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DIFFERENCE BETWEEN DEFAULT TELECOIL AND PROGRAMMED MICROPHONE FREQUENCY RESPONSE IN BEHIND-THE-EAR HEARING AIDS

by

Daniel B. Putterman

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requirements for the degree of:

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Abstract: The notion that the default telecoil (t-coil) frequency response should match the programmed microphone frequency response to provide optimal telephone understanding for hearing aid patients has received little attention. This study addresses differences in the average frequency response of the two transducers in behind-the-ear (BTE) hearing aids.

ACKNOWLEDGEMENTS

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INTRODUCTION

In 1936 Joseph Poliakoff patented a communication device called a magnetic induction loop that transmitted electromagnetic (EM) signals to nearby antennae. In the subsequent year, an induction coil acting as an antenna for EM signals was inserted into the British Multitone hearing aid for use on the telephone, representing the first documented use of the telecoil (t-coil) (Levitt, 2007). Sam Lybarger, however, is heralded for implementation of the t-coil in hearing aids in the United States in 1947, reporting that unintended EM leakage from a telephone receiver results in a field immediately adjacent to the telephone receiver embedded in the hearing aid. This EM field contains the source signal from the telephone receiver with the EM signal proportional to the intended electrical signal (Lybarger, 1947; Ross, 2005; Levitt, 2007). The EM signal is detected by the t-coil, a wire coiled about a permeable metal core, and transduced by the hearing aid into an acoustic signal (Yanz and Preves, 2003). Specifically, successful induction requires that the signal must pass through the metal core while an electric current flows through the coiled wire (Ross, 2005). The result is a technology that provides several distinct advantages over the microphone setting when a hearing aid user listens on the telephone.

One advantage is that, unlike microphone of the hearing aid, the t-coil will only detect EM signals and not any undesired nearby acoustic signals, providing the hearing aid wearer with a more ideal listening situation for achieving maximum speech understanding. A second advantage is that the t-coil allows the telephone receiver to be positioned in close proximity to the hearing aid and ear without the occurrence of feedback. Feedback will naturally occur with the hearing aid microphone activated due to the telephone receiver proximity to the ear and the microphone of the hearing aid (Takahashi, 2005). A third advantage is that reliance on the microphone alone when communicating on the telephone is associated with the potential attenuation of low frequency energy as the user attempts to eliminate the feedback by distancing the hearing aid from the EM telephone receiver (Goldberg, 1975). In addition, the t-coil can receive EM signals from sources other than the telephone such as neckloops as well as inductive loop systems that have been installed in educational settings, homes, and clinics. Inductive loop systems transmit an EM signal to hearing aid via a wire that "loops" around a room. This arrangement provides a high signal-to-noise ratio (SNR), whereby the acoustic signal of interest can effectively circumvent distance and background noise as it is transmitted electromagnetically from the loop to the t-coil.

While the t-coil offers specific advantages, optimal performance of a t-coil is directly influenced by several device characteristics. First, the strength of the t-coil is based on the number of coil turns and overall size; the larger the size of the t-coil, the greater sensitivity it will have to detect an EM signal. Second, the sensitivity, or input-output characteristics of the t-coil can provide as much as 20-25 dB less gain than the microphone. As a result, an internal preamplifier is required to improve the sensitivity of the t-coil in order to achieve gain equivalent to the microphone (Yanz and Pehringer, 2003). The t-coil is referred to as "passive" if it does not have a preamplifier and "active" if the t-coil is integrated with a preamplifier (Thompson, 2002; Ross, 2005). Third, in order for the t-coil to perform optimally, its axis must be oriented parallel to the axis of the EM field and should be positioned within the axial region of the field (Thompson, 2002; Kozma-Spytek, 2003). For telephone use, the t-coil would best be oriented perpendicular to the face of the hearing aid case (horizontal), but for an inductive loop system the t-coil should be oriented parallel (vertical) to the face of the case.

Of the three aforementioned t-coil characteristics, optimal performance as a function of t-coil orientation has led to general industry indecision as to the most effective t-coil position for achieving optimal communication via the telephone and the induction loop. At least one hearing aid manufacturer has taken the approach of installing two t-coils with opposing orientations (one horizontal and one vertical) to provide quality input for both listening conditions (Sinks and Duddy, 2002), but this design has not continued to be implemented. The relatively small size of hearing aids paired with the consumer preference for cosmetically appealing hearing aid designs are likely to be reasons why hearing aid manufacturers to be resistant to installing two t-coils. While researchers are designing a digital multi-axis t-coil that could be immune to the orientation issue (Yanz and Pehringer, 2003; Yanz and Preves, 2003), their availability and use does not yet appear to have penetrated the hearing aid industry. As a result, this has left hearing aid manufacturers with the decision of positioning the t-coil in one of two positions whereby the end result will yield less than desirable performance for either the telephone or inductive loop listening situations (Ross, 2005). They may also elect to compromise and position the t-coil at a 45˚ angle that may be more desirable, but not optimal, for the telephone and inductive loop.

Beyond the issue of orientation, t-coils are inherently susceptible to several different sources of interference that can negatively influence optimal performance. In general, when in the t-coil setting one may experience interference (typically low-frequency buzzing) from unwanted signal sources such as fluorescent lights, video monitors, power lines, and digital wireless telephones (cell phones). This interference is enhanced for any user having an automatic t-coil. The automatic t-coil has a circuit that can "sense" a nearby EM field and automatically switch the hearing aid to t-coil mode (Agnew, 2002). While this eliminates the need for the user to manually activate the t-coil, the automatic t-coil can also be accidentally activated by these extraneous signals when in close proximity. Cell phones can also be most problematic for t-coils because they use high frequency signals (in the gHz range) that can become amplified by metal and wire of short length (Victorian and Preves, 2004). Efforts are underway for cell phone manufacturers to specify EM interference as well as hearing aid manufacturers to specify their immunity to these signals. For example, American National Standards Institute (ANSI) C63.19 (2006) assists hearing aid users and clinicians to identify cell phones that are less likely to cause interference (Levitt et al., 2005). Unfortunately, the implementation of standards specific t-coil use has been historically slow and limited.

For decades, electroacoustic measurement of the t-coil frequency response has received substantially less attention than the microphone frequency response (Ross, 2005; Takahashi, 2005). In fact, the 1976 ANSI standard (S3.22- 1976) only required a test-field strength of 10 mA/M and an output measure at only 1000 Hz (Teder, 2003). Twenty years later, ANSI-1996 (ANSI S3.22- 1996) mandated that t-coil performance be evaluated with a test-field strength of 31.6 mA/M. This is accomplished with a test transducer called a telephone magnetic field simulator (TMFS) which is a hand-held device designed to generate a 31.6 mA/M EM field, simulating the average EM leakage of a conventional telephone. Furthermore, the high frequency average (HFA) (1000, 1600, and 2500 Hz) in sound pressure level of the inductive telephone simulator (SPLITS) is compared to the HFA of the microphone response using a 60 dB SPL input signal with the volume control set at reference test position (RTP) (Teder, 2003). Formerly known as the simulated telephone sensitivity (STS) in ANSI S3.22-1996, this difference between the microphone HFA and t-coil HFA has recently been renamed the relative simulated equivalent telephone sensitivity (RSETS) per ANSI S3.22-2003. The closer the RSETS is to 0 dB, the closer the t-coil frequency response matches the microphone frequency response that has been programmed to a validated prescribed target (Teder, 2003).

Prescriptive fits are typically based on the microphone frequency response to average conversational speech presented at an input level of 65 dB SPL at a distance of one meter. This is conventionally deemed to be an appropriate representation of a "real-life" one-on-one listening condition. There is, however, no accepted protocol for verification of t-coil performance because the listening condition is more of a challenge to emulate (Yanz and Pehringer, 2003). Despite the fact that the conventional telephone's bandwidth ranges from about 300 Hz to 3300 Hz, not all telephones are identical in terms of how much EM leakage is released from the handset (Kozma-Spytek, 2003; Yanz and Preves, 2003). This creates an inconvenience whereby the hearing aid user must manually adjust the volume control of the hearing aid while in the t-coil mode at the beginning of a telephone conversation. Also, the distance from the telephone receiver is only centimeters from the t-coil, which makes the appropriate input level for creating a prescribed target even more difficult to identify.

Furthermore, not all hearing aid t-coil frequency responses are programmable; of those that are, not all allow frequency specific adjustment to the gain of the frequency response. Even if clinicians have the ability to program the t-coil frequency response it has not been determined whether the t-coil frequency response should be the same as the microphone frequency response when the bandwidth of the telephone is narrower than the bandwidth of average conversational speech arriving at the microphone (Rodriguez et al, 1993). Therefore, investigators have made an effort in the last several decades to address this issue.

Previous studies comparing microphone and t-coil sensitivity are inconsistent. For example, Sung et al (1974) measured the microphone and t-coil frequency responses using 14 body-worn and 11 behind-the-ear (BTE) hearing aids in a hearing aid test chamber and sound-treated room with the volume control full-on. These investigators concluded that, in general, the t-coil provided greater gain than the microphone, especially in the low frequencies, although they found this to be dependent upon the individual hearing aid. These results conflict with Tannahill (1983) who reported less output of the t-coil when compared to microphone sensitivity in both the low and high frequencies. The reported difference between the studies was believed to be because Sung et al (1974) used an inductance loop rather than a telephone receiver to transmit the signal.

In an attempt to clarify this issue and further elaborate on microphone and t-coil performance characteristics, Gary Rodriquez and Alice Holmes conducted a series of research projects in the 1980s and early 1990s. Rodriguez et al (1985) explored the possibility that low-frequency average inputs (500 and 800 Hz) and high-frequency average inputs (1000, 1600, and 2500 Hz) could have different frequency responses for microphone and t-coil settings. Thirty hearing aids were randomly selected and tested with a 60 dB SPL input and an induction coil tester with a test-field strength of 10 mA/M. At full-on-gain (FOG), findings indicated that the microphone coupling produced consistently greater gain than the t-coil coupling for both low and high frequency averages. Therefore, the performance could be noticeably different to the individual when changing settings between the two transducers. These results necessitated verification measures to determine the level of gain arriving to the ear in the acoustic and t-coil conditions.

Rodriguez et al (1991) measured the real-ear insertion response (REIR) for microphone and t-coil settings on five normal hearing subjects with 15 hearing aids all set to the reference test gain (RTG) position. An audiometer telephone interface (ATI) designed to match a conventional telephone was used under the t-coil condition. The average gain across the 15 hearing aids was higher for the microphone condition at all frequencies less than 4500 Hz.

Similar to previous findings, these results indicated that switching to the t-coil setting could have a negative effect on user performance.

In another study Rodriguez et al (1993) measured the preferred real-ear aided response (REAR) of 30 subjects with sensorineural hearing loss (SNHL) under acoustic and t-coil listening conditions using the ATI. Prior to REAR measures, the users were required to select their preference of 12 pre-programmed hearing aid responses in each of the two coupling conditions as they listened to a taped passage. The results suggested that listeners preferred more low frequency gain and a flatter frequency response than would be predicted from their hearing loss, for both the microphone and t-coil conditions. This was evident in the comparison of the average REAR selected by the patients to the average National Acoustics Laboratory (NAL) frequency response that would be prescribed. The narrower frequency response of the telephone could be responsible for this preference. No coupler measures were provided, but the t-coil frequency response was about 5 dB less than the microphone across the frequency response. This may have been due to limited output of the t-coil circuitry. Nevertheless, the user preferences for both conditions indicated a desire for increased gain from 250-3000 Hz. Because these aforementioned studies reported that differences exist between these two listening conditions in both 2-cc coupler and real ear measures, other investigators chose to analyze how different coupling modes would affect user performance in word recognition testing.

A study by Holmes (1985) reported that microphone and t-coil coupling strategies were not significantly different for word recognition concluding that the actual amplified telephone represented the main factor in effecting user performance. Nineteen subjects with bilateral SNHL ranging from mild to severe were administered word recognition tests in two conditions; the hearing aid microphone setting and the hearing aid t-coil setting. While overall word recognition scores differed between the two listening conditions, these differences were minimal and not statistically significant. Plyler et al (1998) documented similar word recognition performance results in a study of acoustic versus EM coupling with in-the-ear (ITE) hearing aids. These investigators suspected that telephone performance may be poorer than has been reported with BTE hearing aids. The investigators reported no significant differences in word recognition scores between acoustic and EM coupling strategies when users were allowed to adjust the volume of the ITE hearing aids in both conditions. However, neither of these previous two studies chose to measure changes in word recognition ability as distance is increased.

A study by Upfold and Goodair (1997) investigated the impact of noise and distance on speech recognition for microphone and t-coil responses. REAR measures were used to match the frequency responses of both transducer modes at 1000 Hz. Again, an induction loop situated under the seat of the subject was used rather than a telephone. Participants were ten monaurally fit BTE users seated at one meter and then four meters from the signal source. The study provides evidence that, unlike the microphone response, the inductive loop to t-coil coupling method is capable of maintaining speech intelligibility over a distance of four meters. Also, there was low and high frequency roll-off as was reported in the Tannahill (1983) study. It is also problematic that investigators used an induction loop instead of a telephone receiver or ATI.

In summary, despite comparisons of the microphone and t-coil conditions using word recognition measures that include distance, real ear measures, and 2-cc coupler measures, the appropriate fit for the t-coil frequency response remains ambiguous. Teder (2003) reports that there is little evidence addressing what t-coil frequency response condition is most satisfactory for “real-life” telephone use. Specifically, should the t-coil sensitivity be based on the microphone frequency response, and if so, should the overall gain of the t-coil frequency response be equal to the overall gain of the microphone frequency response?

Most clinicians do not consider the role of the overall gain and frequency response of the t-coil because they are primarily concerned with matching the microphone response to a valid prescriptive target; unfortunately many clinicians fail in this effort as well. Further, during the hearing aid fitting it is probably typical for the clinician to accept the manufacturer default t-coil setting. If the patient then reports poor performance on the telephone, the clinician may suggest an amplified telephone or counsel on the importance of correct telephone receiver position. The clinician might also explain there is a poor history of telephone to hearing aid communication, as well as poor reliability in the coupling success between and across telephones. None of these strategies, however, take into account that the problem could be an inappropriately programmed t-coil.

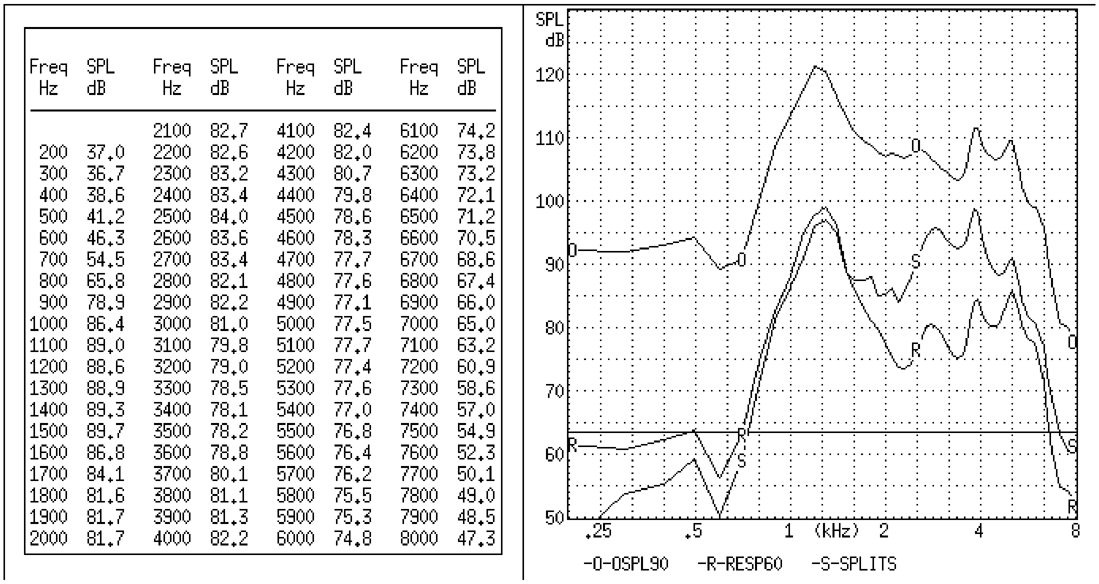
Due to the lack of t-coil consideration, little has been published to support the idea that the t-coil frequency response should match the microphone frequency response to provide optimal performance on the telephone. Until this data becomes available, however, it seems reasonable to assume that the t-coil frequency response should match the microphone frequency response. If the audiologist's goal were to match both frequency responses, it would be useful to know the relative differences that exist between these transducers. The primary purpose of this project was to address differences in the average frequency response between the programmed microphone and default t-coil hearing aid settings through 2-cc coupler and real-ear analysis of programmed BTE hearing aids.

Primary effects on the dependent variable (output in dB SPL at 11 discrete frequencies in the 2-cc coupler condition when a pure-tone signal was used and 15 discrete frequencies as measured on a dummy ear with real-ear equipment when an ANSI-weighted randomly interrupted digital speech signal referred to as “DigiSpeech” was used) include: a) transducer type (microphone or t-coil), and b) measurement frequencies (11 and 15 discrete frequencies from 200-6300 Hz). Fewer discrete frequencies (11) were measured across the pure-tone frequency response because the test equipment provided less detailed output for standard 2-cc coupler analysis. Further explanation for this is described in the methods section. Real-ear measures were taken on a dummy ear to record frequency responses more representative of the amplification that actually arrives at the tympanic membrane of a hearing aid user. DigiSpeech was used instead of the pure-tone signal with the belief that the frequency response would be reduced when using DigiSpeech. This reduction is expected because DigiSpeech negates an artifact known as “blooming” (Frye, 2002). DigiSpeech is also more representative of “real-world” speech stimuli, and may be more useful in determining the “real-life” frequency response of both transducers. Based on these factors, the following null hypotheses were developed for both the coupler and real-ear test conditions:

1. There will be no significant difference in the measured output (dB SPL) of the frequency response between microphone and t-coil transducers averaged across 11 (coupler) or 15 (real-ear) frequencies.
2. There will be no significant difference in the measured output (dB SPL) between the 11 (coupler) or 15 (real-ear) frequencies averaged across the two transducers.
3. There will be no significant difference in measured output (dB SPL) of the two-factor interaction of the transducers and frequencies.

METHODS

Real-ear and HA-2 2-cc coupler measures were completed to determine possible differences between the programmed microphone and non-programmed default t-coil frequency response of BTE hearing aids. The output (in dB SPL) was measured at 15 discrete frequencies (200, 300, 400, 500, 600, 800, 1000, 1200, 1600, 2000, 2500, 3200, 4000, 5000, and 6300 Hz) for real-ear measures using the DigiSpeech ANSI-weighted speech-shaped noise signal (Frye Electronics, Inc.). This is a speech-weighted signal that is randomly interrupted. In addition, a pure-tone sweep (200-8000 Hz) signal was used to measure the frequency response of the programmed microphone and non-programmed default t-coil in the HA-2 2-cc coupler in accordance with ANSI S3.22-2003. In the pure-tone sweep condition, the output (dB SPL) of the frequency response was measured at 11 discrete frequencies (200, 400, 500, 800, 1000, 1600, 2000, 2500, 4000, 5000, and 6300 Hz) due to a limitation in the software of the Frye Fonix 7000 hearing aid analyzer. Specifically, the pure-tone condition only allows for output to be measured in “graph” form. Therefore, the measured output of the frequency response for the real-ear condition using DigiSpeech could be measured and recorded from the analyzer’s “data” display mode (to the nearest tenth of a dB SPL), but the pure-tone frequency output response could only be viewed in “graph” mode (Figure 1). This limited the investigator to a visual examination of the measured output (to the nearest dB SPL tick on the ordinate) based on the vertical lines that denote the 11 frequencies previously listed.



Freq Hz	SPL dB	Freq Hz	SPL dB	Freq Hz	SPL dB	Freq Hz	SPL dB
		2100	82.7	4100	82.4	6100	74.2
200	37.0	2200	82.6	4200	82.0	6200	73.8
300	36.7	2300	83.2	4300	80.7	6300	73.2
400	38.6	2400	83.4	4400	79.8	6400	72.1
500	41.2	2500	84.0	4500	78.6	6500	71.2
600	46.3	2600	83.6	4600	78.3	6600	70.5
700	54.5	2700	83.4	4700	77.7	6700	68.6
800	65.8	2800	82.1	4800	77.6	6800	67.4
900	78.9	2900	82.2	4900	77.1	6900	66.0
1000	86.4	3000	81.0	5000	77.5	7000	65.0
1100	89.0	3100	79.8	5100	77.7	7100	63.2
1200	88.6	3200	79.0	5200	77.4	7200	60.9
1300	88.9	3300	78.5	5300	77.6	7300	58.6
1400	89.3	3400	78.1	5400	77.0	7400	57.0
1500	89.7	3500	78.2	5500	76.8	7500	54.9
1600	86.8	3600	78.8	5600	76.4	7600	52.3
1700	84.1	3700	80.1	5700	76.2	7700	50.1
1800	81.6	3800	81.1	5800	75.5	7800	49.0
1900	81.7	3900	81.3	5900	75.3	7900	48.5
2000	81.7	4000	82.2	6000	74.8	8000	47.3

Figure 1: “Data” mode (left) available for the DigiSpeech real-ear and coupler measure conditions, and “graph” mode (right), which is the only viewing option available in the pure-tone coupler measure condition.

The pure-tone signal was a swept signal presented one specific frequency at a time. DigiSpeech is an ANSI speech-weighted composite signal that is randomly interrupted in order to test the electroacoustic response of digital hearing aids. Unlike a pure-tone test, the frequencies of DigiSpeech are measured simultaneously and the analyzer individually adjusts the amplitude and phase presented at each frequency based on reference microphone placement (Frye, 2002) (Figure 2).

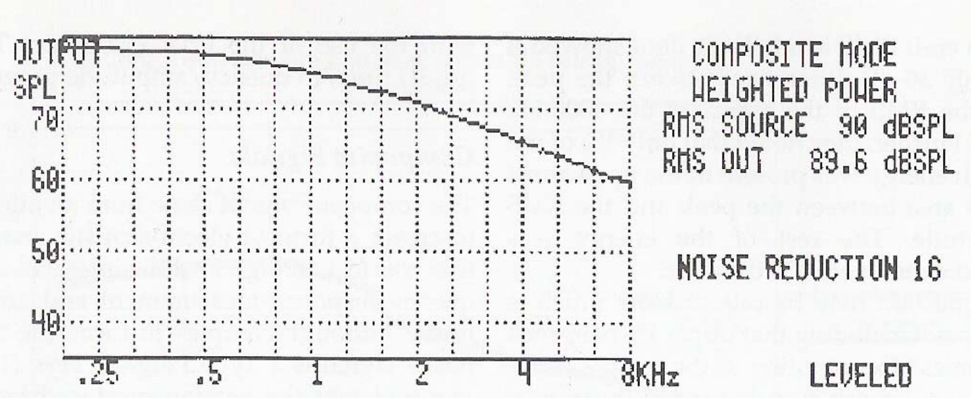


Figure 2: A Fast Fourier Transform (FFT) spectrum generated by an ANSI composite signal. This spectrum is consistent with the DigiSpeech ANSI weighted signal used to test digital hearing aids (Adapted from Frye, In: Valente, 2002).

The use of a DigiSpeech signal bypasses an undesirable “blooming” artifact that can occur with the pure-tone test (Frye, 2002) (Figure 3). Blooming (i.e. an excessive low frequency response) occurs for hearing aids that use compression because the circuit will focus amplification entirely on the input frequency of the sweep signal that is currently being presented to the hearing aid. Measuring the electroacoustic performance of hearing aids using DigiSpeech should provide a measured frequency response that is more indicative of the “real-world” speech signal.

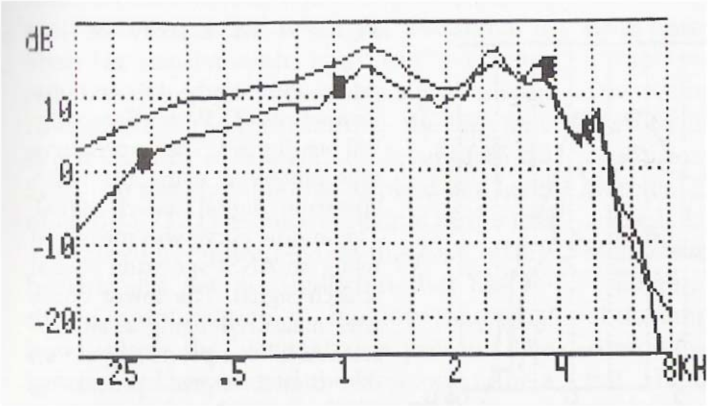


Figure 3: Two frequency gain responses from a digital hearing aid. The upper frequency response was generated with a pure-tone signal, and the lower frequency response was generated with an ANSI composite signal to illustrate the “blooming” artifact evident in the pure-tone frequency response (Courtesy of Frye, In: Valente, 2002).

Thirty-nine hearing aids were measured in the real-ear condition and 52 BTE hearing aids were measured in the HA-2 2-cc coupler condition. All hearing aids measured in this study were recently returned from repair to the Adult Audiology Clinic in the Center for Advanced Medicine at Washington University School of Medicine. For each hearing aid, the microphone frequency response had already been programmed to the NAL-NL1 prescriptive target for the patient’s hearing loss based on an input level of 65 dB SPL (Dillon, 1999). Only Widex brand BTE hearing aids were used in this study, and all hearing aids were modern products to the extent that the microphone and t-coil programs could be individually selected through the manufacturer’s programming software.

All measurements were performed using a Fonix 7000 Hearing Aid Analyzer (Frye Electronics, Inc.) situated inside a double-walled sound suite absent of EM interference. Prior to analysis, each hearing aid was temporarily programmed via the manufacturer's NOAH-integrated software module so that the patient's programmed microphone and default t-coil frequency responses were set to Programs 1 (programmed microphone) and 2 (default t-coil) respectively. The Compass V4.1-V4.4 (Widex) software modules were utilized to make these programming changes.

Real-Ear Measures

For real-ear measures, a left dummy ear (Frye Electronics, Inc.) mounted on a tripod was utilized to emulate the human external auditory meatus (EAM) (Figure 4). A tiny hole was drilled into the anterior face of the silicon block (i.e. 0°azimuth) into the medial portion of the EAM to within 5 mm from where it terminates. A real-ear probe tube designed to connect to the real-ear probe microphone was fed through this hole. Then the tube was permanently affixed so that the tube's tip rested where the bored hole reached the medial EAM.

Figure 4: A coronal view of the dummy ear (Frye Electronics, Inc.) mounted on a tripod with a probe tube fed through a bored hole and into the medial external auditory meatus (EAM).

An ear hanger that houses the reference and probe microphones was placed on the pinna of the dummy ear, and the probe tube was connected to the probe microphone. The test BTE was connected to an earmold fit specifically to the concha of the dummy ear. Finally, the test BTE was positioned on the dummy ear so that the front and rear microphones were level with each other on a horizontal plane (Figure 5).

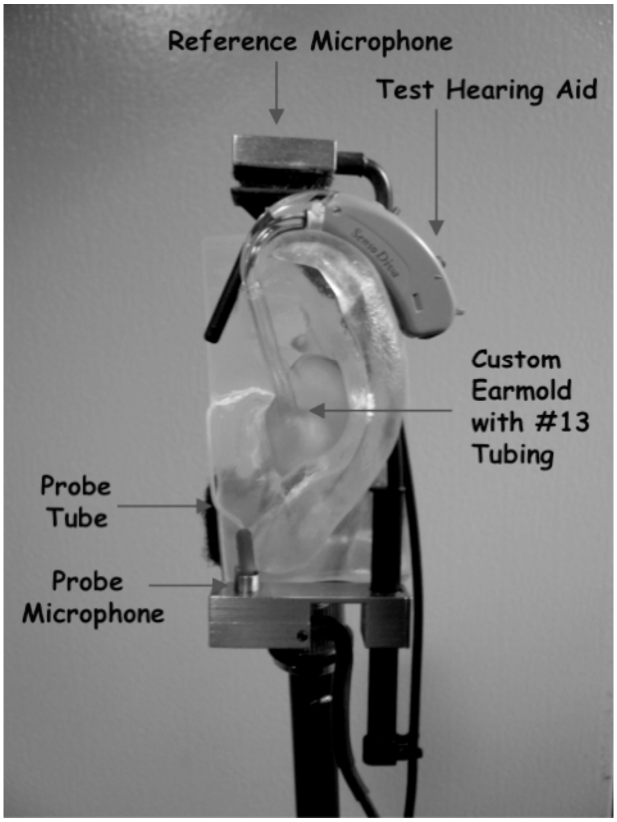


Figure 5: A sagittal view of the dummy ear with real-ear apparatus, custom earmold, and test behind-the-ear (BTE) hearing aid. The hearing aid is situated with front and rear hearing aid microphones oriented atop the pinna on a horizontal (level) plane. The reference microphone is placed medial to the hearing aid and adjacent to the front microphone.

The dummy ear tripod was always positioned with the dummy ear at an equal height (and centered) with respect to the real-ear loudspeaker. The distance from the opening of the EAM in the concha of the dummy ear to the loudspeaker was always 22 inches, consistent with the length of a Widex NOAHLink short programming cable (Figure 6).

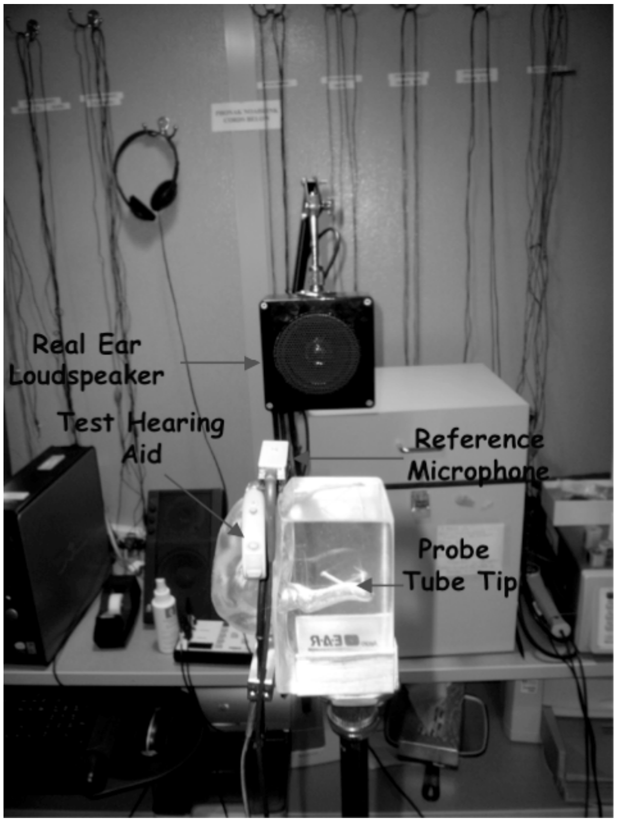
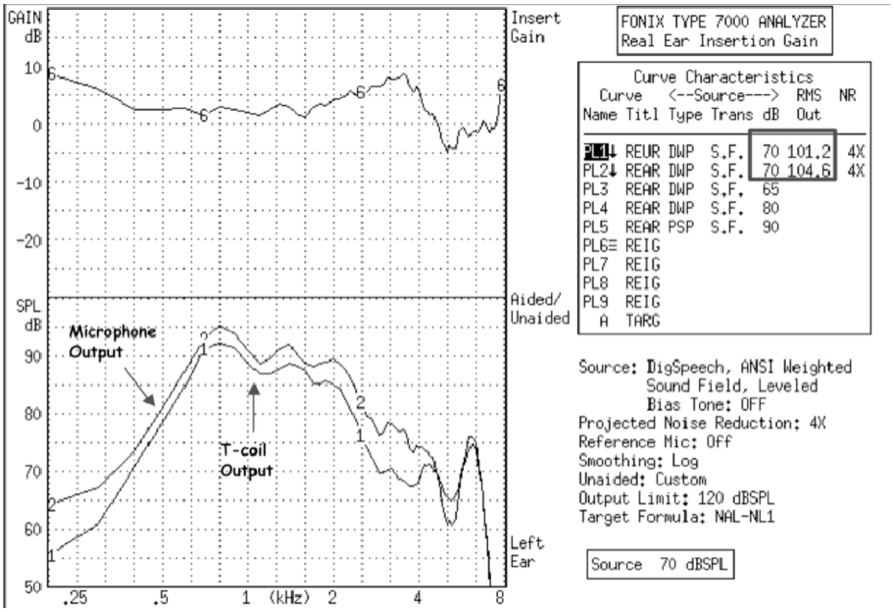


Figure 6: An overhead view of the dummy ear assembly with respect to the real-ear loudspeaker.

Prior to measuring the frequency response of the programmed microphone, the test BTE was turned off, the reference and probe microphones were activated and the sound field leveled to calibrate the loudspeaker with the reference microphone. After leveling, the test BTE was turned on and set to Program 1 (programmed microphone mode). The DigiSpeech signal source was presented at 70 dB SPL and the REAR was measured. The programmed microphone REAR was visualized by the experimenter in “graph” mode to ensure its stability and then the measured REAR was recorded at each of the 15 discrete frequencies by switching the display to “data” mode. To measure the t-coil frequency response, the reference microphone was deactivated and a TMFS, specifically the telewand from the FP40 hearing aid analyzer (Frye Electronics, Inc.), was used to generate a magnetic drive (56.2 mA/M) approximately equivalent to the acoustic drive (70 dB SPL) used to measure the microphone REAR (George Frye, personal communication). Unlike the telewand provided with Fonix 7000 for coupler measures, the FP40 telewand is capable of functioning at an appropriate magnetic drive when recording real-ear measures are selected on the hearing aid analyzer. The test BTE was switched to Program 2 (default t-coil). A foot switch was utilized to route the DigiSpeech signal through the telewand rather than through the loudspeaker. With the signal turned on, the telewand was manipulated adjacent to the hearing aid case until the "sweet spot" (most robust frequency response) was observed (Figure 7).

Figure 7: An FP40 telewand (Frye Electronics, Inc.) positioned to transmit the DigiSpeech signal to the t-coil of the test BTE for real-ear t-coil frequency response measure.

The "sweet spot" was detected by slowly manipulating the telewand about the hearing aid case while observing the maximum output that could be obtained in the analyzer's "graph" mode (bottom graph in Figure 8). Once the "sweet spot" was detected, the display was again switched into "data" mode to document the output at each of the 15 discrete frequencies. By recording the default t-coil frequency response as Curve 1 and programmed microphone response as Curve 2, the hearing aid analyzer automatically calculated the difference in gain between the two transducers (top graph in Figure 8). The investigator calculated the real-ear RSETS value by calculating the difference between the HFA (1000, 1600, and 2500 Hz) of the programmed microphone and default t-coil outputs.



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FONIX TYPE 7000 ANALYZER
Real Ear Insertion Gain

        Curve Characteristics
   Curve    <--Source---> RMS  NR
Name Titl Type Trans dB  Out

PL1↓ REUR DWP  S.F.  70 101.2  4X
PL2↓ REAR DWP  S.F.  70 104.6  4X
PL3  REAR DWP  S.F.  65
PL4  REAR DWP  S.F.  80
PL5  REAR PSP  S.F.  90
PL6≡ REIG
PL7  REIG
PL8  REIG
PL9  REIG
  A  TARG

Source: DigSpeech, ANSI Weighted
        Sound Field, Leveled
        Bias Tone: OFF
Projected Noise Reduction: 4X
Reference Mic: Off
Smoothing: Log
Unaided: Custom
Output Limit: 120 dBSPL
Target Formula: NAL-NL1

Source  70 dBSPL
```

Figure 8: The "graph" mode view of measured real-ear frequency responses (in dB SPL) of the programmed microphone (Curve 2) and default t-coil (Curve 1) of a test BTE hearing aid to a DigiSpeech signal presented at 70 dB SPL (bottom graph). The gain curve (top graph) represents the difference (in dB) between the two frequency responses.

Coupler Measures

For accurate 2-cc coupler measures of the programmed microphone frequency response, the coupler test microphone was leveled at the test point of the test box prior to each measurement. The test BTE hearing aid was then connected to a HA-2 coupler by the earhook via 25 millimeters of standard #13 tubing with the microphone placed appropriately at the test point and facing the right side of the test chamber where the loudspeaker is housed (Figure 9).

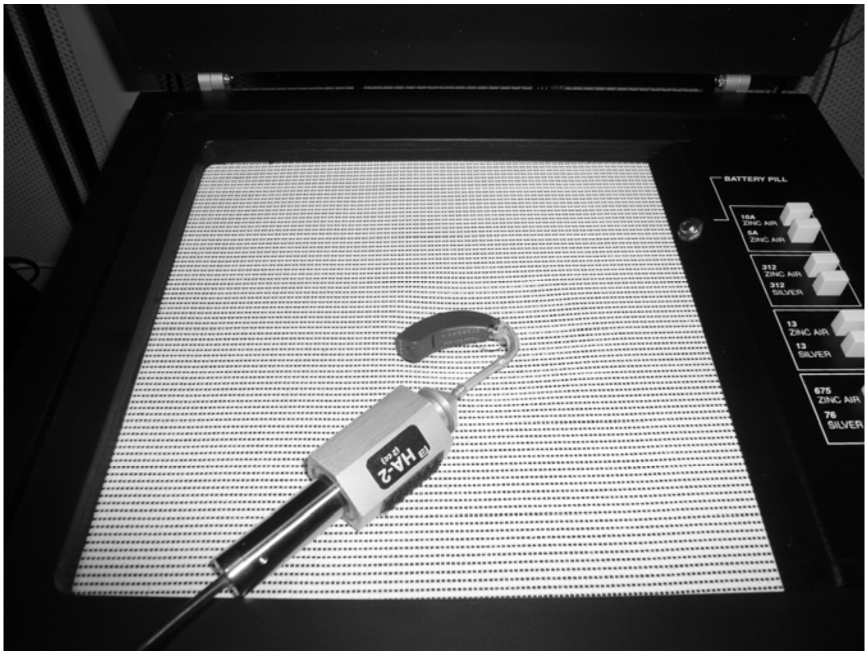
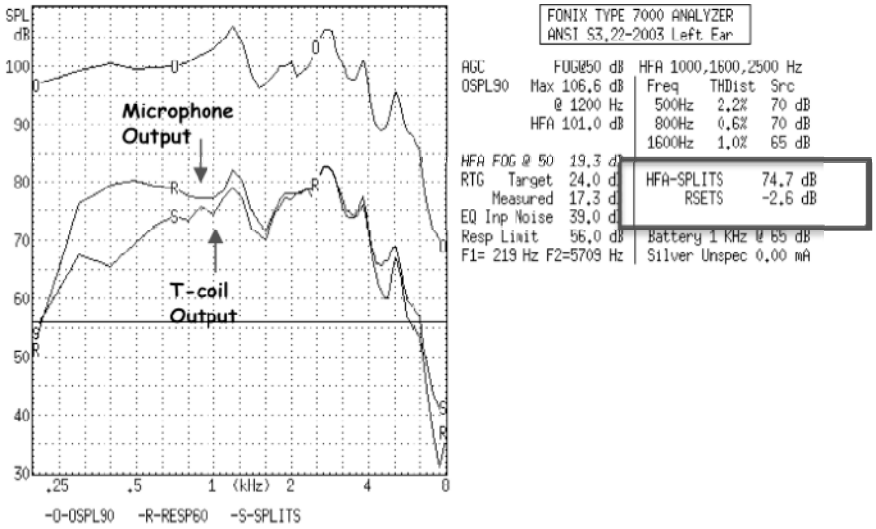


Figure 9: A BTE hearing aid situated in an open test chamber. The hearing aid's microphone is located at the test point of the chamber and facing the test loudspeaker located inside the chamber. The hearing aid is connected to a HA-2 2-cc coupler that houses the test microphone.

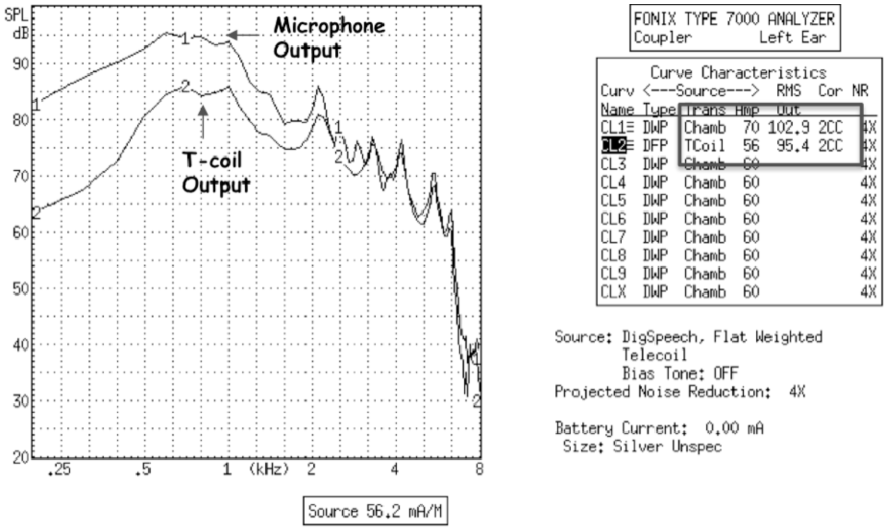
Frequency responses were generated with the hearing aid analyzer via the test chamber loudspeaker using the pure-tone sweep signal (Figure 10) and the DigiSpeech signal (Figure 11).



```
FONIX TYPE 7000 ANALYZER
ANSI S3.22-2003 Left Ear

AGC             FOG@50 dB  HFA 1000,1600,2500 Hz
OSPL90    Max 106.6 dB  |  Freq     THDist   Src
             @ 1200 Hz  |   500Hz    2.2%    70 dB
          HFA 101.0 dB  |   800Hz    0.6%    70 dB
                        |  1600Hz    1.0%    65 dB
HFA FOG @ 50   19.3 d
RTG    Target  24.0 d   |  HFA-SPLITS      74.7 dB
     Measured  17.3 d   |       RSETS      -2.6 dB
EQ Inp Noise   39.0 d
Resp Limit     56.0 dB  |  Battery 1 KHz @ 65 dB
F1= 219 Hz F2=5709 Hz   |  Silver Unspec 0.00 mA
```

Figure 10: Microphone and t-coil frequency responses generated via ANSI S3.22-2003 using a pure-tone sweep.



```
FONIX TYPE 7000 ANALYZER
Coupler          Left Ear

       Curve Characteristics
Curv <---Source--->  RMS  Cor  NR
Name Type Trans Amp  Out
CL1≡ DWP  Chamb  70 102.9 2CC  4X
CL2≡ DFP  TCoil  56  95.4 2CC  4X
CL3  DWP  Chamb  60            4X
CL4  DWP  Chamb  60            4X
CL5  DWP  Chamb  60            4X
CL6  DWP  Chamb  60            4X
CL7  DWP  Chamb  60            4X
CL8  DWP  Chamb  60            4X
CL9  DWP  Chamb  60            4X
CLX  DWP  Chamb  60            4X

Source: DigSpeech, Flat Weighted
        Telecoil
        Bias Tone: OFF
Projected Noise Reduction:  4X

Battery Current:  0.00 mA
 Size: Silver Unspec
```

Figure 11: Programmed microphone and default t-coil frequency responses generated with a DigiSpeech source signal.

By default, the source input level used for ANSI S3.22-2003 could not equal what was used for the real-ear condition. The programmed microphone frequency response had to be generated with the source input level at 60 dB SPL when using a pure-tone sweep. The approximate equivalent magnetic drive in the test-field strength of the Fonix 7000 telewand is 31.6 mA/M, and this was used to obtain the default t-coil frequency response. The hearing aid was placed in the test chamber with the door closed and sealed, attached to the test microphone with the HA-2 coupler, and set to Program 1 (microphone mode). For the default t-coil condition, the hearing aid was removed from the test chamber while remaining coupled to the HA-2 coupler, switched to Program 2 (t-coil mode), and held upright in the researcher's hand. In the other hand, the telewand was manipulated adjacent to the hearing aid case until the "sweet spot" was found (Figure 12).

Figure 12: The Fonix 7000 telewand presents an electromagnetic field to the test BTE t-coil.

The "sweet spot" was detected by observing the maximum output on the Fonix 7000 monitor that could be measured according to the analyzer display. When this occurred, the pure-tone sweep was activated to generate the t-coil frequency response. The analyzer automatically calculated the pure-tone RSETS value (in dB) by subtracting the programmed microphone HFA (1000, 1600, 2500 Hz) from the default t-coil HFA. This RSETS value was recorded in addition to visually estimating the output at discrete frequencies of both transducers in "graph" mode (as was previously described).

Source levels used for the DigiSpeech 2-cc coupler measures could be presented equally to the real-ear values (a 70 dB SPL acoustic drive and 56.2 mA/M magnetic drive). For the programmed microphone frequency response, the hearing aid was switched back to Program 1 and then placed in the test chamber as it was for the pure-tone test. After the frequency response was visualized in "graph" mode, the output could be measured at each discrete frequency in "data" mode (as was done for the real-ear measures). In the default t-coil condition, the hearing aid was again switched to Program 2 and removed from the test chamber, with the experimenter manipulating the telewand to find the "sweet spot" prior to capturing and recording the frequency response in "data" mode. As was found for the real-ear condition, the analyzer cannot automatically calculate an RSETS value for DigiSpeech coupler measures, so the RSETS was calculated manually by finding the difference in the transducer HFAs. It was also discovered, however, that the analyzer would convert the test signal from an ANSI-weighted to a flat-weighted signal (Figure 13) whenever t-coil was selected. This required further microphone and t-coil DigiSpeech coupler measures to be made with a flat-weighted signal, and sufficient for analysis was not collected in this condition.

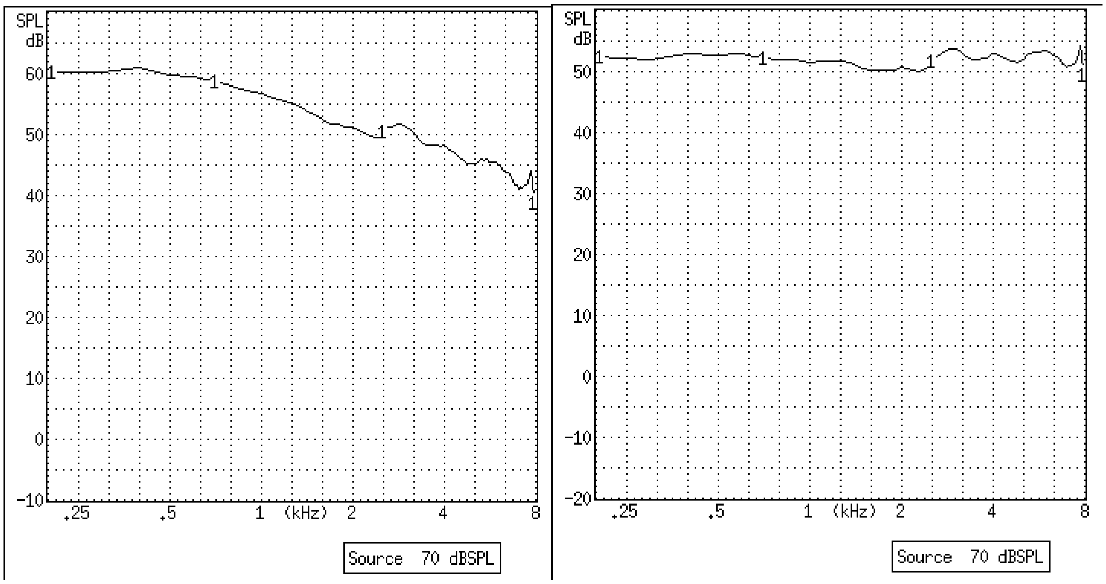


Figure 13: An ANSI weighted signal (left) and a flat weighted signal (right) generated by an equivalent input level and producing an equivalent overall output.

RESULTS

Coupler Measures

For 2-cc coupler measures, hearing aid output (dB SPL) was measured using a pure-tone sweep (200-8000 Hz in 100 Hz increments) at an input level of 60 dB SPL with the hearing aid configured to the programmed microphone memory and at 31.6 mA/M when configured to the default t-coil memory. Independent variables included A) transducer (microphone and t-coil) and B) frequency (11 discrete test frequencies and the HFA).

Transducer Main Effect

The mean (± 1 SD) overall output (dB SPL) of the hearing aids measured in the programmed microphone memory and default t-coil memory averaged across the 11 test frequencies is reported in Figure 14. The mean overall output for the programmed microphone was 77.1 dB SPL (SD = 12.7 dB SPL), whereas the mean overall output for the default t-coil was 77.0 dB SPL (SD = 13.6 dB SPL). A mixed-model repeated measures analysis of variance (ANOVA) revealed no significant difference between transducers (F=0; df=1,102; p<0.98).

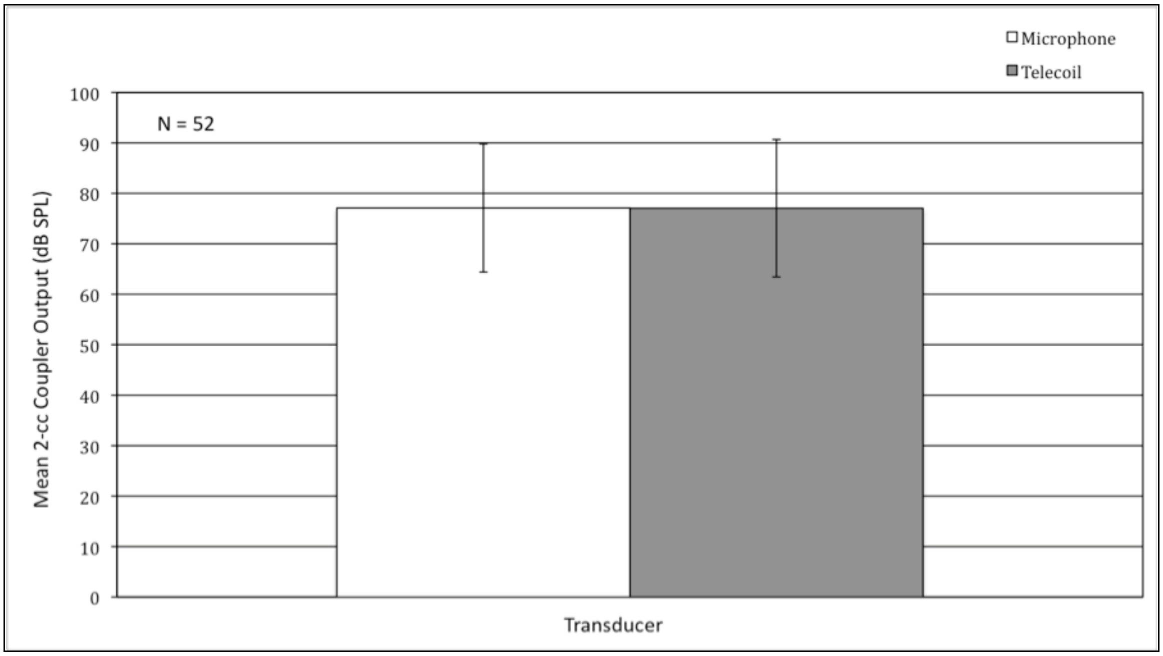


Figure 14: Mean 2-cc coupler output (dB SPL) of Widex BTE hearing aids averaged across 11 discrete frequencies when configured to the programmed microphone and default t-coil memories. Also reported is ±1 SD.

Frequency Main Effect

The mean (± 1 SD) overall output (dB SPL) of the hearing aids measured at 11 discrete test frequencies and averaged across the programmed microphone and default t-coil transducers is reported in Figure 15. A mixed-model repeated measures ANOVA revealed a significant overall difference between test frequencies (F=187; df=10,102; p<0.00001). The mean output at 200 Hz, 400 Hz, and 6300 Hz test frequencies is less than 75 dB SPL, while the mean output at 800 Hz, 1000 Hz, 1600 Hz, 2000 Hz, 2500 Hz, and 4000 Hz nearly meets or exceeds 80 dB SPL.

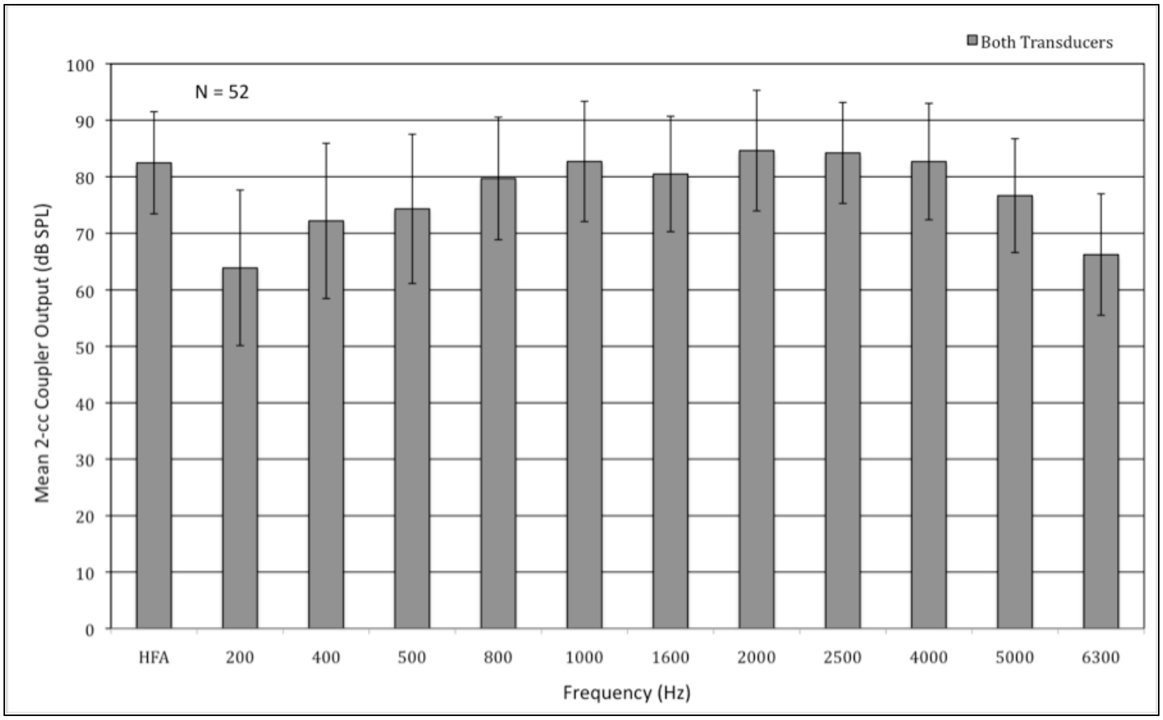


Figure 15: Mean 2-cc coupler output (dB SPL) of Widex BTE hearing aids averaged across the two transducers at each of the 11 discrete test frequencies. The HFA is included on the far left. Also reported is ±1 SD.

Transducer by Frequency Interaction

The mean (± 1 SD) output (dB SPL) of the programmed microphone and default t-coil memories of the BTE hearing aids were compared at 11 discrete test frequencies as reported in Figure 16. The mean output of the programmed microphone is greater than the mean output of the default t-coil at test frequencies from 200 Hz to 800 Hz, whereas the mean output of the default t-coil is greater than the mean output of the programmed microphone at test frequencies from 1600-6300 Hz and the HFA.

A mixed-model repeated measures ANOVA revealed a significant transducer by frequency interaction (F=13.0; df=10,102; p<0.0001). Reported in Figure 17 are post-hoc analyses using the Tukey Honestly Significant Differences (Tukey HSD) test. Statistically significant differences (Delta) were present at 200 Hz (Delta=15.2 dB, SD=8.5 dB) and 400 Hz (Delta=6.0 dB, SD=7.7 dB) where the t-coil output was greater than the microphone, and at 4000 Hz (Delta=-5.9 dB, SD=9.6 dB), 5000 Hz (Delta=-5.7 dB, SD=9.1 dB), and 6300 Hz (Delta=-7.4 dB, SD=9.7) where the microphone output was greater than the t-coil. A paired t-test comparing the average over the HFA frequencies revealed no significant difference between the two transducers (p<0.10). The mean output from 500-2500 Hz were found to be statistically equivalent between the two transducers.

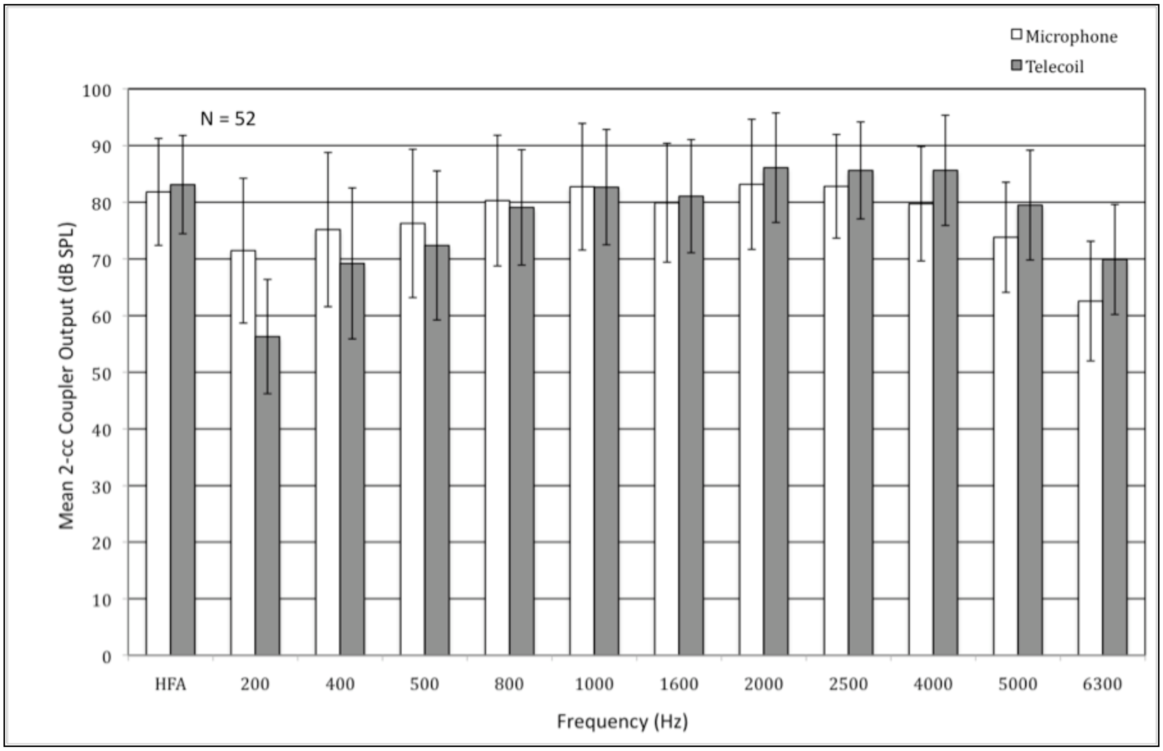


Figure 16: Mean 2-cc coupler output (dB SPL) for the programmed microphone and default t-coil output for HFA and 11 discrete frequencies for Widex BTE hearing aids using a pure-tone sweep of 60 dB SPL (31.6 mA/M for t-coil). The HFA is included on the far left. Also reported is ±1 SD.

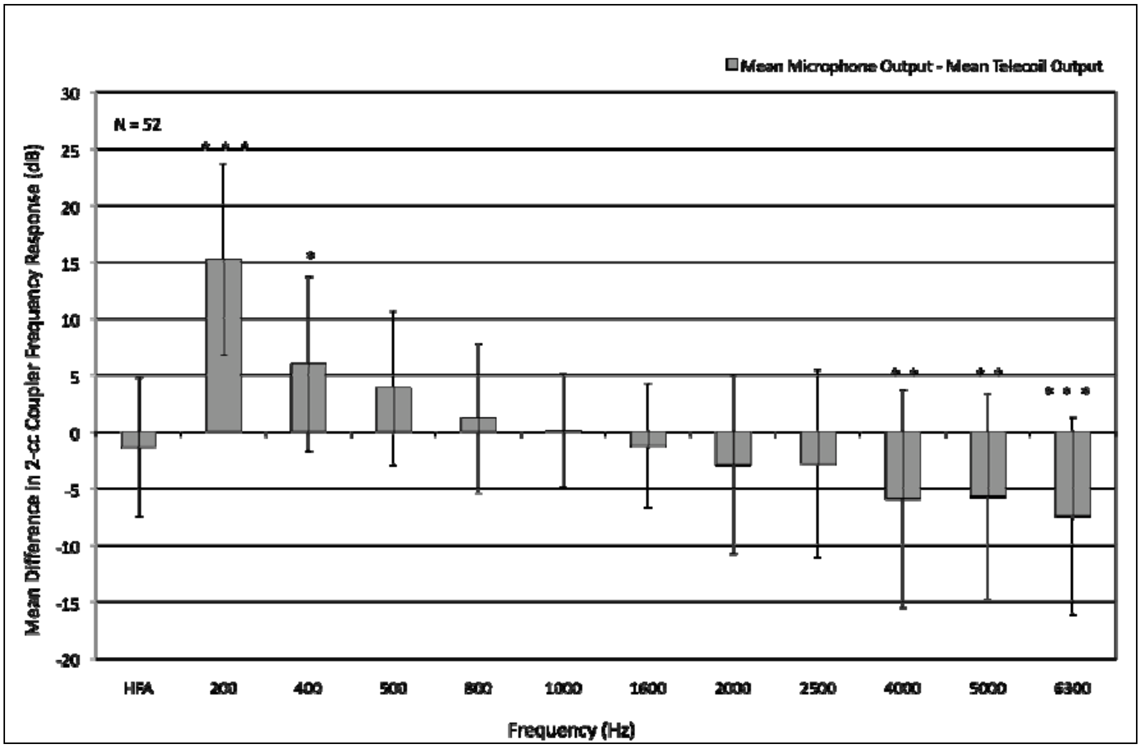


Figure 17: Mean difference (delta) in 2-cc coupler output (dB SPL) differences between the programmed microphone and default t-coil output for HFA and 11 discrete frequencies for Widex BTE hearing aids using a pure-tone sweep of 60 dB SPL (31.6 mA/M for t-coil). *** = p≤0.001, ** = p≤0.01, * = p≤0.05. The HFA is included on the far left. Also reported is ±1 SD.

Real-Ear Measures

In the real-ear condition, hearing aid output (dB SPL) was measured by using a DigiSpeech ANSI speech shaped composite signal presented at 70 dB SPL when set to the programmed microphone memory and at 56.2 mA/M when set to the default t-coil memory. Independent variables included A) transducer (microphone and t-coil) and B) frequency (15 discrete test frequencies).

Transducer Main Effect

The mean REAR (dB SPL) in overall output measured in the programmed microphone memory and default t-coil memory is reported in Figure 18. The mean overall output for the programmed microphone was 77.8 dB SPL (SD = 12.9 dB SPL), whereas the mean overall output for the default t-coil was 70.0 dB SPL (SD = 16.8 dB SPL). A mixed-model repeated measures analysis of variance (ANOVA) revealed a significant difference between transducers (F=18.8; df=1,76; p<0.0001).

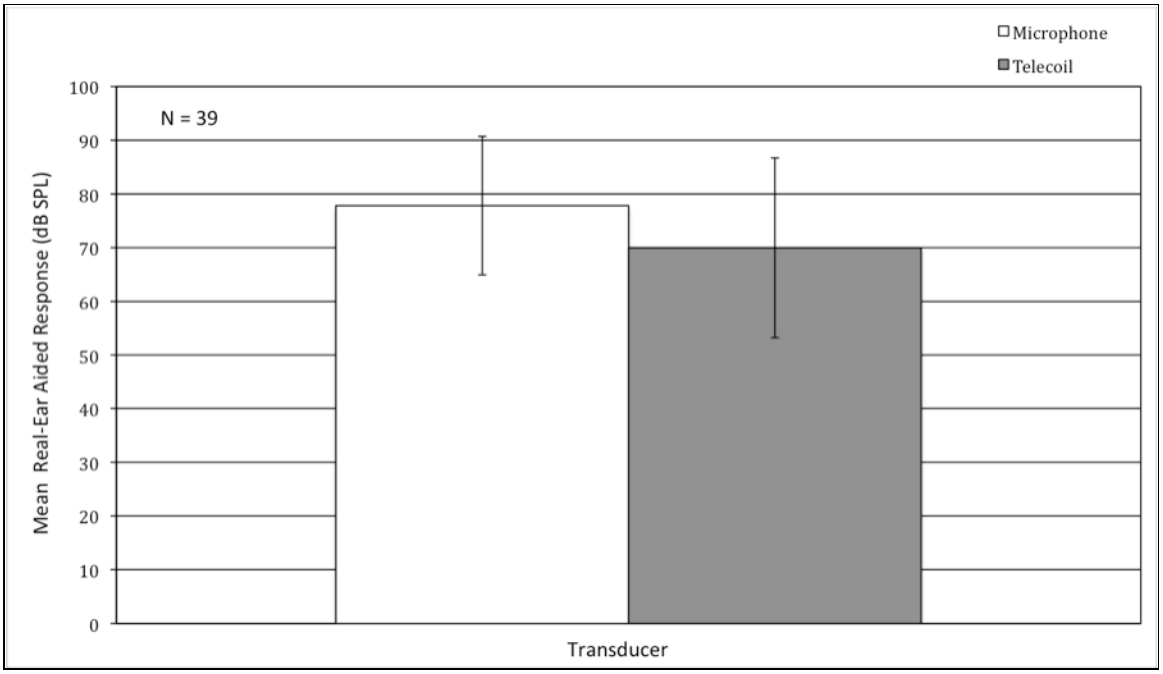


Figure 18: Mean REAR (dB SPL) for Widex BTE hearing aids averaged across 15 discrete frequencies when set to the programmed microphone memory and default t-coil memory. Also reported is ±1 SD.

Frequency Main Effect

The mean (± 1 SD) overall output (dB SPL) of hearing aids measured at 15 discrete test frequencies averaged across the programmed microphone and default t-coil transducers is reported in Figure 19. A mixed-model repeated measures ANOVA revealed a significant overall difference between test frequencies (F=258; df=14,76; p<0.00001). The mean output from 200 Hz to 400 Hz was between 50 dB SPL and 60 dB SPL, the mean output at 500 Hz, 600 Hz, 5000 Hz, and 6300 Hz was between 60 dB SPL and 72 dB SPL, while the mean output from 800 Hz to 4000 Hz approached or exceeded 80 dB SPL.

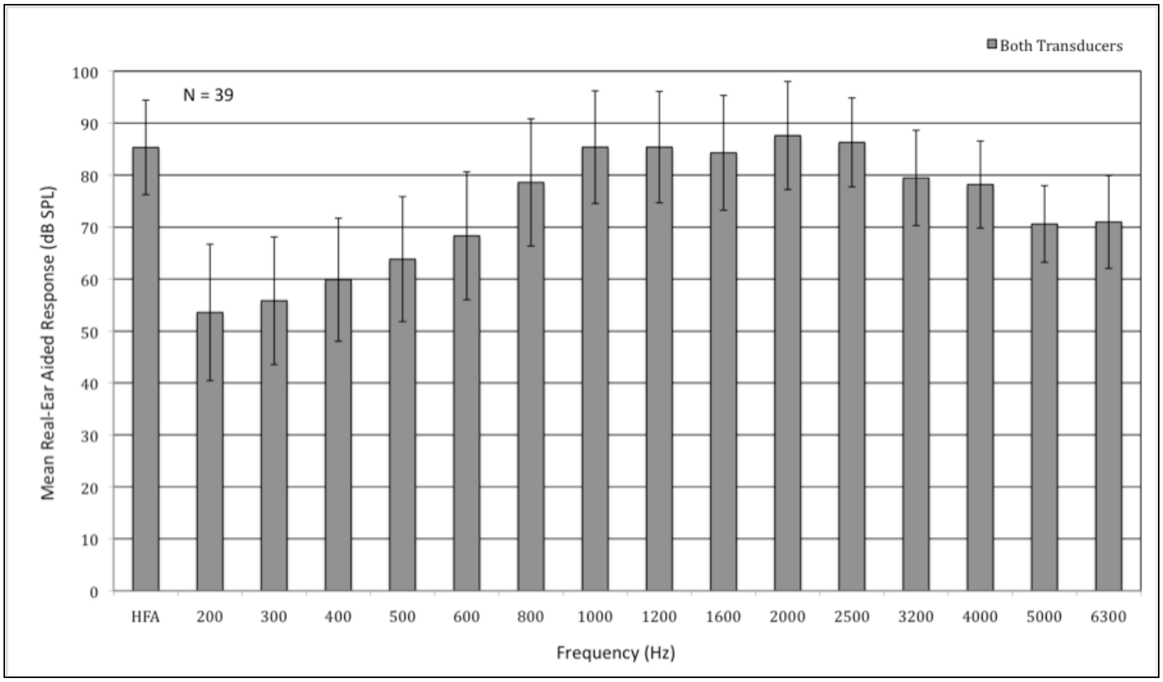


Figure 19: Mean REAR (dB SPL) for Widex BTE hearing aids averaged across transducers at each of the 15 discrete test frequencies. The HFA is included on the far left. Also reported is ±1 SD.

Transducer by Frequency Interaction

The mean (± 1 SD) output (dB SPL) of the programmed microphone and default t-coil memories of the BTE hearing aids were compared at 15 discrete test frequencies and for the HFA as reported in Figure 20. A mixed-model repeated measures ANOVA revealed a significant transducer by frequency interaction (F=31.1; df=14,76; p<0.0001). Reported in Figure 21 are post-hoc analyses using the Tukey HSD test, which revealed that the default t-coil output was significantly lower than the programmed microphone output at 200 Hz (Delta=20.9, dB, SD=6.4 dB), 300 Hz (Delta=17.5 dB, SD=6.5 dB), 400 Hz (Delta=12.6 dB, SD=7.1 dB), 500 Hz (Delta=9.7 dB, SD =5.7 dB), 600 Hz (Delta=7.4 dB, SD=5.0 dB), 1000 Hz (Delta=5.0 dB, SD=3.4 dB), 1200 Hz (Delta=5.7 dB, SD=3.7 dB), 1600 Hz (Delta=4.9 dB, SD=4.0 dB), 2000 Hz (Delta=6.6 dB, SD=4.0 dB), 3200 Hz (Delta=7.7 dB, SD=4.5 dB), and 4000 Hz (Delta=6.0 dB, SD=5.4 dB). The mean output at 800, 5000, and 6300 Hz test frequencies was found to be statistically equivalent between the two transducers. A paired t-test comparing the average over the HFA frequencies revealed significant difference between the two transducers (p<0.0001).

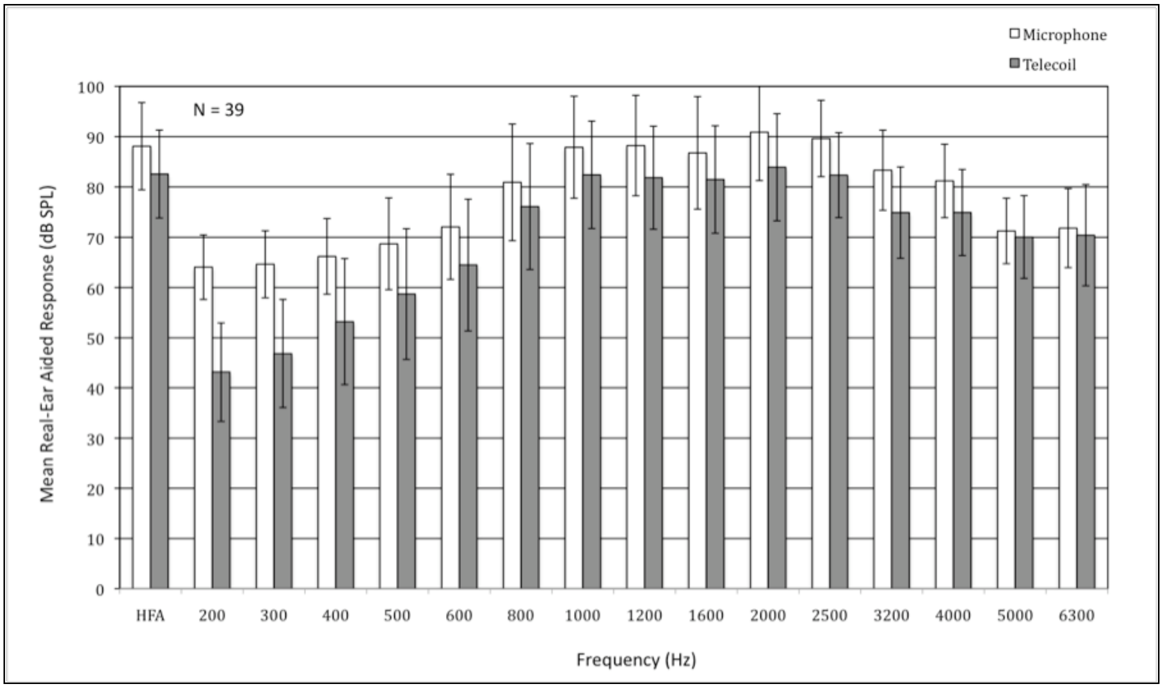


Figure 20: Mean REAR (dB SPL) of the programmed microphone and default t-coil output for 15 discrete test frequencies for Widex BTE hearing aids using a DigiSpeech ANSI speech shaped composite signal of 70 dB SPL (56.2 mA/M for the t-coil condition). The HFA is included on the far left. Also reported is ±1 SD.

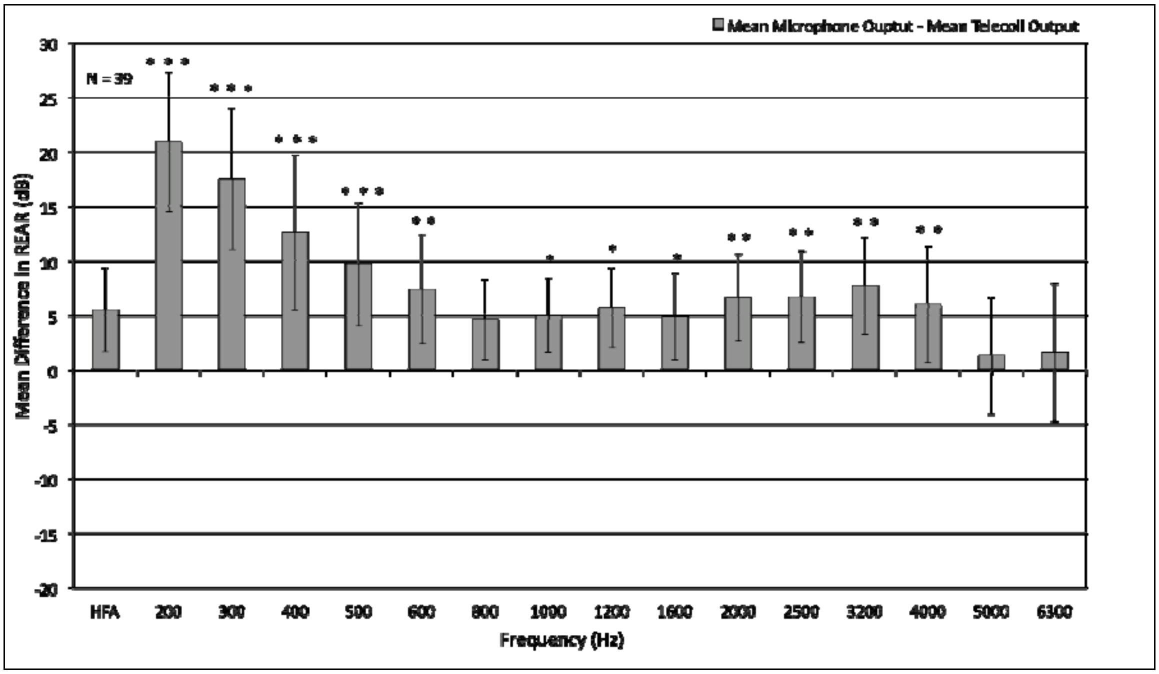


Figure 21: Mean difference (delta) in REAR (dB SPL) differences between the programmed microphone and default t-coil output for 11 discrete frequencies for Widex BTE hearing aids using a DigiSpeech ANSI speech shaped composite signal of 70 dB SPL (56.2 mA/M for the t-coil condition). *** = p≤0.001, ** = p≤0.01, * = p≤0.05. The HFA is included on the far left. Also reported is ± 1 SD.

DISCUSSION AND CONCLUSION

Coupler Measures

Results from this study reveal no significant difference in the overall output (dB SPL) of the programmed microphone and default t-coil response of Widex BTE hearing aids measured in a 2-cc coupler using a pure-tone sweep. Note, however, that post-hoc statistically significant frequency-specific differences were found at 200, 400, 4000, 5000, and 6300 Hz. Figure 16 illustrates how this is possible despite the lack of significant difference in overall output between the transducers, since the mean microphone output is greater in the low frequencies (200 and 400 Hz), yet the mean t-coil output is greater in the high frequencies (4000, 5000, and 6300 Hz). Thus the low and high frequency differences between the two transducers negate each other when the overall output of each transducer is calculated.

The relationship between the mean programmed microphone and default t-coil frequency response shown in Figure 16 is remarkably similar to single hearing aid data (Figure 22) from a publication by Ross (2006), who suggested that a t-coil with a preamplifier could allow the t-coil frequency response to nearly match the microphone frequency response.

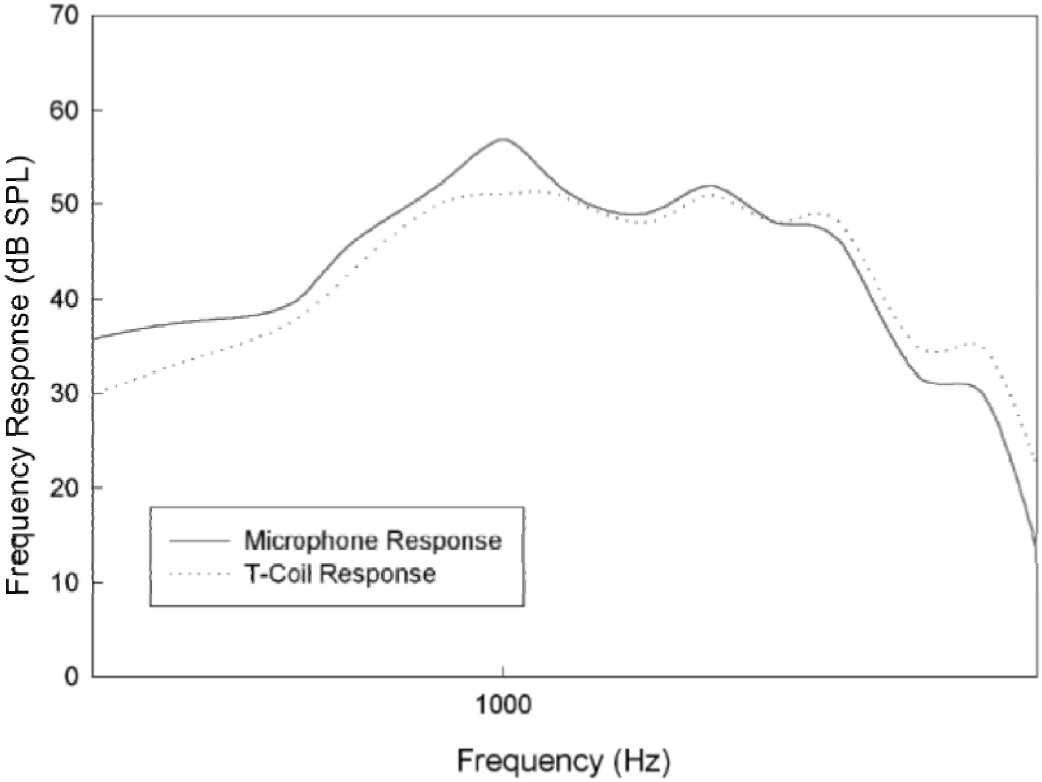


Figure 22: The frequency response of the microphone and t-coil from an individual hearing aid (adapted from Ross, M. (2006) with the permission of The Hearing Journal and its publisher, Lippincott Williams & Wilkins)

Consistent with Figure 16, Figure 22 demonstrates some reduction in the t-coil frequency response in the low frequencies (and an increase in the high frequencies) when compared to the programmed microphone frequency response. Recall that a typical telephone bandwidth is 300 Hz to 3300 Hz (Yanz and Preves, 2003). Importantly, when the telephone bandwidth is taken into consideration then the only significant differences reported from coupler results influential to telephone communication are the low frequency differences (specifically 200 to 400 Hz), where the mean default t-coil output is less than the mean programmed microphone output by 6 dB. While the t-coil response was also 3.9 dB lower at 500 Hz, this was not found to be a significant difference. A reasonable question to ask is whether this magnitude of low frequency attenuation of the t-coil frequency response can be problematic for the listener.

Historically, it has been suggested that low frequencies should not be emphasized in the t-coil position because the t-coil can be sensitive to low frequency interference (i.e. EM noise), which is then amplified in conjunction with the signal of interest (Ross, 2006). Without amplifying the low frequencies, however, patients often complain that the t-coil fails to provide sufficient loudness for telephone communication. In addition, low frequency information below 300 Hz has already been removed from the telephone transmission. If the hearing aid user is fortunate to be fit with hearing aids allowing manipulation of the gain in the t-coil setting via a volume control, a hearing-impaired patient still remains inconvenienced by the need to increase the volume during telephone conversation. Ideally, the transition from the microphone to the t-coil position should be seamless. Moreover, much of the concern related to amplifying the low frequencies in the t-coil position may be reduced in part by the development of commercially available far-field cancelling (FFC) t-coils (Marshall, 2005). If FFC t-coils are incorporated into new hearing aids, then extraneous EM signals that are not in the near field (i.e. within inches of the t-coil) of the hearing aid will no longer contribute to interference of the low frequencies.

Real-Ear Measures

The other segment of this study compared the programmed microphone frequency response to the default t-coil frequency response in a real-ear condition using a modulated composite speech shaped signal (DigiSpeech). Measuring t-coil performance using real-ear is not novel. Grimes and Mueller (1991) proposed a real-ear measurement protocol for t-coil verification nearly twenty years ago. In their study, a speech-shaped signal was directed to one telephone handset, and this signal was delivered to a second telephone handset with the receiver held to the casing of the hearing aid that was fit to the ear. The experimental design required to conduct t-coil real-ear measurements in this manner, however, is not a simple or convenient approach for audiologists to undertake. Regardless, the fact remains that real-ear measurement of the t-coil frequency response has not evolved to become conventional practice for clinicians.

In the present study, the frequency response of the default t-coil was measured in a real-ear condition by using a TMFS (telewand) to present the EM signal to the hearing aid situated on the ear rather than using a series of telephones as described by Grimes and Mueller (1991). This method of real-ear measurement could be performed quickly and easily by any clinician with a Fonix 7000 (Frye Electronics, Inc.) and the FP40 telewand, which would need to be provided as a supplement to the hearing aid analyzer. Importantly, the results from the real-ear measures of this study report a greater mean difference between the microphone and t-coil frequency response than was reported for the coupler measures using a pure-tone signal.

Most notably, unlike the coupler measures, there was a statistically significant greater overall output of the mean programmed microphone frequency response when compared to the mean default t-coil frequency response. Furthermore, there were post-hoc statistically significant differences at almost all specific test frequencies with real-ear measurements, where the programmed microphone output was greater than mean default t-coil output. Unlike the coupler results, these frequency-specific differences were within the frequency bandwidth of 300 Hz to 3300 Hz that is transmitted by a conventional telephone. In fact, the only test frequencies where a significant difference was not present were 800 Hz, 5000 Hz, and 6300 Hz, and the latter two frequencies lie outside the telephone frequency bandwidth.

As a result, the author is left to speculate as to why the results in the coupler and real-ear measures were not similar. Due to an inability to use equivalent measurement conditions for the coupler and real-ear measures (i.e. telewand, input signal, and input signal strength), a direct statistical comparison could not be drawn between the coupler and real-ear measurement conditions without qualifying the clinical utility of the data. The difference, however, between the microphone and t-coil frequency response between the coupler and real-ear segments is undeniable and cannot be overlooked. There are several potential contributing factors to explain the reported difference between the coupler and real-ear test measures.

One potential factor is the difference in telewands (e.g. the Fonix 7000 TMFS and FP40 TMFS) used to the t-coil frequency response in each test condition. As mentioned previously, the FP40 TMFS is not typically supplied with the Fonix 7000, but was necessary in order to generate an EM signal equivalent to the real-ear loudspeaker. The FP40 telewand was recommended by George Frye (Frye Electronics, Inc.) to be used in conjunction with a footswitch in the real-ear condition. According to Frye, the EM input signal from the FP40 telewand during t-coil measurements will be equivalent to a 70 dB SPL input signal presented through the real-ear loudspeaker for microphone measurements. The footswitch was used to divert the input signal to the FP40 telewand instead of taking the typical path through the real-ear loudspeaker. This experimental design, therefore, does not allow the experimenter to view the monitor to be sure that the telewand input signal (in mA/M) is equivalent to the loudspeaker input (in dB SPL) as was possible in the coupler test condition.

A second potential contributing factor is that the swept pure-tone signal was treated differently by hearing aid signal processing from the transition from EM signal and to an acoustic signal, whereas the composite speech shaped signal was not. It is this author's opinion that this factor is more plausible than the differences in the type of telewand used between the coupler and real-ear measures in the study. A detailed description of what specifically occurs during the signal processing within a hearing aid is not always readily made available to clinicians. In fact, hearing aid manufacturers tend to withhold much of this information as they elect to classify it as proprietary. The hearing aid manufacturer does, however, inform clinicians that there are these proprietary algorithms at work in the hearing aid. These are features typically referred to as “noise reduction”, “feedback suppression”, “ adaptive directionality”, and “channel-specific compression” to name a few.

To provide an example of how one feature might influence the integrity of an input signal, consider that the composite digital speech signal in this study was randomly interrupted and was presented until the real-ear analyzer successfully recorded an output signal. The input signal was presented in this manner with the expectation that any fast-acting “noise reduction” algorithm in the hearing aid signal processing would not be activated and thereby reduce any gain supplied to the input signal by the hearing aid amplifier. While it may be just as likely that signal processing will influence the input signal when using the hearing aid microphones as well as when using the t-coil, it remains unclear whether this influence is the same when the signal processing reads to the EM input signal.

According to Widex, the default t-coil should undergo the same signal processing as the programmed microphone response (master program), but with a few exceptions. For example, “feedback management” may not be active and the EM input may be treated as an “omnidirectional” signal (i.e. input is not altered depending on which transducer receives it, as can occur with dual microphones), while “noise reduction” and “channel-specific gain assignment” should be active for both the t-coil and the master program (Widex, personal communication). Hearing aids used in the present study represent only one hearing aid manufacturer (Widex), although several Widex models were analyzed. Appendix A provides information on all hearing aid models and associated hearing aid features used in this study, and Appendix B describes the relevant signal processing features for each model utilized during this study. In addition, the mean microphone and t-coil output by frequency for each hearing aid model is represented in both Appendix C (coupler condition) and Appendix D (real-ear condition).

Support for the suggestion that differences in signal processing between microphone and t-coil modes may be reacting differently to the randomly interrupted digital speech input signal during the t-coil real-ear measures is due to preliminary data that was collected in a 2-cc coupler condition in which an interrupted speech shaped signal with flat-weighting was used in lieu of the pure-tone sweep signal. Initial findings in this condition suggest a relationship between the programmed microphone and default t-coil output that is similar to the real-ear condition, not the pure-tone coupler condition, where the mean programmed microphone frequency response is higher than the mean default t-coil frequency response. An example from this data is provided later in the discussion under “future research”.

T-coil Applications and Solutions

In MarketTrak VIII (Kochkin, 2010), consumers were asked to rate 19 different listening situations as to how “critical” they are as a consumer need. At 64%, telephone communication was rated the third most important, behind only one-on-one (75%) and small group (65%) listening situations. As it has for decades, MarketTrak continues to highlight the importance of telephone communication for hearing aid users, which is important to keep in my mind considering how much evolution is currently taking place in telephone technology. The emergence of novel digital communication technology has created additional obstacles for hearing aid user success when using the telephone. The ability to communicate on a telephone when away from home or business has clearly led to increased cell phone use in the United States, so much so that it is one of many nations now close to 100% prevalence (Kundi, 2009). Because cell phones are considered an important daily convenience to many individuals, including those with hearing impairments, the Federal Communications Commission (FCC) declared in 2003 that wireless carriers cannot be exempt from the hearing aid compatibility (HAC) act of 1988, and therefore must provide cell phone technology that is hearing aid compatible (Victorian and Preves, 2004).

A compatibility issue exists because wireless transmissions sent by cell phones are capable of generating interference in hearing aids that is often audible to the hearing aid user (Levitt et al., 2005). According to Levitt and colleagues, high frequency transmissions in the gigahertz (gHz) range utilized by cell phone carriers can make any short piece of metal, such as those found in hearing aids, a potential antenna that is also capable of receiving the wireless transmission. The high frequency transmission from the cell phone carrier is not in of itself audible to the hearing aid user as it is well outside the frequency range of audibility, but the high frequency signal is also amplitude modulated at a rate that is within the frequency range of audibility. This modulation rate in the carrier signal results in the interference perceived by the hearing aid user, typically reported as a low frequency buzz. For t-coil users, additional EM interference is generated by multiple sources inside the cell phone, including the internal circuitry, visual display, battery, and key backlighting (Preves, 2003).

Studies of cell phone interference such as one by Levitt et al (2005) where hearing aid users rated the level of signal-to-interference ratio (SIR) from cell phones as measured in a real-ear condition, has helped to establish a rating system for cell phone HAC that is determined by the ANSI C63.19 Test and Measurement Standard. According to the Alliance for Telecommunications Industry Solutions (ATIS) as published in *Audiology Today* (2005), by September 2005, the FCC required that at least four models from every cell phone manufacturer must have either a “good” (M3) or “excellent” (M4) rating for interference. The “M” denotes that the SIR is only measured in the hearing aid microphone setting. Fortunately, by September 2006 cell phone manufacturers were also required to have at least two commercially available products with “good” (T3) or “excellent” (T4) ratings in the t-coil mode. As cell phones become more frequently utilized than landline telephones, hearing aid users purchasing cell phones should seek products with M4/T4 ratings. Importantly, note that the focus of the standard is solely on minimizing unwanted interference and therefore has no bearing on the amount of gain or shaping of the frequency response of the intended signal that the t-coil mode provides to the hearing aid user.

The t-coil provides value for the hearing aid user that is beyond just communication on the telephone. In fact, the t-coil allows coupling that a hearing aid user needs to take advantage of several types of hearing assistance technology (HAT) that can provide invaluable benefit beyond the hearing aids themselves. Some examples of HAT include vibratory, flashing and/or amplified alarm clocks and telephones, as well as FM, infrared, and induction loop communication systems (Ross, 2004). Unfortunately, Ross (2004) describes a recent study with several colleagues in which they found that only 31% of 942 hearing aid users surveyed recollected being informed about HAT. Clinicians or hearing aid users should not overlook HAT. HAT may play an important supplemental role to hearing aids in improving quality of life, including the possibility of improved speech recognition in noise.

The t-coil is the required transducer if the hearing aid user is using inductive HAT such as an induction loop for a room or neck-loop worn around the neck. Public and private facilities such as those previously listed in the introduction may have rooms with induction loops installed, allowing hearing aid users to hear speech directed into a microphone and transmitted through the induction loop EM signal instead of straining to hear the voice from across the distance of the room. Additionally, hearing aid manufacturers currently provide technology whereby portable music devices, computers, TVs, cell phones, and conventional telephones with Bluetooth™ technology can wirelessly stream their signals to a unit worn around the neck with an induction loop. This unit then relays the signal to the hearing through the induction loop EM field and t-coil(s).

An obvious advantage to inductive HAT when compared to infrared or FM technology is that once a room or neck is looped, the hearing aid user requires no additional accessories as the t-coil is already incorporated into the hearing aids (Ross, 2006). Ross (2006) proposed to change the name “telecoil” to “audiocoil”, a label that is more representative of this versatile antenna. Because t-coils have applications that extend beyond conventional telephone communication, it follows that there is an even greater responsibility on the part of clinicians to begin to consider how to appropriately program the t-coil mode. Advances in t-coil technology will be crucial as many current limitations can diminish the ability of the t-coil to transfer a clear and sufficiently amplified signal to the hearing aid user. As the demand for miniaturization continues to decrease the size of hearing aids, it remains the manufacturer’s responsibility to continue to accommodate the t-coil inside the hearing aid for an effective transduction of the incoming EM signal. Solutions to some of the problems mentioned in the introduction of the present study, such as t-coil size (Kenney and Kotecki, 2007), orientation (Yanz and Preves, 2003), EM interference

(Yanz and Preves, 2003), and telephone EM leakage strength (Yanz and Pehringer, 2003) are currently underway.

One particular t-coil research design under current investigation appears to actually improve t-coil transduction performance, while simultaneously reducing the overall size of the t-coil (Kenney & Kotecki, 2007). This is accomplished, in part, by replacing the permeable core inherent to currently available commercial t-coils with a magnetic core. This allows for a smaller and therefore more efficient construction of the t-coil in a three-dimensional space, where an optimal number of turns in the copper wire is still achieved.

Another advancement is the previously mentioned FFC t-coil (Marshall, 2005). This technology is apparently capable of preventing the induction of EM leakage whose source is not within close proximity to the hearing aid user. With the elimination of these extraneous and unwanted EM signals, there is greater potential for minimal low frequency interference while using the t-coil on the telephone.

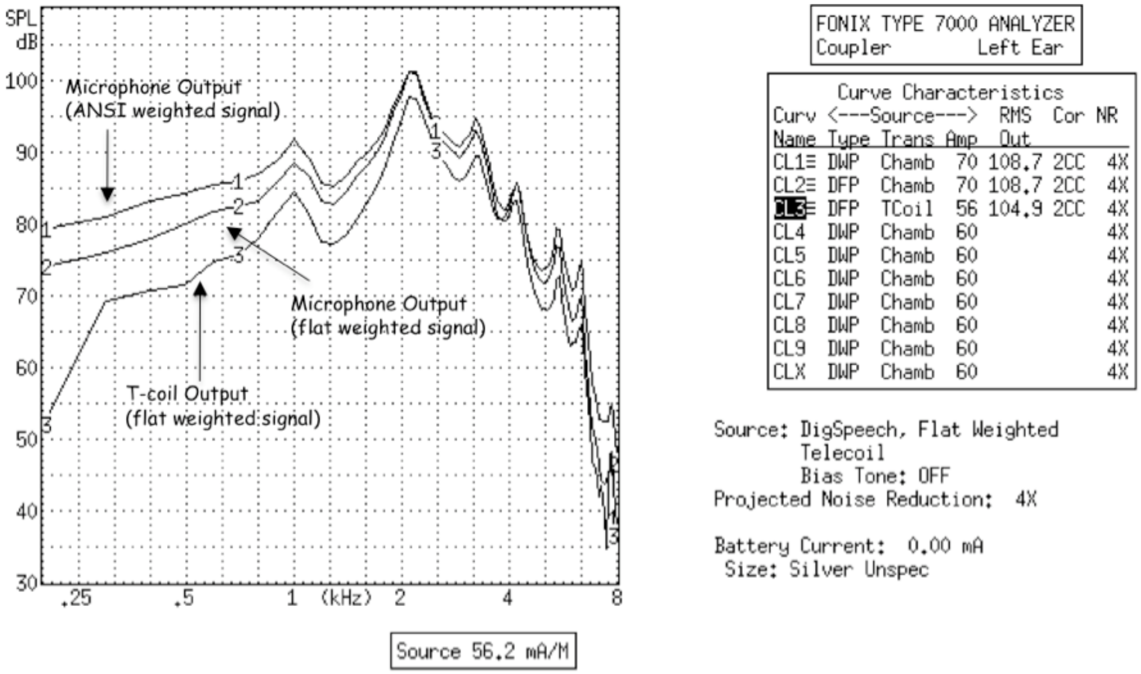
An additional recent development in hearing aid technology now allows bilateral hearing aid users to hear the signal received by the t-coil in one hearing aid to be delivered to both hearing aids (Phonak's "DuoPhone"). Regardless of which hearing aid the telephone handset is held to, that hearing aid can transmit the signal wirelessly to the other hearing aid to allow for bilateral listening on the telephone. To date, it does not appear that there have been any research studies on the efficacy and/or effectiveness of this novel technology.

Despite advancements in t-coil design and flexibility, t-coil utilization is not always straightforward for the clinician. For example, not all manufacturers allow the same flexibility of gain manipulation in the hearing aid t-coil program. Some manufacturers restrict the audiologist by only allowing the ability to increase and decrease the overall gain of the telecoil, but the shape of the frequency response remains fixed (e.g., Widex). Specifically, the extent to which the t-coil gain can be programmed by the audiologist can vary within the product line available from a single manufacturer. For example, some Widex products (e.g., Mind and Inteo) allow the clinician to pair the t-coil frequency response to an acoustic program, whereby adjusting the frequency response of the acoustic setting will be emulated in the t-coil program. Some manufacturers, however, allow audiologists to increase and decrease gain across the frequency response of the hearing aid similarly to any of the microphone programs (e.g., Phonak).

Future Research

Additional data was gathered over the course of this research project from Phonak BTE with the intent of determining if any differences in the relationship of the default t-coil and programmed microphone frequency response exist between manufacturers. Unfortunately, only a limited number of Phonak products were available for measurement. The trend in the data from Phonak hearing aids suggests that the default t-coil frequency response not only matches the programmed microphone frequency response in the pure-tone coupler test condition as Widex products do, but in some cases exceeds the microphone output. There also appears to be less disparity between the transducers in the real-ear condition, although there is not substantial data to perform statistical analyses to determine if any significant differences exist.

In addition to the consideration of Phonak hearing aids, data from all of the hearing aids used in this study were also collected in a 2-cc coupler condition, but using the digital speech signal presented at 70 dB SPL. Unfortunately, unbeknownst to the investigator, much of the initial data collected from the programmed microphone setting was obtained using an ANSI weighted DigiSpeech signal, but the Fonix 7000 automatically switches to a flat weighted signal when testing the t-coil. Upon consulting Frye Electronics, Inc. it was determined that the Fonix 7000 limits the user to using a flat-weighted signal when measuring t-coil output in the coupler. Therefore, additional data will need to be collected in the 2-cc coupler DigiSpeech condition with both an ANSI-weighted and a flat-weighted speech signal when measuring the microphone frequency response (Figure 23).



```
FONIX TYPE 7000 ANALYZER
Coupler          Left Ear

      Curve Characteristics
Curv <---Source---> RMS   Cor NR
Name Type Trans Amp  Out
CL1≡ DWP  Chamb  70 108.7 2CC  4X
CL2≡ DFP  Chamb  70 108.7 2CC  4X
CL3≡ DFP  TCoil  56 104.9 2CC  4X
CL4  DWP  Chamb  60            4X
CL5  DWP  Chamb  60            4X
CL6  DWP  Chamb  60            4X
CL7  DWP  Chamb  60            4X
CL8  DWP  Chamb  60            4X
CL9  DWP  Chamb  60            4X
CLX  DWP  Chamb  60            4X

Source: DigSpeech, Flat Weighted
        Telecoil
        Bias Tone: OFF
Projected Noise Reduction:  4X

Battery Current:  0.00 mA
 Size: Silver Unspec
```

Figure 23: Frequency responses (in dB SPL) of a hearing aid measured in a 2-cc coupler using a DigiSpeech signal. The programmed microphone frequency response is measured with an ANSI weighted DigiSpeech signal (Curve 1) and flat weighted DigiSpeech signal (Curve 2) at 70 dB SPL. The default t-coil frequency response is measured with a flat weighted DigiSpeech signal (Curve 3) presented through the telewand at 56.2 mA/M.

Although there is less measured output in the low frequencies measured with a flat weighted DigiSpeech signal, there is a greater output than the ANSI weighted signal in the high frequencies. Note that the root mean square (RMS) output for both programmed microphone frequency responses (Curves 1 and 2) are actually identical (108.7 dB SPL), regardless of which weighting is used. Nevertheless, because the same flat weighted signal is used to measure both transducers, a direct comparison in any difference in the measured frequency response can be seen. Figure 21 is representative of much of the data collected thus far from other hearing aids, indicating that this condition may eventually be more reflective of the data obtained in the real-ear condition. Specifically, when using a flat weighted DigiSpeech signal in the coupler condition the t-coil frequency response appears to have a lower overall output compared to the programmed microphone frequency response. For the hearing aid measured in Figure 21, the programmed microphone output is greater than the default t-coil response by approximately 20 dB at 200 Hz, 15 dB at 250 Hz, 8 dB at 500 Hz, and 4 dB at 1000 Hz.

Conclusion

There is a disparity in the results between the real-ear and coupler test conditions utilized in this study, and further research is required to determine why this difference is present. Data requiring further collection in a coupler condition using the flat-weighted digital speech signal may provide some evidence to demonstrate whether the type of signal is responsible for the differences between the microphone and t-coil frequency responses. If this test condition proves to provide similar results to those obtained in the real-ear test condition, then there is additional evidence to suggest that a comparison of the microphone and t-coil frequency response using a pure-tone sweep signal could be flawed. Because, however, results from this study are from hearing aids tested from one manufacturer alone, the study results cannot be extrapolated to all hearing aids currently in use.

The purpose of this research study was to determine whether the manufacturer's default t-coil frequency response matches the programmed microphone frequency response in current BTE hearing aids, and analyses of microphone and t-coil frequency responses were performed in a 2-cc coupler measurement condition and a real-ear measurement condition. While the results reported here compare the default t-coil and programmed microphone output, these findings are a preliminary contribution to the question of how to program the t-coil frequency response for hearing aid users to successfully communicate on the telephone. This may require a follow-up study of speech recognition and perceived benefit or satisfaction in the t-coil setting of hearing aid users during telephone listening when the frequency response provided by the two transducers are and are not equivalent.

Prior reports comparing the word recognition ability of hearing aid users with a microphone versus a t-coil coupling strategy on the telephone found no significant differences, despite differences in the frequency responses of the transducers (Plyler et al, 1998; Holmes, 1985). These are dated studies, however, and there have since been changes to measurement technology, t-coil technology, speech recognition measurement, and hearing aid technology (i.e. digital signal and multichannel processing). It may be useful in a future endeavor to compare word recognition abilities on the telephone between t-coil settings where the frequency response is less than, equivalent to, and greater than the programmed microphone frequency response. The experimenter and participants should also be double blinded to the test conditions, and a questionnaire could also be administered asking the participants to provide feedback as to which listening condition was preferred.

Most clinicians are aware of patient reports that speech on the telephone when using a t-coil program sounds softer than everyday speech with their microphone program, but they likely assume that this difference is due to a weak EM signal from the patient’s telephone handset, or improper alignment of the telephone receiver to the hearing aid casing. Currently, t-coil sensitivity is measured using ANSI-2003. This standard uses a pure-tone sweep at 31.6 mA/M and measured in a 2-cc coupler. Pure-tone coupler results from this study revealed little difference in measured between programmed microphone and default t-coil output. This finding does not appear to agree with patient reports of reduced volume when using the t-coil program on the telephone. When measurements were performed in the real-ear condition using the composite digital speech signal, however, there were significant differences in the reported output between the programmed microphone and default t-coil where the mean output for the t-coil was significantly lower than the mean output for the programmed microphone at 200, 300, 400, 500, 600, 1000, 1200, 1600, 2000, 2500, 3200, and 4000 Hz. These results appear to be in better agreement with patient reports. Therefore, one of the conclusions of the study is the suggestion that great face validity (i.e. better agreement between patient reports and objective measures) may be obtained if it were possible to have access to a speech composite signal when measuring t-coil performance to complement the already existing pure-tone sweep.

It is assumed that most audiologists do not routinely measure t-coil performance to ANSI-2003 and simply program the hearing aid with the default t-coil setting. Audiologists need an accurate and reliable method (procedure) using a telewand to measure the t-coil frequency response in the coupler with a speech-weighted signal similar to how audiologists measured the microphone frequency response with ANSI-1992. This procedure must also ensure that the level of the speech-weighted input signal is equivalent to the pure-tone input signal via the telewand that is currently possible with ANSI-2003. Once this is available, audiologists could make quick, reliable, and accurate measurements of the microphone and t-coil using the same coupler (2-cc) with signals (pure-tone and speech-weighted noise) at the same input level. Then, if differences are present they will be related to the transducer (microphone and t-coil), and not the coupler (2-cc and real-ear), input transducer (loudspeaker and telewand), or input level (pure-tone and speech-weighted signals).

Based on the results of this study for the coupler condition, the following conclusions can be drawn based on the original hypotheses:

1. There was no significant difference in the measured output (dB SPL) of the frequency response between microphone and t-coil transducers averaged across 11 frequencies.
2. There was a significant difference in the measured output (dB SPL) between the 11 discrete frequencies averaged across the two transducers, which was expected due individual prescriptive gain targets by frequency.
3. There was a significant difference in measured output (dB SPL) of the two-factor interaction of the transducers and several discrete test frequencies, where the programmed microphone output was significantly higher than the default t-coil output at 200 and 400 Hz, and the opposite was true of the transducer relationship at 4000, 5000, and 6300 Hz.

Based on the results of this study for the real-ear condition, the following conclusions can be drawn based on the original hypotheses:

1. There was a significant difference in the measured output (dB SPL) of the frequency response between microphone and t-coil transducers averaged across 15 frequencies.
2. There was a significant difference in the measured output (dB SPL) between the 15 discrete frequencies averaged across the two transducers, which was expected due individual prescriptive gain targets by frequency.
3. There was a significant difference in measured output (dB SPL) of the two-factor interaction of the transducers and most discrete test frequencies, where the programmed microphone output was significantly higher than the default t-coil output at 200, 300, 400, 500, 600, 1000, 1200, 1600, 2000, 2500, 3200, and 4000 Hz.

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APPENDIX A

Hearing aid make and models measured in each study condition

Coupler Condition

Make	**Model**	**N**
Widex	Flash-19	1
Widex	Senso Diva-19M	5
Widex	Senso Diva-9M	18
Widex	Senso Diva-9Mè	3
Widex	Inteo-19	7
Widex	Inteo-9	14
Widex	Inteo-9è	1
Widex	Mind4-19	1
Widex	Mind4-9	2
Total		**52**

Real Ear Condition

Make	**Model**	**N**
Widex	Flash-19	1
Widex	Senso Diva-19M	5
Widex	Senso Diva-9M	13
Widex	Senso Diva-9Mè	3
Widex	Inteo-19	5
Widex	Inteo-9	8
Widex	Inteo-9è	1
Widex	Mind4-19	1
Widex	Mind4-9	2
Total		**39**

APPENDIX B

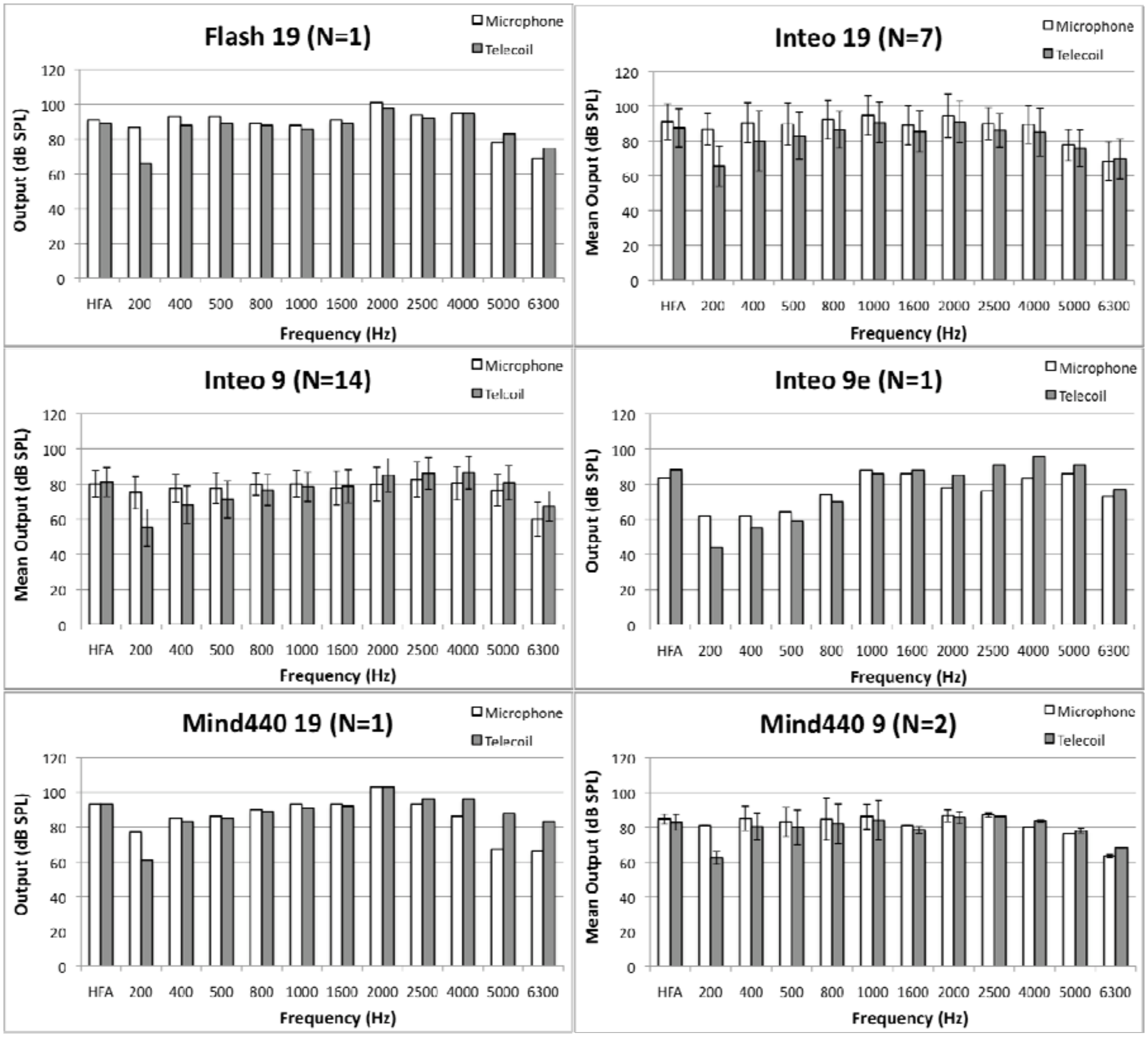
Processing features of hearing aids measured in this study

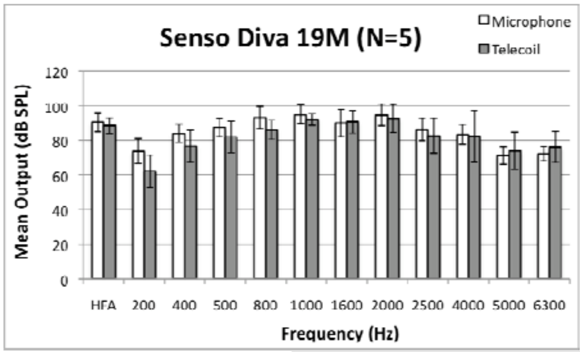
Feature	Mind 440	Inteo	Diva	Flash
Processor:	Dual DSP	ISP	ISP	ISP
Channels:	15	15	15	5
EIDR:	107 dB SPL	107 dB SPL	107 dB SPL	107 dB SPL
MPO Control:	Yes	Yes	Yes	Yes
AOC On:	Broadband and Narrowband	Broadband	Broadband	Broadband
AOC Off:	Broadband	No Compression Limiting	No Compression Limiting	No Compression Limiting
Directional Microphones:	15 Channel, HD Locator, Fully Adaptive	15 Channel, HD Locator, Fully Adaptive	15 Channel, Diva Locator, Fully Adaptive	Broadband, Flash Locator, Fully Adaptive
Noise Reduction:	Off, Classic, Minimal, Enhanced, Comfort	Off, Classic, Minimal, Enhanced, Comfort	Off, Classic, Minimal, Enhanced	Off, Classic, Minimal, Enhanced
Speech Enhancer:	Yes	Yes	No	No
Feedback Management:	Multi-Directional Active Feedback Canceling	Multi-Directional Active Feedback Canceling	Active Feedback Canceling	Active Feedback Canceling
Clearband:	Yes (M Model Only)	No	No	No

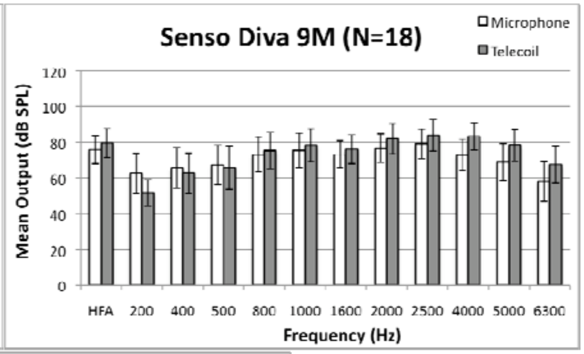
DSP= Digital Signal Processing
ISP= Integrated Signal Processing
EIDR= Extended Input Dynamic Range
MPO= Maximum Power Output
AOC= Automatic Outout Control
HD= High Definition
Speech Enhancer= Noise reduction that detects and separates speech from noise
Clearband= extended bandwidth (beyond 10 kHz)

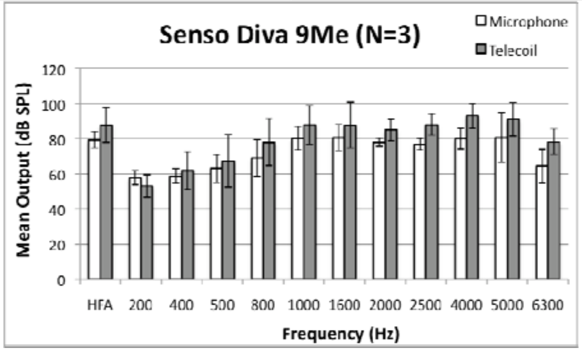
APPENDIX C

Mean transducer frequency responses from the coupler condition by hearing aid model
(Error bars are ±1 SD)



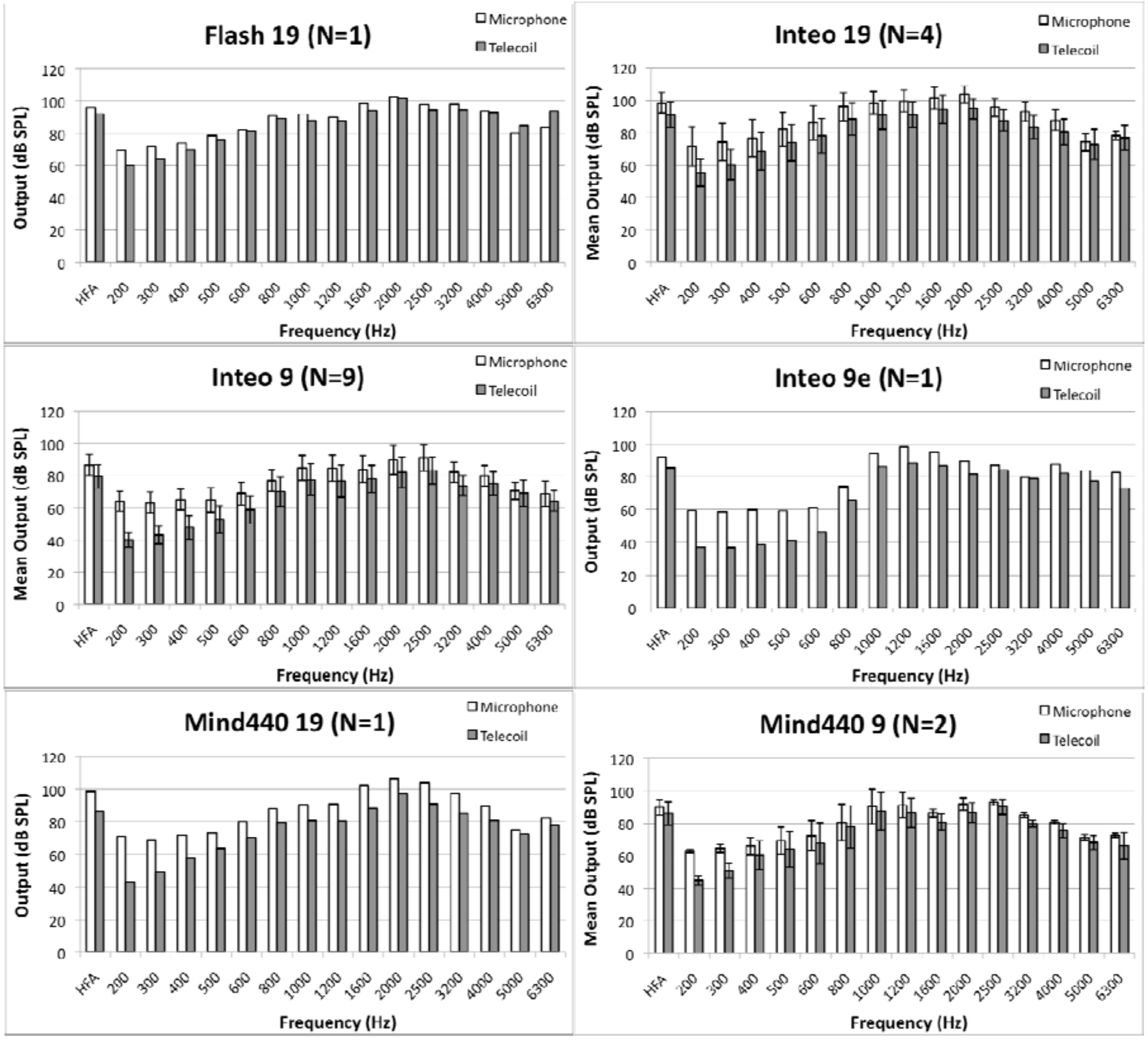

Senso Diva 19M (N=5)
Microphone
Telecoil
Mean Output (dB SPL)
0
20
40
60
80
100
120
HFA
200
400
500
800
1000
1600
2000
2500
4000
5000
6300
Frequency (Hz)

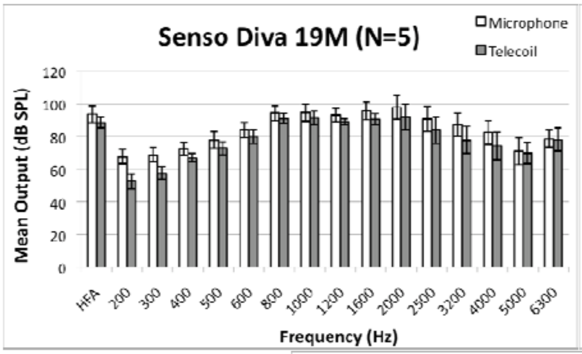

Senso Diva 9M (N=18)
Microphone
Telecoil
Mean Output (dB SPL)
0
20
40
60
80
100
120
HFA
200
400
500
800
1000
1600
2000
2500
4000
5000
6300
Frequency (Hz)

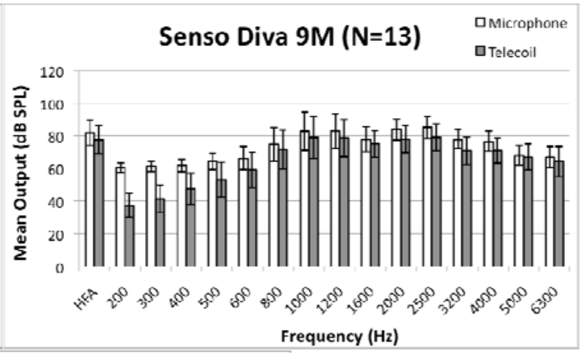

Senso Diva 9Me (N=3)
Microphone
Telecoil
Mean Output (dB SPL)
0
20
40
60
80
100
120
HFA
200
400
500
800
1000
1600
2000
2500
4000
5000
6300
Frequency (Hz)

APPENDIX D

Mean transducer frequency responses from the real-ear condition by hearing aid model
(Error bars are ±1 SD)




Senso Diva 19M (N=5)
Microphone
Telecoil
Mean Output (dB SPL)
0
20
40
60
80
100
120
HFA
200
300
400
500
600
800
1000
1200
1600
2000
2500
3200
4000
5000
6300
Frequency (Hz)


Senso Diva 9M (N=13)
Microphone
Telecoil
Mean Output (dB SPL)
0
20
40
60
80
100
120
HFA
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300
400
500
600
800
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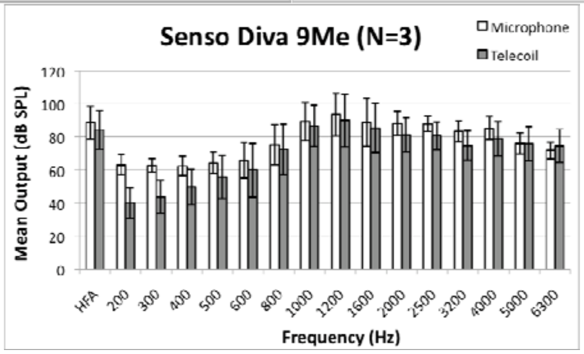
1200
1600
2000
2500
3200
4000
5000
6300
Frequency (Hz)


Senso Diva 9Me (N=3)
Microphone
Telecoil
Mean Output (dB SPL)
0
20
40
60
80
100
120
HFA
200
300
400
500
600
800
1000
1200
1600
2000
2500
3200
4000
5000
6300
Frequency (Hz)