ARMY RESEARCH LABORATORY

Comparison of Bone-Conduction Technologies

by Paula Henry, Phuong Tran, and Tomasz Letowski

ARL-TR-4705 January 2009

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14. ABSTRACT

Bone-conduction technologies have been proposed for use with radio communication for the military. Three manufacturers have made commercially available bone-conduction systems that transmit and receive radio signals through bone conduction. The purpose of this study was to evaluate these three bone-conduction microphones and vibrators separately in order to determine which devices performed best in each capacity. The evaluation of the vibrators was conducted through presentation of speech items over each device while the listener was in background noise levels of 100 and 110 dB A-wtd. The vibrators from manufacturer A outperformed the others on the speech recognition task. The evaluation of microphones was conducted through a presentation over headphones of speech items that were recorded through each microphone in background noise levels of 100 and 110 dB A-wtd. There were no significant differences between the speech recognition performances with the microphones. Sound quality judgments made on paired comparisons of the microphones and vibrators indicated listener preference for the vibrators from manufacturer A but no single microphone. In order to provide the best bone conduction communication system to the Soldier, vibrators from manufacturer A should be used. The results of this study do not allow a recommendation for the best microphone.

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hearing, bone conduction, communication

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1. Background

Humans can hear sound presented through two modalities: air conduction and bone conduction. When hearing through air conduction, sounds travel down the listener's ear canal, excite the tympanic membrane, travel across the bones of the middle ear as mechanical vibration, and excite the fluids within the cochlea. When hearing through bone conduction, sounds from the air or those presented through vibratory devices strike the bones of the skull bypassing the ear canal and stimulate the fluids of the cochlea. Humans hear continuously through both modalities, but hearing through air conduction dominates our perception due to a loss of sound energy when it travels through the air that cannot be picked up by the bones of the skull. One example of when a human hears through bone conduction is when we talk. In this case, the vocal fold vibrations excite the bones of the skull and stimulate the talker's ears. Hearing through bone conduction is why our voice sounds different to us when we talk as opposed to when we listen to it recorded and played back to us.

The idea of presenting sound to listeners through bone conduction as opposed to air conduction has existed for quite some time. Individuals wishing to listen to music often opt for presentation through air conduction because it is the most readily available method, and is typically unimportant whether the listener can hear anything else in the environment. The presentation of radio signals to Soldiers presents a unique situation. Soldiers often do not want others to hear their radio communication, are in the presence of high levels of background noise, or are in quiet environments and need to attend to environmental sounds. In all of these situations, Soldiers must maintain awareness of local events and listen for important sounds. Presentation of radio communications through air conduction via headphones can be undesirably isolating from the environment. The use of bone-conduction transmission supports open ear canals for listening to sounds in the environment, the use of hearing protection, and communication in a stealth mode.

Three manufacturers produce communication systems that utilize bone-conduction transmission that allows the user to both send (microphone) and receive (vibrators) signals. Systems which incorporate bone conduction in both transmission paths are often referred to as two-way bone-conduction systems. If a bone-conduction communication system were to be used by the military, the optimal solution would be a single manufacturer solution, although one manufacturer may not make both the best microphone and the best vibrators. Therefore, it is of interest to the U.S. Army to determine which manufacturer makes the best of each component. Each commercially available system has its own unique design and provides different potential benefits to the user. Optimization of a system for military use might require a combination of components from multiple manufacturers.

This study was designed to compare the three bone-conduction microphones and vibrators in speech recognition performance and sound quality. Both objective data (frequency response) and subjective data (speech-recognition performance and sound-quality judgments) were collected as part of this study. Results of the study should allow us to identify which manufacturer of each device is superior within the confines of the testing parameters.

2. Methods

A single communication system from each of three manufacturers (referred to as manufacturer A, B, and C) was selected for use in the study. These three manufacturers were selected because they each manufacture bone-conduction microphones and vibrators. Three modifications were made to the devices in order for them to be used in the study. First, all devices were re-wired with 1/4-in phone connectors to plug in to amplifiers and recording hardware. Manufacturers of communication devices provide connectors for specific military or commercial radios but, for the purpose of the study, each of the devices was re-wired to remove the radio from the evaluation. Second, the microphone and vibrators were separated from each system. Third, in order to fit the devices to a listener's head, one manufacturer's vibrators were fit into the headband from another manufacturer. In all three cases, the headsets located the vibrators on the listeners' facial bones directly in front of their ear canals.

2.1 Objective Evaluation

2.1.1 Measurement of Microphone Frequency Response

Frequency response measurements were made for each microphone using a Metra Mess-und Frequenztechnik (MMF) VC110 vibration-calibrating system and a personal computer. The calibrated vibrator was located on the upper surface of the system and vibrated at a constant value of 1 m/s^2 (rms). The microphone was mounted onto the vibrator with hot glue. A sine wave sweep from 100 to 10 kHz was used for this measurement, and the sensitivities were recorded. Five measurements were made for each microphone and the average of the frequency responses was calculated. This frequency response was then converted into dB units with a reference of 1 $V/m/s^2$. Figure 1 shows the average frequency responses of the microphones. Note that the frequency response of the microphone from manufacturer A was not smooth when compared to the other microphones. It was damped around 1 kHz and had three prominent peaks. The difference in frequency response of the microphone from manufacturer A was likely due to the unusual structure of the microphone. This microphone was embedded into a square frame which made it impossible to separate the effect of any extraneous vibrations from the mounting system of the microphone itself.

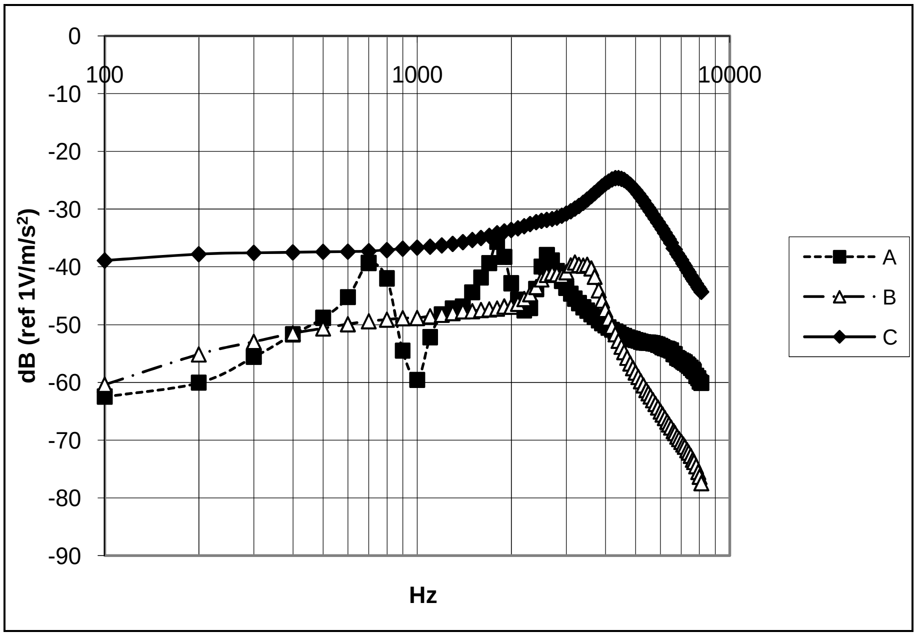

Figure 1. Average frequency responses from the three microphones.

2.1.2 Measurement of Vibrator Frequency Response

Figures 2–4 show the frequency responses measured from the vibrators. The frequency response of each bone vibrator was measured by using a combination of a Brüel & Kjaer (B&K) type 4930 artificial mastoid and a maximum length sequence system analyzer (MLSSA) from DRA Laboratories. The B&K artificial mastoid was built to simulate the mechanical characteristics of the human mastoid and has a built-in force transducer to monitor the output. MLSSA, as its name indicates, utilizes the maximum length sequence (MLS), a pseudo-random signal, to measure the frequency response.

The vibrator was placed on the artificial mastoid with a static force of 450 g. An MLS signal with length of 65,535 points at 0.59 Vpk was used to excite the vibrator. The output of the vibrator was monitored by the force transducer inside the B&K mastoid and fed to MLSSA for calculating the frequency response. An average of five repeated measurements was used to obtain the frequency response of each vibrator.

2.2   Subjective Evaluation

Subjective evaluation of each of the microphones and vibrators consisted of two parts: speech recognition and sound-quality judgments. Speech recordings were presented to participants who indicated what was heard. In the case of the microphones, recordings were made through these and played back to participants through studio quality headphones. In the case of the vibrators, recordings were made through a studio-quality microphone and played back through the vibrators.

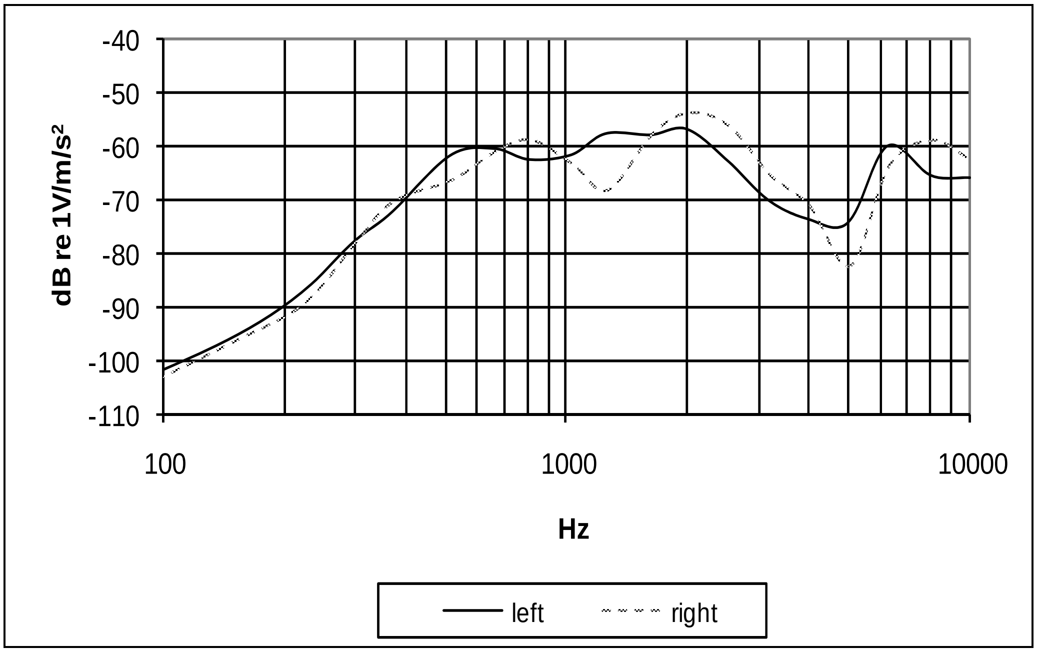

Figure 2. Frequency responses measured from the left and right vibrators from manufacturer A.

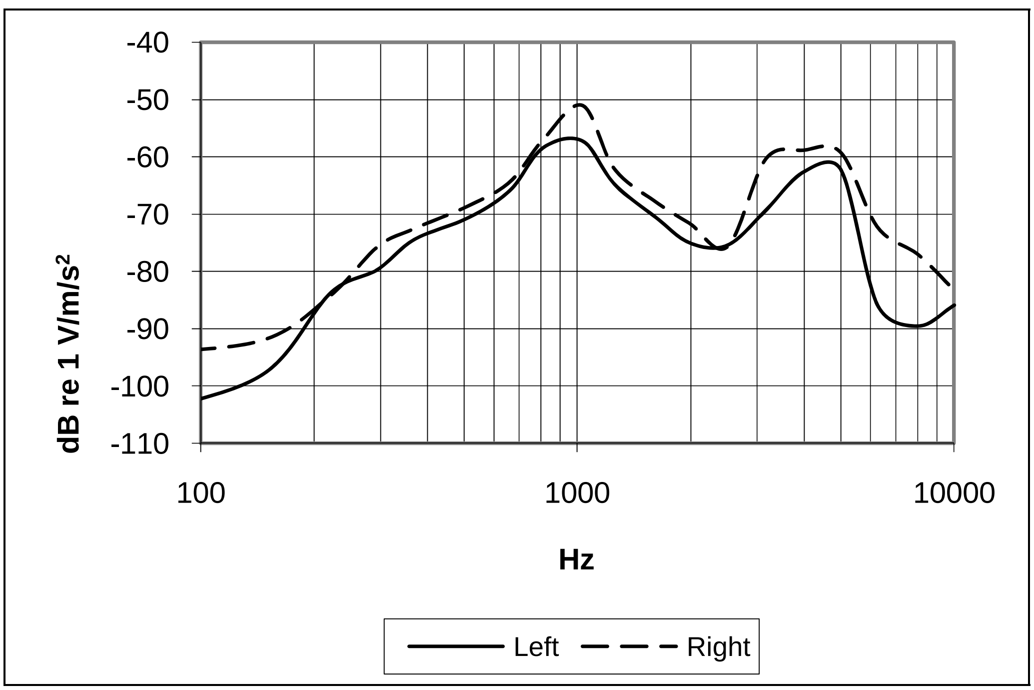

Figure 3. Frequency responses measured from the left and right vibrators from manufacturer B.

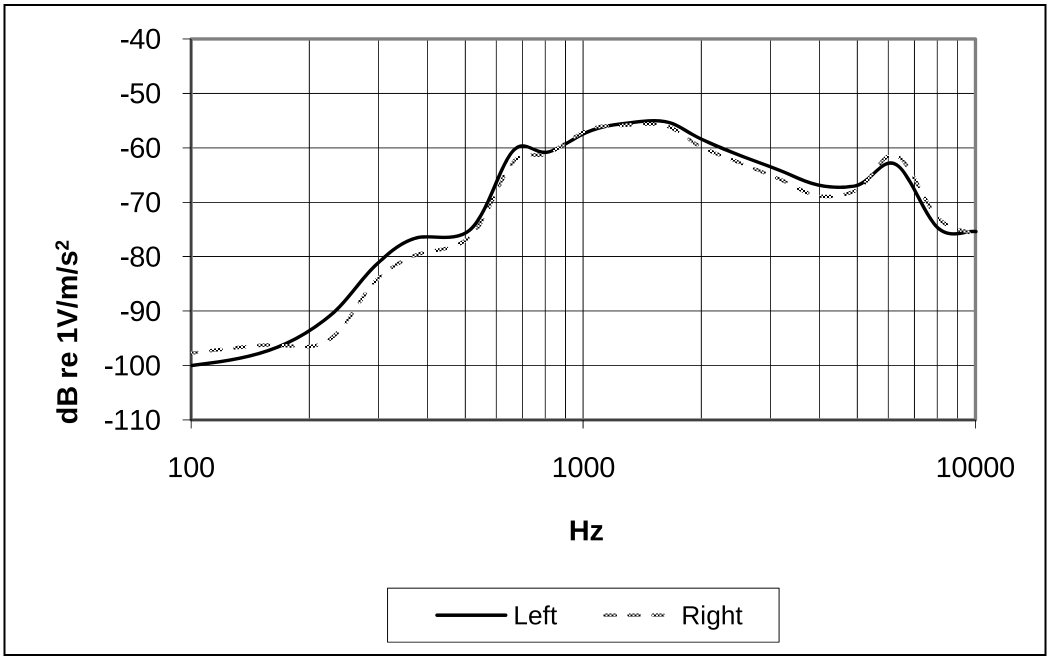

Figure 4. Frequency responses measured from the left and right vibrators from manufacturer C.

2.2.1 Microphone Recordings

Recordings of a male talker were made from the bone conduction microphones in the presence of background noise. The recordings took place in a 17- × 13- × 7-m room located in building 518 at Aberdeen Proving Ground, MD. This room is equipped with loudspeakers and amplifiers that allow for the production of high levels of background noise.

The following steps were taken to make simultaneous recordings from the three microphones in order to minimize variability across recordings. As previously noted, the microphones were removed from their respective headsets and re-wired with common connectors. A triangular mounting plate was designed and fabricated to provide equal force on the microphones when placed in contact with the top of the skull. It has been previously established that the bones of the skull are not uniform and that sensitivity to vibration varies across areas of the skull (McBride et al., 2005). It was not possible to simultaneously co-locate all three microphones in the exact same location on the talker's skull. Therefore, three recordings were made, rotating the mounting device 120° between recordings. The mounting device was coupled to the head through the use of a pair of headphones with a wide headband that was fit tightly over the talker's ears. This provided the maximum assurance of simultaneous equal pressure across the three microphones.

The talker's voice was monitored through the use of an additional bone conduction microphone that was located on the talker's forehead and routed into the microphone port of a laptop computer. The bone conduction microphone on the talker's forehead was held in place with a hook and loop band that went horizontally around the circumference of the talker's head. The talker was able to observe the output of the bone conduction microphone to monitor his vocal intensity in order to maintain the same vocal effort on each of the speech tokens.

The outputs of all three microphones were routed through an eight-channel Firefox microphone pre-amplifier to a portable computer. Background noise consisted of a recording from the interior of an M113 armored personnel carrier traveling at 10 mph on a gravel track. Two levels of background noise were used: 100 and 110 dB A-wtd as measured at the position of the listener. The noise was presented through a number of loudspeakers aimed at the center of the room.

The stimuli for the evaluation were 24 items of the Callsign Acquisition Test (CAT). The CAT consists of all 126 possible combinations of the 18 two-syllable phonetic alphabet and the seven one-syllable numbers from one through eight (nine is not used because it is pronounced "niner" in radio communications), e.g., alpha 3, kilo 6 (Rao and Letowski, 2003; Rao et al., 2002). A reduced list of 24 CAT items was chosen to minimize data collection time on the part of the participants and thereby reduce effects of fatigue. Research in the area of list reduction indicated equivalent performance with these 24 items and the entire 126-item test (Gripper, 2006). Table 1 shows the items that were used.

Table 1. Reduced list of CAT items used in the present study.

CHARLIE	4	VICTOR	5
CHARLIE	3	VICTOR	3
CHARLIE	8	WHISKEY	6
CHARLIE	5	WHISKEY	1
ECHO	8	WHISKEY	8
HOTEL	8	YANKEE	8
HOTEL	1	YANKEE	4
KILO	3	ZULU	8
PAPA	4	ZULU	1
PAPA	2	ZULU	3
TANGO	2	ZULU	4
VICTOR	4	ZULU	2

Recordings from the microphones were played back to the listeners through a pair of studio-quality AKG Acoustics GmbH* K240DF headphones routed through a Symetrix Inc. SX204 headphone amplifier while the listener was seated in a 3.5- × 3.5-m quiet sound-treated room.

*Gesellschaft mit beschränkter Haftung.

2.2.2 Vibrator Recordings

Recordings of the reduced set of 24 CAT items were made in quiet in a sound treated room through a professional quality Shure Inc. M57 cardioid microphone positioned 6 in from the talker's mouth. The recordings were played back to listeners through each of the pairs of bone conduction vibrators while the listener was in the presence of the two levels of M113 background noise (100 and 110 dB A-wtd as measured at the position of the listener).

2.2.3 General Methods

All participants completed 18 lists of CAT items for evaluation of the microphones (1 list × 3 manufacturers × 3 positions × 2 noise levels) and 6 lists of CAT items for evaluation of the vibrators (1 list × 3 manufacturers × 2 noise levels). The orders of evaluation of the devices (microphones, vibrators) and noise levels (100 dB A-wtd, 110 dB A-wtd) were counterbalanced across participants. Furthermore, the manufacturer presentation was ordered following a partial Latin square to reduce the effects of order on performance.

Participants completed a volunteer agreement affidavit (VAA) prior to any testing. Following completion of the VAA, participants' hearing was tested to verify normal hearing sensitivity. Normal hearing was defined as air conduction thresholds of less than or equal to 20 dB HL at octave frequencies from 250 through 8000 Hz. Hearing sensitivity was tested by a certified audiologist using an Interacoustics[*] AC40 audiometer. Participants were then taken to either the large room in building 518 or a 3.5- × 3.5-m sound-treated booth in building 520 to begin the study. A computer system was set up in each area and the test procedures were the same with the exception of the method of presentation of the stimuli (headphones or vibrators).

Customized computer software was used to present the CAT stimuli to the user and record user responses. The computer software tracks the test condition, item presented, listener response, and calculates the percent correct performance for each condition. Following the presentation of a test item, the listener uses a keyboard to indicate the letter and number heard. For instance, if "Alpha 2" was presented, the user would type "A2." The computer program is participant-driven in that trials are initiated by the user.

In both evaluations, the participant was able to adjust the output volume to a comfortable level. Although this allowed for differences in output across participants, the investigators decided to evaluate the systems as they would be used by a Soldier. Therefore, the volume should be individually set. In the evaluation of the vibrators, listeners typically selected an output level that was near maximum. In the evaluation of the microphones, the output level for the headphones was set far lower. Participants were fit with E•A•R[†] Classic[†] foam earplugs with a

[*]Interacoustics is a registered trademark of the William Demant Group.

[†]E•A•R and Classic are registered trademarks of Aearo Company.

noise reduction rating (NRR) of 29 for the vibrator evaluation in order to provide adequate protection from the background noise levels.

Following completion of the speech recognition task, nine of the participants were asked to make paired comparisons on the sound quality of each of the devices. Stimuli that were used in the speech recognition portion of the evaluation were played to the participant and the participant was asked to select which of the pairs was superior. Again, the volume was adjusted to user comfort and there were no qualifications made on the definition of sound quality. The investigators were simply interested in the user's preference.

In the evaluation of the vibrators, six items from the CAT were loop played in a wave file to the listener and the participant listened to the tokens in the presence of 100-dB A-wtd background noise. The listener was provided with two of the three sets of bone conduction vibrator headsets and instructed to listen as long as necessary to make a selection. The listener then donned and doffed the vibrator headsets until a selection was made. Three paired comparisons were made and the user's preference was recorded. Data analysis was based on the number of preferences for each device.

In the evaluation of the microphones, the same six tokens from the CAT were used, with two tokens presented from each of the three microphone locations. Individual wave files were selected for each of the three manufacturers and the listener alternated playing two at time. The listener wore the same headphones that were used during the speech recognition portion of the evaluation and selected the preferred recording. Three paired comparisons were made and the user's preference was recorded. Data analysis was based on the number of preferences for each device.

3. Results

Twelve listeners with normal hearing between the ages of 24 and 43 (mean = 32) completed the speech recognition portion of the study. Of those participants, nine completed the sound quality portion. Percent correct scores on the CAT items were converted to rationalized arcsine units (raus) prior to analysis (Studebaker, 1985).

Two separate two-factor mixed model analyses of variance (ANOVA) were conducted on the speech recognition scores, one for the microphones and one for the vibrators. In each case, the speech recognition scores served as the dependent variable, and the manufacturer of the device and noise level served as the independent variables. Descriptive statistics are provided for the sound quality data.

3.1 Microphones

Figure 5 shows the average performance of the listeners in percent correct on the speech recognition task for the recordings made through the bone conduction microphones and played back to the listeners through headphones. The data are graphed by manufacturer and background noise level with each bar representing the average of the three microphone locations (left, right, and front). As seen in the figure, performance is very similar across the three manufactures and is poorer in the higher background noise level than the lower background noise level. The two-factor mixed model ANOVA revealed a significant effect of noise level ($F(1,11)=28.49$, $p<0.001$) as well as a significant interaction between noise level and manufacturer ($F(2,22)=13.80$, $p<0.001$).

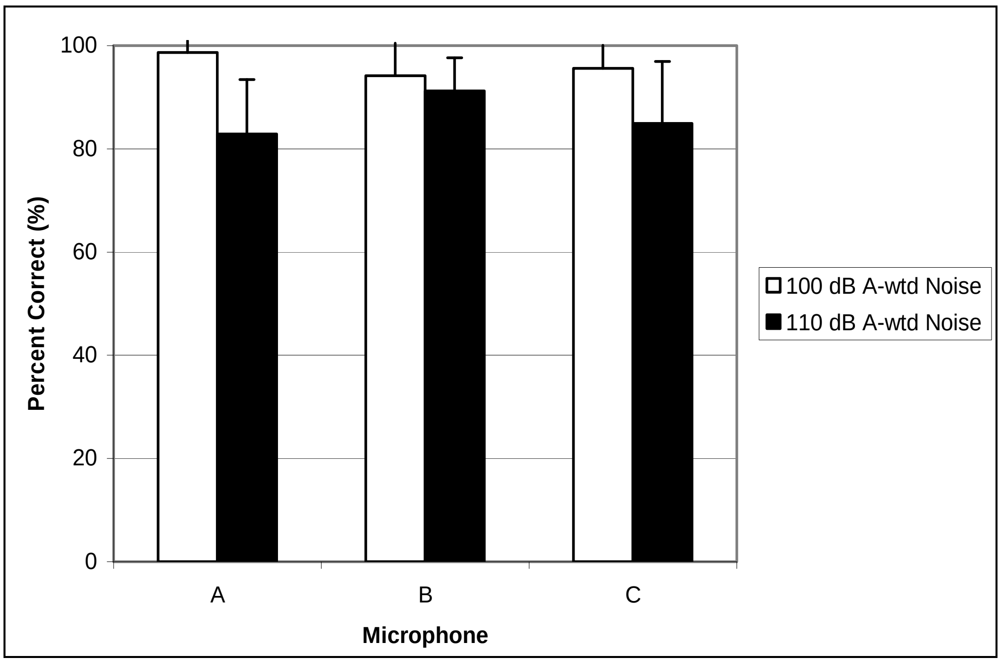

Figure 5. Speech recognition performance as a function of microphone manufacturer averaged across locations for each of two background noise levels. Error bars indicate +1 standard deviation.

To evaluate the interaction, pair-wise comparisons were made between pairs of manufacturers within each of the two noise levels. Within the 100-dB A-wtd noise condition, the only significant difference in speech recognition was between manufacturers A and B ($F(1,22)=8.50$, $p<0.05$). Thus, the rank ordering of speech recognition from best to worst was A, C, and B. The pair-wise analysis of manufacturers within the 110-dB A-wtd noise condition indicated significant differences between manufacturers A and B ($F(1,22)=8.82$, $p<0.05$), and between manufacturers B and C ($F(1,22)=5.01$, $p<0.05$). In the 110-dB A-wtd noise condition, speech recognition was significantly better with the microphone from manufacturer B than with the microphones from the other two manufacturers with no significant difference in speech recognition with microphones from manufacturers A and C.

Figure 6 shows the data graphed as a function of microphone location on the head during the recordings. A two-factor ANOVA with speech recognition score as the dependent variable and noise level and location (averaged across manufacturers) as the independent variables was conducted to determine if there was an effect of microphone location. The results showed significant effects of noise level ($F(1,11)=28.57$, $p<0.001$), location ($F(2,22)=38.14$, $p<0.001$), and a significant interaction between the two ($F(2,22)=22.20$, $p<0.001$).

Pair-wise comparisons were conducted to evaluate the interaction between locations within each of the noise levels. Within the 100 dB A-wtd noise condition, there were no significant differences between the locations. Within the 110 dB A-wtd noise condition, there were significant differences between each pair of locations, right vs. left ($F(1,22)=66.77$, $p<0.05$), right vs. front ($F(1,22)=7.67$, $p<0.05$), and left vs. front ($F(1,22)=119.72$, $p<0.05$). Thus, the effect of location is not evident until the noise is increased to the higher level.

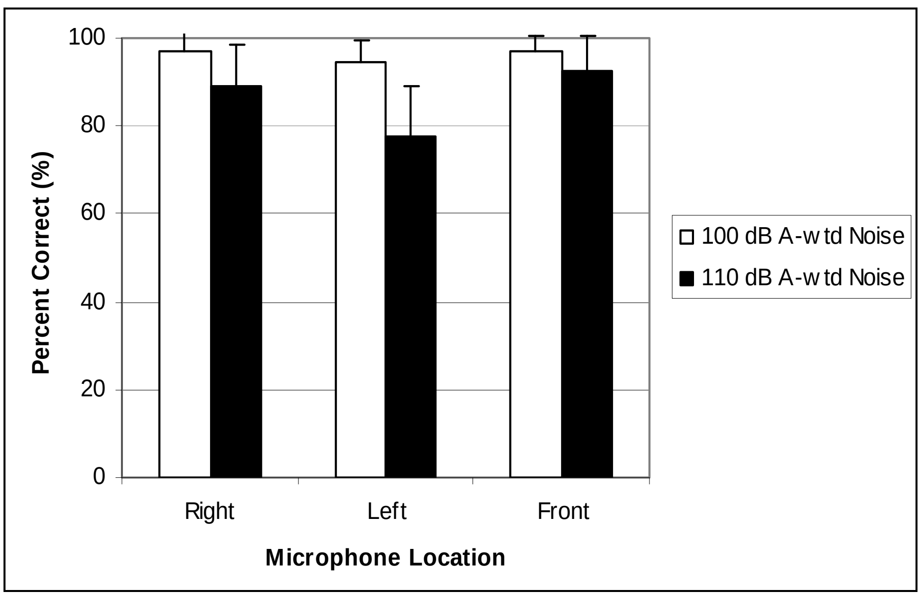

Figure 6. Average speech recognition for each of the three microphone locations in the two background noise levels. Each bar is the average across the three manufacturers for a single microphone location. Error bars indicate +1 standard deviation.

Figure 7 shows the average sound quality ratings assigned to each of the microphones following completion of the speech recognition task. Each bar indicates the number of times that the microphone was ranked as first, second, or third in sound quality. A Kruskal-Wallis test was conducted to compare the rankings across manufacturers. The result indicated no significant difference between the manufacturers.

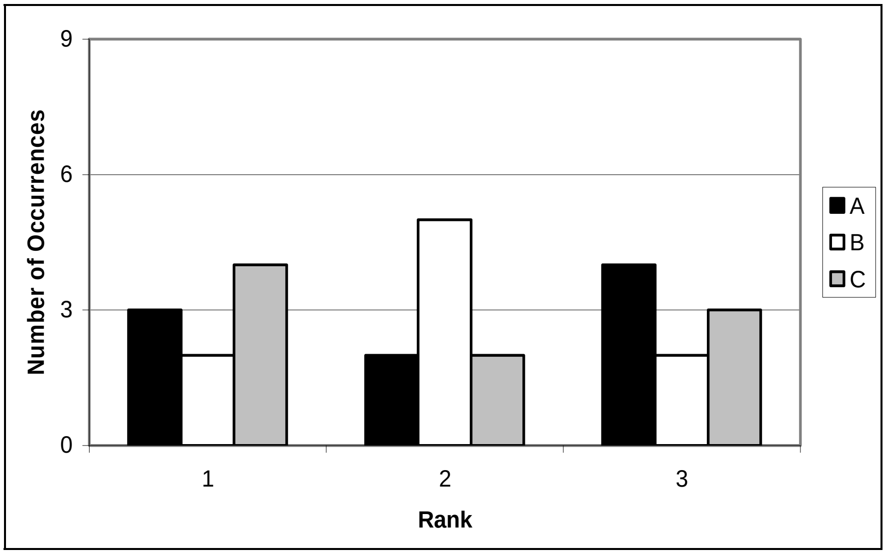

Figure 7. Sound quality comparisons made of the microphones. Each bar represents the number of times each manufacturer's microphone was ranked as first, second, or third choice from a sound quality standpoint.

3.2 Vibrators

Figure 8 shows the average performance of the listeners on the speech recognition task with each vibrator headset. A two-factor ANOVA was conducted with manufacturer and noise level as the independent variables and speech recognition score as the dependent variable. Results of the analysis showed significant effects of manufacturer ($F(2,22)=12.44$, $p<0.001$), noise level ($F(1,11)=18.71$, $p<0.01$), and a significant interaction between the two ($F(2,22)=9.17$, $p<0.01$). Pair-wise comparisons were made between each of the manufacturers within each of the two noise levels to evaluate the interaction. Within the 100-dB A-wtd noise level, the only significant difference in performance was between manufacturers A and B ($F(1,22)=10.72$, $p<0.05$). Within the 110 dB A-wtd noise level, significant differences in speech recognition performance were found between manufacturers A and B, ($F(1,22)=121.86$, $p<0.05$), and between manufacturers A and C ($F(1,22)=115.41$, $p<0.05$). Larger differences in performance occurred in the higher level of noise with the vibrators from manufacturer A revealing significantly better performance than either of the other two manufacturers.

Figure 9 shows the sound quality ratings of the vibrators following completion of the speech recognition task. Each bar indicates the number of times that the vibrators were ranked, first, second, or third in sound quality. As shown in the figure, manufacturer A was rated most often as the first choice (seven out of nine times) with large differences in the ratings between it and the other two manufacturers. A Kruskal-Wallis test was conducted to compare the rankings (Howell, 1997). The results indicated a significant effect of manufacturer ($H(2)=8.45$, $p<0.05$). As opposed to the sound quality ratings for the microphones, the ratings for the vibrators are more clearly delineated between manufacturer A and manufacturers B and C.

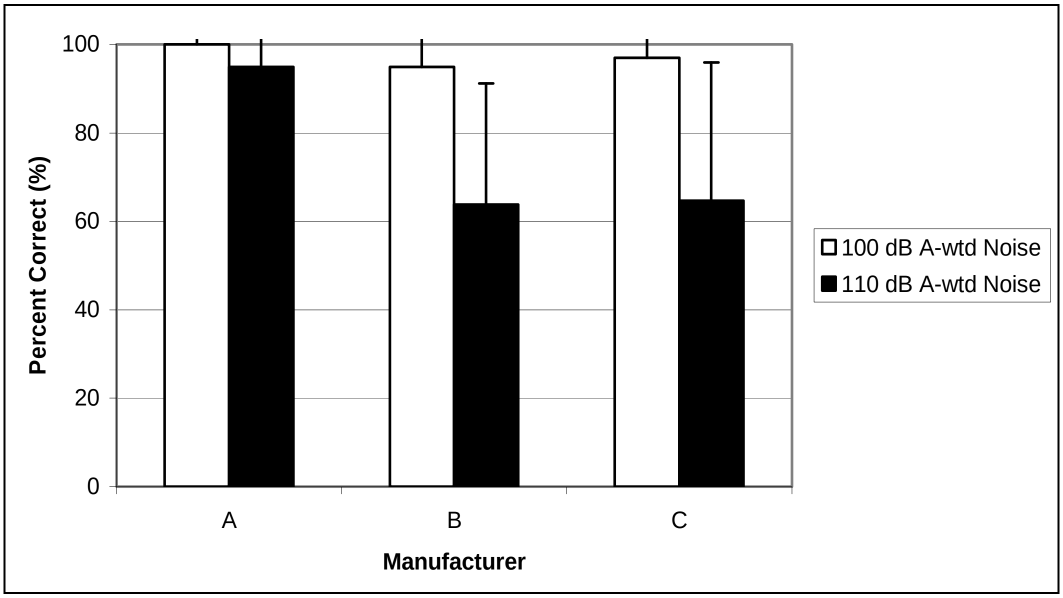

Figure 8. Average speech recognition performance for the vibrators from each of the three manufacturers in the two levels of background noise. Error bars indicate +1 standard deviation.

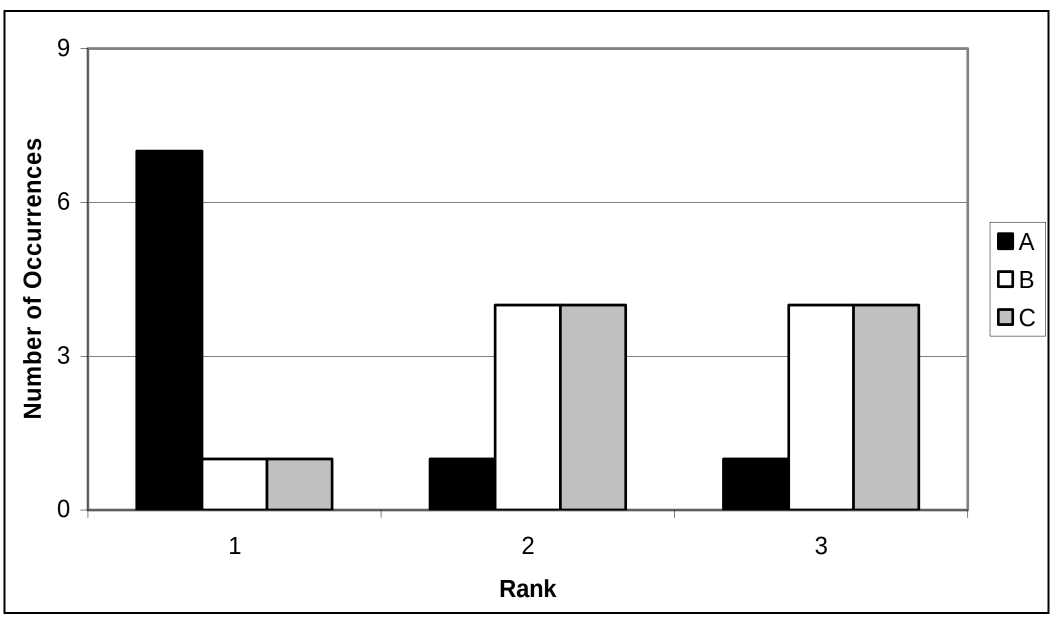

Figure 9. Sound quality comparisons made of the vibrators. Each bar represents the number of times each manufacturer's microphone was rated as first, second, or third in sound quality.

4. Discussion

The purpose of this study was to evaluate the microphones and vibrators of three commercially available bone-conduction communication systems to determine if there was a superior vibrator or microphone from any particular manufacturer. Subjective (speech recognition and sound quality) and objective (frequency response) measures were conducted on bone conduction communication system components from three manufacturers.

Simultaneous recordings in the presence of background noise were made from the three microphones and played to listeners. The resulting scores were compared to determine if the speech recognition performance differed across the microphones. The results showed an interaction between manufacturer and noise level. Performance differences between the manufacturers were not revealed until the microphones were tested under the 110-dB A-wtd noise level. Although the three manufacturers show equal performance at lower noise levels, not all of them can transmit well in high noise. At the 100-dB A-wtd noise level, the microphone from manufacturer B resulted in the poorest performance with no clear superior device between manufacturers A and C. At the 110-dB A-wtd noise level, the microphone from manufacturer B performed the best and the microphones from manufacturers A and C were indistinguishable. The inability to determine a single superior microphone is supported by the sound quality data, although the sample size of the present study was quite small.

Increases in differential performance at high noise levels as opposed to low noise levels are intriguing. First, the skull is relatively insensitive to airborne vibrations and that the recordings from the microphones were made in the presence of background noise. The amount of background noise transmitted across the microphones was fairly low, which allowed for equivalency in speech recognition for these devices. The placement of the three microphones on the top of the skull of the talker during the making of the recordings could have led to the lack of significant differences across microphones. The analysis conducted on the location of the microphones on the top of the head (front, left, right) showed worse performance in the left position, but this was likely due to the variability in the contact between the microphones and the talker's head. The methodological decision to use one-third of the items from each of the three microphone locations allowed for comparison of general performance across manufacturers without regard to specific locations.

Not all of the manufacturers have designed their microphones for placement on the top of the head. In fact, manufacturer A recommends locating the microphone on the back of the skull near the nape of the neck. However, for the purposes of the present study, the investigators aimed to equalize all potential differences in methods in order to evaluate the devices in isolation. Had the microphones been located at different locations based on the manufacturers' recommendations, the results may have been different.

For the vibrators, results of the speech recognition measures showed significant effects of background noise level indicating poorer performance at 110 dB A-wtd than at 100 dB A-wtd. The detrimental effect of increasing noise on speech transmission is not surprising and has been found in previous studies conducted in our laboratory (Henry and Letowski, 2007). The bone conduction systems that are currently available have not been optimized for military use or for use in high levels of background noise. One of the improvements needed for these devices is to increase the output level of the vibrators to improve communication in noise.

Across the speech-recognition performance for the vibrators, there was a significant effect of manufacturer that was driven by the differences in performance between the manufacturers at the 110-dB A-wtd noise level. In this case, the devices from manufacturer A outperformed those from manufacturers B and C which did not differ from each other. The clearly superior performance with the vibrators from manufacturer A at the 110 dB A-wtd noise level was reduced but still present at the lower noise level. The sound-quality judgments made for the vibrators clearly support the preference for manufacturer A.

5. Conclusions

Three manufacturers who have commercial-off-the-shelf bone-conduction communication systems were compared to determine which manufacturer of each component (microphone or vibrator) resulted in the best speech recognition performance and sound quality. The results of the speech recognition portion of the study suggest that there was no clearly superior microphone. Sound-quality judgments indicated a user preference for the device from manufacturer C; however, there were small differences in the numbers of rankings across the three manufacturers. The evaluation of the vibrators demonstrated significant differences in speech recognition performance between the vibrators revealing the device manufactured by manufacturer A as being superior. Sound-quality judgments supported the findings from the speech recognition task.

In order to provide the best bone-conduction communication system to the Soldier, vibrators from manufacturer A should be used. However, improvements in the output level of the vibrators are necessary for maximizing speech recognition in high noise environments. The results of this study do not allow for the determination of the best microphone to be used.

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