.) *Note.* On scale, 5=okay but not easy; 6=pretty good, 7=good, 8=great. HA=hearing aid; FM=frequency modulation system. Vertical lines represent one standard deviation.

parent declined to complete the ratings scales because the child (Participant 18) chose to use the FM system more at school versus home, and two children were excluded due to non-use of personal hearing aids (Participants 11 and 20). The ratings in each listening situation were analyzed in separate one-factor RM ANOVAs and post-hoc analyses. Results are provided in Table 3, and on average, the family member rated the FM system significantly higher than the personal aid and the study aid in every condition. Also, the study aid was rated significantly higher than the personal aid for media, in social situations, in noise, and at a distance.

APS-FM. Ratings were collected from 18 of the 20 participants (Participants 11 and 20 excluded), and average ratings are provided in Figure 5. On this questionnaire, lower ratings (i.e., closer to zero) represent more favorable ratings. The RM ANOVAs on listening at home and in social situations yielded statistically significant benefit for the FM system over the study and personal hearing aid. In addition to the situation ratings, all 20 children completed 12 questions about the functionality of the FM transmitter and receiver. Average ratings on all 12 questions ranged from .57 to 1.67, indicating that the children 'liked it very much' or 'it was pretty good'. Specifically, most children indicated that the FM receiver was comfortable, easy to use, reliable, clear, cosmetically appealing, and helped them hear. Also, according to the ratings, most children reported that the FM transmitter was comfortable, cosmetically appealing, good sized, easy to use, and worked well. Answers to the open ended questions on the APS-FM are provided in Table 1. Overall, this questionnaire suggested that the FM system was highly beneficial at home and in social situations. Most children liked using the system, thought it was helpful, and would recommend its use to other children.

Table 3. Statistical Results from the C.H.I.L.D. Questionnaire Ratings Across Three Device Conditions: Personal Hearing Aid, Study Hearing Aid, and FM System

	Listening Situation	*F*-ratio	*p* value	Significant Post-hoc results *(p < .05)*
Participant C.H.I.L.D.	Quiet	12.3	.00009	FM better than personal aid
	Media	12.8	.00007	FM better than personal aid
	Social	8.6	.0009	FM better than personal aid
	Noise	13.5	.00004	FM better than study aid & personal aid
	Distance	10.9	.0002	FM better than study aid & personal aid
Family C.H.I.L.D.	Quiet	26.3	< .00001	FM better than study aid & personal aid
	Media	19.1	< .00001	FM better than study aid & personal aid; study aid better than personal aid
	Social	40.6	< .00001	FM better than study aid & personal aid; study aid better than personal aid
	Noise	52.1	< .00001	FM better than study aid & personal aid; study aid better than personal aid
	Distance	45.7	< .00001	FM better than study aid & personal aid; study aid better than personal aid
Auditory Performance Scale - FM	Home	6.2	.005	FM better than study aid & personal aid
	Social	6.2	.005	FM better than study aid & personal aid

Note. FM=study aid plus FM with VoicePriority *i*.

Behavioral Measures

Speech recognition in noise. Figure 6 displays the average speech-recognition performance of the 20 children across the three SNRs, two loudspeaker arrangements, and two FM conditions. On average, scores in the VP*i* condition were always higher than scores in the traditional FM condition, and as expected, scores decreased in higher noise levels.

The speech-recognition data were analyzed using a three-factor RM ANOVA with the repeated variables of SNR (65/55; 70/63; 74/70), loudspeaker arrangement (localized; diffuse), and FM technology (traditional; VP*i*). The analysis revealed a significant main effect of SNR, F (2, 240) = 45.9, $p < .00001$, significant main effect of loudspeaker arrangement, F (1, 240) = 9.7, $p = .006$, and significant main effect of FM condition, F (1, 240) = 10.6, $p = .004$. In addition, there were significant interaction effects between loudspeaker arrangement and SNR, F (2, 240) = 12.1, $p = .00009$, between loudspeaker arrangement and FM condition, F (1, 240) = 7.2, $p = .01$, and between SNR and FM condition, F (2, 240) = 6.8, $p = .003$.

Post-hoc analyses on the main and interaction effects were conducted with the Tukey-Kramer Multiple Comparisons Test. First, the post-hoc analysis on SNR revealed significant differences ($p < .05$) in the comparisons between all three SNRs, with the best performance in the 65/55 dB condition followed by the 70/63 dB and 74/70 dB conditions. Second, significantly better performance ($p < .05$) was measured in the diffuse noise loudspeaker arrangement when compared to the localized noise conditions. Finally, across all conditions, performance with VP*i* was significantly better ($p < .05$) than performance with the traditional FM.

Post-hoc analyses on interaction effects on loudspeaker arrangement and SNR suggested that performance in the 74/70 localized noise condition was significantly worse ($p < .05$) than performance in all remaining conditions. Additionally, performance in the 74/70 diffuse condition was significantly poorer ($p < .05$) than all remaining conditions, with the exception of the 74/70 localized noise condition. Finally, performance in the localized and diffuse 65/55 conditions were significantly better ($p < .05$) than all 74/70 and 70/63 conditions.

Post-hoc analyses on the loudspeaker arrangement versus FM condition showed that performance with the traditional FM in the localized noise conditions were significantly worse ($p < .05$) than traditional FM in diffuse noise and VP*i* in diffuse or localized noise conditions. The analysis on the SNR by FM condition interaction effect suggested that performance in the 74/70 condition with traditional FM was significantly poorer ($p < .05$) than all remaining conditions. No other significant differences ($p > .05$) were detected when comparing conditions within the same noise levels.

Acceptable noise levels (ANL). All but one young child were able to complete the ANL condition. Average MCLs, BNLs, and ANLs are shown in Figure 7. First, the participants' ANLs across three conditions (hearing aid alone; traditional FM; VP*i*) were analyzed with a one-way RM ANOVA. According to this analysis, there was a significant main effect of condition (F [2, 57] = 22.5, $p = < .00001$) with post-hoc analyses suggesting significant differences ($p < .05$) across all conditions. The best (lowest) ANL was measured in the VP*i* condition, followed by traditional FM and hearing aid alone. To further examine the differences in ANL across the conditions, a second ANOVA was conducted to examine if these results were due to significant changes in MCL or BNL levels. This two-factor RM ANOVA revealed no significant main effect of measure (i.e., MCL vs. BNL; F [1, 114] = .28, $p = .60$), but a significant main effect of test condition (F [2, 114] = 12.1, $p = .00009$). Additionally, there was an interaction effect between measure and test condition (F [2, 114] = 15.3, $p = .00002$). Post-hoc analyses suggested that the hearing aid alone condition resulted in significantly higher MCLs and BNLs across the two measures

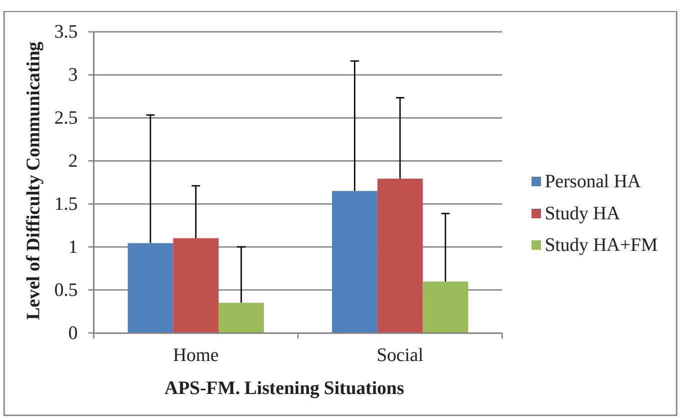

Figure 5. Average participant ratings on the Auditory Performance Scale for FM (APS-FM). *Note.* On the scale, 0=can do this well; 1=small difficulty; 2=some difficulty. HA=hearing aid; FM=frequency modulation system. Vertical lines represent one standard deviation.

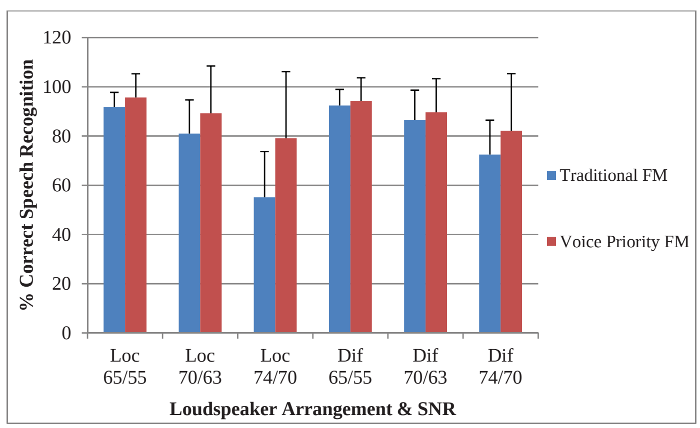

Figure 6. Average speech-recognition performance in noise on the Hearing in Noise Test. *Note.* Numbers represent speech/noise intensities. Dif=diffuse noise; Loc=localized noise; FM=frequency modulation system; vertical lines represent one standard deviation.

when compared to the traditional FM or VP*i* levels. The post-hoc analysis on the interaction effect revealed the most important findings. First, the hearing aid alone MCL was significantly higher in intensity ($p < .05$) than all remaining conditions. Second, the MCL and BNL with the traditional FM did not differ significantly ($p < .05$). Finally, between the two VP*i* conditions, the average BNL was significantly higher ($p < .05$) than the MCL, which suggested that participants could tolerate the most background noise with VP*i*.

Speech intelligibility ratings. All 20 children were able to complete the SIR. The average intelligibility ratings on a 0% to 100% scale across the three listening conditions are shown in Figure 8. A one-way RM ANOVA suggested a significant main effect of condition (F [2, 57] = 118.9, $p < .00001$), and post-hoc analysis suggested that children provided significantly higher ($p < .05$) intelligibility ratings for the traditional FM and VP*i* conditions relative to the hearing aid alone condition, with no significant differences ($p > .05$) between the two FM conditions.

Discussion

Subjective Measures

Participant C.H.I.L.D. On average, children rated the FM system significantly higher than their personal aid alone in every listening situation and the FM system significantly higher than the study aid alone in noise and at a distance. Specifically, these results suggest that the FM system was beneficial in quiet, in noise, in social situations, at a distance, and with media, such as televisions, computers, and personal audio devices (i.e., MP3 player).

Family C.H.I.L.D. Average parent ratings for the FM system were significantly higher than those for the personal aid alone and the study aid alone in every condition. In addition, the study aid alone was rated significantly higher than the personal aid for media, in social situations, in noise, and at a distance. As a result, parents perceived a high level of listening benefit when children were using the FM system as well as the study aid in most situations. One interesting aspect of the ratings was that parents rated the study hearing aids alone higher than the personal aids in most situations. The children had hearing aids from various manufacturers including Oticon, Phonak, Unitron, and Starkey, and the examiners were in no way involved in these fittings and were not aware of the fitting strategy used. Therefore, the difference between personal and study aids could be related to the prescriptive strategy (DSL v5 in this study; unknown for personal aids) or the fitting approach in the present study with real ear measures. The investigators do not know whether the personal aids were fit and verified using real ear measures. Additionally, parents may have comingled perceptions about the study aids alone and the study aids with the FM system, thus inflating the study aid alone ratings. If this occurred, some parents may have rated the study aid alone higher because of enhanced SNR and the Super Silencer function that was active when the FM system was in use. As stated previously, Super Silencer aims to reduce circuit noise, which would be audible to children with some low-frequency residual hearing when listening in quiet situations with the FM system. Additionally, the reported child and parent benefit from the devices could be simply because they were using a new device (i.e., Halo effect; Thorndike, 1920). At the same time, the subjective ratings are well-supported by the significantly improved behavioral performance on three separate measures.

APS-FM. The results on this subjective measure were similar to what was found on the participant and parent C.H.I.L.D. scales. The participants reported significantly less difficulty hearing at home and in social situations when using the FM system relative to the study and personal aids. On this scale, however, the study aid was not rated higher than the personal aid. This finding may be related to the different situations on the two questionnaires as well as the lengthier, more detailed description of the listening situations on the C.H.I.L.D.

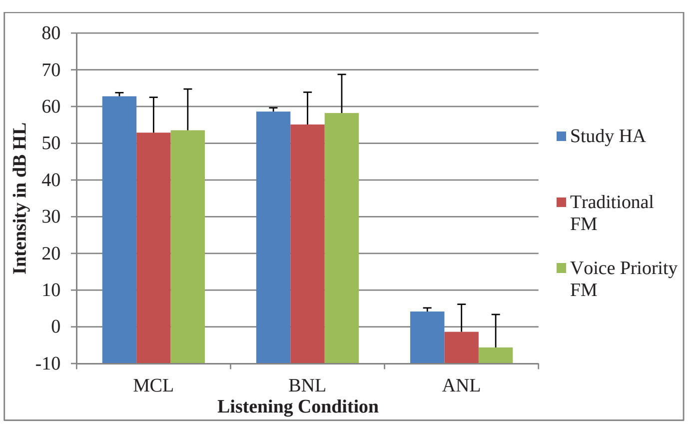

Figure 7. Most comfortable listening levels (MCL), background noise levels (BNL), and acceptable noise levels (ANL) averaged across participants. *Note.* Vertical lines represent one standard deviation.

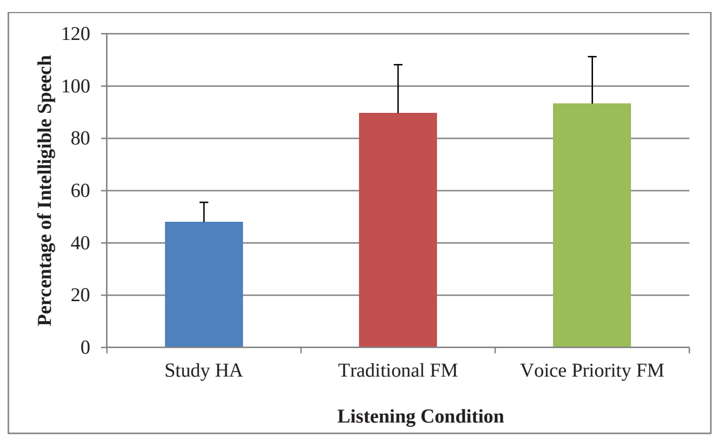

Figure 8. Participant-rated percentage of speech understood from passage on the Revised Speech Intelligibility Rating (SIR) test. *Note.* Vertical lines represent one standard deviation.

Behavioral Measures

Speech recognition in noise. Performance across the speech-recognition conditions yielded several notable findings related to the effects of SNR, noise location, and the benefit of VP*i* in FM systems. First, as expected, performance across all FM conditions declined significantly as the SNR declined and noise level increased. Each post-hoc comparison between SNRs yielded significant differences. Similar declines in speech-recognition performance in increasing noise levels were reported in previous studies with FM systems (Thibodeau, 2010; Wolfe et al., 2009).

Second, there was a significant effect of loudspeaker location on speech-recognition performance across all FM conditions despite the fact that the same intensity levels were used between the diffuse and localized conditions. The localized noise loudspeaker arrangement resulted in poorer speech-recognition performance than the diffuse noise, which has been used previously in classroom-based speech-recognition studies on adaptive FM systems (Thibodeau, 2010; Wolfe et al., 2009). In the present study, the largest deficit due to localized noise occurred at the 74/70 dBA signal levels with the traditional FM system where an average difference of 17% between diffuse and localized noise was found. This novel finding, in particular, provides evidence that localized noise is highly detrimental to children's speech-perception performance, and identification of this type of noise in a classroom may provide further support toward a child's need for hearing assistance technology with adaptive FM gain.

Third, across all SNR conditions and loudspeaker arrangements, performance was significantly better with VP*i* when compared to scores with the traditional FM. As the noise level increased above 65 dB SPL, VP*i* in the hearing aid systematically increased up to an additional 13-dB emphasis for the FM signal. Therefore, the greatest benefit from VP*i* occurred in at the highest noise level (74/70) with a difference between traditional FM and VP*i* of 27%. Even with the less detrimental diffuse noise arrangement, the benefit of VP*i* over traditional FM was 10%. In fact, one of the most notable findings on the speech-recognition testing was the fact that the loudspeaker arrangement had less of an effect on a listener's speech recognition when VP*i* was used. Specifically, at the highest noise level (74/70 dBA), the percent correct difference between localized and diffuse scores for traditional FM was 17% and for VP*i* was 3%. Although less noteworthy, differences between localized and diffuse scores were also found in the moderate noise condition (70/63 dBA) with a 6% difference for traditional FM and a 0.4% difference for VP*i*. The benefit achieved from VP*i* (up to 27%) in the present study was comparable to the benefit achieved in a previous study (Thibodeau, 2010) on Phonak systems with adaptive FM gain (36%). The percent-correct differences between these two studies may be explained by device differences including compression characteristics of the hearing aids, compression and gain settings within the FM systems, and the location where the adaptive gain was determined. In the Thibodeau (2010) study, the gain was determined at the location of the FM transmitter while in the present study, the gain was determined at each child's hearing aid. In addition, the goal of the Oticon system is to quickly restore audibility of others through the hearing aid when the teacher/parent is not speaking; this is achieved with the fast attack and release times with VP*i* functionality. Also, differences between studies could be due to methodological variances including classroom environments, stimuli (HINT vs. HINT-C), SNRs, and the younger sample used in the present study. Overall, the results of the speech-recognition testing suggested that VP*i* significantly improves performance relative to a fixed-gain FM system, particularly in high levels of noise that is localized and directed toward the participant's head.

Acceptable Noise Levels (ANL). The participants' ANLs were better (lower) with VP*i* when compared to the study hearing aid alone and the traditional FM system. Additionally, the ANL for the traditional FM was better than that of the hearing aid alone. An additional analysis revealed that these differences were primarily due to acceptance of an increased background noise level (BNL) in the FM conditions.

The ANLs obtained in the present study are much better than those obtained in previous investigations (Freyaldenhoven & Smiley, 2006; Moore, Gordon-Hickey, & Jones, 2011) because of the spatial separation of the speech (0 degrees) and noise (180 degrees) loudspeakers in the present study. For example, Freyaldenhoven and Smiley measured an average ANL of 11 dB (range -3 to +22 dB) in children with normal hearing. Therefore, the average ANL of +4 dB for the children in the aided condition in the present study makes sense given the substantial listening advantage of separating the speech and noise sources. Both FM settings resulted in negative ANLs, which suggest that when the FM system is in use, participants could tolerate a higher background noise level than speech level. Because VP*i* increased the FM emphasis as the examiner increased the BNL, the participants could tolerate a slightly higher BNL (and lower ANL) when compared to the traditional FM condition. These results suggested that children may be more comfortable in higher noise levels when using VP*i* over a traditional FM system.

Speech Intelligibility Ratings (SIR). The results of the SIR showed that both FM conditions provide equal intelligibility for a speech passage at a fixed SNR when compared to a rating with the hearing aid alone. The examiners purposefully found the dB SNR for 40 to 50% intelligibility with the hearing aid alone and then completed the traditional FM and VP*i* conditions at the same fixed SNR. The lack of difference between the FM conditions for this measure was likely related to the fixed SNR. Future investigations may include increasing levels of noise to examine potential FM differences at varying SNRs.

Study Limitations

As stated earlier the first two potential limitations in this study relate to (1) the potential for comingled perceptions about the study aids alone and the study aids with the FM system and (2) the potential of inflated ratings because they were using a “new” device. Another limitation of the questionnaires relates to the inability to verify the validity of the subjective responses. Although the average use time of the FM system is reported in Table 1, the investigators could not determine exactly how long and where the FM system was used or how these factors potentially influenced participant and parent ratings. The ability to adequately judge benefit for the FM system across a variety of listening conditions could be different for children who used the FM systems for a longer versus a shorter period of time.

Another limitation of the study was that children were only acclimatized to the hearing aid and FM system with VP*i* and not the traditional, fixed-gain FM system. However, an acclimatization effect was not expected because the investigators have previously examined this potential effect with FM systems used by adolescents and adults, and there were no significant changes in speech-recognition performance in noise after a four- to six-week trial period with an FM system (Schafer, et al., in press; Schafer, Romine, Huynh, Jimenez, 2012-c).

Conclusions

The behavioral measures in this study showed significant benefit of the FM system with VP*i*. Specifically, speech-recognition performance in noise was significantly better with VP*i* as compared to a traditional FM, especially in conditions with high-level, localized noise. The ANLs were significantly better with both of the FM settings over the study hearing aids alone. Further, the FM system with VP*i* resulted in better ANLs than the traditional FM due to an increased acceptance of background noise levels. The SIRs with both FM settings were significantly higher than the SIR with study aid alone. Parent and child questionnaires yielded similar findings to the behavioral results, with significantly higher ratings for the FM system with VP*i* over the study and/or personal hearing aids alone. In summary, the FM systems with VP*i* provided superior performance and subjective ratings relative to traditional, fixed-gain FM systems or hearing aids alone.

Acknowledgements

Funding for this study was provided by Oticon Denmark. The funds were used to compensate participants for their time, efforts, and mileage to the test center and to fund a research assistant. The primary investigator received no monetary compensation related to the study.

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