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Comparison of methods for evaluating horizontal-plane sound localization

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COMPARISON OF METHODS FOR EVALUATING HORIZONTAL-PLANE SOUND LOCALIZATION

by

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Abstract: This study compared three methods for evaluating sound localization abilities in normal hearing listeners and listeners with unilateral hearing loss. Rear-facing localization performance with the Direct Connect (DC) Binaural Test System was compared to front- and rear-facing soundfield localization. Behavioral chance performance in rear-facing DC and soundfield testing was established, as well as test-retest reliability for all three localization test setups.

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ABBREVIATIONS

Age of Onset (AAO)

CI: Cochlear Implant

dB: Decibel

DC: Direct Connect

HL: Hearing Loss

HRTF: Head-Related Transfer Function

ILD: Interaural Level Difference

ITD: Interaural Timing Difference

NH: Normal Hearing

SF-FF: Soundfield Front-Facing

SF-RF: Soundfield Rear-Facing

SPL: Sound Pressure Level

SSD: Single-Sided Deaf

UHL: Unilateral Hearing Loss

WUSM: Washington University School of Medicine

INTRODUCTION

The integration of information that the brain receives from the two ears, or binaural hearing, is essential for localizing sound. Binaural hearing allows the listener to take advantage of auditory cues necessary for horizontal sound localization, such as interaural differences in time and level. Cues provided by interaural timing differences (ITDs) are useful for low frequency sounds (<1500 Hertz [Hz]) and interaural level differences (ILDs) provide cues for high frequency sounds (>1500 Hz) (Rayleigh, 1907; Middlebrooks & Green, 1991). The auditory system encodes information about sound direction by combining and comparing incoming ITD and ILD information from the two ears.

Patients with asymmetric or unilateral hearing loss (UHL) receive degraded or absent binaural cues and often demonstrate decreased sound localization abilities in the horizontal plane (Häusler, Colburn, & Marr, 1983; Slattery & Middlebrook, 1994; Van Wanrooij & Van Opstal, 2004; Firszt, Reeder, Dwyer, Burton, & Holden, 2015). While patients with UHL by definition have hearing abilities that preclude them from traditional cochlear implant (CI) candidacy, recent studies have looked at whether patients with UHL could benefit from cochlear implantation. Studies of patients with asymmetric or UHL receiving a cochlear implant in the poorer hearing ear have shown improved sound localization abilities, in contrast to performance with other UHL treatment options (Arndt et al., 2010; Firszt, Holden, Reeder, Cowdry, & King, 2012a; Firszt, Holden, Reeder, Waltzman, & Arndt, 2012b; Dorman et al., 2015; Cabral Junior, Pinna, Alves, Malerbi, & Bento, 2015).

Sound localization plays an important role in individuals' abilities to interact safely and accurately with their environment. While the importance of sound localization for every day function is well known, there are challenges to evaluating sound localization in a clinical setting.

Testing localization in the soundfield requires equipment and dedicated space that few clinical CI programs have available. An alternative to soundfield localization testing is technology that incorporates signals based on head-related transfer functions (HRFTs) to simulate binaural cues. The Direct Connect (DC) Binaural Test System presents direct electrical input to the CI via the auxiliary input jack on the sound processor, or acoustic input via insert earphones for normal hearing (NH) listeners (Chan et al., 2008). Aronoff et al. (2012) reported that performance on rear-facing soundfield and direct connect localization tasks were comparable for both CI and (NH) participants.

The aim of this study was to compare sound localization results obtained with the Washington University School of Medicine (WUSM) soundfield system to results in the same individuals using the Direct Connect Binaural Test System in two hearing groups: bilateral NH and UHL listeners. Previous WUSM sound localization studies have assessed localization performance in the soundfield only (Potts, Skinner, Litovsky, Strube, & Kuk, 2009; Firszt et al., 2012a; Reeder, Firszt, Holden, & Strube, 2014). Of particular interest was the relation between localization performance with the loudspeaker array arranged in an arc in front of the participant (the WUSM system test setup) and behind the participants. Also of interest was behavioral chance-level performance on localization to the rear of the participants, for both the WUSM soundfield and DC systems. Chance-level performance for the WUSM system with the participant facing the 15 loudspeaker array (140˚) is 59° (Firszt et al., 2015), and is unknown for the DC system and the WUSM soundfield system with the participant facing away from the loudspeaker array. In addition, to better interpret participant results, especially for longitudinal studies, it was important to determine test-retest performance on all localization tasks.

While the DC system was designed, in part, to evaluate localization abilities in CI users, there is still much to be learned about its reliability and accuracy in evaluating localization abilities in NH listeners and listeners with UHL. It is for this reason that the scope of this study was restricted to evaluating the DC system in relation to the two previously mentioned hearing groups, with future efforts expanding to SSD-CI recipients.

METHODS

All participants provided informed consent in compliance with the guidelines approved by the Human Research Protection Office at Washington University in St. Louis, MO, USA. Study procedures received institutional review board (IRB) approval through the Human Research Protection Office at Washington University in St. Louis (ID# 201511044). Participants were compensated for their time and travel.

Twenty-four adults ages 23 - 79 years participated; twelve adults with NH (mean age 51.9 years, standard deviation [SD] 12.2; 5 males, 7 females) and twelve adults with UHL (mean age 52.3 years, SD 20.4; 5 males, 7 females). For the purposes of this study, NH was defined as having an air conduction 4 frequency pure-tone average (4fPTA: .5, 1, 2, and 4k Hz) of 25 dB HL or less. NH participants had a mean 4fPTA of 13.1 (SD 6.4). Table 1 shows demographic information for the NH group. UHL participants had a mean 4fPTA of 13.0 (SD 11.2) in the better hearing ear and a moderate to profound hearing loss (mean 101.0, SD 17.2) in the other ear. Figures 1 and 2 display mean (+/-1 SD) audiometric air conduction thresholds for NH and UHL participants, respectively. Mean length of deafness for UHL participants was 27.6 years (range 1 – 79 years); 3 of the 12 participants were pre-lingually deafened. Table 2 shows demographic information for individual UHL participants.

Experiment 1

Participants were tested over the course of two test sessions, with a minimum of two weeks between sessions. Each session was 1.5 hours in length.

Hearing Thresholds.

Audiometric air conduction thresholds were obtained (unless a hearing test obtained within 6 months was available) for both ears of NH participants and for the NH ear of UHL participants using insert earphones from 250-8000 Hz. For UHL participants, thresholds obtained during previous studies that identified them as having a unilateral hearing loss were used in lieu of re-testing the poorer ear.

Front-facing soundfield localization.

Participants were seated facing a 15 loudspeaker array in a 140° arch (Figure 3, Panel A). Loudspeakers were 10° apart and participants sat facing the center loudspeaker (#8) at 0° azimuth. Loudspeakers were numbered from #1 (-70°) to #15 (70°) and participants were unaware that some loudspeakers were inactive. One hundred consonant-nucleus-consonant (CNC) words were presented pseudo-randomly at 55 dB SPL (roved 6 dB, in 2 dB steps), preceded by the carrier "ready." The 10 active loudspeaker locations were ±70°, ±50°, ±30°, ±20°, and ±10°. Participants were asked to identify the loudspeaker source by number, and were allowed to turn their head towards the perceived sound source once stimuli presentation began. Twelve practice trials were presented prior to test administration and no feedback was provided during testing.

Rear-facing soundfield localization.

The loudspeaker set-up for rear-facing testing was identical to front-facing, except the participant was turned 180° (Figure 3, Panel B). One hundred CNC words were again presented at 55 dB SPL (roved 6 dB, in dB steps). In the rear-facing set-up, loudspeakers were arranged from #1 (-110°) to #15 (110°) and the participant faced an inactive loudspeaker placed at 180° azimuth. Active loudspeaker locations for rear-facing localization were ±110°, ±130°, ±150°, ±160°, and ±170°. Participants were again asked to identify the loudspeaker source by number and were allowed to turn their head once stimuli presentation began, but not a full head turn to visualize the loudspeakers. A numbered figure of the loudspeaker array was provided to the participant to aid in source loudspeaker identification. Twelve practice trials were presented prior to test administration and no feedback was provided during testing.

Direct Connect (DC) system localization.

DC System localization testing was administered using insert earphones for the NH participants and the better hearing ear of the UHL participants. Stimuli were two presentations of a broadband impulse noise (similar to a gunshot), after which the participants were asked to identify the location from which the stimuli originated. Stimuli were presented pseudo-randomly from 12 virtual locations to the rear of the participant, numbered from #1 (97.5°) to #12 (262.5°) and spaced 15° apart. After twelve practice trials, 96 presentations (eight blocks of 12) were administered at 55 dB SPL (roved as designed by the software for each specific HRTF). Participants were given a numbered rear-facing localization diagram to aid in virtual sound source localization (Figure 4). No feedback was provided.

Experiment 2

Participants included ten adults (18 years or older) with unspecified hearing abilities. Testing was completed in a single session and lasted approximately 1 hour.

Chance rear-facing soundfield localization.

Chance rear-facing soundfield localization set-up was identical to rear-facing soundfield localization but without sound. Participants were instructed to guess the source location as each inaudible word was “presented”. A small hand-held bone oscillator was used to cue to participants to guess. One hundred presentations were cued to the participants, after the administration of twelve practice trials. No feedback was provided.

Chance DC system localization.

Chance DC system localization set-up was identical to DC system localization but without sound or earphones. Participants were again given a figure of 12 virtual loudspeakers and visually cued to guess a loudspeaker number by the examiner (wearing earphones). After twelve practice trials, 96 presentations (eight blocks of 12) were administered with no feedback.

RESULTS

Mean chance performance in Root-Mean-Square (RMS) error score for the WUSM soundfield rear-facing localization task was 60.5° (range 55.3 – 67.0, SD 3.5). This finding was comparable to chance level performance in the front-facing condition with the WUSM soundfield system of 58.9°, as reported by Firszt et al (2015). Mean chance performance for rear-facing localization with the Direct Connect system was 69.5° (range 63.0 – 73.0, SD 3.1).

Figures 5 and 6 display mean NH and UHL group RMS error scores, respectively, for visits 1 and 2. A paired sample t-test found no significant differences between test and retest RMS error scores, in any test setup, for the NH ($p > 0.05$) or UHL ($p > 0.05$) groups. Since test-retest scores for both groups were similar, performance scores averaged across test sessions were used in the following analyses.

An independent-samples t-test was conducted to compare mean RMS error scores for the two hearing groups. There were significant differences in the mean scores of the NH and UHL groups for all three localization test setups: 1) SF-FF $t(11.69) = -6.9$, $p < 0.001$; 2) SF-RF $t(12.25) = -8.37$, $p < 0.001$; 3) DC-RF $t(11.85) = -9.12$, $p < 0.001$. These results suggested that group differences were present in all testing conditions, and further analysis was performed on each hearing group separately. The boxplots in Figure 7 represent the first quartile, median, and third quartile of the data distribution of individual NH and UHL participants, with whiskers representing the max and min RMS error scores for each test setup.

Figures 8 and 9 display individual RMS error score distributions for each test setup, for NH and UHL participants, respectively. A one-way ANOVA was conducted for each hearing group, to compare RMS error scores between soundfield front-facing, soundfield rear-facing, and Direct Connect rear-facing localization. There was a significant effect of test setup on localization performance (in RMS error scores) at the $p < 0.001$ level for the three localization test setups for the NH group [$F(2, 22) = 62.44$, $p < 0.001$] and the UHL group [$F(2, 22) = 18.24$, $p < 0.001$]. Post hoc pairwise comparisons indicated that for the NH group there was a sig difference in RMS error scores between each of the three test setups ($ps < 0.001$) where as for the UHL group there was a significant difference between DC-RF and the two SF test setups (DC-RF vs. SF-FF, $p < 0.001$; DC-RF vs SF-RF, $p < 0.05$) but not between the two SF test setups ($p > 0.05$).

Pearson product-moment correlation coefficient was computed to assess the relationships between participant factors, localization performance, and test setups. For the NH group, there was a positive correlation between age and hearing, or 4fPTA [right ear ($r = 0.65$, $p < 0.05$), left ear ($r = 0.66$, $p < 0.05$)]. Neither age nor hearing, however, was correlated with localization performance. For the UHL group, there was a positive correlation between age and hearing in the better ear ($r = 0.66$, $p < 0.05$), age and SF-FF RMS error score ($r = 0.8$, $p < 0.01$) and age and SF-RF RMS error score ($r = 0.67$, $p < 0.05$). The relationships between age and SF-FF and SF-RF RMS error scores are shown in Figures 10 and 11, respectively. There was a relationship between 4fPTA in the better hearing ear and SF-FF ($r = 0.58$, $p < 0.05$), SF-RF ($r = 0.597$, $p < 0.05$), and DC-RF ($r = 0.64$, $p < 0.05$) RMS error scores. A positive correlation as found between age of onset and SF-FF ($r = 0.61$, $p < 0.05$) and DC-RF RMS error scores ($r = 0.80$, $p < 0.01$). Figure 12 displays the relationship between age of onset and DC-RF localization scores for the UHL group. For the NH group, no significant relationships between localization scores on any test setups were found ($p > 0.05$). Figure 13 displays the relationship between SF-RF and DC-RF for the NH group. A positive correlation in localization scores was found between all test setups for the UHL group: 1) SF-FF and SF-RF ($r = 0.79$, $p < 0.01$); 2) SF-FF and DC-RF ($r = 0.79$, $p <$

0.01); 3) SF-RF and DC-RF ($r = 0.80$, $p < 0.01$). The relationship between SF-RF and DC-RF for the UHL group is displayed in Figure 14.

A paired-samples t-test was conducted to compare RMS error scores obtained in the soundfield test setups (SF-FF and SF-RF) at the side of the right and left ears for the NH group, and at the side of the better and poorer hearing ears for the UHL group. There was no significant difference in scores for right and left sides in the NH group for SF-FF ($p > 0.05$) or SF-RF ($p > 0.05$). For the UHL group, difference in RMS error scores in the SF-RF test setup for the better hearing side and poorer hearing sides approached significance; $t(11) = 2.14$, $p = 0.056$. No significant difference between better and poorer hearing sides for the SF-FF test setup for the UHL group ($p > 0.05$). Figure 15 displays the effect of side in SF-FF and SF-RF test setups for the UHL and NH groups.

DISCUSSION

The aim of this study was to compare sound localization results obtained with the WUSM soundfield system to results in the same individuals using the DC System. Additional aims included evaluating the test-retest reliability of the WUSM and DC systems, and evaluating behavioral chance performance for the WUSM system in the rear-facing test setup and for the DC system.

Accuracy in sound localization with a defined set of sound source locations is quantified as RMS error in degrees. Behavioral chance performance for the WUSM system in the rear-facing test setup, measured in RMS error, was comparable to previously reported performance in the front-facing test setup of 58.9° (Firszt et al., 2015). Establishing chance behavioral performance for the WUSM system in each of these test setups provides a framework for interpreting localization test results in patients with hearing loss. Chance behavioral performance with the rear-facing DC system yielded a greater mean RMS error (69.5°), as compared to the WUSM rear-facing soundfield system (60.5°). This difference in RMS error could be attributed to differences in loudspeaker array between the DC and WUSM systems. The WUSM system utilized 15 loudspeakers, spaced 10° apart, whereas the DC system simulated loudspeakers that were 15° apart and only represented 12 loudspeaker locations. With the DC system, speaker choices were more limited than the WUSM system, and incorrectly identifying a loudspeaker as the sound source yielded a greater discrepancy in degrees.

Comparison of test and retest performance for both hearing groups, in all localization test setups showed that localization abilities, as measured by our study, to be reliable. This is an important finding in that localization ability can be measured in a clinical setting without repeated visits to ensure accuracy. This finding also has implications for monitoring performance in regards to treatment and intervention.

Analysis of RMS error scores between test setups showed a significant difference in performance between all three test setups for the NH group, and between the WUSM and DC system for the UHL group. For the NH group, these differences might be attributed to 1) the loss of direct visual input to aid localization in the rear-facing test setup as compared to the front-facing test setup, and 2) the differences in WUSM and DC system loudspeaker arrays, previously described in regards to chance performance. While these findings of differences in performance between rear-facing WUSM and DC test setups are in disagreement with a previous study comparing soundfield and DC systems, the previous study utilized a soundfield loudspeaker array that was identical to the simulated DC loudspeaker array (Aronoff et al., 2012). Although significant, differences in performance between the WUSM and DC systems for the UHL group ($p < 0.05$) were not as strong as the NH group ($p < 0.001$). Further testing with more UHL participants would potentially aid in clarifying the relationship between UHL participant performance and localization test setup.

For the UHL group, there was a positive correlation between localization performance in soundfield test setups and age. That is, younger participants appeared to make smaller RMS errors in both front-facing and rear-facing localization in the soundfield, but not in rear-facing DC. Earlier age at onset of hearing loss was associated with smaller RMS errors for the soundfield front-facing and DC rear-facing localization test setups, but not soundfield rear-facing. A subset of our UHL group, for whom younger age co-occurred with both early age of onset and consequently shorter duration of deafness, made smaller RMS errors in all localization test setups. However, this subgroup finding of smaller RMS error co-occurring with shorter duration of deafness (younger age and early age of onset yielding a shorter duration of deafness) did not hold true for the group in total. A larger group of UHL participants may be helpful in further clarifying the role played by age and age of onset in localization, and of the relationship between age and localization test setups. Lastly, no significant relationships were found between any test setups for the NH group. Conversely, a positive correlation in mean RMS error between all test setups was found for the UHL group. As mentioned previously, the differences in performance between the front- and rear-facing WUSM test setups, and WUSM and DC systems may be attributed to the presence or absence of visual cues and discrepancy in loudspeaker arrays for the NH group. Similar performance in all test setups for the UHL group may originate from a generally poor ability to localize sound sources, which may obscure differences in performance with test setup found in the NH group.

Localization performance, when separated by array side, differed at a level that approached significance in the rear-facing soundfield test setup for the UHL group. As previously mentioned, the presence of visual cues on the front-facing test setup may have played a part in the difference in localization performance for the NH group when compared to rear-facing performance. This may also hold true for the UHL group, in that the decrease in performance at the side of their good ear with rear-localization follows a similar trend as the NH group with two good ears. Also of note was the greater restriction on participants' head movements in the rear-facing test setup; participants were allowed to move their head freely to localize in the front-facing test setup, but were restricted to smaller movements to prevent loudspeaker visualization in the rear-facing test setup.

A paired-samples t-test was conducted to compare RMS error scores obtained in the soundfield test setups (SF-FF and SF-RF) at the side of the right and left ears for the NH group, and at the side of the better and poorer hearing ears for the UHL group. There was no significant difference in scores for right and left sides in the NH group for SF-FF ($p > 0.05$) or SF-RF ($p > 0.05$). For the UHL group, difference in RMS error scores in the SF-RF test setup for the better hearing side and poorer hearing sides approached significance; $t(11) = 2.14$, $p = 0.056$. No significant difference between better and poorer hearing sides for the SF-FF test setup for the UHL group ($p > 0.05$). Figure 13 displays the effect of side in SF-FF and SF-RF test setups for the UHL and NH groups.

In summary, findings from NH and UHL participants indicate that performance on clinical tests of localization is significantly different than chance performance. Moreover, performance on both the WUSM and DC systems indicate that localization ability are repeatable and can be measured reliably by both the WUSM and DC systems. Future directions for this study include the testing of a larger number of UHL participants, and expansion of testing to include SSD-CI recipients.

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Table 1: Normal Hearing Group Demographic Information

Mean (SD) Range	Age (years)	Right ear 4fPTA (dB)	Left ear 4fPTA (dB)
NH (n = 12)	51.9 (12.2) (30 - 72)	12.6 (7.4) (3.75 - 30)	13.5 (5.5) (3.75 - 21.25)

Table 2:Unilateral Hearing Loss Individual Participant Demographics Information

Participant ID	Age (years)	Better ear 4fPTA (dB)	Poorer ear 4fPTA (dB)	Poorer ear	Age Onset SPHL (years)	Length of Deafness (years)	Etiology
UHL101	79	16.25	113.75	L	0	79	Unknown
UHL102	23	0	106.25	R	0	23	Narrow AN
UHL103	63	25	113.75	R	33	30	Acoustic neuroma
UHL104	69	8.75	95	R	59	10	Acoustic neuroma
UHL105	34	1.25	113	L	3	31	EVA
UHL106	67	23	68.75	L	67	1	Unknown
UHL107	50	33	113.75	L	41	9	Unknown
UHL108	55	6.25	113.75	R	6	49	Mumps
UHL109	26	-1.25	113.75	L	0	26	Unknown
UHL110	66	16.25	91.25	L	63	3	Unknown
UHL111	72	23.75	103	R	8	64	Unknown
UHL112	24	5	68	R	14	7	Unknown

Note: An onset age of 0 indicates presumed congenital hearing loss.

Figure 1. Normal Hearing Average Audiometric Thresholds (+/-1 SD)

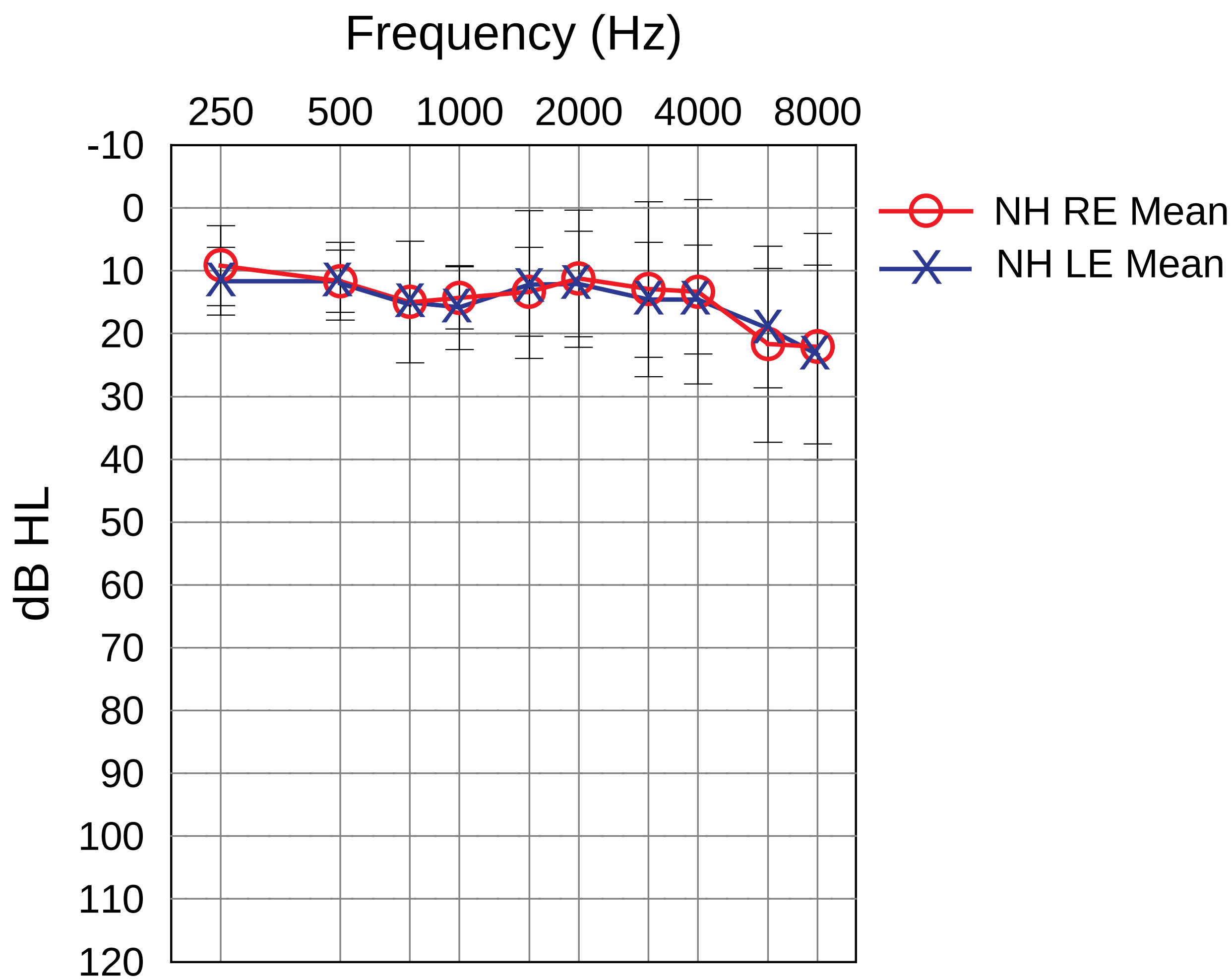


Figure 2. Unilateral Hearing Loss Average Audiometric Thresholds (+/-1 SD)

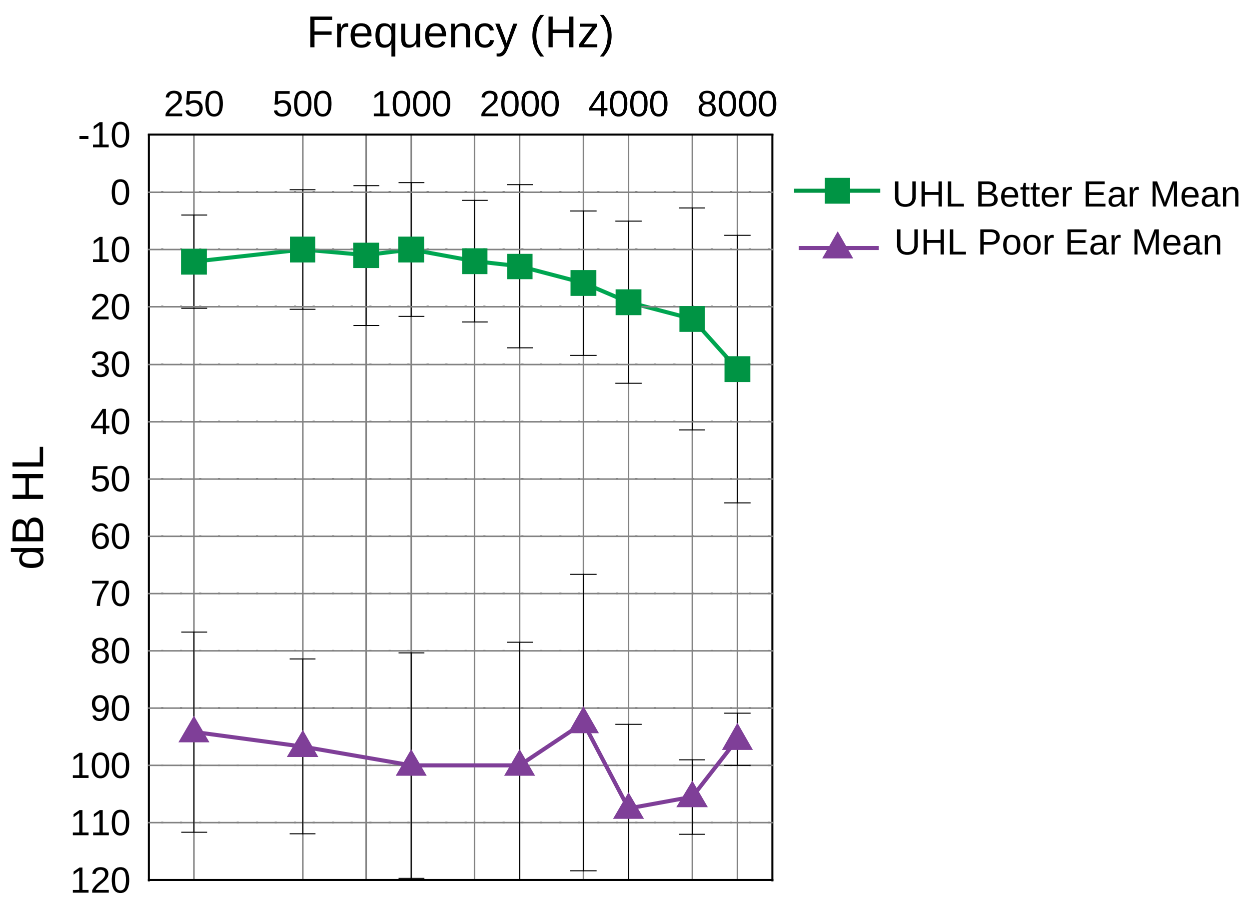


Figure 3.A. WUSM Front-Facing Soundfield Localization Test Setup

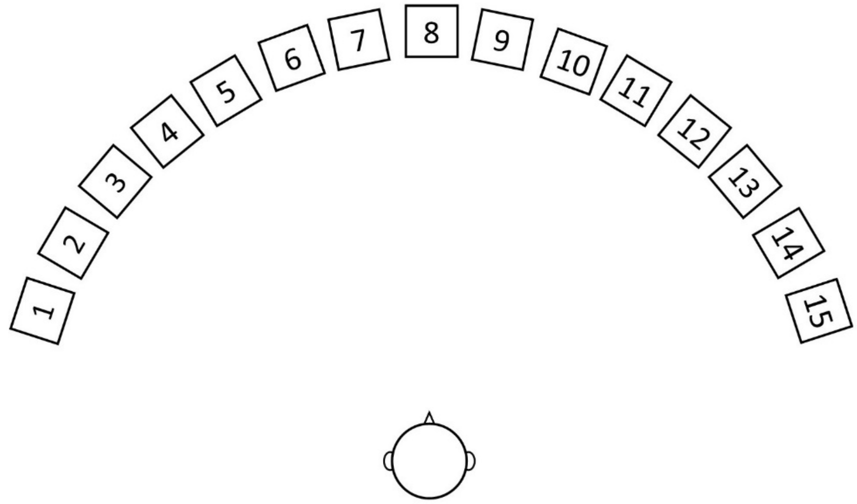


Figure 3.B. WUSM Rear-Facing Soundfield Localization Test Setup

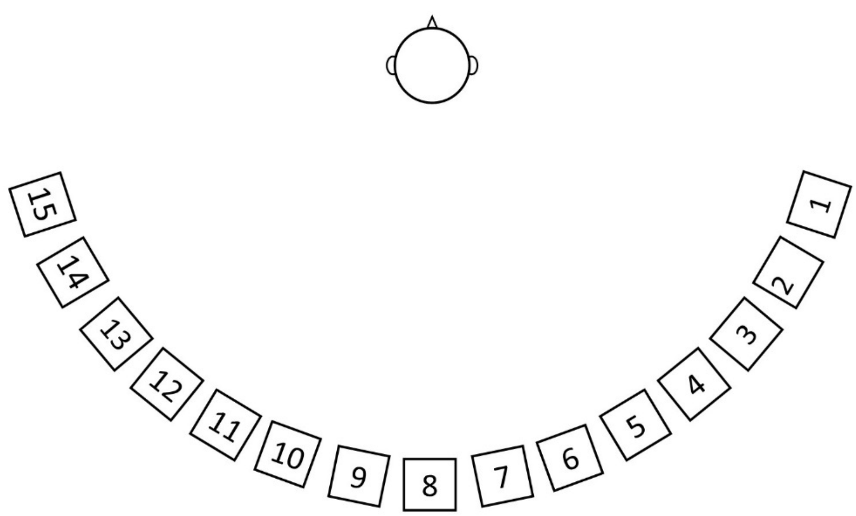


Figure 4. Direct Connect Binaural Test System Rear-Facing Test Setup

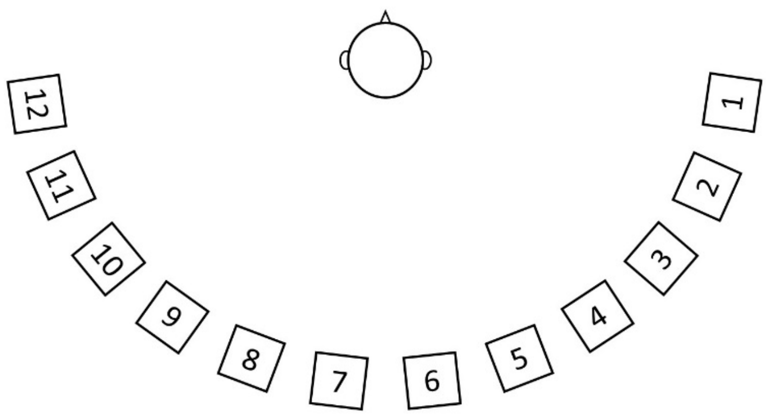


Figure 5. Normal Hearing Group RMS Errors for Test Sessions 1 and 2

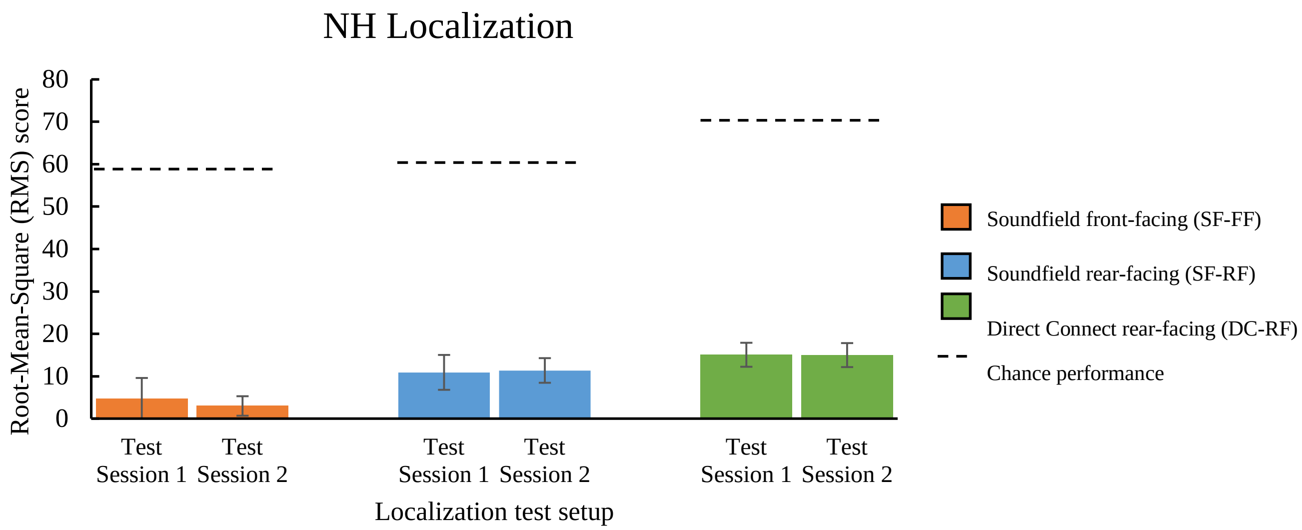


Figure 6. Unilateral Hearing Loss Group RMS Errors for Test Sessions 1 and 2

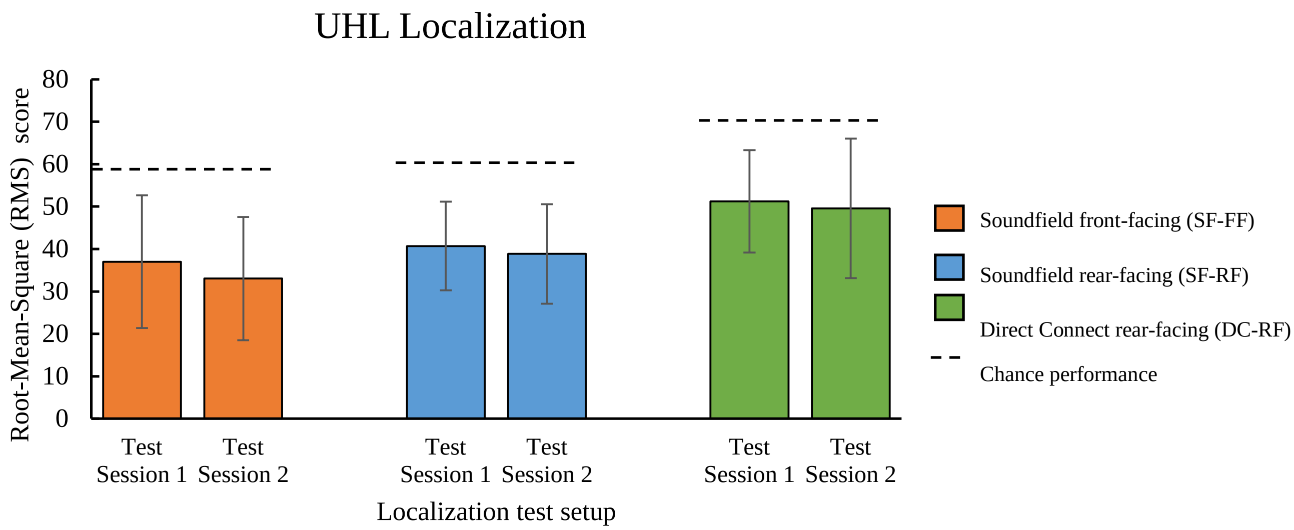


Figure 7. Individual Participant RMS Score Distributions *(boxplots representing Q1, median, Q3; whisker representing min and max)*

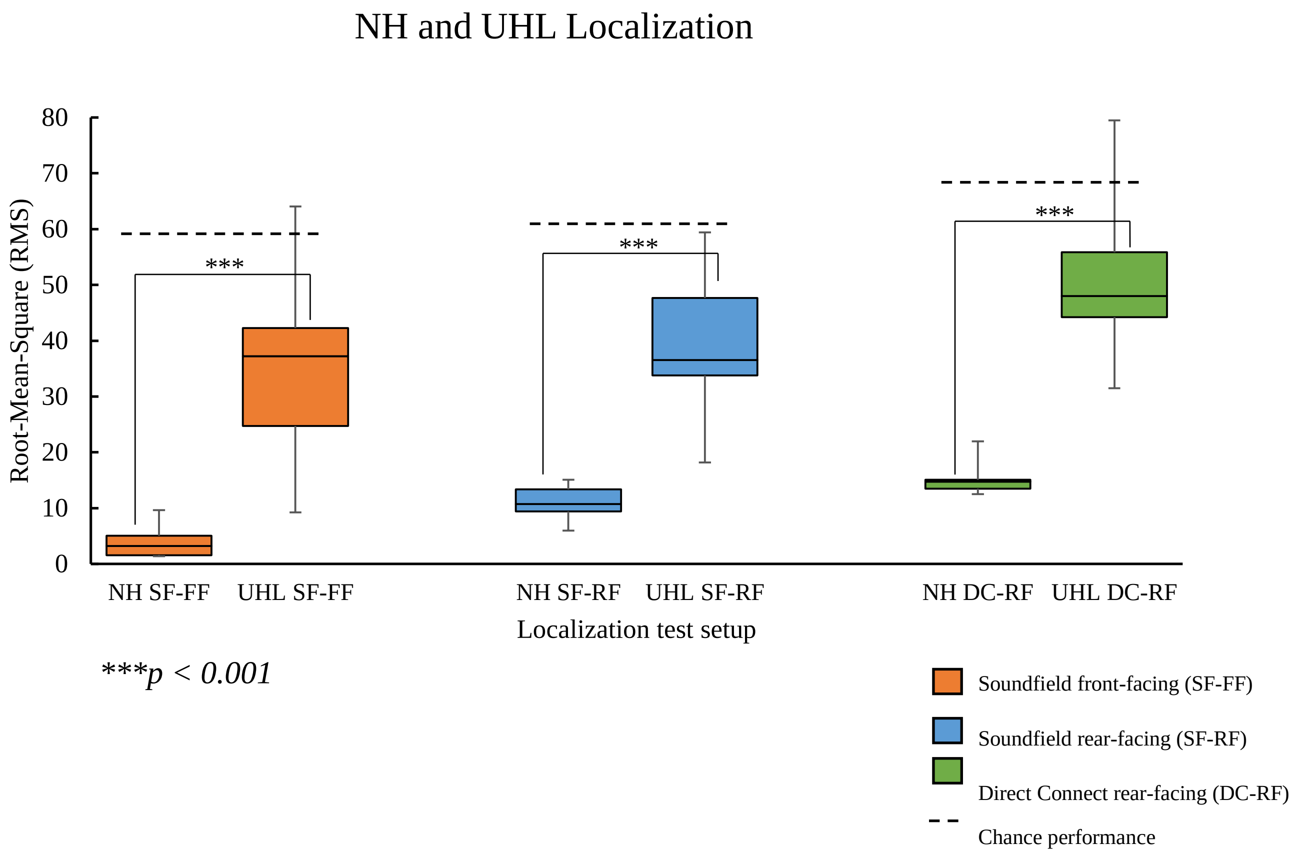
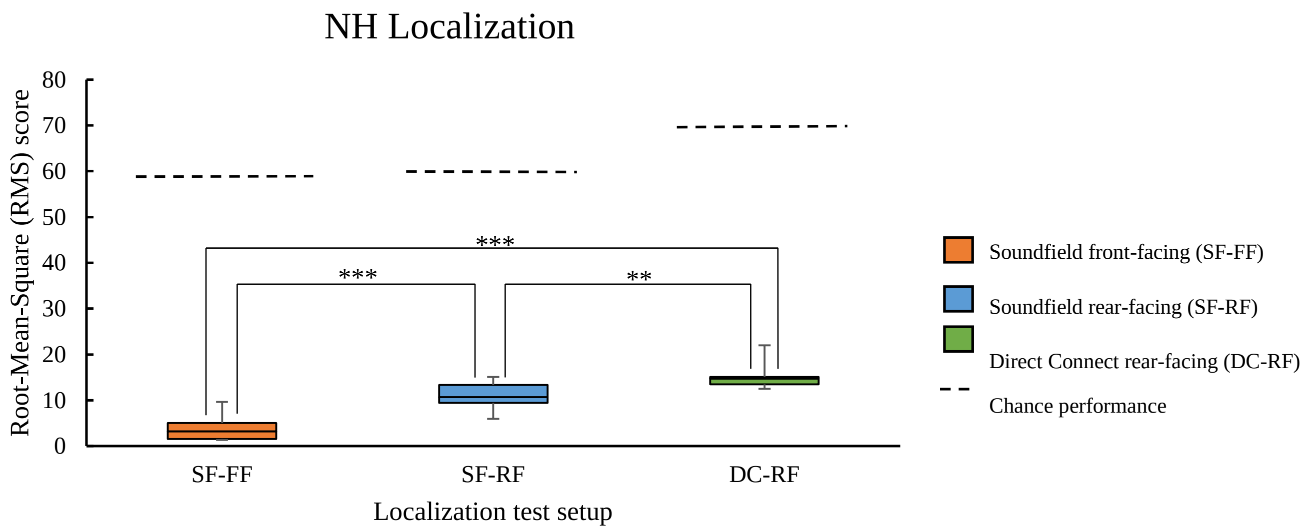
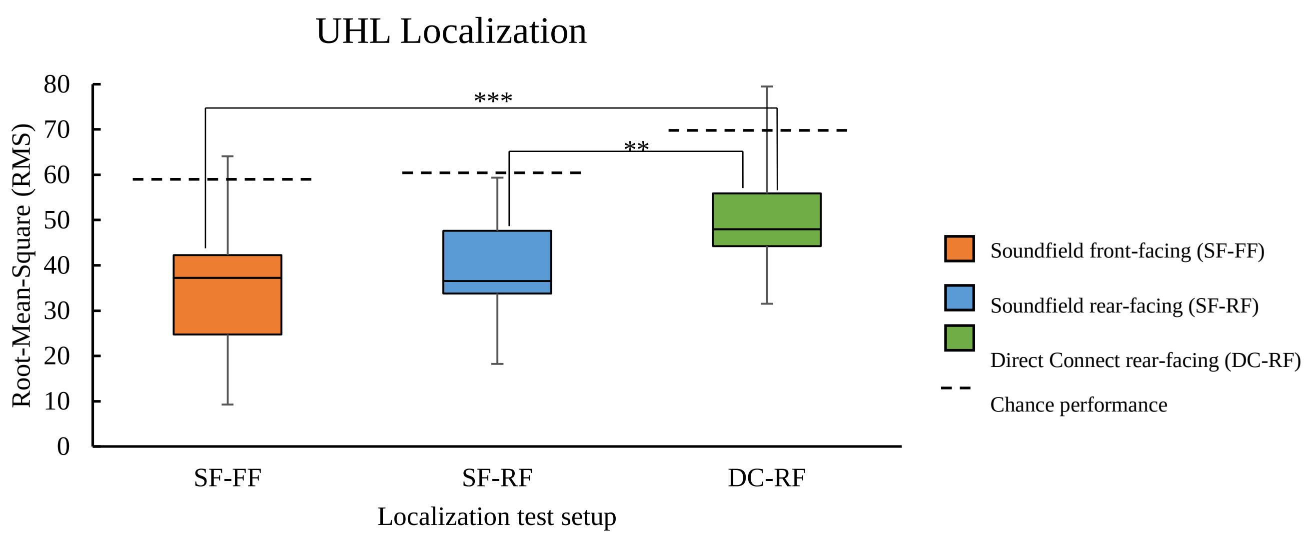


Figure 8. Normal Hearing Group RMS Error Scores by Test Setup



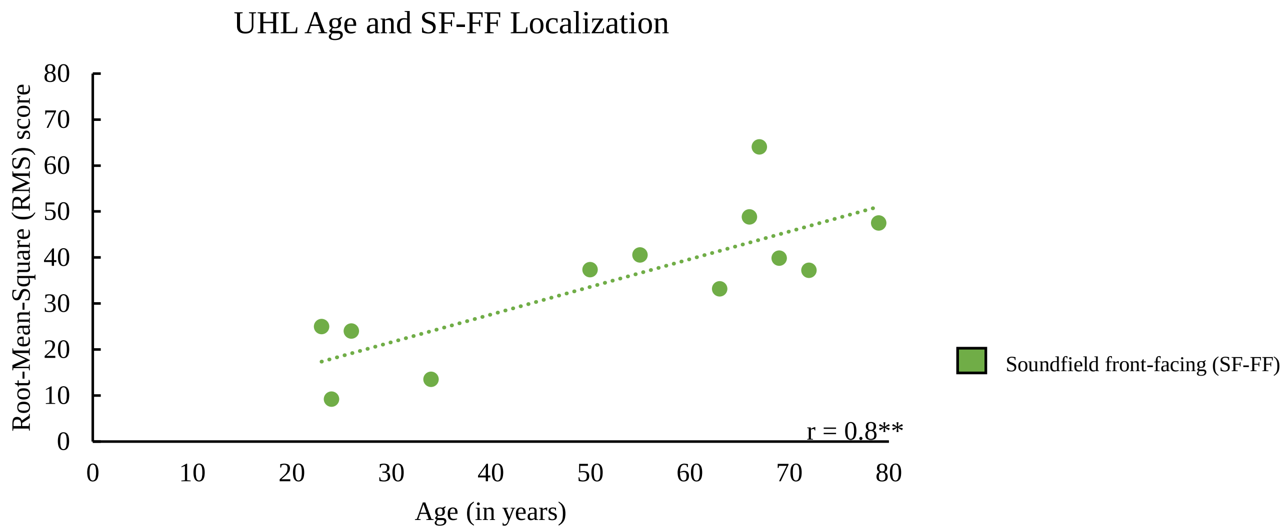
****p < 0.001; **p < 0.01*

Figure 9. Unilateral Hearing Loss Group RMS Error Scores by Test Setup



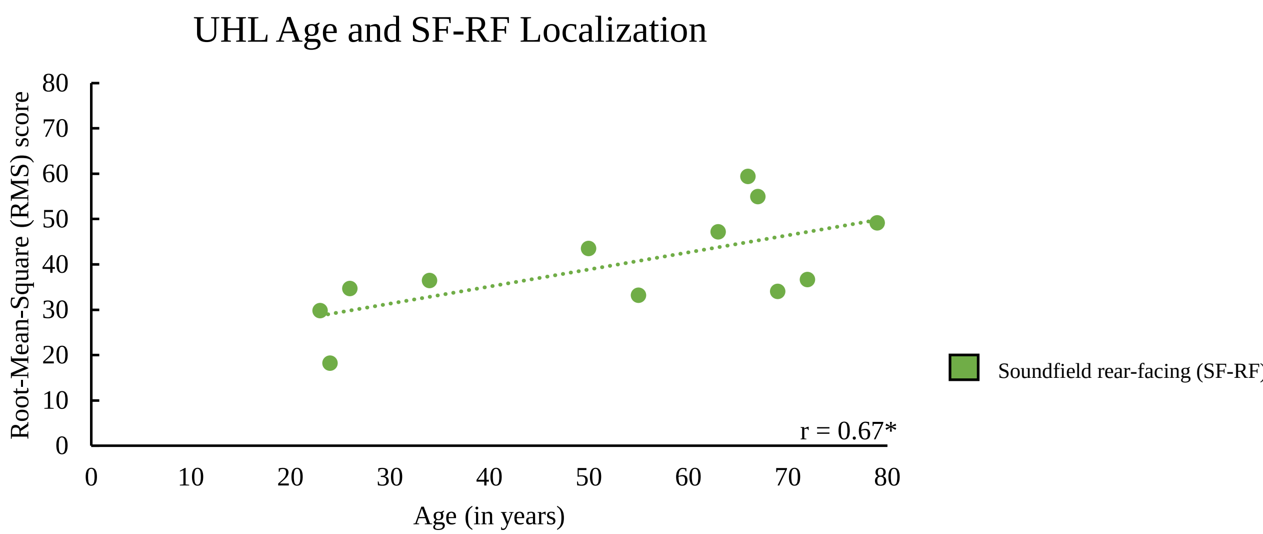
****p < 0.001; **p < 0.01*

Figure 10. Correlation between Age and Soundfield Front-Facing RMS Error Scores – Unilateral Hearing Loss



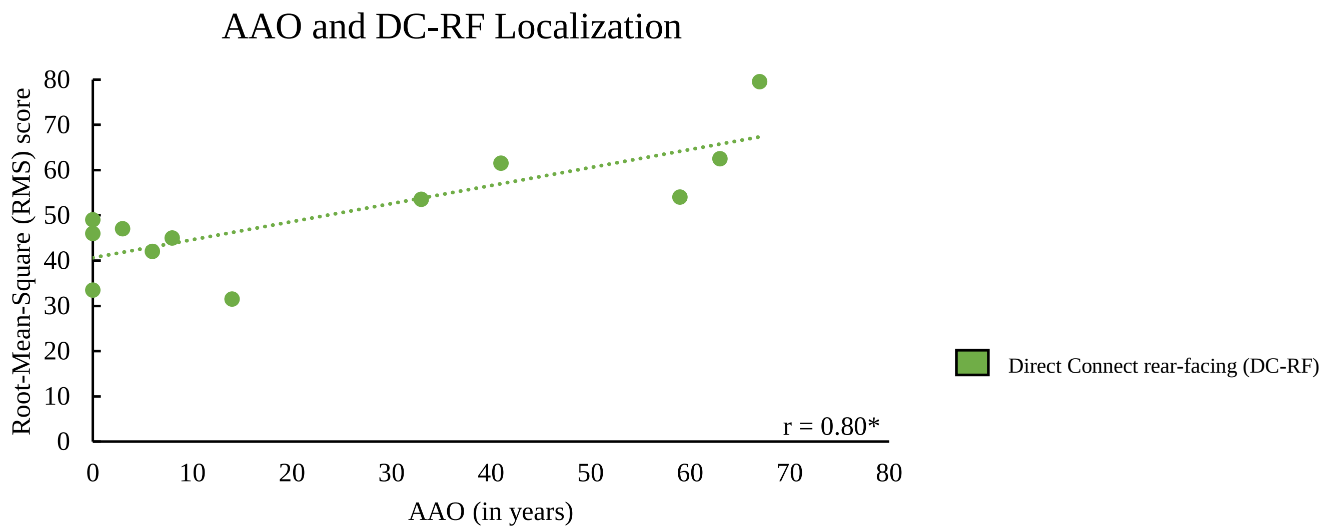
***p < 0.01*

Figure 11. Correlation between Age and Soundfield Rear-Facing RMS Error Scores – Unilateral Hearing Loss



*$p < 0.05$

Figure 12. Correlation between Age of Onset and Direct Connect Rear-Facing RMS Error Scores – Unilateral Hearing Loss



$*p < 0.05$

Figure 13: Correlation between Soundfield Rear-Facing and Direct Connect Rear-Facing – Normal Hearing

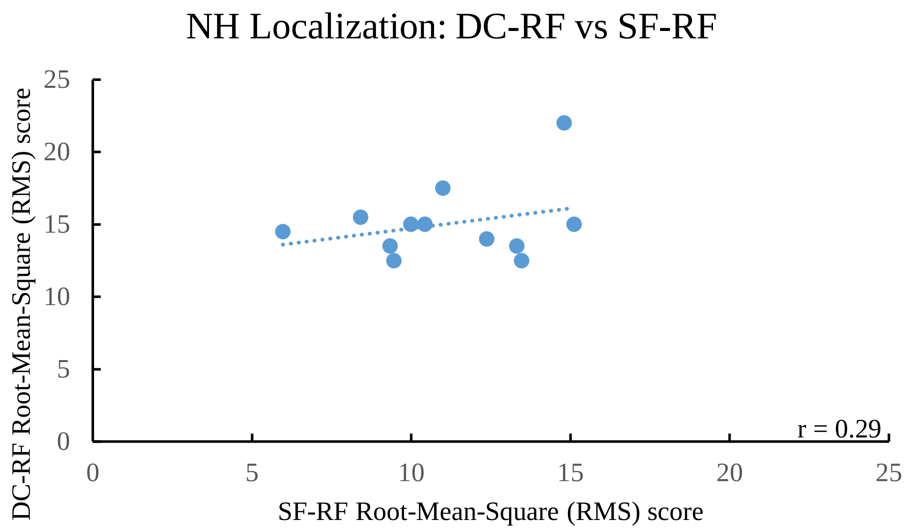
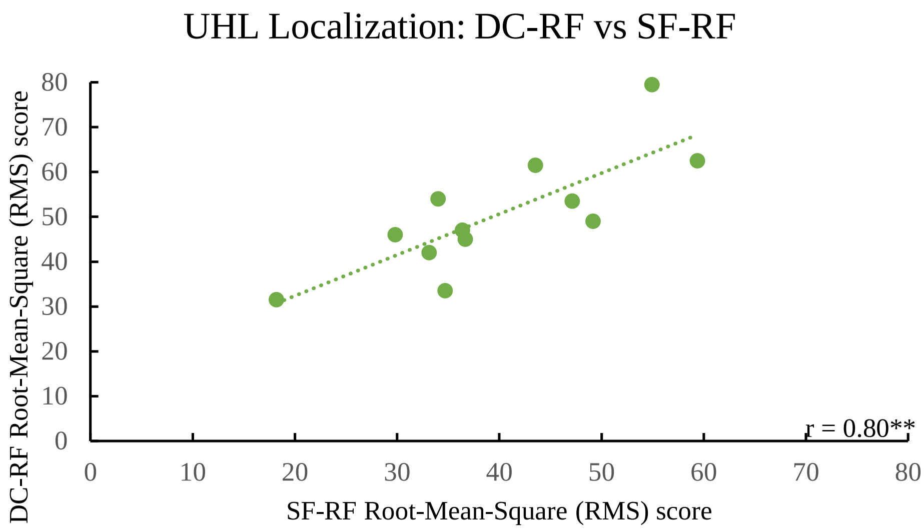


Figure 14: Correlation between Soundfield Rear-Facing and Direct Connect Rear-Facing – Unilateral Hearing Loss



***p < 0.01*

Figure 15. Effect of Side on RMS Error Scores for Soundfield Test Setups - Normal Hearing and Unilateral Hearing Loss