NIH Public Access
Author Manuscript
Ear Hear. Author manuscript; available in PMC 2012 July 1.

Published in final edited form as:
Ear Hear. 2011 ; 32(4): 468–484. doi:10.1097/AUD.0b013e31820dd3f0.

The effect of different cochlear implant microphones on acoustic hearing individuals' binaural benefits for speech perception in noise

Justin M. Aronoff, Ph.D., **Daniel J. Freed, M.S.**, **Laurel M. Fisher, Ph.D.**, **Ivan Pal, M.D.**, and **Sigfrid D. Soli, Ph.D**

Abstract

Objectives—Cochlear implant microphones differ in placement, frequency response, and other characteristics such as whether they are directional. Although normal hearing individuals are often used as controls in studies examining cochlear implant users' binaural benefits, the considerable differences across cochlear implant microphones make such comparisons potentially misleading. The goal of this study was to examine binaural benefits for speech perception in noise for normal hearing individuals using stimuli processed by head-related transfer functions (HRTFs) based on the different cochlear implant microphones.

Design—HRTFs were created for different cochlear implant microphones and used to test participants on the Hearing in Noise Test. Experiment 1 tested cochlear implant users and normal hearing individuals with HRTF-processed stimuli and with sound field testing to determine whether the HRTFs adequately simulated sound field testing. Experiment 2 determined the measurement error and performance-intensity function for the Hearing in Noise Test with normal hearing individuals listening to stimuli processed with the various HRTFs. Experiment 3 compared normal hearing listeners' performance across HRTFs to determine how the HRTFs affected performance. Experiment 4 evaluated binaural benefits for normal hearing listeners using the various HRTFs, including ones that were modified to investigate the contributions of interaural time and level cues.

Results—The results indicated that the HRTFs adequately simulated sound field testing for the Hearing in Noise Test. They also demonstrated that the test-retest reliability and performance-intensity function were consistent across HRTFs, and that the measurement error for the test was 1.3 dB, with a change in signal-to-noise ratio of 1 dB reflecting a 10% change in intelligibility. There were significant differences in performance when using the various HRTFs, with particularly good thresholds for the HRTF based on the directional microphone when the speech and masker were spatially separated, emphasizing the importance of measuring binaural benefits separately for each HRTF. Evaluation of binaural benefits indicated that binaural squelch and spatial release from masking were found for all HRTFs and binaural summation was found for all but one HRTF, although binaural summation was less robust than the other types of binaural benefits. Additionally, the results indicated that neither interaural time nor level cues dominated binaural benefits for the normal hearing participants.

Conclusions—This study provides a means to measure the degree to which cochlear implant microphones affect acoustic hearing with respect to speech perception in noise. It also provides measures that can be used to evaluate the independent contributions of interaural time and level cues. These measures provide tools that can aid researchers in understanding and improving binaural benefits in acoustic hearing individuals listening via cochlear implant microphones.

Correspondence information: Justin Aronoff, House Ear Institute, 2100 W. 3rd St., Los Angeles, CA 90057, Phone: (213) 273–8040, Fax: (213) 413–0950, jaronoff@hei.org.

Keywords

Hearing in Noise Test; cochlear implant; binaural benefits

Introduction

One of the major focuses of recent research on cochlear implants (CIs) is the improvement in performance with bilateral CIs compared to monolateral CIs (Dunn et al. 2010; Dunn et al. 2008; Ricketts et al. 2006;R. van Hoesel et al. 2002;R. J. van Hoesel 2004), with a number of studies demonstrating that bilateral CIs yield improved speech perception in noise (Chan et al. 2008; Dunn et al. 2010; Laszig et al. 2004; Litovsky et al. 2009; Nava et al. 2009; Schleich et al. 2004;R. J. van Hoesel 2004; Wackym et al. 2007). This improvement can primarily be classified into one of three types of benefits thought to involve binaural processing at a level higher than the cochlea: Binaural summation, binaural squelch, and spatial release from masking, described in detail below.

Binaural summation reflects an improvement in performance for bilateral testing over monolateral testing when both a target and masker are presented from the same location. It is important to make a distinction between better ear effects, where improvements result from the addition of the better performing ear, and true binaural summation. In better ear effects, performance improves when the better ear is added, but the resulting performance is no better than would occur with only the better ear, suggesting that there is no binaural interaction and thus no true binaural summation. True binaural summation can occur with the addition of either the better or worse ear, but in order to determine that the resulting performance does not simply reflect better ear performance, the bilateral performance must be better than that of the better ear alone. Because a distinction between better ear effects and binaural summation is not always made in the literature, it is difficult to determine the prevalence of binaural summation, but binaural summation has been found for at least some CI users in a number of studies (Laszig et al. 2004; Litovsky et al. 2009; Schleich et al. 2004; Tyler et al. 2007).

Binaural squelch occurs when the target and noise are spatially separated and an improvement in performance results from the addition of the ear with the worse signal-to-noise ratio (SNR) (i.e., the ear closest to the noise). As with binaural summation, some bilateral CI users demonstrate binaural squelch (Litovsky et al. 2009; Schleich et al. 2004), although it appears to require more listening experience than binaural summation (Eapen et al. 2009; Litovsky et al. 2009). Unlike binaural summation, binaural squelch relies heavily on interaural timing difference (ITD) and interaural level difference (ILD) cues, and part of the effort to understand binaural benefits such as binaural squelch has involved investigating bilateral CI users' ITD and ILD sensitivity (Aronoff, Yoon, Freed et al. 2010; Grantham et al. 2008; Poon et al. 2009; Schoen et al. 2005; Seeber et al. 2008; R. J. van Hoesel et al. 2003).

Spatial release from masking reflects an improvement in bilateral performance when the location of the masker changes from being the same as the target to being spatially separated from the target. Spatial release from masking is likely the combination of two effects: The auditory system using binaural cues to create a perception of the target and background as two separate auditory streams (Johansson et al. 2002; Schimmel et al. 2008) and a head shadow effect whereby sound is attenuated by the head before reaching the ear that is furthest from the masker. Although less studied than binaural summation and squelch, there is evidence that some bilateral CI users demonstrate spatial release from masking (Chan et

NIH-PA Author Manuscript

NIH-PA Author Manuscript

al. 2008). As with binaural squelch, spatial release from masking also depends heavily on ITD and ILD cues.

There are a variety of microphones used across cochlear implant processors, and those microphones differ in placement, frequency response, and other characteristics such as whether they are directional. This study was designed to generate a normal hearing (NH) reference for binaural benefits specific to different CI microphones by presenting NH individuals with stimuli processed by HRTFs based on the different CI microphones. We previously validated the HRTFs used in this study for localization testing (Aronoff, Yoon, Freed et al. 2010; Chan et al. 2008), demonstrating comparable performance with the HRTFs and with sound field (SF) testing using the same microphones. A subset of the HRTFs used in this study (the HRTFs for the Advanced Bionics Tmic and BTE microphones) were also validated for the Hearing in Noise Test (HINT; Nilsson et al. 1994) by Chan et al. (2008), where comparable performance was also found for testing with the HRTFs and for SF testing using the same microphones. The first goal of the current study was to validate HRTFs for HINT testing for the microphones in Cochlear's Freedom processor and Med-El's Tempo+ and Opus 2 processors, as well as an HRTF designed to simulate acoustic hearing. The second goal of this study was to determine the measurement error and performance-intensity (PI) function of HINT with the various HRTFs. The third goal was to test NH individuals listening to the HRTF-processed stimuli to determine whether binaural thresholds were affected by the different HRTFs. Because the microphones varied in terms of directionality, it was expected that the Freedom's directional microphone would outperform the omnidirectional microphones when the speech was presented from the front and spatially separated from the noise. Additionally, it was expected that the directional shaping of sound by the pinna will cause a small improvement in performance for the microphones that are located near or within the ear canal. The fourth goal was to test NH individuals using the HRTF-processed stimuli to determine the magnitude of binaural summation, squelch, and spatial release from masking yielded by the different HRTFs. The fifth goal was to determine the degree to which ITDs and ILDs underlie squelch and spatial release from masking with HINT for NH individuals, and how that differs when stimuli are processed by various HRTFs. The sixth goal was to test NH individuals using the different HRTFs to create NH norms for binaural benefits for the various microphones. The creation of those norms provides clinicians and researchers a tool to use to measure the degree to which different CI microphones affect the acoustic hearing.

Validating the HRTFs and test measures

Expt. 1: Comparing testing in the sound field and with the HRTFs

Since cochlear implant users' binaural benefits are typically measured with SF testing, it is important to demonstrate that the HRTF-processed stimuli yield similar performance as SF testing with the same microphones. Thus, the first goal of this study was to verify that the HRTFs adequately simulated SF testing. This was done by testing participants in the SF and with the appropriate HRTF-processed stimuli. CI users were tested with the HRTF corresponding to their processor's microphone. NH individuals were also tested, using an HRTF corresponding to a microphone in a Zwislocki coupler on a Knowles Electronics Manikin for Acoustic Research (KEMAR).

Methods

Participants: Two groups of participants took part in this experiment. The NH group consisted of 12 individuals with pure tone thresholds ≤ 25 dB HL from .25 to 8 kHz. The CI group consisted of seven individuals with bilateral cochlear implants. The details for the CI participants are presented in Table 1.

Stimuli: Participants were tested with HINT in the SF and using the HRTF-processed signals either presented over headphones (NH group) or sent directly to the auxiliary input of the processor (CI group). For this experiment, four different HRTFs were employed, with each participant being tested with one of the four. All HRTFs were made following the procedure used in Chan et al. (2008) and were created using the same sound booth and loudspeaker. Three HRTFs were made by placing different cochlear implant processors on KEMAR and recording directly from the processor's microphone. The HRTFs created were for Cochlear Freedom's directional microphone (Freedom HRTF), Med-El's Tempo+ microphone (Tempo+ HRTF), and Med-El's Opus 2 microphone (Opus 2 HRTF). One HRTF, representing unaided acoustic hearing, was also created based on recordings from the microphone in KEMAR's Zwislocki coupler (AH HRTF) for use with the NH group. The AH HRTF used here was also used in Chan et al. (2008). The HRTFs for Advanced Bionic's BTE microphone (AB BTE HRTF) and Advanced Bionics' Tmic microphone (Tmic HRTF) used in Experiments 2–4 were created with the same procedure and validated by comparing SF and HRTF-based thresholds in Chan et al. (2008). The various CI microphones were chosen because they represent the majority of processors currently used in the United States, including all of the processors that were on the market at the time that this study was conducted. It should be noted that the AB BTE and the Tmic HRTF represent two microphones which are both found in four Advanced Bionics processors (CII, Platinum, Harmony, and Auria BTE processors), which all share a common processor body and the same BTE and Tmic microphones, yielding the same AB BTE and Tmic HRTFs, respectively, for all processors. It should also be noted that the Tempo+ HRTF also corresponds to the microphone for the Opus 1 processor, which unlike the Opus 2, shares a common processor body and microphone with the Tempo+ processor. All microphones except the Freedom processor's were omnidirectional, and all but the Tmic and AH microphones were located behind-the- ear. Although most of the microphones were both omnidirectional and behind-the-ear, differences in the processor body and the microphone used in each processor were expected to yield differences in HRTFs. These differences can be seen in Figure 1.

Each HRTF was generated following the procedures in Chan et al. (2008) and represented as the impulse response of a 100-tap FIR filter at a sampling rate of 24 kHz. The HRTFs were measured for locations with the following azimuths: 0°, 90°, 97.5°, 112.5°, 127.5°, 142.5°, 157.5°, 172.5°, 180°, 187.5°, 202.5°, 217.5°, 232.5°, 247.5°, 262.5°, and 270°, where 90° indicates a source on the right. Only the measurements for 0°, 90°, and 270° were used for the experiments described below. The remaining azimuths were used for a localization task described elsewhere (Aronoff, Yoon, Freed et al. 2010; Chan et al. 2008). Separate filters were created for the left and right ear at each azimuth. Anatomical symmetry was assumed, so the right ear HRTF for azimuth A° was identical to the left ear HRTF for azimuth 360–A°. The test signals were presented over a Radio Shack XTS-40 speaker located approximately at the level of KEMAR's ears at a distance of 1 meter. Details of the measurement and filter design process are given in Chan et al. (2008). The frequency response of the loudspeaker and room acoustics was removed by deconvolution from the response measured at the CI microphone, which contained the effects of both the HRTF and the loudspeaker and room response.

The setup for SF testing was identical to that in Chan et al. (2008). Stimuli were presented in a double-walled IAC sound booth over two JBL Studio Monitor 4406 speakers, located approximately 1 meter from the center of the listener's head. The angle between the two speakers was 90°, with speaker A to the left of speaker B. The speech was always presented at 0 degrees, with the listener repositioned across conditions such that Noise Front (NF) and Noise Right (NR) testing was conducted with the listener facing speaker A and the Noise Left (NL) testing was conducted with the listener facing speaker B. Each speaker was

NIH-PA Author Manuscript

NIH-PA Author Manuscript

separately calibrated using a microphone (B&K 4134) located at the position corresponding to the center of the listener's head, along with a microphone pre-amplifier (B&K 2639) and a measuring amplifier (B&K 2609).

For headphone testing, stimuli were presented using TDH-50P or TDH-39P headphones. The left and right headphone were separately calibrated using a microphone (Larson Davis 2575) coupled to an artificial ear (B&K 4152), along with a microphone pre-amplifier (B&K 2639) and a measuring amplifier (B&K 2609). The same setup was used for headphone testing in the remaining experiments. For testing the HRTFs with the CI users, stimuli were presented using either an Edirol UA-1X or a HeadRoom BitHead external sound card, with the signal delivered directly to the processor via the auxiliary input port.

Procedures: HINT testing material consists of equivalent-difficulty lists of 20 short sentences in speech shaped noise. Throughout the test, the level of the noise was held constant and the level of the speech was varied to determine a final threshold using a one-up/one-down adaptive procedure. The first sentence was repeated at increasing SNRs until it was correctly identified to assure that the test was starting at a level that would allow an accurate threshold estimate. The SNR for the first four sentences was varied with a step size of 4 dB for NH individuals and 5 dB for CI users. The SNR for the remaining sentences was varied with a step size of two dB for NH individuals and three dB for CI users. The threshold score was based on the average of 17 SNRs, including the SNRs of the final 16 sentences as well as the SNR dictated by the response to the final sentence. The differing step sizes for NH and CI users were based on pilot data indicating that larger step sizes were needed to obtain a stable and accurate threshold for the CI users.

HINT is scored by evaluating each response as either completely correct or incorrect (referred to here as Rule 1). This scoring procedure, coupled with the adaptive nature of the test, assumes that the listener is able to accurately identify sentences in quiet. This is not always the case for CI users. As a result, two variants of the traditional scoring method have been developed (Chan et al. 2008). These variants score sentences correct if either at least 75% (Rule 2) or at least 50% (Rule 3) of the words in the sentence are correctly repeated. Chan et al. (2008) found that NF thresholds obtained with Rule 1 correspond to 79.1% intelligibility (i.e., 79.1% of words will be correctly identified when presented at the SNR corresponding to threshold), whereas Rule 2 thresholds yield an average score of 64.9% intelligibility, and Rule 3 thresholds yield a score of approximately 47.4% intelligibility.

All NH participants were tested using Rule 1. For the CI participants, the scoring rule used was determined by the participant's score on a HINT test with no background noise. If the participant was able to accurately repeat all of the words correctly, Rule 1 was used to evaluate their HINT (with noise) performance. If the participant was able to accurately identify at least 75% but less than 100% of the words correctly, they were tested with Rule 2. If the participant was able to accurately identify between 50% and 74% of the words correctly, they were tested with Rule 3. All participants were able to identify at least 50% of the words correctly. Participants were tested using Rule 3 if their performance on HINT with no background noise indicated that they should be tested with Rule 1 or 2, but their performance in noise required SNRs beyond the limits of the equipment. In all cases, the same rule was used for both SF and HRTF-based testing.

The NH group was tested using the NR condition. The CI group was tested using both the NR and NL conditions, collectively referred to as the Noise Side (NS) condition. All NH participants were tested with the noise presented at 65 dB(A). Equipment limitations, coupled with the high SNRs required for the CI group, prevented the use of a 65 dB(A) noise level with that group. When possible, participants were tested with noise at 50 dB(A).

However, when the scoring rule indicated by testing with stimuli at 50 and 60 dB(A) with no background noise differed, suggesting that the audibility of the stimuli was diminished at 50 dB(A), the noise was presented at 60 dB(A). All participants were tested in the SF and with only one HRTF. For the NH participants, this was the AH HRTF. For all other participants, this was the HRTF that matched the microphone that they used during everyday use, which was also the microphone used for the SF testing. All participants were tested listening binaurally.

Results—Robust statistical techniques and measures were adopted to minimize the potential effect of any outliers or non-normality in the data. Because some readers may not be familiar with a number of these statistical techniques and measures, detailed explanations and justifications are provided in the appendix. For all bootstrap analyses in this paper, the number of bootstrap samples used to create each bootstrap distribution was the same as the number of data points in the underlying dataset. Unless otherwise noted, the number of bootstrap distributions generated for each analysis was 500. To determine whether HRTF-based testing adequately simulated SF testing, a split-plot percentile bootstrap ANOVA using 20% trimmed means was conducted. The analysis was based on the NS data with modality (SF, HRTF) as the within-subject variable and group (NH, CI) as the between-subject variable. For the CI groups, the average of each participant's NL and NR thresholds was used. The NH group was only tested with the NR condition. There was no significant main effect of modality (p = .94), and no significant interaction between group and modality (p = .29). Additionally, performance in the two modalities was significantly correlated (r = .92, p =.02). Because participants were tested using different scoring rules, which by their nature result in a shift in thresholds, it was not possible to test for a main effect of Group. See Figure 2.

Discussion—The validity of the HRTFs for HINT testing was determined by comparing performance in the SF with testing with the appropriate HRTF. The results revealed that performance in the two modalities was significantly correlated, indicating a strong relationship between results obtained in the SF and with the HRTFs. Additionally, thresholds obtained with SF and HRTF-based testing were not significantly different. Finally, there was no significant interaction between the group of participants (NH or CI) and the modality, indicating that the relationship between thresholds based on SF stimuli and those based on stimuli processed by HRTFs was similar for the NH and CI group. These results are consistent with Chan et al. (2008) and indicate that the HRTFs adequately simulated SF HINT testing.

Expt. 2: Test-retest reliability and the performance-intensity function

The second goal of this study was to measure the reliability of the HINT test and the relationship between changes in SNR and changes in intelligibility (i.e., the PI function) when using Rule 3 and the various HRTFs. Rule 3 was adopted here and in Experiment 4 because it is the least restrictive rule (i.e., all listeners who are able to perform with an accuracy of at least 50% for HINT in quiet can be tested using Rule 3, whereas only those who can perform with an accuracy of 100% can be tested using Rule 1). Because many CI users are not able to understand 100% of speech in quiet, validating the reliability, measuring the PI function, and obtaining the norms for HINT using Rule 3 will allow the results to be relevant for more CI users.

Reliability and the PI function are important for interpreting any change in performance that occurs across conditions. If, for example, a participant's threshold improves when the noise is spatially separated from the speech, the measurement error, indicated by the test-retest reliability, will indicate whether that improvement reflects a meaningful change in threshold or simply normal variability. If the improvement is considered meaningful, the PI function will provide an interpretation of the effect size.

Methods

Participants: The participants consisted of 42 individuals with pure tone thresholds ≤ 25 dB HL from .25 to 8 kHz. None of these individuals participated in Experiment 1. Each participant was tested using HINT with two separate HRTFs. Test-retest reliability was measured for one of the HRTFs and the PI function was measured for the other HRTF. Table 2 presents a list of the HRTFs used by each participant as well as which HRTF was used for each measure. Because of the large number of bilateral CI users who have a Tempo + processor on one side and an Opus 2 processor on the other, a corresponding HRTF set (T/O HRTF) was also included. Each HRTF was paired twice with every other HRTF. With seven HRTF sets (AH, AB BTE, Tmic, Freedom, Tempo+, Opus 2, T/O), this resulted in 42 pairs, with each HRTF set tested twelve times. Since the test-retest and PI function measures were each tested with only one of the two HRTFs in each pair, there were six data points for each measure for each HRTF.

Procedures: HINT test-retest reliability was measured by obtaining HINT thresholds twice. Half of the participants' test-retest reliability was measured for the first HRTF they were tested with. The remaining participants' test-retest reliability was measured for the second HRTF they were tested with. The HRTF used for measuring test-retest reliability is indicated by the asterisks in Table 2. HINT thresholds were obtained using Rule 3 (at least 50% correct) and 60 dB(A) noise. Participants' test-retest reliability was measured with either the NF or NS condition, but not both. For test-retest reliability, the selection of NF or NS testing was counterbalanced within each HRTF. The direction of the noise was pseudo-randomly selected for the NS condition.

Prior to determining the PI function, an initial HINT NF threshold was determined using Rule 3, in the manner described in Experiment 1. The PI function was measured using HINT sentence lists, each containing 20 sentences, presented using the NF condition with 60 dB(A) noise at three fixed SNRs: the participant's threshold SNR, 1.5 dB above the participant's threshold SNR, and 3 dB above the participant's threshold SNR. The order of the fixed SNR tests was pseudo-randomly selected. Percent intelligibility was calculated for each SNR.

Results

Test-retest reliability: Before analyzing the test-retest reliability for HINT, a percentile bootstrap analysis based on 2,000 bootstrap distributions was used to determine if test-retest reliability significantly differed between the NF and NS conditions based on the 20% trimmed means of the test-retest difference scores for the NF and NS conditions (each participant was only tested with one of those two conditions). This analysis revealed similar test-retest reliability for both conditions (95% confidence interval for the 20% trimmed mean of the difference scores: −1.1 to 0.6 dB). As a result, test-retest difference scores were pooled across condition. To verify that HINT testing was reliable and that that reliability was not affected by the choice of HRTF, a split-plot percentile bootstrap ANOVA using 20% trimmed means was conducted based on the thresholds with HRTF as the between-subject variable and Test (test, retest) as the within-subject variable. There was no significant main effect of HRTF ($p = .99$), no significant main effect of Test ($p = .62$), and no significant interaction between HRTF and Test ($p = .13$). Additionally, the test and retest scores were highly correlated ($r = .9$, $p < .0001$). The 95% confidence interval for the trimmed mean of the difference between the test and retest scores based on 1,000 bootstrap distributions was −0.3 to 0.5 dB. These results indicated that there were no significant differences in scores across repeated testing and that the test-retest reliability was not significantly affected by the choice of HRTF. The relationship between the test and retest scores is shown in Figure 3.

Measurement error was determined based on the standard deviation of the difference between the test and retest scores estimated using S_n, a robust method that is less sensitive to the influence of outliers than the traditional estimate of standard deviation (Croux et al. 1992; Rousseeuw et al. 1993; see Appendix). The results indicated that the measurement error was 1.3 dB, shown as parallel dashed lines in Figure 3. Thus, a difference in thresholds between two conditions that was greater than 1.3 dB indicates a difference that is meaningful and cannot be accounted for by the measurement error.

PI function: To verify that changes in SNR did yield changes in intelligibility and that such changes were not affected by the choice of HRTF, the PI function was first analyzed by conducting a split-plot percentile bootstrap ANOVA using 20% trimmed means based on the percent intelligibility scores for the fixed level HINT with HRTF as the between-subject variable and SNR (threshold, 1.5 dB above threshold, and 3 dB above threshold) as the within-subject variable. There was no main effect of HRTF (p = .69), a significant main effect of SNR (p = .002), and no significant interaction between HRTF and SNR (p = .18). To further investigate the main effect of SNR, a pairwise comparison using a percentile bootstrap with 20% trimmed means and 1,000 bootstrap distributions was conducted. This revealed that all changes in SNR resulted in significant changes in percent intelligibility (95% confidence interval: threshold versus 1.5 dB above threshold = −20.0% to −13.2%; 1.5 dB above threshold versus 3 dB above threshold = −15.5% to −10.2%; threshold versus 3 dB above threshold = −33.2% to −26.6%). The 20% trimmed mean for percent intelligibility was 57% for the threshold SNR, 74% for an SNR 1.5 dB above threshold, and 87% for an SNR 3 dB above threshold. To determine the slope of the sensitivity curve, a mixed effect regression analysis was conducted with SNR (threshold, 1.5 dB above threshold, and 3 dB above threshold) as the fixed effect and subject as the random effect. This analysis yielded a slope of 10.0% per dB (see Figure 4), which is consistent with other research on the HINT PI function (e.g., Chan et al. 2008;Eisenberg et al. 1998).

Discussion—Experiment 2 measured the test-retest reliability and PI function for HINT. The test-retest reliability measure indicated that the measurement error was 1.3 dB, meaning that 68.3% of the repeated tests are expected to be within 1.3 dB of the original threshold measured. The results also indicated that measurement error did not differ significantly across HRTFs. The value for the measurement error is very similar to that obtained by Nilsson et al. (1994), who found a measurement error (using Rule 1) of 1.23 dB for a 10-sentence list version of HINT and 1.13 dB for a 12-sentence list version of HINT. The measurement error provides a metric for determining whether changing a parameter in the test, such as the location of the noise, results in a meaningful change in the measured threshold.

The PI function provides a means to interpret changes in thresholds in terms of how they would affect intelligibility. The PI function indicated that a change in SNR of 1 dB around the threshold reflects a change in intelligibility of 10%, similar to the 12% per dB slope found in Chan et al. (2008) and the 11.8% per dB found in Eisenberg et al., (1998). Although the percent intelligibility at threshold was higher than that found in Chan et al. (2008), this difference did not reflect a shift in threshold greater than the measurement error. The analyses also indicated that the PI function did not differ significantly across HRTFs. These test metrics will be used to interpret the magnitude of binaural benefits in Experiment 4.

Binaural benefits

Expt. 3: Comparison of HRTFs

The third goal of the study was to determine whether the HRTFs significantly affected performance. Such a difference in performance would indicate that meaningfully different information is available across the HRTFs and emphasize the importance of examining binaural benefits for each HRTF. One HRTF in particular was expected to yield performance that was significantly better than the others: The Freedom HRTF. Unlike the other processors' microphones, the Freedom microphone is directional, and as such, the HRTF derived using that microphone was expected to outperform the others when the noise source originated from 90 or 270 degrees (with the speech originating from 0 degrees). Because both the Tmic and the AH microphones are located near or in the entrance to the ear canal, it was also expected that these microphones will yield better performance than the non-directional BTE microphones when the noise is moved to the side as a result of directional shaping of sound by the pinna.

Methods

Participants: The 12 NH participants from Expt. 1 also participated in this experiment.

Procedures: All participants completed HINT testing using Rule 1 (100% correct). Participants were tested in both the NF and NR condition (bilateral symmetry was verified based on the audiograms), with spatial release from masking measured as the NR threshold minus the NF threshold. All participants completed testing with the AH, AB BTE, Tmic, Freedom, Tempo+, and Opus 2 HRTFs. The order of the HRTFs was chosen pseudo-randomly for each participant. Noise was presented at 65 dB(A).

Results—To compare performance across HRTFs, a percentile-*t* bootstrap repeated measures ANOVA with 20% trimmed means and 599 bootstrap distributions was conducted for NR testing. There was a significant effect of HRTF (F_{crit} = 2.32, F_t = 3.01, where $F_t > F_{crit}$ indicates significant results for alpha = .05; this analysis does not provide an exact *p* value); see Figure 5. Pairwise comparisons for the HINT NR condition using trimmed means and percentile bootstraps based on 5,000 bootstrap distributions indicated that performance was significantly better with the Tmic HRTF than with the AB BTE (95% confidence interval: 0.2 to 2.4 dB; 20% trimmed mean = 1.3 dB), Tempo+ (95% confidence interval: 0.1 to 1.9 dB; 20% trimmed mean = 0.7 dB), or Opus 2 (95% confidence interval 0.2 to 2.2 dB; 20% trimmed mean = 1.4 dB) HRTFs. Additionally, performance was significantly better with the Freedom HRTF than with the AB BTE (95% confidence interval: 0.4 to 3.5 dB; 20% trimmed mean =1.5 dB), Tempo+ (95% confidence interval: 0.2 to 2.7 dB; 20% trimmed mean = 1.6 dB), or Opus 2 (95% confidence interval: 0.4 to 3.3 dB; 20% trimmed mean = 1.8 dB) HRTFs.

An additional percentile-*t* bootstrap repeated measures ANOVA was conducted using 599 bootstrap distributions comparing spatial release from masking across the HRTFs, using the difference between the NR and NF scores. This analysis revealed a significant effect of HRTF (F_{crit} = 2.6, F_t = 5.5). Pairwise comparisons using percentile bootstraps and 5,000 bootstrap distributions indicated that spatial release from masking was significantly greater with the Freedom HRTF than with the AH (95% confidence interval: 0.3 to 3.5 dB; 20% trimmed mean = 2.0 dB), AB BTE (95% confidence interval: 1.0 to 4.0 dB; 20% trimmed mean = 2.4 dB), Tempo+ (95% confidence interval: 0.1 to 3.0 dB; 20% trimmed mean = 1.6 dB), or Opus 2 (95% confidence interval: 1.3 to 3.7 dB; 20% trimmed mean = 2.8 dB) HRTFs. Additionally, performance was significantly better with the Tempo+ HRTF than with the Opus 2 HRTF (95% confidence interval: 0.02 to 2.0 dB; 20% trimmed mean = 0.9 dB).

Discussion—This experiment compared the performance of NH individuals using the AH, AB BTE, Tmic, Freedom, Tempo+, and Opus 2 HRTFs. The results indicated that the HRTFs had significant effects on performance when the noise was spatially separated from the talker, with the Tmic and Freedom HRTFs yielding the best performance. The AH HRTF also yielded good performance, although it was not significantly better than the other microphones. The results suggest that both a directional microphone and, to a lesser degree, the directional shaping of the pinna result in better performance when the noise is to the side. However, the significantly greater spatial release from masking for the Freedom HRTF than the AH HRTF likely reflects both the relatively good NR performance and relatively poor NF performance with the Freedom HRTF (see Figure 5). These results raise the possibility that directional microphones may be beneficial in some situations and detrimental in others. The results from this experiment indicate that, although other differences across processors are likely to have a significant effect on performance, the different microphones provide potentially meaningfully different input to the processors.

Expt. 4: Binaural benefits with various CI microphones

Experiment 3 demonstrated that the different microphones used in the various CI processors can have a significant, albeit moderate effect on performance. The fourth goal of the study was to determine the magnitude of binaural summation, binaural squelch, and spatial release from masking for NH listeners for the various HRTFs. This experiment tested NH listeners monaurally and binaurally with each of the HRTFs to quantify those effects.

This experiment also addressed the fifth goal of the study, which was to determine the degree to which ITD and ILD cues contributed to binaural squelch and spatial release from masking across HRTFs. One of the advantages of using HRTF-processed stimuli is that it allows ITD and ILD cues to be independently controlled. This experiment manipulated the HRTFs to create HRTFs that preserved either the ITDs or ILDs, which were used to evaluate the role of each cue in binaural squelch and spatial release from masking.

Finally, this experiment addressed the sixth goal of the study, which was to use the data collected from the NH listeners to determine microphone-specific NH norms that can be used to determine the degree to which CI microphones affect the acoustic hearing.

Methods

Participants: The 42 NH participants from Experiment 2 participated in this experiment.

Procedures: Each participant was tested with two HRTFs. Each HRTF was paired twice with every other HRTF. With seven HRTFs (AH, AB BTE, Tmic, Freedom, Tempo+, Opus 2, and T/O), this resulted in twelve data points per HRTF per test. Table 2 presents a list of the HRTFs used by each participant. Each participant was tested using the same HRTFs, presented in the same order, as in Experiment 2. All HINT testing was conducted using Rule 3 (at least 50% of words correct), with noise presented at 60 dB(A). Participants were tested both binaurally and monaurally. All participants tested with the T/O HRTF pairing were tested with the Tempo+ HRTF for the left ear and the Opus 2 HRTF for the right ear. Monolateral testing for the T/O HRTF conditions was counterbalanced such that half of the participants were tested monolaterally with the left ear (Tempo+ HRTF) and half with the right ear (Opus 2 HRTF). For all other HRTFs, the test ear for monolateral testing was pseudo-randomly chosen. For bilateral NS testing, the direction of the noise was always contralateral to the ear chosen for monolateral testing so that binaural squelch could be calculated.

In addition to the HRTFs used in the previous experiments, participants were also tested with versions of the seven HRTFs where either only the ITDs or ILDs of the original HRTFs were preserved. These HRTFs will be referred to collectively as the ITD and ILD HRTFs, respectively. For clarity, the HRTFs from the previous experiments, which preserved both the original ITD and ILD cues will be referred to collectively as the ITD+ILD HRTFs. The ITD HRTFs for each ear had the phase response of the original HRTFs, with the ILD cues replaced by the identical magnitude response for both ears, derived from the right ear HRTF for a source at 0°. The ILD HRTFs for each ear had the magnitude responses of the original HRTFs, with the ITD cues replaced by the identical phase responses for both ears, derived from the right ear HRTF for a source at 0° (i.e., front center). All participants were tested using seven conditions, pseudo-randomly ordered, for each HRTF: ITD+ILD binaural NF, ITD+ILD binaural NS, ITD binaural NS, ILD binaural NS, monaural NF, monaural NR, and monaural NL.

Three types of binaural benefit were examined: Binaural summation, binaural squelch, and spatial release from masking. Table 3 provides the calculations for each of these binaural benefits. Briefly, binaural summation is the improvement in thresholds when listening binaurally as opposed to monaurally when the speech and noise are collocated. Binaural squelch reflects the improvement in thresholds when adding the ear closest to the noise source. Spatial release from masking indicates the improvement in threshold for binaural listening when the noise changes from being collocated with the speech to being spatially separated from the speech.

Results—The data for each type of binaural benefit described above were analyzed for each ITD+ILD HRTF using a percentile bootstrap analysis based on 20% trimmed means and 2,000 bootstrap distributions. Except for the Tempo+ HRTF ($p = .35$; trimmed mean: −0.4 dB), there was significant binaural summation for all HRTFs ($p < .05$ for all tests; trimmed means: AH: −0.9 dB, AB BTE: −1.4 dB, Tmic: −1.7 dB, Freedom: −0.8 dB, Opus: −1.6 dB, T/O: −1.3 dB; see Figure 6). However, the effect size was relatively small and often within the measurement error, indicating only an 8 to 17% increase in intelligibility. The data for all HRTFs indicated significant spatial release from masking ($p < .05$ for all tests; trimmed means: AH: −7.1 dB, AB BTE: −6.5 dB, Tmic: −6.6 dB, Freedom: −8.3 dB, Tempo+: −6.3 dB, Opus: −6.0 dB, T/O: −5.7 dB; see Figure 7) that was consistently greater than the measurement error and represented a 57 to 83% increase in intelligibility. There was also significant binaural squelch for all HRTFs ($p < .05$ for all tests; trimmed mean: AH: −2.9 dB, AB BTE: −3.0 dB, Tmic: −3.3 dB, Freedom: −3.5 dB, Tempo+: −2.5 dB, Opus 2: −3.8 dB, T/O: −2.4 dB; see Figure 8). All binaural squelch effect sizes were greater than the measurement error and indicated a 24 to 38% increase in intelligibility.

Although the data in Experiment 3 were obtained using Rule 1, it is possible to compare the amount of spatial release from masking obtained for the participants in Experiments 3 and 4 since spatial release from masking reflects a difference between two scores, and as such, it should not be affected by the rule choice as long as both tests contributing to the difference score utilized the same rule. The 20% trimmed means for spatial release from masking for the same HRTF for both experiments were within 1 dB for all HRTFs (difference between the trimmed means for the two experiments: AH: 0.2 dB, AB BTE: 0.4 dB, Tmic: −0.4 dB, Freedom: −0.3 dB, Tempo+: −0.9 dB, Opus 2: −0.1 dB), which is less than the measurement error.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

To determine the role of ITD and ILD cues in spatial release from masking and binaural squelch, repeated measures percentile-*t* bootstrap ANOVAs were conducted using 20% trimmed means and 599 bootstrap distributions for the NS condition with Cue (ITD+ILD, ITD, and ILD) as the repeated measure. Since the difference between the ITD+ILD, ITD, and ILD conditions for both spatial release from masking and binaural squelch relies entirely on the difference between the ITD+ILD, ITD, and ILD NS thresholds, the results are identical for both binaural benefits. There was a significant main effect for all HRTFs ($F_t > F_{crit}$ for all). Pairwise comparisons with percentile bootstraps and 20% trimmed means using 1,000 bootstrap distributions revealed that the condition with both ITD and ILD cues yielded the best performance for all HRTFs ($p < .05$ for all comparisons). The relative role of ITD and ILD cues differed across HRTFs, but for most HRTFs there was no significant difference between performance with ITD cues and performance with ILD cues (95% confidence interval of the 20% trimmed mean: AB BTE = −1.5 to 0.7 dB; Tmic = −0.2 to 1.7 dB; Tempo+ = −0.6 to 1.3 dB; and T/O = −0.5 to 0.5 dB; see Figure 7). Performance with ILD cues was significantly better for two HRTFs (95% confidence interval of the 20% trimmed mean: AH: 0.2 to 1.8 dB and Freedom: 1.0 to 2.7 dB; trimmed mean: AH: 1.1 dB and Freedom: 1.9 dB), indicating an 11% improvement in intelligibility for the AH HRTF, which was within the measurement error, and a 19% improvement in intelligibility for the Freedom HRTF, which was greater than the measurement error. Performance with ITD cues was significantly better for one HRTF (95% confidence interval for Opus 2 = −2.0 to −0.4 dB; trimmed mean: −1.1 dB), and the improvement indicated an 11% improvement in intelligibility but was within the measurement error.

To determine if, regardless of the relative difference between ITD and ILD cues, there was significant spatial release from masking with either ITD or ILD cues, the data for each ITD and ILD HRTF were analyzed using a percentile bootstrap based on 20% trimmed means and 2,000 bootstrap distributions. This revealed significant spatial release from masking for all HRTFs regardless of whether ITD or ILD cues were preserved ($p < .05$ for all tests), with all instances of spatial release from masking being greater than the measurement error. See Figure 7.

The data for each ITD and ILD HRTF were analyzed using a percentile bootstrap based on 20% trimmed means and 2,000 bootstrap distributions to determine if either cue was sufficient for binaural squelch. This revealed that binaural squelch was rare with either ITD or ILD cues, despite the significant binaural squelch described above when both ITD and ILD cues were present. There was significant binaural squelch with ITD cues for the Opus 2 HRTF (95% confidence interval: −2.6 to −0.8 dB; trimmed mean: −1.6.), which was greater than the measurement error and indicated a 16% improvement in intelligibility. There was significant binaural squelch with ILD cues for the Tmic HRTF (95% confidence interval: −1.6 to 0.0 dB; trimmed mean: −0.8 dB), which was within the measurement error and indicated an 8% improvement in intelligibility. For the Freedom HRTF, not only was there no binaural squelch when using ITD cues, but performance on the bilateral NS condition was significantly worse than performance on the monaural contralateral NS condition (95% confidence interval: 0.4 to 2.3 dB; trimmed mean = 1.3), although the difference was within the measurement error. See Figure 8.

The 5th through 95th percentile for each HRTF and test measure are presented in Tables 4, 5, 6, 7, 8, 9, and 10 to facilitate the use of norm-based scoring by researchers and clinicians. Percentiles were calculated based on a normal distribution with a standard deviation and mean that was estimated using the S_n (Croux and Rousseeuw 1992;Rousseeuw and Croux 1993; see Appendix) and the 20% trimmed mean of the appropriate test measure and HRTF. This method relies on the assumption that the distribution from which the data were sampled is a normal distribution, although the true mean and standard deviation may be contaminated by outliers in the limited dataset. The assumption of normality was tested using the Lilliefors test (Lilliefors 1967), with alpha adjusted per HRTF using Rom's method (Rom 1990). The results of those tests indicated that none of the data from the conditions differed significantly from normality.

Discussion—This experiment examined the binaural benefits for NH individuals using the HRTFs generated from the various CI microphones, as well as the HRTF generated from KEMAR's microphone. The results demonstrated that all HRTFs yielded significant binaural squelch and spatial release from masking, although spatial release from masking was a considerably more robust effect. Additionally, all but the Tempo+ HRTF yielded significant binaural summation, although the magnitude of the effect was relatively small. The contribution of ITD and ILD cues for the observed binaural squelch and spatial release from masking was examined by testing participants using the HRTFs where either ITD of ILD cues were preserved. Those tests revealed that neither ITDs nor ILDs were consistently dominant, although some differences occurred across HRTFs. Only the Freedom HRTF, based on a directional microphone, showed a difference between the ITD and ILD thresholds greater than the measurement error, indicating a bias for ILD cues. This may indicate that directional microphones, by enhancing the level difference between sources in front and those to the side, provide enhanced ILD cues.

While both ITD and ILD cues were generally sufficient on their own to yield spatial release from masking, they often were not sufficient for binaural squelch. This resulted in part from binaural squelch being a less robust effect than spatial release from masking. Comparison of spatial release from masking with the ITD+ILD HRTFs in Experiment 3 and 4, which did not include any of the same participants, found that the difference in the trimmed means for spatial release from masking for the same HRTF for both experiments was within the measurement error, providing further evidence of the reliability of the test. In addition to quantifying the magnitude of binaural benefits, this experiment also created norms that can be used to determine the degree to which CI microphones affect the acoustic hearing.

General discussion

This study examined speech perception in noise for NH individuals listening to signals processed by HRTFs generated using different CI microphones. The resulting data can be used to determine the degree to which CI microphones affect the acoustic hearing. Experiment 1 demonstrated that testing with the HRTFs appropriately simulated SF HINT testing, yielding similar results for both SF and HRTF-based HINT testing. Experiment 2 examined the reliability and PI function for the various HRTFs. This experiment demonstrated that, consistent with previous results (Chan et al. 2008; Eisenberg et al. 1998; Nilsson et al. 1994), the measurement error was 1.3 dB, and a change of SNR of 1 dB represented a 10% change in intelligibility near threshold. Experiment 3 compared the performance of NH individuals using the AH, AB BTE, Tmic, Freedom, Tempo+, and Opus 2 HRTFs. The results indicated that the choice of HRTF had significant effects on thresholds when the noise and speech were spatially separated, with lower thresholds for the Tmic and Freedom HRTFs than for the AB BTE, Tempo+ and Opus 2 HRTFs. Experiment 4 examined binaural benefits in NH listeners using the various HRTFs. Binaural squelch and spatial release from masking were found for all HRTFs, and binaural summation was found for all but the Tempo+ HRTF. Testing with the ITD and ILD HRTFs indicated that, in general, neither ITDs nor ILDs were dominant cues in terms of binaural benefits. The amount of spatial release from masking found in Experiment 4 was comparable to that found with a separate group of participants in Experiment 3, with the differences across experiments being less than the measurement error, providing additional evidence of the reliability of the test. The results obtained in Experiment 4 suggest that both summation and

NIH-PA Author Manuscript

NIH-PA Author Manuscript

squelch are moderate binaural benefits, representing at most a 1.7 and 3.8 dB improvement in thresholds for the NH participants, respectively. In contrast, spatial release from masking is a more robust binaural benefit, representing up to an 8.3 dB improvement in thresholds for the NH participants.

Experiment 4 also created norms that allow researchers and clinicians to measure the degree to which CI microphones affect the acoustic hearing with respect to speech perception in noise. These norms provide information that can be useful to clinicians for counseling purposes. They can also provide researchers with a reference with which to compare the performance of acoustic hearing individuals listening via one of the tested microphones. Given the various processes by which sound is transformed by CIs as it is translated into a neural response (e.g., those related to the microphone, the processing strategy, the stimulation rate, and the nature of electrical stimulation), as well as the underlying etiology that resulted in an individual being a candidate to receive a cochlear implant, it is not expected that the norms will predict CI performance.

Although the norms were collected using CI microphones with individuals with normal pure tone thresholds, these norms (Table 4) can also be useful in interpreting the performance of individuals with hearing impairments as long as they use one of the tested microphones. Currently, HINT norms are only available for testing using Rule 1 (Vermiglio 2008). Because many individuals with hearing impairments are not able to understand 100% of HINT sentences in quiet, Rule 1 testing, and by extension, Rule 1-based norms, are often not an appropriate reference for that population. The NH norms presented here, based on Rule 3, can be used for HINT testing when using the AH HRTF (i.e., headphone version of commercially available HINT) with hearing impaired individuals who can understand at least 50% of HINT sentences in quiet.

Because this study relied on nonindividualized HRTFs, it is relevant to consider how such HRTFs can affect performance. There is some indication that the use of nonindividualized HRTFs did have an effect on the thresholds obtained, as seen by the range of the SF-HRTF difference scores in Experiment 1. This variability likely reflects the degree to which the non-individualized HRTFs differ from those that would be obtained from each individual participant (Middlebrooks 1999). However, the performance between SF and HRTF testing was strongly correlated, suggesting that the effect of using nonindividualized HRTFs was minimal.

Although nonindividualized HRTFs generally yield poorer performance than what would be obtained with one's natural HRTFs (Middlebrooks 1999; Morimoto et al. 1980; Wenzel et al. 1993), two factors suggest that using nonindividualized HRTFs only minimally affected the results of this study. The first factor is that the locations of the speech and noise in HINT vary in terms of azimuth. The errors that occur when using nonindividualized HRTFs tend to be errors in elevation not azimuth (Middlebrooks 1999; Wenzel et al. 1993), in part because nonindividualized HRTFs provide considerable cues in terms of azimuth location (Begault et al. 1993). The second factor is that HINT includes only locations to the side and front of the listener. Errors in azimuth localization with nonindividualized HRTFs are generally front-back confusions (Wenzel et al. 1993), and thus are unlikely to significantly affect HINT testing, where all source locations are situated from 90 to 270°. Although the most accurate measure of an individual's speech perception in noise ability would come from SF testing or individualized HRTFs, we feel that using the non-individualized HRTFs is a sufficiently accurate approach to estimate speech perception in noise ability.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Comparison to other studies with NH listeners

The thresholds obtained here are similar to those found in other studies using HINT. Chan et al. (2008) tested individuals with HINT using the NF condition and Rule 3 and found an average threshold of −4.9 dB. This is very similar to the trimmed mean threshold of −4.5 dB obtained in Experiment 4 for the same condition and rule. Vermiglio (2008) presented norms for HINT from a separate group of participants using Rule 1 and the same AH HRTF included in this study. He found that the 50th percentile for bilateral testing was −2.6 dB for NF testing and −10.1 dB for NS testing. Those values are close to the trimmed means of the scores found in Experiment 3 for the AH HRTF (using Rule 1) of −3.5 and −10.2 dB for NF and NR testing, respectively. Using the threshold conversion provided in Chan et al. (2008), the Experiment 4 results reflect an approximate Rule 1 equivalent threshold of −1.9 and −9.1 dB for NF and NS testing, respectively. The difference between the results obtained in Experiment 3 and Experiment 4 and those obtained in Vermiglio (2008) are small and generally within the measurement error of HINT, providing additional evidence of the reliability of the test. The average spatial release from masking with the AH HRTF was −6.9 dB for Experiment 4. This is comparable to the −6 to −7.5 dB spatial release from masking found for versions of HINT in other languages (Wong et al. 2005; Wong et al. 2007). The slope of the PI function measured in Experiment 2 is also similar to that found in other studies using HINT (Chan et al. 2008; Eisenberg et al. 1998). A comparison of the PI slope for versions of HINT in 13 languages revealed that the average slope is 10.3% (range = 9.0 to 14.6%; Soli et al. 2008), very similar to the 10.0% slope found here. Taken together, these comparisons suggest that the current results are consistent with those from other studies using HINT.

The particular thresholds obtained here are not expected to be the same as thresholds obtained using different test materials or scoring rules. For example, Freyman et al. (1999) found a 5.5 dB improvement in spatial release from masking for nonsense sentences when changing from speech-shaped noise to a female talker masker. Similarly, when testing normal hearing listeners with HINT sentences presented monaurally with ipsilateral noise, Peters et al. (1998) obtained thresholds ranging from −3.8 dB to −22.6 dB depending on the characteristics of the masker. Despite these differences in absolute thresholds when using different test parameters, the general patterns seen in the current data still occur when test parameters change. For example, binaural summation remains a small effect (Cox et al. 1981; MacKeith et al. 1971), whereas spatial release from masking remains a large effect (Bronkhorst et al. 1988; Freyman et al. 1999). Similarly, as was seen with the AH HRTF, the same pattern of spatial release from masking being greatest when both ITD and ILD cues were preserved is also found when using other sentence materials (Bronkhorst and Plomp 1988). These comparisons suggest a general similarity between the pattern of results obtained here and those obtained using different test parameters, but they also caution against interpreting results from other tests using the norms presented here.

ITD and ILD cues

The results from the current experiment indicated that neither ITD nor ILD cues played a dominant role in NH individuals’ binaural benefits for speech perception, and that the removal of either cue resulted in a decreased magnitude of binaural benefit. These results are consistent with those found in other studies with NH individuals when the noise is similarly restricted to one hemifield (Culling et al. 2004; Edmonds et al. 2005). However, other studies using non-speech tasks have indicated a dominance for ITD cues, such as when detecting a antiphasic tone in homophasic noise (van der Heijden et al. 2010) or when localizing broadband sounds (Macpherson et al. 2002; Wightman et al. 1992). The similar dependence on ITD and ILD cues for HINT may reflect the considerable distance between target and masker locations (90°). Consistent with that interpretation, using the same HRTFs as were used in the current study, we have also found an ITD dominance for NH listeners' localization with sources separated by 15°(Aronoff, Yoon, Pal et al. 2010).

The results for spatial release from masking in Experiment 4 indicated that ILD cues were dominant for the Freedom HRTF, suggesting that the directional microphone magnifies the relevant ILD cues. This magnification of ILD cues with the two HRTFs seen with the NH individuals suggests that directional microphones may be particularly important for populations that rely disproportionately on ILD cues, such as CI users (Aronoff, Yoon, Freed et al. 2010; Schoen et al. 2005; Seeber and Fastl 2008; R. J. van Hoesel and Tyler 2003).

Conclusions

This research provides a way to measure the degree to which CI microphones affect acoustic hearing with regard to speech perception in noise. The experiments described above demonstrated that the HRTF-based HINT testing is reliable and accurately simulates SF testing. They also generated NH control data for binaural benefits for each CI microphone, including the independent contributions of ITD and ILD cues in those binaural benefits. These measures provide valuable tools that can aid researchers in understanding and improving binaural benefits when listening via CI microphones.

Acknowledgments

We thank our participants for their time and effort. We also thank Advanced Bionics, Cochlear Ltd., and Med-El for providing equipment and expertise for this study. The authors greatly appreciate the comments provided by the section editor, Dr. D. Wesley Grantham, and anonymous reviewer 2. This work was supported by NIH grant No. R44DC005759.

References

Aronoff JM, Yoon Y-S, Freed DJ, et al. The use of interaural time and level difference cues by bilateral cochlear implant users. J Acoust Soc Am. 2010; 127:EL87–EL92. [PubMed: 20329812]

Aronoff, JM.; Yoon, YS.; Pal, I., et al. The role of interaural time and level cues in spatial release from masking and localization abilities for cochlear implant users. Poster presented at the Association for Research in Otolaryngology 33rd Annual Midwinter Research Meeting; 2010.

Begault DR, Wenzel EM. Headphone localization of speech. Hum Factors. 1993; 35:361–376. [PubMed: 8349292]

Bronkhorst AW, Plomp R. The effect of head-induced interaural time and level differences on speech intelligibility in noise. J Acoust Soc Am. 1988; 83:1508–1516. [PubMed: 3372866]

Chan JC, Freed DJ, Vermiglio AJ, et al. Evaluation of binaural functions in bilateral cochlear implant users. Int J Audiol. 2008; 47:296–310. [PubMed: 18569102]

Cox RM, DeChicchis AR, Wark DJ. Demonstration of binaural advantage in audiometric test rooms. Ear Hear. 1981; 2:194–201. [PubMed: 7297783]

Croux, C.; Rousseeuw, PJ. Time-efficient algorithms for two highly robust estimators of scale. In: Whittaker, YDaJ, editor. Computational Statistics. Heidelberg: Physica-Verlag; 1992. p. 411-428.

Culling JF, Hawley ML, Litovsky RY. The role of head-induced interaural time and level differences in the speech reception threshold for multiple interfering sound sources. J Acoust Soc Am. 2004; 116:1057–1065. [PubMed: 15376672]

Dunn CC, Noble W, Tyler RS, et al. Bilateral and unilateral cochlear implant users compared on speech perception in noise. Ear Hear. 2010; 31:296–298. [PubMed: 19858720]

Dunn CC, Tyler RS, Oakley S, et al. Comparison of speech recognition and localization performance in bilateral and unilateral cochlear implant users matched on duration of deafness and age at implantation. Ear Hear. 2008; 29:352–359. [PubMed: 18453885]

Eapen RJ, Buss E, Adunka MC, et al. Hearing-in-noise benefits after bilateral simultaneous cochlear implantation continue to improve 4 years after implantation. Otol Neurotol. 2009; 30:153–159. [PubMed: 19180675]

Edmonds BA, Culling JF. The role of head-related time and level cues in the unmasking of speech in noise and competing speech. Acta Acustica United with Acustica. 2005; 91:546–553.

Eisenberg LS, Dirks DD, Takayanagi S, et al. Subjective Judgments of Clarity and Intelligibility for Filtered Stimuli With Equivalent Speech Intelligibility Index Predictions. J Speech Lang Hear Res. 1998; 41:327–339. [PubMed: 9570586]

Freyman RL, Helfer KS, McCall DD, et al. The role of perceived spatial separation in the unmasking of speech. J Acoust Soc Am. 1999; 106:3578–3588. [PubMed: 10615698]

Grantham DW, Ashmead DH, Ricketts TA, et al. Interaural time and level difference thresholds for acoustically presented signals in post-lingually deafened adults fitted with bilateral cochlear implants using CIS+ processing. Ear Hear. 2008; 29:33–44. [PubMed: 18091105]

Johansson MS, Arlinger SD. Binaural masking level difference for speech signals in noise. Int J Audiol. 2002; 41:279–284. [PubMed: 12166687]

Keselman HJ, Algina J, Lix LM, et al. A generally robust approach for testing hypotheses and setting confidence intervals for effect sizes. Psychol Methods. 2008; 13:110–129. [PubMed: 18557681]

Keselman HJ, Wilcox RR, Lix LM. A generally robust approach to hypothesis testing in independent and correlated groups designs. Psychophysiology. 2003; 40:586–596. [PubMed: 14570166]

Laszig R, Aschendorff A, Stecker M, et al. Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-month postoperative results. Otol Neurotol. 2004; 25:958–968. [PubMed: 15547426]

Lilliefors HW. On the Kolmogorov-Smirnov Test for Normality with Mean and Variance Unknown. Journal of the American Statistical Association. 1967; 62:399–402.

Litovsky RY, Parkinson A, Arcaroli J. Spatial hearing and speech intelligibility in bilateral cochlear implant users. Ear Hear. 2009; 30:419–431. [PubMed: 19455039]

MacKeith NW, Coles RR. Binaural advantages in hearing of speech. J Laryngol Otol. 1971; 85:213–232. [PubMed: 5550604]

Macpherson EA, Middlebrooks JC. Listener weighting of cues for lateral angle: the duplex theory of sound localization revisited. J Acoust Soc Am. 2002; 111:2219–2236. [PubMed: 12051442]

Middlebrooks JC. Virtual localization improved by scaling nonindividualized external-ear transfer functions in frequency. J Acoust Soc Am. 1999; 106:1493–1510. [PubMed: 10489706]

Morimoto M, Aokata H. On the simulation of sound localization. Journal of the Acoustical Society of Japan (E). 1980; 1:167–174.

Nava E, Bottari D, Portioli G, et al. Hearing again with two ears: Recovery of spatial hearing after bilateral cochlear implantation. Neuropsychologia. 2009; 47:928–932. [PubMed: 19100277]

Nilsson M, Soli SD, Sullivan JA. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. J Acoust Soc Am. 1994; 95:1085–1099. [PubMed: 8132902]

Peters RW, Moore BC, Baer T. Speech reception thresholds in noise with and without spectral and temporal dips for hearing-impaired and normally hearing people. J Acoust Soc Am. 1998; 103:577–587. [PubMed: 9440343]

Poon BB, Eddington DK, Noel V, et al. Sensitivity to interaural time difference with bilateral cochlear implants: Development over time and effect of interaural electrode spacing. J Acoust Soc Am. 2009; 126:806–815. [PubMed: 19640045]

Ricketts TA, Grantham DW, Ashmead DH, et al. Speech recognition for unilateral and bilateral cochlear implant modes in the presence of uncorrelated noise sources. Ear Hear. 2006; 27:763–773. [PubMed: 17086085]

Rom DM. A sequentially rejective test procedure based on a modified Bonferroni inequality. Biometrika. 1990; 77:663–666.

Rousseeuw PJ, Croux C. Alternatives to the median absolute deviation. Journal of the American Statistical Association. 1993; 88:1273–1283.

Schimmel O, van de Par S, Breebaart J, et al. Sound segregation based on temporal envelope structure and binaural cues. J Acoust Soc Am. 2008; 124:1130–1145. [PubMed: 18681602]

Schleich P, Nopp P, D'Haese P. Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. Ear Hear. 2004; 25:197–204. [PubMed: 15179111]

Schoen F, Mueller J, Helms J, et al. Sound localization and sensitivity to interaural cues in bilateral users of the Med-El Combi 40/40+cochlear implant system. Otol Neurotol. 2005; 26:429–437. [PubMed: 15891645]

Seeber BU, Fastl H. Localization cues with bilateral cochlear implants. J Acoust Soc Am. 2008; 123:1030–1042. [PubMed: 18247905]

Soli SD, Wong LL. Assessment of speech intelligibility in noise with the Hearing in Noise Test. Int J Audiol. 2008; 47:356–361. [PubMed: 18569108]

Tyler RS, Dunn CC, Witt SA, et al. Speech perception and localization with adults with bilateral sequential cochlear implants. Ear Hear. 2007; 28:86S–90S. [PubMed: 17496655]

van der Heijden M, Joris PX. Interaural correlation fails to account for detection in a classic binaural task: dynamic ITDs dominate N0Spi detection. J Assoc Res Otolaryngol. 2010; 11:113–131. [PubMed: 19760461]

van Hoesel R, Ramsden R, Odriscoll M. Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. Ear Hear. 2002; 23:137–149. [PubMed: 11951849]

van Hoesel RJ. Exploring the benefits of bilateral cochlear implants. Audiol Neurootol. 2004; 9:234–246. [PubMed: 15205551]

van Hoesel RJ, Tyler RS. Speech perception, localization, and lateralization with bilateral cochlear implants. J Acoust Soc Am. 2003; 113:1617–1630. [PubMed: 12656396]

Vermiglio AJ. The American English hearing in noise test. Int J Audiol. 2008; 47:386–387. [PubMed: 18569120]

Wackym PA, Runge-Samuelson CL, Firszt JB, et al. More challenging speech-perception tasks demonstrate binaural benefit in bilateral cochlear implant users. Ear Hear. 2007; 28:80S–85S. [PubMed: 17496654]

Wenzel EM, Arruda M, Kistler DJ, et al. Localization using nonindividualized head-related transfer functions. J Acoust Soc Am. 1993; 94:111–123. [PubMed: 8354753]

Wightman FL, Kistler DJ. The dominant role of low-frequency interaural time differences in sound localization. J Acoust Soc Am. 1992; 91:1648–1661. [PubMed: 1564201]

Wilcox RR. The goals and strategies of robust methods. British Journal of Mathematical and Statistical Psychology. 1998; 51:1–39.

Wilcox RR, Keselman HJ. Modern robust data analysis methods: measures of central tendency. Psychol Methods. 2003; 8:254–274. [PubMed: 14596490]

Wilcox RR, Keselman HJ, Kowalchuk RK. Can tests for treatment group equality be improved?: The bootstrap and trimmed means conjecture. British Journal of Mathematical and Statistical Psychology. 1998; 51:123–134.

Wong LL, Soli SD. Development of the Cantonese Hearing In Noise Test (CHINT). Ear Hear. 2005; 26:276–289. [PubMed: 15937409]

Wong LL, Soli SD, Liu S, et al. Development of the Mandarin Hearing in Noise Test (MHINT). Ear Hear. 2007; 28:70S–74S. [PubMed: 17496652]

Appendix: Statistical Techniques

Although considerable advances have occurred in statistical techniques in recent years, yielding more accurate statistical results, many researchers are unfamiliar with newer statistical techniques, the merits of such approaches, and the shortfalls of more traditional techniques. This appendix describes some of these newer approaches to statistical parameter estimation as well as a class of modern inferential statistical tests referred to as bootstrap analyses.

Parameter Estimation

Means are ubiquitous in the literature. In addition to being an exceedingly common estimation of central tendency, means also underlie many traditional statistical parameters, such as standard deviations and standard error, and traditional statistical tests such as t-tests and ANOVAs. Despite its common use, the mean performs poorly when distributions are not normal and is particularly sensitive to the tails of the distribution (Keselman et al. 2003; Wilcox et al. 2003). In contrast, methods such as trimmed means maintain good power when testing both normal and non-normal distributions (Wilcox et al. 1998). In this paper, means were replaced with the more robust trimmed means, which are calculated by rank ordering the data, removing the highest and lowest values, and calculating the mean of the remaining values. The number of highest and lowest values removed is based on the percent of trimming applied, with 20% trimming removing the most extreme 20% of the highest and lowest values. When trimmed means are used, the traditional standard error is replaced by the appropriate measure of standard error for trimmed means, which is the winsorized standard error ($S.E._w$), shown in Equation 1.

$$S.E._w = \frac{\sigma_w}{(1-\gamma_h-\gamma_l)\sqrt{n}}$$ Equation 1

where σ_w is the standard deviation of the winsorized data (i.e., values greater than that at the γ_h percentile are replaced by the value at the γ_h percentile and values less than that at the γ_l percentile are replaced by the value at the γ_l percentile), with the amount of winsorizing equal to the amount of trimming for the trimmed mean, γ_h is the percent of the highest values that are trimmed and γ_l is the percent of the lowest values that are trimmed when calculating the trimmed mean, and n is the total number of data points.

Standard deviation (σ) is traditionally calculated as

$$\sigma = \sqrt{\frac{\sum (x_i-\bar{x})^2}{n-1}}$$ Equation 2

where x_i is a particular data point, $\bar{x}$ is the mean, and n is the total number of data points. Because this equation includes the mean, it is very sensitive to even a single outlier. As a result, in this paper, the more robust measure S_n (Croux and Rousseeuw 1992; Rousseeuw and Croux 1993) was used:

$$S_c = c_n \cdot 1.19266 \cdot lomed_{i=1\ldots n}\{lomed_{j\neq i}|x_i - x_j|\}$$ Equation 3

where c_n is a correction factor from Croux and Rousseeuw (1992) that corrects for a bias that occurs when calculating S_n with small samples ($c_n = 1$ for all N>9 that are even; for N=6, used in some analyses in this paper, $c_n = 0.993$), and lomed is a variant of the median defined as the lower of the two middle-ranked values when there is an even number of values and the median when there is an odd number of values.

As an example of how the choice of traditional versus robust statistical techniques affects the estimation of a particular parameter, Figure 9 shows three distributions: A normal distribution with a mean of 0 and a S.D. of 2 (A), the same normal distribution with 10% of the data replaced by data sampled from a normal distribution with a mean of 0 and a S.D. of 10, resulting in a heavy-tailed distribution (B), and the original normal distribution with 10% of the data replaced with a log normal distribution, resulting in a skewed distribution (C). Importantly, the three distributions appear to be nearly identical, and it would be difficult to visually identify the distributions labeled B and C as non-normal. A simulation was conducted with each distribution generated 999 times, with 1000 data points per distribution. Statistical parameters were measured for each generated distribution, and the results from all simulations were ordered and the values bounding 95% of the data were determined. Since the distributions were generated with known means and standard deviations, it is possible to compare the parameter estimations to the true value of those parameters (i.e., the value used to generate the underlying normal distribution). The results of the simulation are shown in Table 11. As can be seen from the table, under normality the traditional parameter estimations are very accurate (i.e., close to the true value), but small deviations in the distribution can severely affect the traditional parameter estimations, much more so than the robust methods used in this paper.

Bootstrap Analyses

Bootstrap analyses were chosen rather than using traditional ANOVAs and t-tests because bootstrap analyses avoid the assumptions of normality and equal variance, which can greatly reduce power (Wilcox 1998; Wilcox and Keselman 2003). Instead they estimate parameters such as the trimmed mean by creating a bootstrap distribution generated by repeatedly sampling with replacement from the original dataset. This bootstrapping technique can be used with many kinds of analyses, as well as various measures of central tendencies (Keselman et al. 2008; Keselman et al. 2003; Wilcox et al. 1998) and is often more sensitive than traditional techniques.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

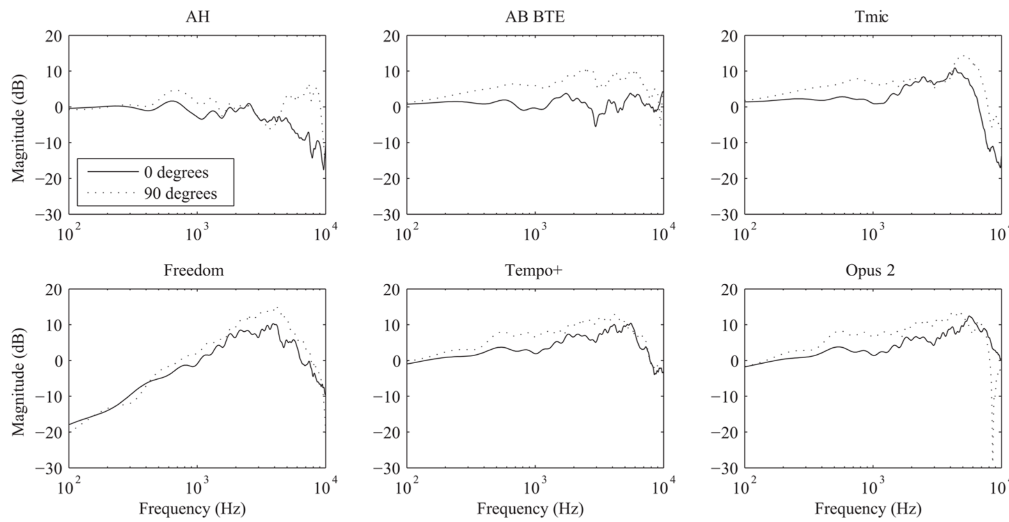

Figure 1.

Spectral characteristics of the HRTFs.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

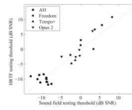

Figure 2.

Relationship between sound field testing and testing with the HRTF-processed stimuli for the Noise Side condition. The symbols labeled AH represent data from normal hearing individuals, who used the AH HRTF; all other symbols represent data from cochlear implant users. Each data point represents one participant and condition. Because the CI users (Freedom, Tempo+, and Opus 2 HRTFs) were tested with both Noise Left and Noise Right conditions, there are two data points for each of those participants, one for each condition. The acoustic hearing individuals were only tested in the Noise Right condition. The dashed line indicates equivalence between the two testing modalities.

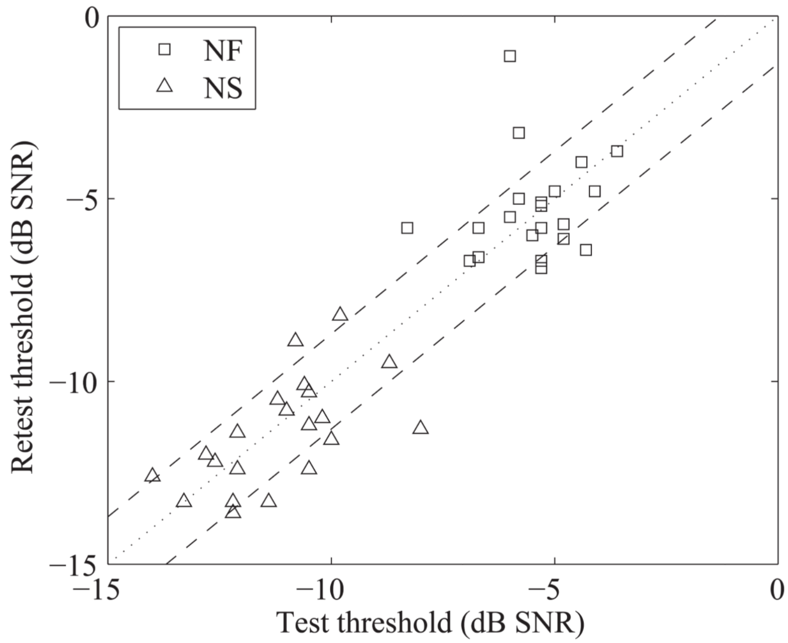

Figure 3.
Test-retest scores for Noise Front (NF) and Noise Side (NS) testing. Each data point represents one participant. The dotted line indicates test-retest equivalence. The parallel dashed lines indicate the measurement error.

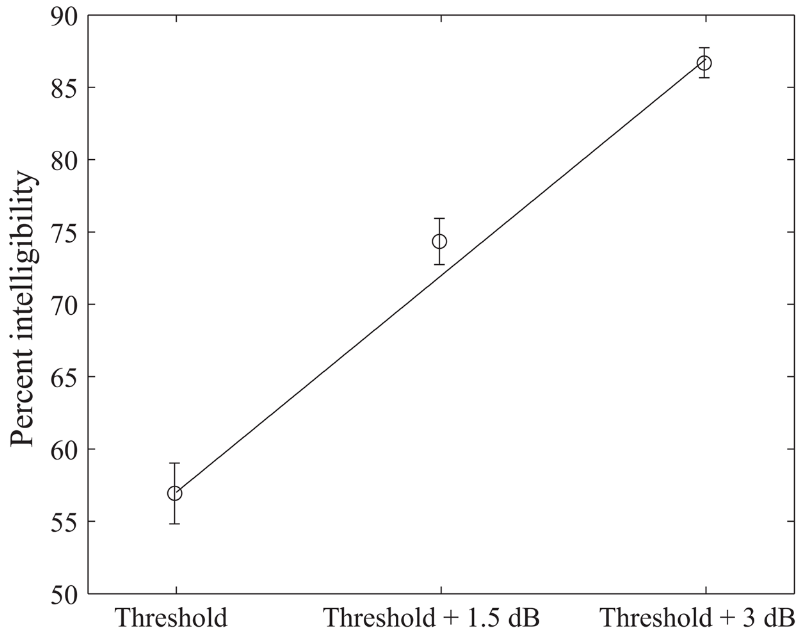

Figure 4.
Percent intelligibility as a function of signal-to-noise ratio along with the regression line indicating the relationship between the two. Each data point indicates the trimmed mean and winsorized standard error.

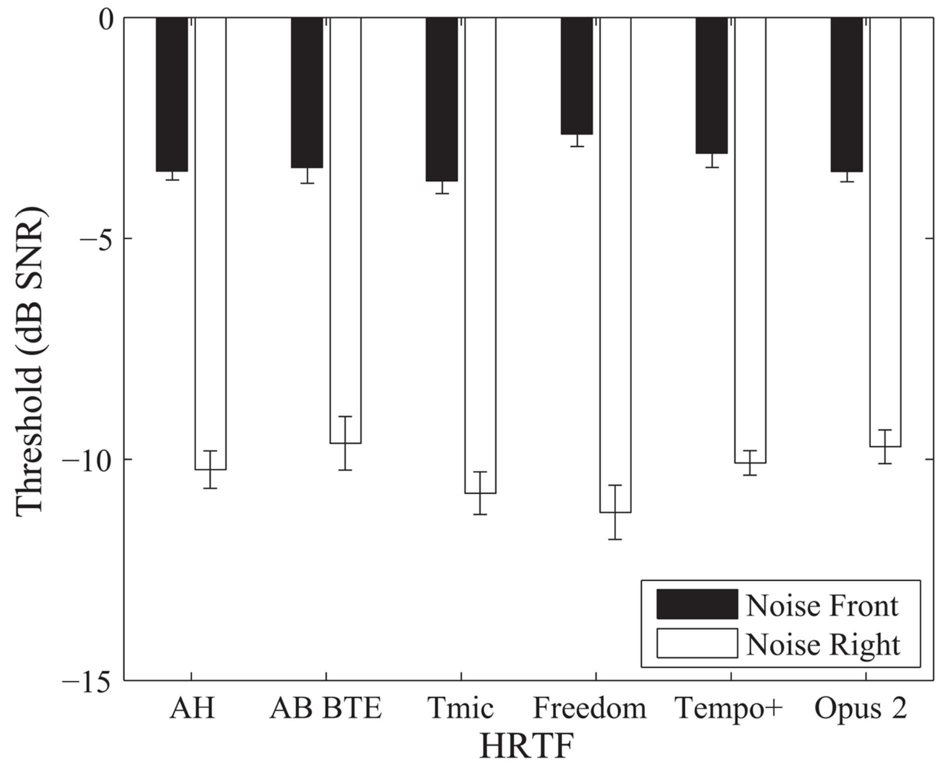

Figure 5.

Differences in performance on the Noise Front and Noise Right conditions for acoustic hearing individuals listening to stimuli processed by the various HRTFs. Bars represent trimmed means with winsorized standard errors.

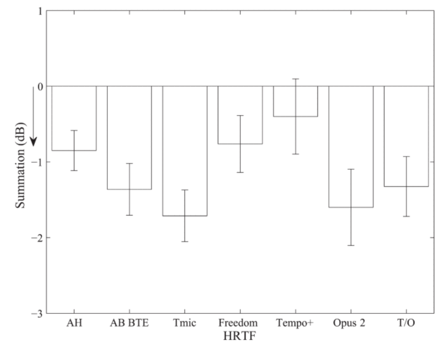

Figure 6.
Binaural summation for acoustic hearing individuals listening to stimuli processed by the various HRTFs. Bars represent trimmed means with winsorized standard errors. The arrow indicates that negative scores represent binaural summation, with a greater magnitude reflecting increased binaural summation.

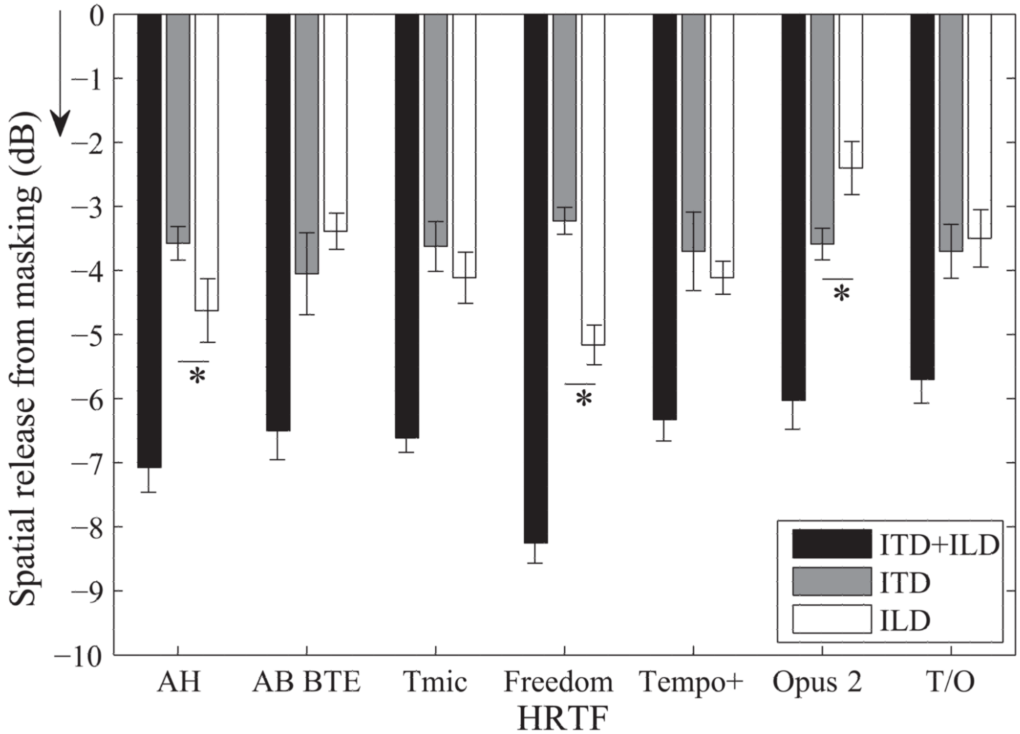

Figure 7.
Spatial release from masking for acoustic hearing individuals listening to stimuli processed by the various HRTFs, including modified HRTFs with either ITD or ILD cues preserved. Bars represent trimmed means with winsorized standard errors. Asterisks indicate a significant difference between performance using the ITD and ILD HRTFs. The arrow indicates that negative scores represent spatial release from masking, with a greater magnitude reflecting increased spatial release from masking.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

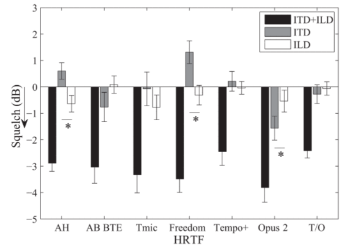

Figure 8.

Binaural squelch for acoustic hearing individuals listening to stimuli processed by the various HRTFs, including modified HRTFs with either ITD or ILD cues preserved. Bars represent trimmed means with winsorized standard errors. Asterisks indicate a significant difference between performance using the ITD and ILD HRTFs. The arrow indicates that negative scores represent binaural squelch, with a greater magnitude reflecting increased binaural squelch.

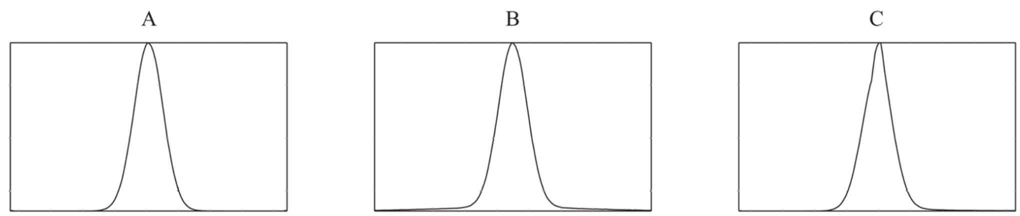

Figure 9.

Histograms of three types of distributions: A normal distribution with a mean of 0 and a S.D. of 2 (A); The same normal distribution with 10% of the data replaced by data sampled from a normal distribution with a mean of 0 and a S.D. of 10, resulting in a heavy-tailed distribution (B); The original normal distribution with 10% of the data replaced with a log normal distribution, resulting in a skewed distribution (C).

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table 1

Cochlear implant users' information.

Participant (gender, age)	Etiology (patient report)	Processor		Length of use (years)	
		Left	Right	Left	Right
F,62	Ototoxic	Cochlear Freedom	Cochlear Freedom	7	11
F, 42	Ototoxic	Cochlear Freedom	Cochlear Freedom	0.5	0.5
F, 82	Hereditary	Cochlear Freedom	Cochlear Freedom	16	0.5
F, 48	Unknown	Med-El Tempo+	Med-El Tempo+	6	6
M, 58	Mumps/Measles	Med-El Opus 2	Med-El Opus 2	1	1*
M, 68	Meniere's	Med-El Opus 2	Med-El Opus 2	2	0.5
F, 51	Unknown	Med-El Opus 2	Med-El Opus 2	6	6

*This participant originally was implanted on the right side three years before testing, but the device started to malfunction within three months, and was replaced approximately one year before testing.

Table 2

HRTFs used by each participant for Experiment 2 and 4.

Subject number	First HRTF tested	Second HRTF tested
1	Opus 2	Tempo+ *
2	T/O	Opus 2 *
3	Tempo+	AH*
4	AH	Tmic*
5	Tmic	Opus 2*
6	AB BTE	Freedom*
7	AH	Opus 2*
8	Freedom	AH*
9	AB BTE	Tempo+*
10	Opus 2	T/O*
11	Freedom	Tmic*
12	Opus 2	Tmic*
13	AB BTE	AH*
14	AH	Freedom*
15	AH	Tempo+*
16	AB BTE*	Freedom
17	T/O*	Tmic
18	T/O*	AH
19	Opus 2*	Freedom
20	Tempo+*	Freedom
21	Opus 2*	AB BTE
22	Tempo+*	Tmic
23	Tempo+*	T/O
24	Freedom*	Tempo+
25	Tmic*	Tempo+
26	Freedom*	Tmic
27	Tmic*	AB BTE
28	AH*	Opus 2
29	AB BTE*	Opus 2
30	AB BTE*	Tempo+
31	AH	AB BTE*

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Subject number	First HRTF tested	Second HRTF tested
32	AB BTE	T/O*
33	Tempo+	Opus 2*
34	Freedom	T/O*
35	Tmic	AB BTE*
36	Opus 2	Freedom*
37	T/O*	Tempo+
38	AB BTE*	T/O
39	AH*	Tmic
40	AH*	T/O
41	Freedom*	T/O
42	Tmic*	T/O

*HRTF used for test-retest reliability measurement. The PI function was determined using the HRTF not used to measure test-retest reliability.

Table 3

Threshold comparisons used to calculate binaural benefits.

	Available Binaural Cues		
	ITD+ILD	**ITD**	**ILD**
Binaural summation	$NF_{Bi} - NF_{Monaural}$		
Binaural squelch	$NS_{ITD+ILD}$ -$NS_{Contralateral}$	NS_{ITD} -$NS_{Contralateral}$	NS_{ILD} -$NS_{Contralateral}$
Spatial release from masking	$NS_{ITD+ILD}$ -NF_{Bi}	NS_{ITD} -NF_{Bi}	NS_{ILD} -NF_{Bi}

NF = Noise Front; NS = Noise Side; Bi = binaural, diotic presentation; Contralateral = monaural presentation, noise contralateral to implant; ITD +ILD = binaural presentation including ITD and ILD cues; ITD = binaural presentation with only ITD cues preserved; ILD = binaural presentation with only ILD cues preserved.

Table 4

Norms for the AH HRTF.

AH		Percentile													
	Condition	**5**	**10**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**75**	**80**	**90**	**95**	**S.D.**
Binaural	**Noise Front**	−3.1	−3.5	−3.8	−4.0	−4.1	−4.3	−4.5	−4.7	−5.0	−5.1	−5.2	−5.6	−5.9	0.8
	Noise Side	−9.9	−10.3	−10.8	−11.0	−11.1	−11.4	−11.7	−12.0	−12.3	−12.4	−12.6	−13.1	−13.5	1.1
Monaural	**Noise Front**	−2.6	−2.9	−3.3	−3.4	−3.6	−3.8	−4.0	−4.2	−4.5	−4.6	−4.7	−5.1	−5.4	0.8
	Noise Side$_{ipsilateral}$	−0.9	−1.3	−1.8	−2.0	−2.1	−2.4	−2.7	−2.9	−3.2	−3.4	−3.6	−4.1	−4.4	1.1
	Noise Side$_{contralateral}$	−7.1	−7.5	−8.0	−8.2	−8.3	−8.6	−8.9	−9.2	−9.5	−9.6	−9.8	−10.3	−10.7	1.1
	Noise Side$_{contralateral}$−Noise Front	−2.9	−3.3	−3.9	−4.1	−4.2	−4.6	−4.9	−5.2	−5.5	−5.7	−5.9	−6.4	−6.8	1.2
	Head shadow	−4.0	−4.5	−5.1	−5.3	−5.5	−5.8	−6.2	−6.5	−6.9	−7.1	−7.3	−7.9	−8.3	1.3
Binaural Benefit	**Spatial Release from Masking**	−5.2	−5.6	−6.0	−6.2	−6.4	−6.7	−6.9	−7.2	−7.5	−7.7	−7.8	−8.3	−8.7	1.1
	ITD Spatial Release from Masking	−2.2	−2.5	−2.9	−3.0	−3.1	−3.4	−3.6	−3.8	−4.0	−4.1	−4.3	−4.6	−4.9	0.8
	ILD Spatial Release from Masking	−2.3	−2.8	−3.4	−3.7	−3.9	−4.3	−4.6	−5.0	−5.4	−5.6	−5.8	−6.5	−7.0	1.4
	Summation	1.3	0.8	0.3	0.0	−0.2	−0.5	−0.8	−1.2	−1.5	−1.7	−2.0	−2.5	−3.0	1.3
	Squelch	−0.9	−1.4	−1.9	−2.1	−2.3	−2.6	−2.9	−3.2	−3.5	−3.7	−3.9	−4.4	−4.8	1.2
	ITD Squelch	2.6	2.1	1.6	1.4	1.2	0.9	0.6	0.3	0.0	−0.2	−0.4	−0.9	−1.4	1.2
	ILD Squelch	0.9	0.6	0.2	0.0	−0.1	−0.4	−0.6	−0.9	−1.1	−1.3	−1.4	−1.9	−2.2	1.0

All values are in dB.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 5

Norms for the AB BTE HRTF.

AB BTE		Percentile													
	Condition	**5**	**10**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**75**	**80**	**90**	**95**	**S.D.**
Binaural	**Noise Front**	−4.1	−4.4	−4.6	−4.7	−4.8	−5.0	−5.1	−5.3	−5.4	−5.5	−5.6	−5.9	−6.1	0.6
	Noise Side	−9.3	−9.8	−10.5	−10.8	−11.0	−11.4	−11.8	−12.2	−12.6	−12.9	−13.1	−13.8	−14.4	1.6
Monaural	**Noise Front**	−1.3	−1.8	−2.5	−2.8	−3.0	−3.4	−3.8	−4.2	−4.6	−4.9	−5.1	−5.8	−6.4	1.6
	Noise Side$_{ipsilateral}$	2.1	1.7	1.2	1.1	0.9	0.6	0.3	0.1	−0.2	−0.4	−0.6	−1.0	−1.4	1.1
	Noise Side$_{contralateral}$	−7.1	−7.5	−7.8	−8.0	−8.1	−8.3	−8.5	−8.7	−9.0	−9.1	−9.2	−9.6	−9.9	0.8
	Noise Side$_{contralateral}$- Noise Front	−2.8	−3.3	−3.9	−4.2	−4.4	−4.8	−5.1	−5.5	−5.9	−6.1	−6.3	−7.0	−7.5	1.4
	Head shadow	−7.5	−7.9	−8.3	−8.5	−8.6	−8.9	−9.1	−9.3	−9.6	−9.7	−9.9	−10.3	−10.7	1.0
Binaural Benefit	**Spatial Release from Masking**	−4.1	−4.7	−5.3	−5.5	−5.7	−6.1	−6.5	−6.9	−7.3	−7.5	−7.7	−8.3	−8.9	1.4
	ITD Spatial Release from Masking	−1.5	−2.1	−2.8	−3.1	−3.4	−3.8	−4.2	−4.7	−5.1	−5.4	−5.6	−6.4	−7.0	1.7
	ILD Spatial Release from Masking	−2.0	−2.3	−2.7	−2.8	−2.9	−3.2	−3.4	−3.6	−3.8	−4.0	−4.1	−4.5	−4.8	0.8
	Summation	0.9	0.4	−0.3	−0.5	−0.7	−1.1	−1.5	−1.8	−2.2	−2.4	−2.7	−3.3	−3.8	1.4
	Squelch	−0.1	−0.7	−1.5	−1.8	−2.1	−2.6	−3.0	−3.5	−4.0	−4.2	−4.5	−5.3	−6.0	1.8
	ITD Squelch	1.8	1.2	0.5	0.2	−0.0	−0.5	−0.9	−1.3	−1.8	−2.0	−2.3	−3.1	−3.7	1.7
	ILD Squelch	2.6	2.1	1.4	1.1	0.9	0.5	0.1	−0.3	−0.7	−1.0	−1.2	−1.9	−2.5	1.6

All values are in dB.

Table 6

Norms for the Tmic HRTF.

Tmic		Percentile													
	Condition	**5**	**10**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**75**	**80**	**90**	**95**	**S.D.**
Binaural	**Noise Front**	−3.6	−4.0	−4.5	−4.7	−4.8	−5.1	−5.4	−5.7	−6.0	−6.1	−6.3	−6.8	−7.2	1.1
	Noise Side	−10.2	−10.7	−11.3	−11.5	−11.7	−12.0	−12.4	−12.7	−13.1	−13.3	−13.5	−14.0	−14.5	1.3
Monaural	**Noise Front**	−1.9	−2.3	−2.8	−3.0	−3.1	−3.4	−3.7	−4.0	−4.3	−4.4	−4.6	−5.1	−5.5	1.1
	Noise Side$_{ipsilateral}$	1.7	1.1	0.4	0.2	−0.0	−0.5	−0.9	−1.3	−1.7	−1.9	−2.2	−2.8	−3.4	1.6
	Noise Side$_{contralateral}$	−6.7	−7.2	−7.7	−7.9	−8.1	−8.4	−8.7	−9.0	−9.3	−9.5	−9.7	−10.2	−10.7	1.2
	Noise Side$_{contralateral}$- Noise Front	−3.8	−4.0	−4.3	−4.4	−4.5	−4.6	−4.8	−5.0	−5.1	−5.2	−5.3	−5.6	−5.8	0.6
	Head shadow	−6.5	−6.8	−7.2	−7.4	−7.5	−7.8	−8.0	−8.3	−8.6	−8.7	−8.9	−9.3	−9.6	1.0
Binaural Benefit	**Spatial Release from Masking**	−5.4	−5.7	−6.0	−6.2	−6.3	−6.5	−6.7	−6.9	−7.2	−7.3	−7.4	−7.8	−8.1	0.8
	ITD Spatial Release from Masking	−1.2	−1.7	−2.3	−2.6	−2.8	−3.2	−3.5	−3.9	−4.3	−4.5	−4.7	−5.4	−5.9	1.4
	ILD Spatial Release from Masking	−2.0	−2.4	−3.0	−3.2	−3.4	−3.8	−4.1	−4.4	−4.8	−5.0	−5.2	−5.8	−6.3	1.3
	Summation	−0.1	−0.5	−0.9	−1.1	−1.2	−1.5	−1.7	−2.0	−2.2	−2.4	−2.5	−2.9	−3.3	1.0
	Squelch	0.4	−0.5	−1.5	−1.8	−2.2	−2.8	−3.4	−3.9	−4.6	−4.9	−5.3	−6.3	−7.1	2.3
	ITD Squelch	3.1	2.4	1.5	1.2	0.9	0.4	−0.1	−0.6	−1.1	−1.4	−1.7	−2.5	−3.2	1.9
	ILD Squelch	1.6	1.1	0.4	0.2	−0.0	−0.4	−0.8	−1.1	−1.5	−1.7	−2.0	−2.6	−3.1	1.4

All values are in dB.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 7

Norms for the Freedom HRTF.

Freedom		Percentile													
	Condition	**5**	**10**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**75**	**80**	**90**	**95**	**S.D.**
Binaural	**Noise Front**	−2.8	−3.1	−3.6	−3.8	−4.0	−4.3	−4.5	−4.8	−5.1	−5.2	−5.4	−5.9	−6.3	1.1
	Noise Side	−10.3	−10.8	−11.4	−11.7	−11.9	−12.3	−12.6	−13.0	−13.4	−13.6	−13.8	−14.5	−15.0	1.4
Monaural	**Noise Front**	−3.1	−3.2	−3.4	−3.4	−3.5	−3.6	−3.7	−3.8	−3.9	−3.9	−4.0	−4.1	−4.3	0.4
	Noise Side$_{ipsilateral}$	0.4	0.1	−0.3	−0.5	−0.6	−0.9	−1.1	−1.4	−1.6	−1.8	−1.9	−2.4	−2.7	1.0
	Noise Side$_{contralateral}$	−7.3	−7.7	−8.1	−8.3	−8.5	−8.8	−9.1	−9.3	−9.6	−9.8	−10.0	−10.4	−10.8	1.1
	Noise Side$_{contralateral}$- Noise Front	−3.1	−3.6	−4.2	−4.4	−4.6	−5.0	−5.3	−5.6	−6.0	−6.2	−6.4	−7.0	−7.5	1.3
	Head shadow	−5.4	−6.0	−6.7	−6.9	−7.2	−7.6	−8.0	−8.4	−8.8	−9.0	−9.3	−10.0	−10.5	1.6
Binaural Benefit	**Spatial Release from Masking**	−6.9	−7.2	−7.5	−7.7	−7.8	−8.0	−8.3	−8.5	−8.7	−8.8	−9.0	−9.3	−9.6	0.8
	ITD Spatial Release from Masking	−1.7	−2.0	−2.4	−2.6	−2.7	−3.0	−3.2	−3.5	−3.7	−3.9	−4.0	−4.4	−4.8	1.0
	ILD Spatial Release from Masking	−3.8	−4.1	−4.5	−4.6	−4.7	−5.0	−5.2	−5.4	−5.6	−5.7	−5.9	−6.2	−6.5	0.8
	Summation	1.2	0.8	0.2	0.0	−0.1	−0.5	−0.8	−1.1	−1.4	−1.6	−1.8	−2.3	−2.7	1.2
	Squelch	−0.5	−1.2	−2.0	−2.3	−2.5	−3.0	−3.5	−3.9	−4.4	−4.7	−5.0	−5.8	−6.4	1.8
	ITD Squelch	3.3	2.8	2.3	2.1	1.9	1.6	1.3	1.0	0.7	0.5	0.3	−0.2	−0.6	1.2
	ILD Squelch	1.6	1.2	0.7	0.5	0.3	−0.0	−0.3	−0.6	−0.9	−1.1	−1.3	−1.8	−2.3	1.2

All values are in dB.

Table 8

Norms for the Tempo+ HRTF.

Tempo+		Percentile													
	Condition	5	10	20	25	30	40	50	60	70	75	80	90	95	S.D.
Binaural	Noise Front	−2.8	−3.3	−4.0	−4.3	−4.5	−4.9	−5.3	−5.7	−6.1	−6.4	−6.6	−7.3	−7.9	1.6
	Noise Side	−9.2	−9.7	−10.3	−10.6	−10.8	−11.2	−11.5	−11.9	−12.3	−12.5	−12.7	−13.4	−13.9	1.4
Monaural	Noise Front	−2.7	−3.1	−3.7	−3.9	−4.0	−4.4	−4.7	−5.0	−5.3	−5.5	−5.7	−6.2	−6.6	1.2
	Noise Side$_{ipsilateral}$	1.0	0.6	0.2	−0.0	−0.2	−0.5	−0.7	−1.0	−1.3	−1.5	−1.6	−2.1	−2.5	1.1
	Noise Side$_{contralateral}$	−7.0	−7.5	−8.1	−8.3	−8.5	−8.8	−9.2	−9.5	−9.9	−10.1	−10.3	−10.9	−11.3	1.3
	Noise Side$_{contralateral}$-Noise Front	−3.1	−3.4	−3.7	−3.9	−4.0	−4.2	−4.5	−4.7	−4.9	−5.0	−5.2	−5.5	−5.8	0.8
	Head shadow	−6.5	−6.9	−7.4	−7.6	−7.7	−8.0	−8.3	−8.6	−8.9	−9.0	−9.2	−9.7	−10.1	1.1
Binaural Benefit	Spatial Release from Masking	−4.4	−4.8	−5.3	−5.5	−5.7	−6.0	−6.3	−6.6	−7.0	−7.1	−7.3	−7.9	−8.3	1.2
	ITD Spatial Release from Masking	−0.6	−1.2	−2.0	−2.3	−2.6	−3.0	−3.5	−4.0	−4.4	−4.7	−5.0	−5.8	−6.4	1.8
	ILD Spatial Release from Masking	−2.2	−2.6	−3.1	−3.3	−3.5	−3.8	−4.1	−4.4	−4.7	−4.9	−5.1	−5.6	−6.1	1.2
	Summation	2.7	2.0	1.2	0.9	0.7	0.2	−0.3	−0.7	−1.2	−1.5	−1.8	−2.6	−3.2	1.8
	Squelch	0.5	−0.2	−0.9	−1.2	−1.5	−2.0	−2.5	−2.9	−3.4	−3.7	−4.0	−4.7	−5.4	1.8
	ITD Squelch	2.4	1.9	1.3	1.1	0.9	0.5	0.2	−0.1	−0.5	−0.7	−0.9	−1.5	−1.9	1.3
	ILD Squelch	1.6	1.2	0.8	0.7	0.5	0.3	0.0	−0.2	−0.5	−0.6	−0.8	−1.2	−1.6	1.0

All values are in dB.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table 9

Norms for the Opus 2 HRTF.

Opus 2		Percentile													
	Condition	**5**	**10**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**75**	**80**	**90**	**95**	**S.D.**
Binaural	**Noise Front**	−3.8	−4.1	−4.6	−4.8	−5.0	−5.3	−5.5	−5.8	−6.1	−6.2	−6.4	−6.9	−7.3	1.1
	Noise Side	−8.8	−9.3	−10.0	−10.2	−10.4	−10.8	−11.2	−11.5	−11.9	−12.1	−12.4	−13.0	−13.5	1.4
Monaural	**Noise Front**	−3.2	−3.4	−3.6	−3.7	−3.8	−3.9	−4.0	−4.1	−4.3	−4.3	−4.4	−4.6	−4.8	0.5
	Noise Side$_{ipsilateral}$	2.1	1.4	0.5	0.2	−0.1	−0.6	−1.1	−1.6	−2.1	−2.4	−2.7	−3.5	−4.2	1.9
	Noise Side$_{contralateral}$	−4.7	−5.3	−6.0	−6.3	−6.6	−7.0	−7.4	−7.9	−8.3	−8.6	−8.9	−9.6	−10.2	1.7
	Noise Side$_{contralateral}$- Noise Front	−0.9	−1.5	−2.2	−2.5	−2.7	−3.2	−3.6	−4.0	−4.5	−4.7	−5.0	−5.8	−6.4	1.7
	Head shadow	−4.8	−5.1	−5.5	−5.7	−5.8	−6.1	−6.3	−6.6	−6.8	−7.0	−7.1	−7.6	−7.9	1.0
Binaural Benefit	**Spatial Release from Masking**	−4.3	−4.6	−5.1	−5.3	−5.5	−5.8	−6.0	−6.3	−6.6	−6.7	−6.9	−7.4	−7.8	1.1
	ITD Spatial Release from Masking	−2.3	−2.6	−2.9	−3.0	−3.1	−3.3	−3.5	−3.7	−3.9	−4.0	−4.1	−4.4	−4.7	0.7
	ILD Spatial Release from Masking	−0.4	−0.9	−1.4	−1.6	−1.8	−2.1	−2.4	−2.7	−3.0	−3.2	−3.4	−3.9	−4.4	1.2
	Summation	0.6	0.1	−0.5	−0.7	−0.9	−1.3	−1.6	−1.9	−2.3	−2.5	−2.7	−3.3	−3.8	1.3
	Squelch	−0.7	−1.4	−2.2	−2.5	−2.8	−3.3	−3.8	−4.3	−4.8	−5.1	−5.4	−6.3	−7.0	1.9
	ITD Squelch	1.0	0.4	−0.3	−0.5	−0.7	−1.2	−1.6	−2.0	−2.4	−2.6	−2.9	−3.5	−4.1	1.6
	ILD Squelch	1.6	1.1	0.6	0.3	0.2	−0.2	−0.5	−0.9	−1.2	−1.4	−1.6	−2.2	−2.7	1.3

All values are in dB.

Table 10

Norms for the Tempo+ HRTF on one side and the Opus 2 HRTF on the other side.

T/O		Percentile													
	Condition	**5**	**10**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**75**	**80**	**90**	**95**	**S.D.**
Binaural	**Noise Front**	−3.5	−3.8	−4.2	−4.3	−4.4	−4.7	−4.9	−5.1	−5.3	−5.4	−5.6	−5.9	−6.2	0.8
	Noise Side	−8.6	−9.1	−9.6	−9.8	−10.0	−10.3	−10.6	−10.9	−11.2	−11.4	−11.6	−12.1	−12.6	1.2
Binaural Benefit	**Spatial Release from Masking**	−3.9	−4.3	−4.8	−5.0	−5.1	−5.4	−5.7	−6.0	−6.3	−6.4	−6.6	−7.1	−7.5	1.1
	ITD Spatial Release from Masking	−1.7	−2.2	−2.7	−2.9	−3.1	−3.4	−3.7	−4.0	−4.3	−4.5	−4.7	−5.2	−5.7	1.2
	ILD Spatial Release from Masking	−0.9	−1.5	−2.2	−2.5	−2.7	−3.1	−3.5	−3.9	−4.3	−4.5	−4.8	−5.5	−6.1	1.6
Binaural Benefit (re Tempo+)	**Summation**	1.3	0.9	0.4	0.2	0.1	−0.2	−0.5	−0.8	−1.1	−1.2	−1.4	−1.9	−2.3	1.1
	Squelch	−0.9	−1.2	−1.6	−1.7	−1.9	−2.1	−2.3	−2.5	−2.7	−2.9	−3.0	−3.4	−3.7	0.8
	ITD Squelch	0.7	0.6	0.3	0.3	0.2	0.1	−0.1	−0.2	−0.3	−0.4	−0.4	−0.7	−0.8	0.5
	ILD Squelch	1.6	1.2	0.7	0.6	0.4	0.1	−0.2	−0.4	−0.7	−0.9	−1.0	−1.5	−1.9	1.1
Binaural Benefit (re Opus 2)	**Summation**	−0.6	−0.9	−1.4	−1.5	−1.7	−1.9	−2.1	−2.4	−2.6	−2.8	−2.9	−3.4	−3.7	1.0
	Squelch	0.0	−0.6	−1.2	−1.5	−1.7	−2.1	−2.5	−2.9	−3.3	−3.6	−3.8	−4.5	−5.1	1.5
	ITD Squelch	1.5	1.0	0.4	0.2	0.0	−0.3	−0.7	−1.0	−1.3	−1.5	−1.7	−2.3	−2.8	1.3
	ILD Squelch	1.4	1.1	0.7	0.6	0.5	0.2	0.0	−0.2	−0.4	−0.5	−0.7	−1.0	−1.3	0.8

All values are in dB.

Table 11

95% confidence intervals of estimates of traditional and robust statistical parameters for simulations of various types of distributions.

Statistic	Traditional statistic	True value	Estimate for normal distribution	Estimate for mixed normal, heavy tailed	Estimate for mixed normal, asymmetric
Mean		0	(−.13, .12)	(−.22, .23)	(.29, 1.76)
Trimmed mean	Mean	0	(−.14, .13)	(−.14, .14)	(.04, .29)
S.D.		2	(1.91, 2.08)	(3.30, 4.06)	(2.80, 32.63)
S_n	S.D.	2	(1.88, 2.11)	(2.14, 2.41)	(1.84, 2.09)
S.E.		.06	(.06, .07)	(.10, .13)	(.09, 1.03)
Winsorized S.E.	S.E.	.06	(.06, .07)	(.08, .09)	(.06, .07)