Binaural-cue weighting in sound localization with open-fit hearing aids and in simulated reverberation

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Dissertation
Submitted to the Faculty of the
Graduate School of Vanderbilt University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY
in

Hearing and Speech Sciences
August, 2016
Nashville, Tennessee

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Acknowledgements

I am incredibly thankful for the amazing support system I have in both my personal life and career. I could not have predicted the incredibly rewarding life I live and I am so excited for what the future holds.

To my best friend Sarah Moyer – you have always been there for me when I needed you the most by lending an ear, giving a shoulder to cry on and by providing the *best* advice. You’ve been there for me through all of the ups and downs in my adult life and I am forever grateful for your friendship. I look forward to years of sitting on porches chatting about life with you and your beautiful family.

To my family – including my many cousins, my siblings, and most importantly, my parents. You are the best a girl could ask for.

To John and Betty Diedesch - your work ethics, family values, dedication and good-natured souls are undeniable. The five beautiful and successful children you nurtured are proof of this. Thank you for always being there to encourage me with my life goals, but allowing me the freedom to make mistakes and find myself along the way. I am forever grateful for your love and support.

To Nathan Pearson – life brought us together in the most unconventional way and time. I wouldn’t change a minute of it. Thank you for all of the adventures we’ve taken together and I look forward to the adventures that lie ahead. Most importantly, thank you bringing me a sense of balance over the last few years. Being away from my support system as I relocated to Tennessee to continue my research proved to be very challenging. Your calming presence has helped me finish what I started. I’m so thankful to be closer to you, both in proximity and in life, and I can’t wait to see what the future presents to us next.

Finally, to my work colleagues and friends.

To Marjorie Leek and Erick Gallun – thank you for encouraging my involvement with research as an Au.D. student, offering me a job as a research audiologist, and supporting my pursuit for a Ph.D. Erick, you especially have been there every step of the way. I thank you for your friendship and collegiality. I look forward to many years of collaboration in the future.

Last, but not least, Chris Stecker – thank you for believing in me. It was difficult to move to Nashville, but you, your lab, and your immediate family have made me feel like part of a community. Thank you for your mentorship and I look forward to working with you in the future.

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Chapter 1 - Introduction

In the past decade, personal amplification has evolved to smaller behind-the-ear (BTE) hearing aids with open-fit coupling as an option for some patients. Psychophysical measures and physical recordings of sound (e.g. sound localization performance and binaural acoustic recordings) have not been specifically described for open-fit hearing aid technology. The goals of the current study were to evaluate interaural cues, and the perceptual weighting of those cues, when using open-fit hearing aids in simulated rooms.

1.1 Background

Sound source localization in the horizontal plane relies on two acoustic cues: interaural time differences (ITD) and interaural level differences (ILD). Ideally, listeners receive ITD and ILD cues that are in agreement with one another. For example, if a sound source in an anechoic space is presented at 45º azimuth to the right of a listener, both ITD and ILD will contain right-leading cues. However, localizing sounds is complicated through the addition of reflective surfaces in rooms. In more complex environments, interaural cues from the direct and reflected sound are added together causing the source to appear at a different (e.g. appear more to the front of the listener) or ambiguous (e.g. diffuse) location. Several studies have shown that aged and hearing-impaired populations tend to have difficulty listening in reverberant conditions (Helfer 1992, Helfer and Wilber 1990). Difficulty localizing in reverberation could be a result of how listeners weight available interaural cues, and weighting of those cues may vary with increasing reverberation.

Aside from the acoustically complex scene in reverberant rooms, hearing aids are also known to alter interaural cues. For example, studies have shown that ILD cues can be altered by hearing aid processing such as dynamic-range compression (Wiggins and Seeber, 2011) and strong directional microphone technology (Picou *et al.,* 2014). In both studies, the percept of a signal appears to be more in front of the listener (15º-30º azimuth), rather than at the actual source location (45º azimuth). Although ITD cues should be accurately represented by hearing aids, it is possible that acoustical interactions of direct and processed sound may alter both interaural cues analogous to listening in rooms with direct and reflected sounds. In both scenarios (rooms with reflective surfaces and listening with open-fit hearing aids), binaural cues from a sound source may be altered and degraded in a frequency- and cue-dependent manner. As a result, listeners may adjust their strategies for localizing sounds by weighting the available interaural cues differently across these conditions. For instance, a listener may put greater weight on ITD cues when ITD and ILD are redundant and stable. However, as ITD becomes erratic in reverberation, a listener may rely more heavily on ILD cues.

Here, I will review how reflective surfaces in rooms and hearing aids independently alter interaural cues, and perceptually, how weighting of interaural cues can be evaluated in a cue- and frequency-dependent manner.

1.1.1 Alteration of acoustical cues in reverberation

Reflective surfaces, such as walls in rooms, are known to alter interaural cues in the horizontal plane. Effects of interaural cues in reverberation have been examined in a few different ways. Most simply, reverberation can be evaluated by adding a single reflective surface (SRS) in an otherwise anechoic space (Rakerd and Hartmann 1985). Additional surfaces can added to further complicate a scene such as by testing in a reverberation chamber or using real rooms, such as a classroom at a University. In any of these environments, reverberation time (T60) can be measured and controlled by altering the number of reflective surfaces and/or the absorption characteristics of existing surfaces. Regardless of room type (i.e. SRS, classroom), if room characteristics are set and reflective patterns are consistent, listeners can be trained to predict and use reflections to improve sound localization performance in reverberation over time (Shinn-Cunningham 2000, Irving and Moore 2011, Kopčo and Shinn-Cunningham 2011).

Reverberation causes interaural cues to be diminished, altered or smeared. For example, conflicting ITD cues from the direct sound source and reflective surfaces will combine over short durations. This scenario could cause an individual to report that a sound occurred on the right one trial, and on the left the next trial when the target location was identical for both trials. Additionally, intensity levels of the direct and reflected sounds interact, causing the ILD cue for a lateral source to decrease in magnitude, resulting in a more centered percept. If a listener attends to the later reflections, different spectral content will present as well, since a delayed copy of the original stimulus would then be present at a different location due to the reflection off surrounding surfaces. Shinn-Cunningham et al. (2005) measured binaural room impulse responses (BRIR) on KEMAR placed at four different locations (i.e. corner of the room, middle of the room, one ear closer to a wall, back to a wall) in a classroom. Measures of BRIR were recorded at seven source azimuths (0º, 15º, 30º, 45º, 60º, 75º and 90º) to the right for each of the four locations. The measurements contained an altered spectral image for the direct plus reflected copies of the sound in comparison to an "anechoic" condition. Specifically, the original spectral notches were filled, and the overall energy in the far ear was increased. Comb-filtering–a pattern seen when delayed copies of an acoustic signal are added to the original signal–was occasionally observed in conditions where the far ear was near a wall, compared to conditions such as those measured in the middle of the room. Frequency-specific alterations were seen for both interaural cues. For example, in conditions where the manikin was near a wall, rightward and leftward ILD cues were observed across the frequency spectrum, when the actual source was located at 0º azimuth. Additionally, large and variable ILD cues were observed across the frequency spectrum for signals presented at 90º azimuth. ITD cues were also distorted with reverberation, in comparison to an "anechoic" condition. Across frequency analysis of ITD in conditions where the manikin had an ear near a wall revealed no consistent ITD values across the frequency spectrum. In other words, ITD in those conditions contained both rightward and leftward leading cues. In comparison, when the manikin was located in the middle of the room, noisy–or diffuse–ITD was observed to the side of the source. No behavioral data were collected in this study.

Ihlefeld and Shinn-Cunningham (2011) later examined sound localization of high- (6000Hz) and low- (750Hz) frequency, octave-wide noises presented over headphones. Reverberant energy was included in the stimuli by way of virtual acoustics to include BRIRs recorded in a typical office room, measured similar to the methods described by Shinn-Cunningham et al. (2005). This study collected behavioral data from seven young normal hearing college students. Two experiments were conducted, and findings from the first experiment suggest that localization of low- and high-frequency noise bands were similar when the source was located in front of the listener. In contrast, when source locations were positioned to the side, high-frequency noise was localized more accurately than low-frequency noise. Because of the extreme differences in the frequencies chosen for the noises, where ITD mostly codes 750 Hz and ILD 6000 Hz, their results from experiment one suggest that performance when using ITD is more difficult than ILD in a typical office room containing some reverberation. In a second experiment, low- and high-frequency noises were presented simultaneously. In this competing condition, localization of high- plus low-frequency noise was less accurate than high-frequency noise presented in isolation. The results from experiment two suggests that listeners weight low-frequency cues more heavily when high- and low-frequencies are presented together, even though they are more accurate localizing high-frequency noise in isolation.

Despite the acoustical complexity of sound in typical rooms such as classrooms or offices, listeners tend to do quite well in these environments. This may be due to clear and redundant interaural cues present early in a sound, prior to reflective energy adding to the direct signal. In their discussion, Ihlefeld and Shinn-Cunningham (2011) mention that a good strategy for listening in rooms containing reverberation may be to attend to, or weight, the onset of interaural cues more heavily while attempting to ignore ongoing cues, which may contain distorted and/or inaccurate spatial information. Previously, researchers have observed that while the onset cue is weighted most heavily, later arriving interaural cues influence perception as well (Hartmann 1983, Stecker and Hafter 2002, Devore et al. 2009). Stronger weighting to the onset, and influence of the later arriving energy have been observed both behaviorally, as well as through measures of spatially tuned neurons in the midbrain of anesthetized cats (Devore et al. 2009). Specifically, Devore et al. (2009) measured the firing rate of neurons in the presence of a right leading stimulus. The firing rate in response to stimuli presented in three conditions (i.e. anechoic, moderate reverb, strong reverb) is reduced systematically from anechoic to strong reverberation. Similar behavioral patterns were observed for four human subjects adjusting ILD cues to match lateral positions of sounds, where less ILD was needed to match a lateral position in strong reverberation compared to the same position in an anechoic condition.

For the few studies which measured interaural cue distortion in reverberation utilizing either simple methods such as use of a single reflective surface (Rakerd and Hartmann 1985), or by convolving BRIR to simulate real rooms (Shinn-Cunningham et al. 2005, Devore et al. 2009, Ihlefeld and Shinn-Cunningham 2011), their results show that early portions of a sound source (direct) carry clear and redundant interaural cues. However, later portions of the signal (direct + reflected) acoustically mix with opposing interaural cues from reflective surfaces present in the room. This acoustically complex scene creates either a diffuse percept, containing frequency specific cues in competing directions, or alters the location of a lateral source to appear more in front of the listener. Despite these distortions, young normal hearing listeners are only slightly affected by listening in reverberation, compared to listening in noise or performance of an older population (Helfer, 1992).

1.1.2 Alteration of acoustical cues by hearing aids

Modern hearing aid features are also known to alter interaural cues in the absence of reverberation. Specifically, features such as wide dynamic range compression, strong directional microphones, microphone location, and venting can alter ITD and ILD cues.

Dynamic Range Compression Dynamic-range compression can cause a lateral sound source to appear more in front of a listener due to a reduction in ILD. Wiggins and Seeber (2011) used virtual acoustics to investigate the lateral perception of seven types of sounds varying in speed of onset, rate of pulse trains, and by using a speech stimulus. All stimuli were presented in two conditions: full bandwidth and high-pass filtered (2000 Hz cut-off frequency). Wiggins and Seeber (2011) were interested in evaluating these two conditions because full bandwidth allows for presence of low-frequency ITD while the high-pass condition may force listeners to rely on high-frequency ILD. They observed that processed stimuli (using dynamic range compression), compared to unprocessed stimuli, caused sounds to appear more "centered" (e.g. a 45º azimuth source appearing at 15-30º azimuth) in high-pass conditions. Further, they found that stimuli with slow onsets and speech often appeared to be moving, broadening in their location (diffuse) or appearing as a split image. Split images often occurred for speech and sinusoidally amplitude modulated stimuli. When the same seven stimuli were presented at full bandwidth, perception of sounds appearing more "centered" was significantly reduced. The authors hypothesized that this is likely due to availability of reliable low frequency ITD compared to using ILD, which is altered by compression. However, in the full bandwidth condition, compression still negatively affects slow onset stimuli, but it no longer has detrimental effects on speech.

Directional microphones When testing three types of directional microphone settings – mild, moderate and strong, with strong being a bilateral beamformer – in behind-the-ear (BTE) hearing aids, Picou et al. (2014) found that moderate and strong directional microphone settings showed significantly greater sentence recognition in noise across several signal-to-noise ratios (SNR). With the addition of low and moderate amounts of reverberation added to the task, listeners' speech recognition performance improved when using bilateral beamformer technology compared to moderate directionality. For moderate amounts of reverberation, this difference between strong and moderate directionality was significant, and a similar trend was observed in low reverberation as well.

In this study, the beamformer technology used by Picou et al. (2014) eliminated interaural cues. Thus, the same copy of the directional sound is presented through both hearing aids. While using this beamformer technology, listener's localization ability and speech recognition were analyzed. In their experiment, sentences were presented with four competing talkers, a condition in need of strong directionality to improve signal-to-noise ratio to recognize the target talker over the maskers. However, the bilateral beamformer may make it difficult to detect a target that was not located in front of the listener. This is seen in the localization accuracy of Picou et al.'s listeners, where strong amounts of directionality brought their localization performance down to ~50% correct when the target was located ±60º to the left or right. In comparison, moderate directionality improved localization performance at ±60º. Performance with moderate directionality was consistent across azimuthal condition while performance with strong directionality (beamformer) was similar to moderate directionality at ±45º azimuth.

Venting As discussed above, Picou et al. (2014) analyzed different types of directionality, with bilateral beamformer technology being their "strong" directional microphone setting, which sends the same signal to both ears eliminating naturally occurring interaural cues. ITD and ILD cues for mild, moderate and strong levels of directionality were measured on an acoustic manikin in an anechoic chamber. For mild and moderate settings, ITD and ILD cues were both present and reflected similar azimuthal location. In comparison, strong directional settings resulted in a reduction of ILD cues beginning at ~35º azimuth, and found no measurable ITD cues. One method to note, this study coupled hearing aids to the manikin and research participants using foam inserts. Using temporary coupling, such a foam inserts, is ideal for use of the same device across participants, but hearing aids are mostly either fit with open-fit coupling or using custom ear molds containing some amount of venting. Venting allows for acoustic, or unprocessed sound (typically low frequency information) to enter the ear canal. Having access to low-frequency acoustic sound is an important factor considering a common audiometric configuration is normal or near normal in the low frequencies with a sloping loss in the mid and high frequencies.

Access to low frequencies through venting would allow for ITD cues to be present in the bilateral beamformer condition. Whether or not this addition of natural ITD cues is beneficial or detrimental for understanding speech stills needs to be evaluated. It is possible that venting would improve localization accuracy, which Picou et al. (2014) saw drop off after +/- 45 degree azimuth. However, when acoustic and processed cues are combined at the level of the ear canal, it is unclear if this additional low-frequency information would be detrimental to speech recognition. Low-frequency cues tend to be powerful maskers, and if the acoustic signal appeared slightly before the processed, this interaction may cause adverse effects.

Previously, a series of studies were accomplished evaluating effects of BTE hearing aid venting and sound localization for listeners with and without hearing impairment. The majority of the significant findings were regarding alteration of spectral cues from the vertical plane due to microphone placement (see explanation below), but there were a few results shown for the horizontal plane as well. Generally, when evaluating BTE localization performance with close (occluded), open (large vent) and "sleeve" (most similar to modern open-fit coupling), horizontal sound localization was worse for closed earmolds (Byrne et al. 1996, Byrne et al. 1998, Byrne and Noble 1998, Noble et al. 1998). Most findings, however, were based off of trends and were statistically inconclusive. The effect of multi-path acoustic through venting (acoustic) the hearing aids (processed) on interaural cues is an area of research that requires further investigation.

Microphone location – monaural/binaural spectral cues The head, torso and pinna provide spectral cues to assist with sound localization in the vertical plane as well as help distinguish front-back reversals. Such reversals occur because the only difference between sound located directly in front and behind a listener (ITD and ILD = 0) is the presence and specific characteristics of the pinna. The intricate shape of the outer ear contributes specific spectral content to the listener, even for minor changes in location, to assist with localization in the vertical plane and front-back confusions. These spectral differences tend to be high-frequency cues (Hofman et al. 1998, Carlile 2014).

Spectral cues assisting with sound localization are likely coded at a high auditory processing level. Hofman and colleagues (1998) showed that listeners are unable to localize changes in elevation immediately after altering pinna shape. After 5-10 days of exposure to altered pinnae, listeners improved elevation localization ability. Finally, after completing the experiments, localization with individuals' own pinna, performance was similar to baseline. Thus, plasticity can occur to recode localization cues from specific spectral cues available by an altered pinna, however, coding for each individuals' own pinna was retained suggesting this cue is hard-coded in the auditory system.

Alterations to pinna cues are important to think about in hearing aid research because BTE hearing aids, which are very popular in the clinic, remove such pinna cues. BTE microphones are placed at the top of the pinna, which causes a loss of natural spectral cues to assist with localization. Wearing BTE hearing aids may cause increased front-back confusions, or hurt localization performance in the vertical plane. Alternatively, microphones may be placed in-the-ear (ITE) or completely-in-the-canal (CIC) to allow for retention of pinna cues, but in-the-ear style custom products are less popular for a variety of reasons (i.e. more time and money for custom products, cosmetic reasons, damage by cerumen, comfort, etc.). An area lacking in research is whether or not open-fit BTE hearing aids reduce or eliminate the adverse effects of microphone location in terms of binaural sound localization cues (ITD, ILD, and spectral). A few studies have evaluated sound localization performance across different styles of hearing aids. Findings suggest CIC hearing aids are better than ITE or BTE hearing aids (Byrne and Noble 1998), however acclimatization was not controlled. For instance, there were a few BTE wearing subjects who performed well with BTE's. Despite controlling for acclimatization, it appears that microphones located in the ear canal improve performance compared to BTE microphones located on top of the pinna.

1.1.3 Approaches for measuring interaural cue weighting

Interaural cues used to localize a sound source are not always in agreement, as evidenced by acoustic recordings collected in reverberant rooms discussed previously. For instance, if a listener was seated near a wall, ILD may cause perception of an object to the right of the listener to appear more in front of the listener. At the same point in time, ITD from that rightward source may be perceived leftward due to the reflective surface near the left ear. In this scenario, the relative weight placed on each interaural cue can be quantified by asking the listener where he perceived the source location. The weighting of interaural cues in the described scenario may vary depending on the frequency (Moushegian and Jeffress, 1959; Harris, 1960), intensity

(David et al., 1959; Deatherage and Hirsh, 1959) and across listeners (Moushegian and Jeffress, 1959). Classically, there are two approaches to measure weighting of interaural cues, which are then quantified through a trading ratio (TR) of μsec/dB. Through classical and hybrid TR experiments examining various stimulus conditions, mentioned above, previous studies have quantified TRs to be either small or large, indicating that listeners place greater weight on ITD or ILD cues, respectively.

One method to measure TR is by using a centering task. Traditionally, centering was conducted using a single interval task with competing ITD and ILD cues; one cue, determined by the experiment, was fixed and the listeners' controlled the other cue. For example, Shaxby and Gage (1932), prompted listeners to adjust one interaural cue (e.g. adjust a right leading ITD, while a left leading ILD is fixed) until the lateralized percept was in the center of the head. An issue with this method, as noted by Hafter and Jeffress (1968), is that these stimuli containing large offset ITD and ILD information can be perceived as diffuse or even two separate images. When trying to "center" a diffuse stimulus, listeners may end up interpreting the definition of "centered" differently, which could result in listeners using different strategies. For example, if a sound is diffuse, or perceived as a stimulus with some width, one listener may say the sound is centered once one of the edges of that wide sound approaches the center of his head. A second listener may approach the centering task more literally, and while there is no one exact location of a wide sound, this second listener may try to find the actual center of sound rather than match the edge. Finally, another issue may be that listeners do not have a clear perception of the center of their head. For these reasons, Hafter and Jeffress (1968) developed a hybrid centering approach by using a two-interval task where the first interval contained a diotic (0 ITD, 0 ILD) target, and the second interval contained the classic centering stimulus (e.g. fixed left leading ILD, allowing for adjustment of a right leading ITD). Listeners were then instructed to adjust the stimulus of the pointer contained in the second interval to match the target (diotic) stimulus. Further, they were instructed to adjust the sound until the one edge approached the target, to ensure all listeners were responding similarly throughout the experiment.

A second classic TR approach is a matching method. Matching is similar to the hybrid centering approach defined by Hafter and Jeffress (1968). Traditionally, matching is accomplished through a two-interval task where the first interval, the target, is at a fixed location (e.g. fixed ILD, 0 ITD) and the ITD of the second interval, the pointer (containing 0 ILD) is adjusted to match the target. To measure TRs by matching, similar stimuli, such as tones, can be used for both the target and pointer (Whitworth and Jeffress 1961) or alternatively, noise can be used as the target for a tonal pointer (Feddersen et al. 1957, Moushegian and Jeffress 1959). Other scaling responses such as visual or tactile may also be used as a pointer.

Similar to alterations made for the traditional centering approach, the matching task can be altered as well. For instance, rather than having a target with a fixed ILD and 0 ITD, both ITD and ILD can contain fixed values. Then the pointer, in this hybrid matching approach, would allow for adjustment of one cue while fixing the other cue at 0 (e.g. 0 ILD, adjust ITD). This may seem like a minor adjustment to the matching approach, but the interesting part about this method of having a fixed ITD and ILD for the target, is that when sound is played from a speaker in a free-field environment, ITD and ILD cues will be fixed and will vary with speaker location. A hybrid matching TR approach could be considered similar to matching the location of a speaker in the lateral plane, while using the pointer to adjust one interaural cue at a time, if presented over headphones. Listeners can be trained to use a pointer to indicate an absolute position, such as pointing to a speaker location, when using a hybrid matching approach by having participants seated in an array of speakers while listening over headphones.

With a similar goal in mind, but moving even farther from the classic ITD/ILD TR studies, Rakerd and Hartmann (1985) measured behavioral responses to 500 Hz tonal stimuli presented in an anechoic chamber with the presence of a single-reflective surface. The benefit of their approach is that interaural cues from the direct and reflected sound are combined in a way that is more similar to realistic rooms, as opposed to headphone tests. This approach may offer an explanation of acoustical consequences of interaural cues in real rooms. In addition to asking where the listeners perceived the location of the source, binaural recordings on an acoustic manikin were collected and used to quantify the available ITD and ILD cues. As the source location varied in azimuth, in the presence of the single-reflective surface, the ITD information became increasingly erratic. At this point, weighting of interaural cues moved from ITD to the more stable ILD cue information. Rakerd and Hartmann (1985) explained this by suggesting the reliability and plausibility of the signal is altered in this reflective environment, resulting in listeners adjusting their method of weighting the interaural cues. The limitation of this method, however, is the lack of experimental control to ITD and ILD values.

Few studies have measured alterations of interaural cues in hearing aids or in reverberation. Here, we combine hearing aid and reverberant conditions in a manner similar to the methodology described by Rakerd and Hartmann (1985) to measure across frequency alterations of interaural cues and the perceptual consequences, if any, in listeners.

1.2 Purpose of current study (specific aims)

Aim 1: Acoustic measures of interaural time and level differences across vent size and reverberation. Probe-tube measurements of interaural cues in low-gain hearing aids will be assessed in the ear canal on a binaural recording manikin (e.g. KEMAR) and human subjects in the sound field using low-frequency, high-frequency and broadband stimuli. *We will measure and analyze acoustic recordings in the sound field to determine relationships between source location and ITD/ILD, investigating the effects of reverberation and vent size of the hearing aid coupling as a function of frequency.* Acoustical interactions are expected to differ across frequency, in part because greater amplification is typically provided at higher frequencies, and because processing delays may introduce comb-filtering. *We will test the hypothesis that acoustical interactions lead to distortions such as diminished ILD cues and directionally unstable ITD cues with increased amounts of venting and reverberation. Distortions may affect both the magnitude of localization cues, and/or their consistency across frequency, as measured by probe-tube microphones placed in the ear canal.*

Aim 2: Behavioral measures of interaural cue weighting across vent size and reverberation. Few studies have investigated the relative weighting of ITD and ILD cues in the sound field, and to our knowledge, none have investigated the effects of room types and physical parameters of hearing aid coupling on ITD and ILD weighting. Here, interaural-cue weighting will be evaluated across 3 vent sizes and 3 room types in young normal-hearing listeners using Broadband (BB) and narrowband (NB) noise. Probe-tube recordings (Aim 1) will be collected for human subject to compare to behavioral performance. *We will test the hypothesis that listeners' weighting of ITD and ILD cues will systemically vary across conditions, with changes in cue weighting favoring the more stable of the available interaural cues (e.g., increasingly favoring ILD as the ITD becomes more unstable).*

Binaural Acoustic Recordings

Chapter 2 - General Methods

2.1 Participants and Test Conditions

2.1.1 Research participants

Two separate, yet similar, experiments were conducted for the binaural acoustic recordings. The first set of experiments was collected on a 1972 model Knowles Electronic Manikin for Acoustic Research (KEMAR). This model of acoustic manikins was developed for hearing aid research and comes fit with steel ear canals, Zwislocki couplers and rubber pinnae. Acoustic recordings were measured using Etymotic Research (ER) ER-11 ½" microphones available on KEMAR, and separately with ER-7 probe-tube microphones. Since probe-tube microphones will be used for human subject recordings, all data presented will be from ER-7 probe-tube recordings.

	Frequency											
	250		500		1000		2000		4000		8000	
	R	L	R	L	R	L	R	L	R	L	R	L
0507	5	10	0	5	0	0	10	10	-5	0	-10	-5
0509	10	10	10	15	10	10	10	5	15	10	5	5
1402	15	15	20	20	20	30	25	30	30	35	10	15
1403	10	15	10	10	15	5	10	15	25	15	0	-5
1404	10	10	10	5	10	5	5	10	10	10	5	15
1406	10	5	10	5	10	10	5	10	10	10	-5	0
1501	5	10	10	5	5	10	10	15	15	0	15	0
1503	10	10	15	10	5	5	10	10	10	5	5	-10
1603	0	0	0	0	10	-5	10	10	5	0	0	-5
1617	5	5	10	0	5	10	5	5	5	5	10	0

Table 1. Audiometric thresholds in dB HL are listed for octave frequencies. Research participant numbers listed in the left column. 0507 is the author, 0509 and 1503 are lab members. 1402, 1403, 1404, and 1406 have previously participated in other binaural hearing experiments.

Guided by the results collected from KEMAR, ten listeners participated using the same room conditions and a subset of hearing aid conditions, described below. Ten listeners (2 males), mean age 28 (7.1 SD) years, participated in both acoustic recordings and behavioral testing. Nine of the ten listeners had normal hearing, and one had a mild hearing impairment (Table 1). All procedures, including recruitment, consenting, and testing of human subjects, were approved by Vanderbilt University's Institutional Review Board, and non-lab members were compensated $15/hour for their time.

2.1.2 Hearing Aid Venting

During exploratory data collection on KEMAR, a total of six hearing aid conditions were evaluated. Both KEMAR and research participants were fit with Siemens Motion 700 P behind-the-ear (BTE) hearing aids. This brand and model was chosen because programming allows for linear processing, as well as fast- and slow-compression. A standard earhook was used for all hearing aid conditions. Comply foam tips and Comply size 13 sound tube adaptors were used to couple four of the five aided conditions tested on KEMAR. The open-fit hearing aid condition also used a standard earhook, size 13 M tubing custom modified using an EARtone tube socket to fit a Phonak silicone open dome to the thicker tubing. Tubing for the open-fit condition was trimmed to ensure that Comply and custom open-fit coupling were the same length. These details were controlled to ensure microphone location was the same across all aided conditions, and frequency output was not altered by tube size. A standard slim tube for open-fit hearing aids would have had significant spectral differences caused both the tubing and microphone location.

To evaluate effects of hearing aid venting on interaural cues, "aided" conditions tested on KEMAR included: Comply foam inserts with zero, one, two and three vents, open-domes coupled to size 13 tubing, and unaided. Acoustic recordings on research participants were measured for a subset of "aided" conditions: occluded Comply foam inserts, open-domes and unaided.

2.1.3 Room Type

To evaluate effects of reverberation while constraining speaker location, source distance, and listeners' head orientation, acoustic recordings for all "room" conditions were measured in Bill Wilkerson Center's anechoic chamber at Vanderbilt University. That is, reverberant scenes were simulated and presented in the anechoic chamber. Three scenes with increasing amounts of reverberation were used to evaluate effects of interaural cue distortion: anechoic, single reflective surface (SRS), and simulated room.

Using the anechoic chamber for each room type, the image method (Allen and Berkley 1979) was used to locate lateral reflection points, and the speaker nearest to that point would play attenuated sounds at requested delays. For the SRS condition, attenuation was set to $\alpha = .2$, or 80% reflective and delay corresponded to a lateral distance of 5m to the right. In the most reverberant condition, thirteen orders of reflection were used to simulate a classroom size room (10m x 10m), with virtual walls corresponding to distances of 5m left/right, 6.67 in front and 3.33 behind. Simulated scenes did not have a floor or ceiling. Attenuation for each thirteen lateral reflections was $\alpha = .5$, or 50% reflective. T60 reverberation time was approximately 298ms using broadband noise.

2.2 Recording Methods

2.2.1 Stimuli

A broadband noise, generated by a customized program developed in Matlab (The Mathworks, Inc.), was used for both KEMAR and research participants. Specifically, a Gaussian white noise, 500ms duration (5ms ramp duration) was used for all aided and room conditions. Intensity was set to -20 average binaural level (dB re: 1 volt peak) for hearing aid conditions, and -10 dB unaided, to compensate for lack of hearing aid gain. Additionally, low-pass (4 octave noise centered at 375 Hz) and high-pass (4 octave noise centered at 6000 Hz) noises were recorded for KEMAR. These data are not shown, but were used to ensure reliability of measured ITD and ILD cues across BB, Low-pass and High-pass stimuli.

2.2.2 Setup and arrangement

The anechoic chamber at Vanderbilt University's Bill Wilkerson Center was used to make all acoustic recordings. The room is equipped with a circle array of 64-speakers, 5.625º apart. Twenty-three speakers, ranging from ±61º, were used for these experiments. All data shown below were recorded using ER-7 probe-tube microphones. Recordings were always collected from left to right.

Eight, 8-channel Ashly amplifiers were used to send sounds simultaneously to the 64 speakers located in the anechoic chamber. Rednet Focusrite, 16-channel input/output Ethernet-networked audio interface, powered by Dante, was used to drive the Ashly amplifiers and simultaneously make two-channel recordings. Using Matlab, BB noise was generated, played to the speakers in the anechoic chamber and simultaneously saved waveform data from the binaural recordings. A Focusrite pre-amplifier was used to amplify the probe-tube acoustic recordings.

Hearing aids were manually set to linear amplification. Noise reduction, feedback suppression and directional microphones were disabled. Exploratory level data were measured on KEMAR. Approximate gain settings, as measured on KEMAR, are shown in Table 2. Hearing aid gain was fixed and levels vary slightly across research participants and hearing aid conditions. Real-ear measurements for each listener are displayed in Appendix A to show variations across participants and aided conditions. A fixed gain approach was used as an alternative to matching NAL-NL2 targets to a fixed mild-to-moderate simulated hearing impairment, as this method would allow for variable hearing aid programmed levels across listeners. Additionally, having one hearing aid setting for all participants reduced fitting time and eliminated fitting sessions prior to each experimental visit.

	Frequency-specific Gain													
	250		500		1000		2000		3000		4000		6000	
	R	L	R	L	R	L	R	L	R	L	R	L	R	L
Occluded	14	13	17	16	21	21	27	28	29	30	28	31	13	15
Open	-1	0	1	1	5	7	21	20	21	22	14	16	6	8

Table 2. Frequency-specific gain for occluded and open-fit hearing aids as measured on KEMAR. Values represent differences between amplified levels used for acoustic recordings and hearing aids measured on KEMAR with no gain, as depicted in Figure 1. Measurements made with speechmap test at 65 dB SPL using an Audioscan Verifit system.

In Figure 1, hearing aid output for occluded and open-fit conditions are displayed and compared to output of hearing aids turned off. While hearing aids kept the same programming across all aided conditions and research participants, the measureable low-frequency gain was minimal or absent when hearing aids were coupled to open-domes. Also, some listeners had increased gain in mid-to-high frequencies with occluded hearing aids (Appendix A). For KEMAR, increased gain was visible at 2000 Hz. This boost is likely due to ear canal resonance, and while no adjustments were made during the recordings, these differences were adjusted for the behavioral methods (see section 4.1.2).

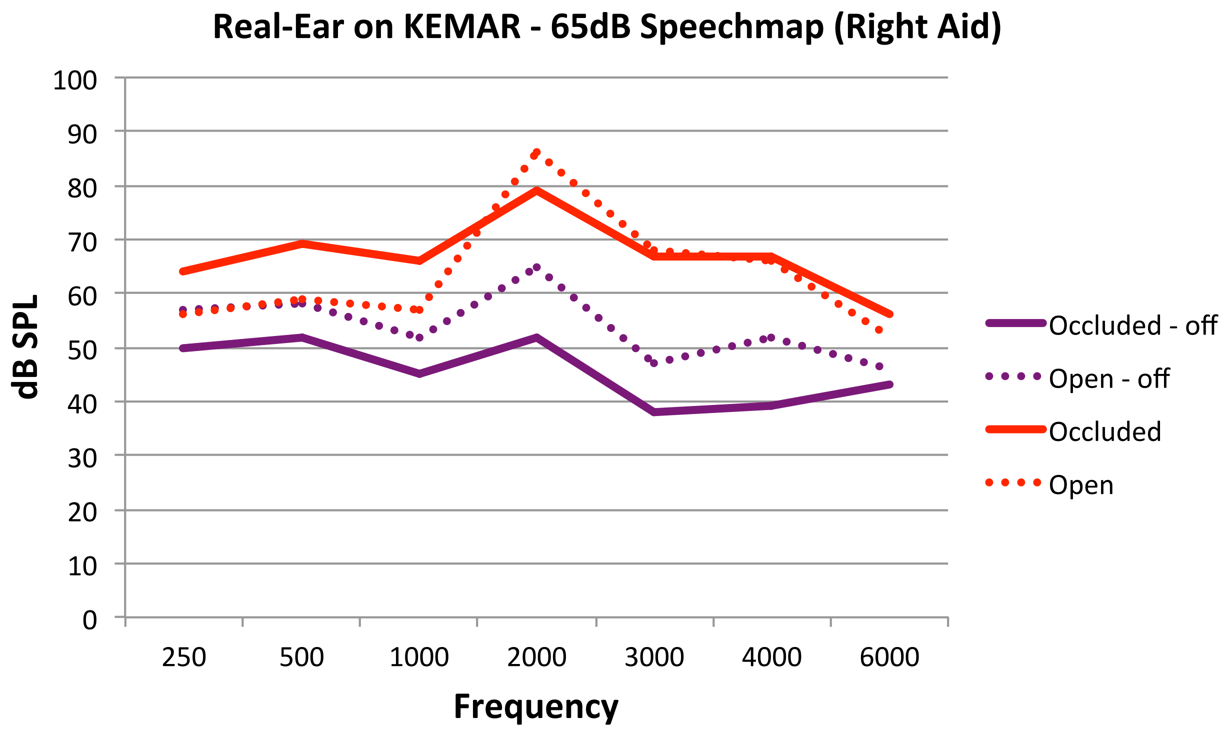


Figure 1. Lines plot real-ear measurements using speechmap test presented at 65 dB SPL. Purple lines represented output levels recorded on KEMAR with hearing aids turned off for occluded (solid line) and open-fit (dotted line) conditions. Red lines plot hearing aid output, as measured on KEMAR, which were used for all listeners. Individual real-ear output measurements available in Appendix A for unaided, open-fit and occluded hearing aids.

Hearing aid fitting session lasted approximately 1.5 hours for real-ear measurements and creating customized hearing aid coupling. Binaural acoustic recordings were collected at the second session, which lasted approximately 2.5 hours.

2.2.3 Calibration

To calibrate the 64 speakers in Vanderbilt's anechoic chamber, a 1000 Hz calibration tone was presented at 94 dB. Test chair was moved and measurements were taken on a ½" microphone placed at the center of circle speaker array. Height of the microphone matched that of the speakers. The target measurement, recorded on a Bruell & Kjaer 2250 sound level meter, was 70 dB SPL for each speaker individually. Using protia software on a Viao computer that communicates with the Ashley amplifiers, adjustments were made to ensure equal 70dB SPL output for each speaker. Using the protia software, knobs on the amplifiers were disabled, attenuators were set to -20, digital signal processing output gain set to 20 dB, and brickwall limiter to 80dB SPL max.

2.2.4 Stimulus presentation and listener's task

Research participants were seated at the center of a speaker array in Vanderbilt's anechoic chamber, ears at the level of the speakers. KEMAR was placed on the chair using a small pillow to approximate a similar height to human subjects. KEMAR was restrained to prevent movement during the probe-tube recordings. Research participants were instructed to have their nose face the speaker in front and to not move their head while sounds are playing. Camera and audio were used to monitor listeners during the recordings and participants were reinstructed as needed.

A set of recordings was determined by the aided conditions. Three sets were collected for research participants and six sets for KEMAR. Unaided probe-tube measurements were collected first, then either open-fit or occluded as the final two sets. Unaided probe-tube recordings were measured first because listeners do not move as much at the beginning of the session and any movement could alter probe-tube placement. Each set consisted of 15 blocks, 5 blocks for each room condition (anechoic, SRS, simulated room). A frozen broadband noise was generated for each block and played across all 23-target locations from left to right (-61º to +61º). Multiple repetitions were collected and averaged across five different noises to ensure any random spikes generated in the frozen noises were averaged. Having multiple repetitions also ensured appropriate average recordings in the case that listeners moved during a recording. If research participants did move, or recordings were at all noisy (i.e. head or jaw movements, clearing throat, electronic noise, etc), that waveform was not averaged. Up to five recordings were collected for each aided x room x target location, and at least three were averaged for any condition. A block of recordings lasted approximately 2.5 minutes and listeners were given a break at the conclusion of each set.

Similar to the protocol for research participants, recordings for KEMAR included five repetitions of BB noise recordings played from left to right for the three room conditions. In addition to the three aided conditions testing above, KEMAR also had recordings made for three additional hearing aid venting conditions (comply tips with 1, 2, and 3 vents) and measurements using low- and high-pass noise. The filtered noise results matched the BB, and thus, will not be discussed further.

2.3 Binaural cue estimation

The following methods were used to analyze binaural acoustic recordings for frequency specific ITD and ILD cues measured with probe-tube microphones placed near the eardrum.

2.3.1 Binaural cross-correlation model

To evaluate ITD in a frequency specific manner, binaural acoustic recordings were band-pass filtered and processed through a binaural cross-correlation model. Akeroyd's (2001) binaural cross correlation toolbox for Matlab was utilized to evaluate ITD. Frequency filter parameters were restricted to 250 – 8000 Hz, a frequency range commonly evaluated by audiologists. Use of a gammatone filterbank across this frequency range with one equivalent rectangular bandwidths (ERB) per channel resulted in 28 frequency channels listed here:

250, 305, 365, 433, 508, 592, 685, 789, 905, 1034, 1178, 1338,
1517, 1715, 1937, 2183, 2457, 2763, 3104, 3483, 3905, 4376,
4900, 5483, 6133, 6857, 7663, and 8561 Hz

Window of interaural differences evaluated were limited to -1500 to 1500 µsec. An example of the cross-correlation output is shown in Figure 2. Note that interaural correlations oscillate in a pattern equivalent to specific frequency channels. Exception to this is very low frequencies where the chosen time window only allows for one cycle of those frequencies.

2.3.2 Normalization of ITD

As mentioned previously, interaural correlations displayed in Figure 2 tend to oscillate across delays at a rate equivalent to the specific frequency channels. This is most noticeable in anechoic, but is true for reverberant conditions as well. Thus, interaural correlation for a given frequency may be highly correlated at multiple time delays within the specified time window (here, ±1500µsec). Thus, the largest interaural correlation is similar to that one phase cycle away.

The model used here simply picks the peak with the largest correlation. That largest correlation peak, however, may not make sense for a particular condition. For example, interaural correlations are calculated separately for each target speaker and neighboring speakers should have small interaural differences. To normalize measured ITD, we assumed that for a given frequency channel, ITD should not shift in large steps across azimuth. If large differences in ITD were observed for neighboring speakers, evaluated from left to right (-61º to +61º), and ITD values within one or more phase cycle steps away makes more sense than the peak ITD, then phase unwrapping was used to normalize measured ITD values.

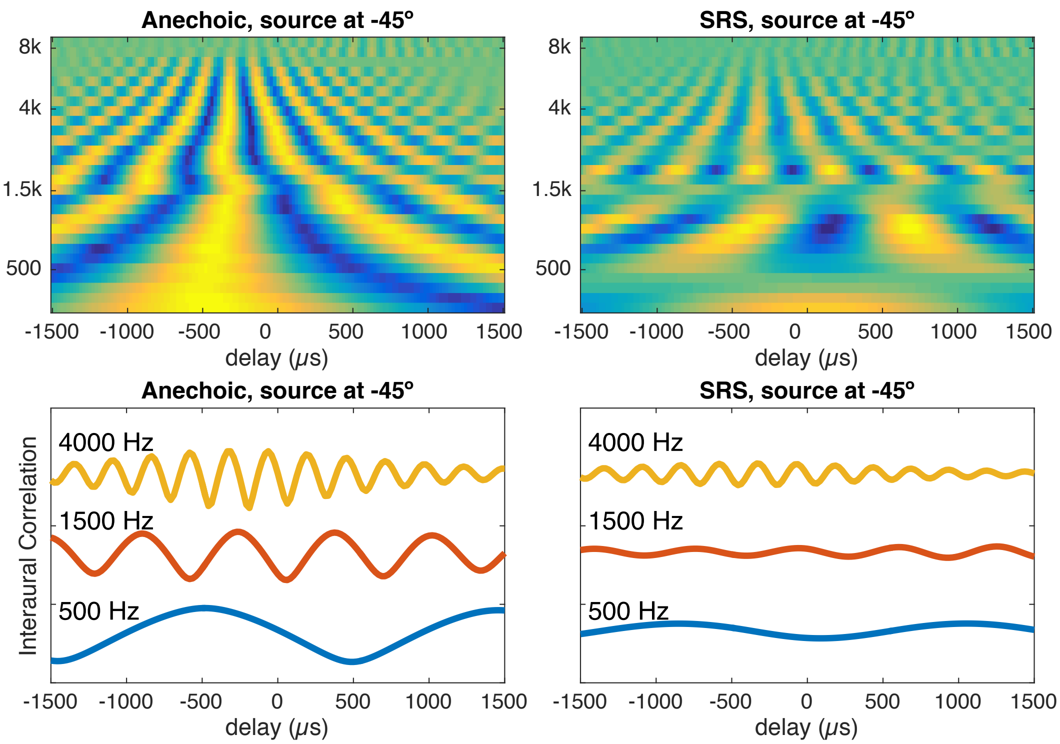


Figure 2. An example of a binaural cross-correlation output for sounds presented at 45º for Anechoic (left panels) and SRS (right panels) conditions. Top panels display cross-correlation across all frequency bands with yellow colors indicating high interaural correlation and blue colors low correlation. Lower panels demonstrated cyclical interaural correlation patterns observed for three frequency channels. Note reduction in interaural correlation in the presence of reverberation.

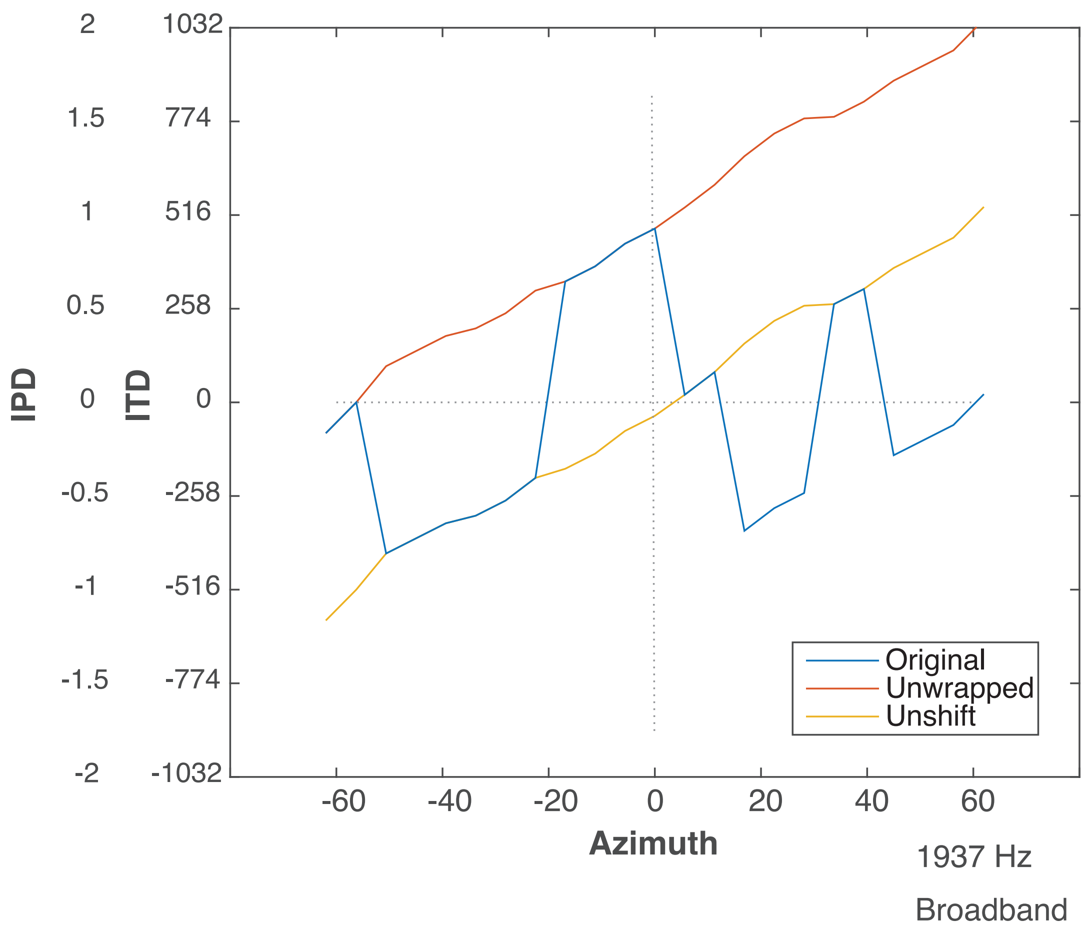


Figure 3. Lines plot process for phase unwrapping interaural time difference data. Example shown here is for a 1937 Hz frequency band processed from a broadband unaided acoustic recordings presented in anechoic. ITD data were first converted from ITD (y-axis) to IPD (leftmost y-axis) across speakers plotted by azimuth (x-axis). Blue line plots original IPD data across 23 speaker locations ranging from ±61º. Orange line displays unwrapped data. Yellow line displays unshifted data. Dotted lines represent 0 µsec ITD and 0º azimuth for reference.

To go about phase unwrapping, two steps were accomplished, visually outlined in Figure 3. Normalization process was conducted across all 23-speaker locations separately for each frequency channel. Here, 1937 Hz is shown for example. The blue line is the original data. Data were converted from ITD to IPD to evaluate for one-cycle steps. Next, the orange line plots unwrapped data (used unwrap function in Matlab) with the assumption that moving left to right across speakers, that sound would not jump a full cycle away from the previous speaker. Finally, the yellow line follows the assumption that when sound is directly in front (0º) that the IPD should be nearest to the midline. Thus, the entire line for this frequency was shifted in one-phase degree steps to be near midline. To conclude, IPD was converted back to ITD and data are now presented as normalized ITD. Figures 4 and 5 show an example of unprocessed and normalized ITD across frequency, respectively, for aided and room conditions.

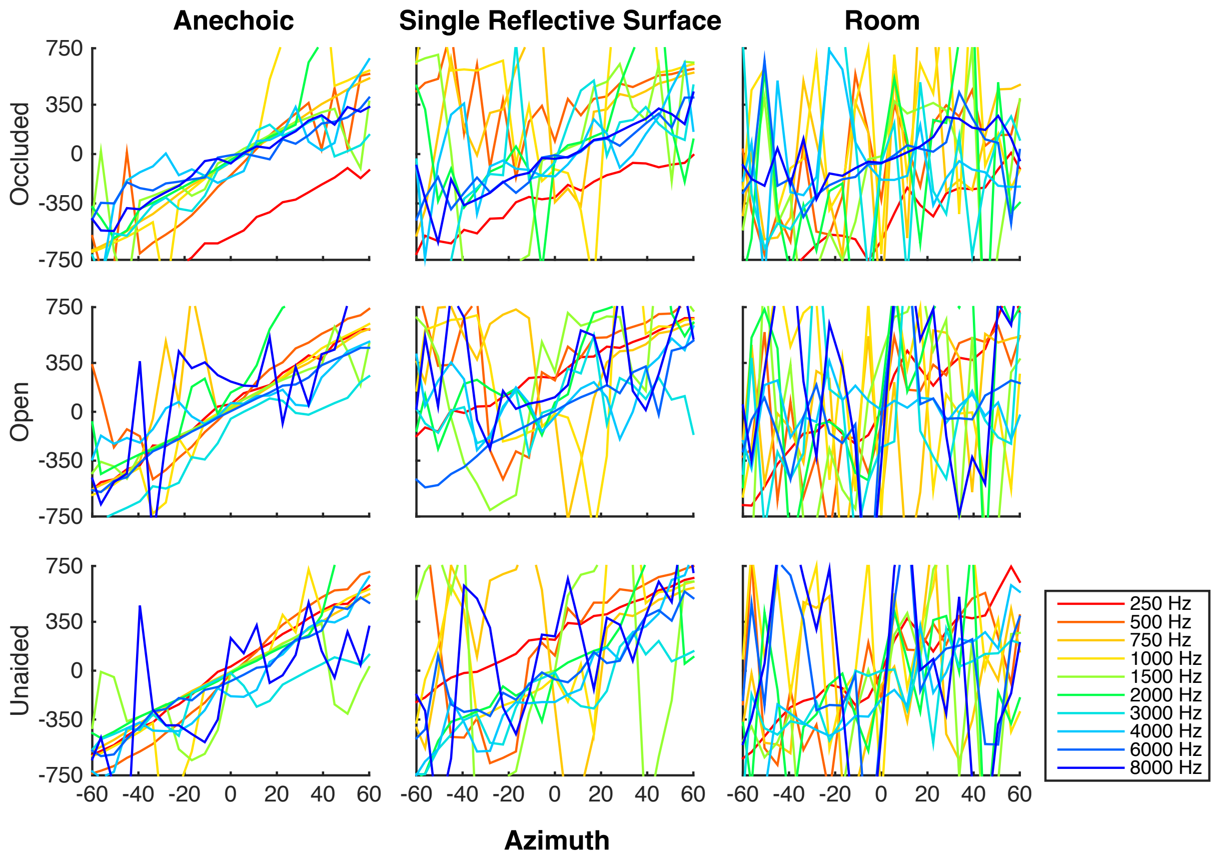


Figure 4. Individual data for listener 1403. Lines plot raw ITD values for 10 of the 28 frequency channels. Within each subplot, x-axis represents speaker location by degree azimuth and y-axis measured ITD. Negative numbers represent leftward speakers and ITD values, and positive values for rightward speakers and ITD. Columns represent room conditions and rows, aided conditions.

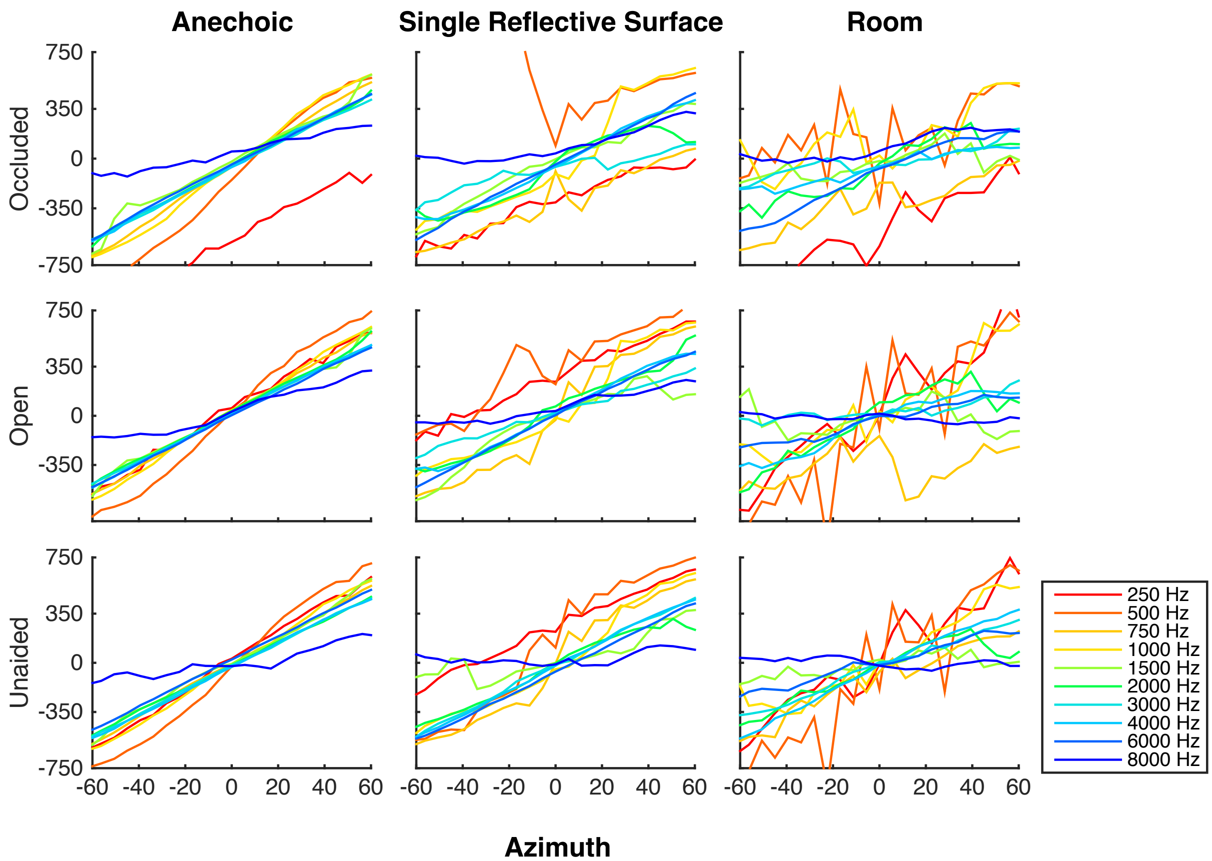


Figure 5. Lines plot normalized (phase unwrapped and shifted) ITD data from Figure 4 for listener 1403.

2.3.3 Calculating frequency specific ILD

To calculate frequency specific ILD, 28-frequency channels listed in section 2.3.1, were analyzed separately. ILD was calculated for each frequency using Equation 1, where RMSleft and RMSright are root mean square measures of average intensity level for left and right gammatone filtered waveforms.

$$ILD = 20 \times \log_{10}(RMSleft/RMSright) \qquad (1)$$

In this calculation, as for ITD analysis, an average of three to five recordings were evaluated to show interaural differences for each speaker x aid x room combination. As mentioned previously, some recordings were removed to due visible or audible noise in the waveforms.

2.3.4 Normalization of ILD

As with ITD, some raw ILD measurements appeared to be incorrect. Measured ILD can biased by several factors such as head test chair placement, listener head location and orientation, and any tilt by the chair, speakers or listeners. Overall, ILD data were cleaner than ITD, but ILD values were sometimes skewed to one direction. This is most noticeable if ILD values are not zero at 0º azimuth. To correct for skewed data, we assumed that measurements collected in an anechoic setting, at 0º azimuth, should have an ILD of zero. Thus, across frequency, anechoic ILD was set to zero and all other ILD was expressed relative to this value across SRS and simulated room. ILD normalization was conducted separately for each aided condition and Figures 6 and 7 display normalized data as measured on one of our research participants. In Figure 6, note high-frequency offsets which are corrected in Figure 7, and ILD is zero across frequency for each aided condition at 0º azimuth.

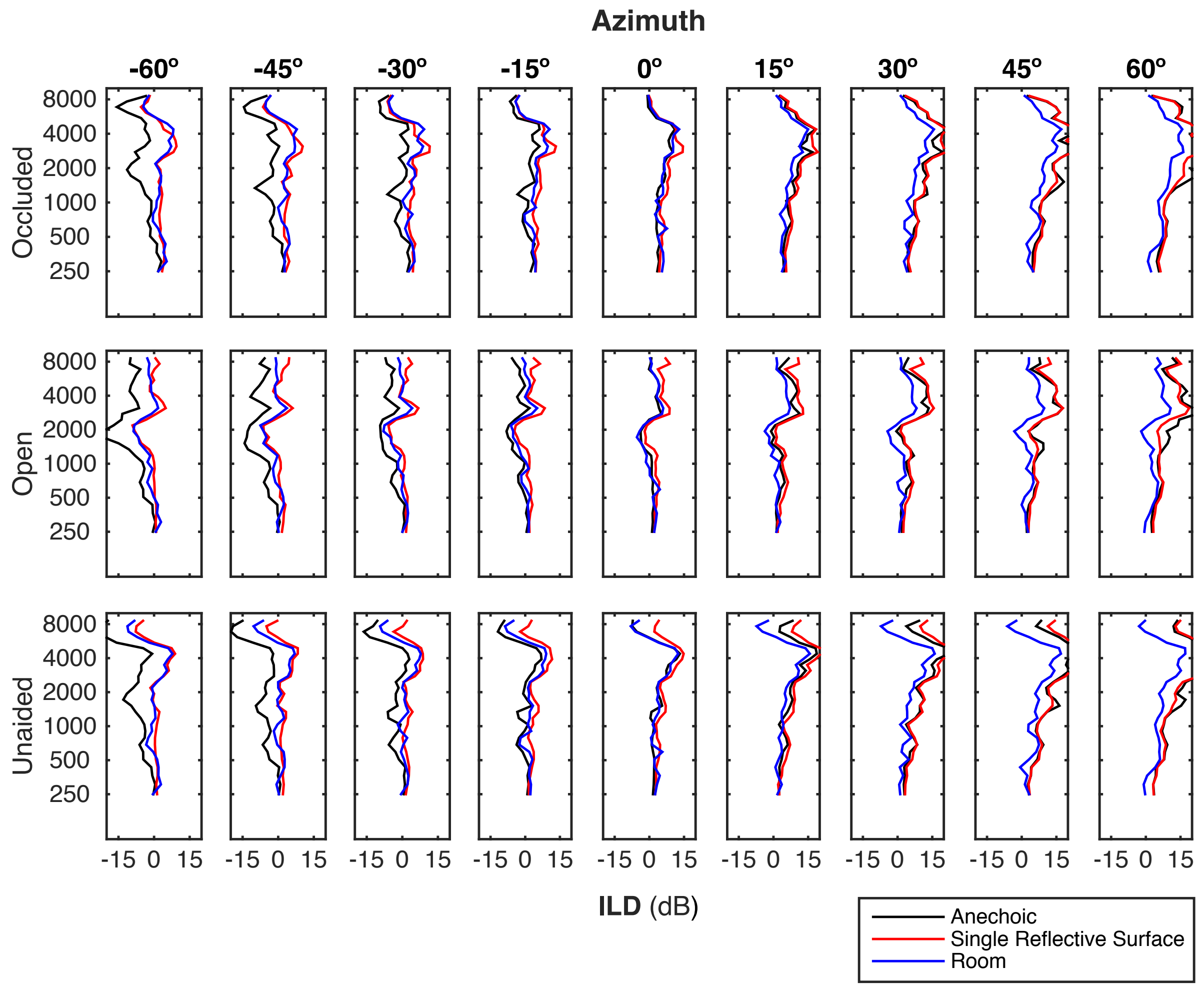


Figure 6. Raw ILD measured for listener 1403. Rows display hearing aid conditions and columns represent a sample of speaker locations. Y-axis represent 28 frequency channels used for binaural cross-correlation, x-axis represents measured ILD (dB). Lines plot ILD for anechoic (black), SRS (red) and room (blue).

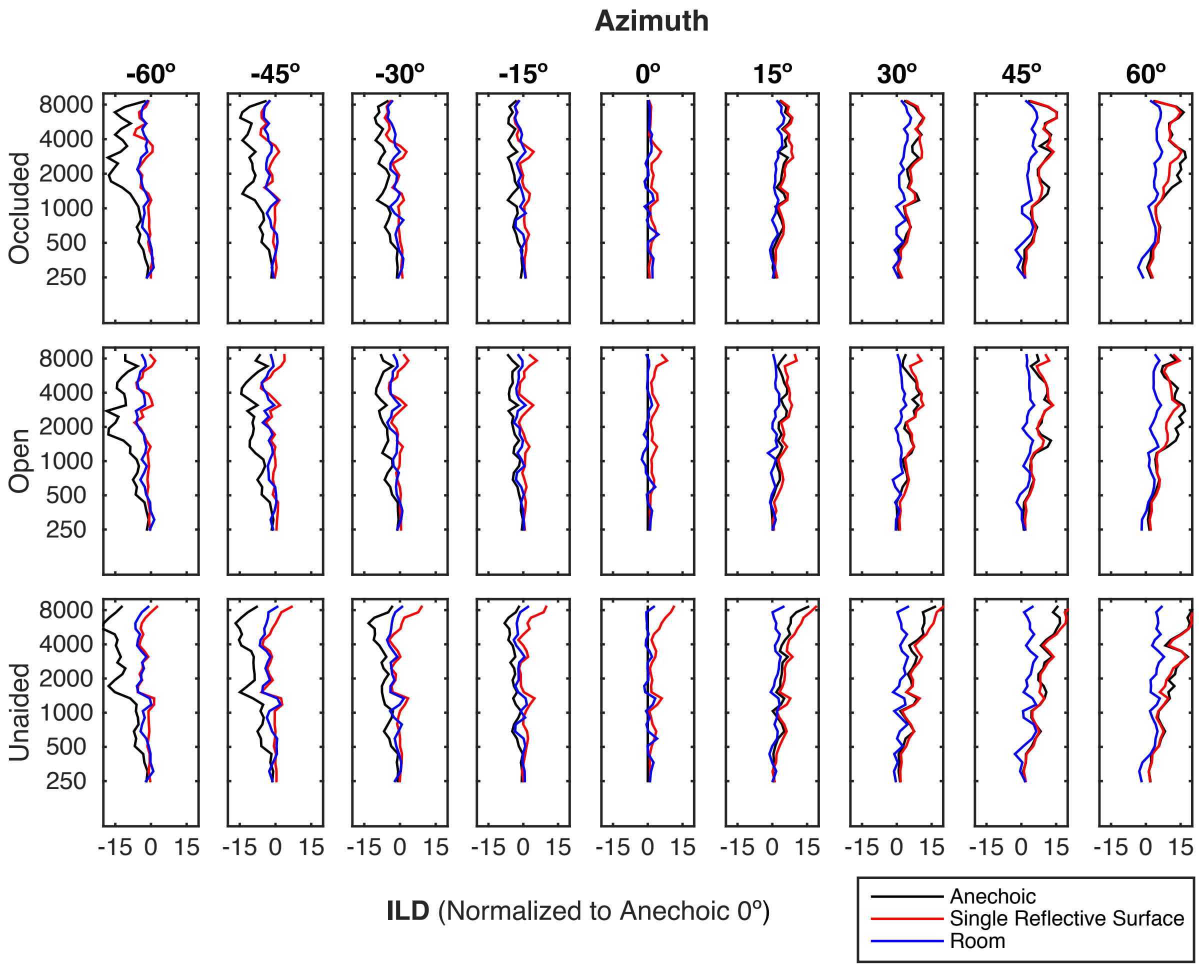


Figure 7. Lines plot normalized ILD from Figure 6 for listener 1403.

Chapter 3 - Effects of hearing aid venting and reverberation on interaural cues

3.1 ITD Results

To observe differences across frequency and azimuth, data are displayed using color plots where the color represents interaural cue values. Figures 8 and 9 plot normalized ITD with negative values representing leftward ITD (μsec) and positive values indicating rightward ITD. Overall, ITD becomes erratic with increasing reverberation (anechoic → SRS → room). This finding is consistent with recordings collected for research participants and KEMAR. Additionally, in the presence of reverberation (SRS and room), clear low-frequency distortions can be observed. Specifically, neighboring low-frequency channels appear to have competing ITD cues, as apparent by yellow (rightward ITD) and blue (leftward ITD) colors in Figures 8 and 9.

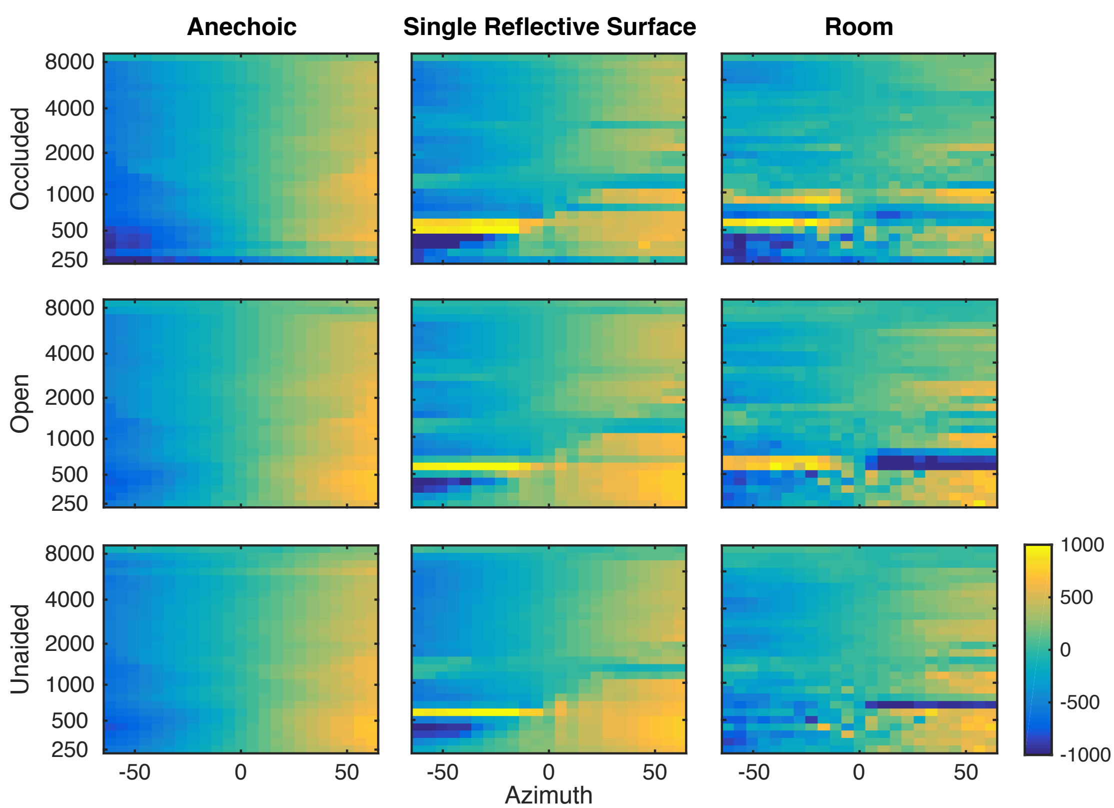


Figure 8. Color plots display normalized ITD for listener 1403. Panel layout is identical to Figures 4 and 5, with data displayed for 23 speaker locations (x-axis) and 28 frequency channels (y-axis). ITD is represented by color, with yellows indicating rightward ITD and blues leftward.

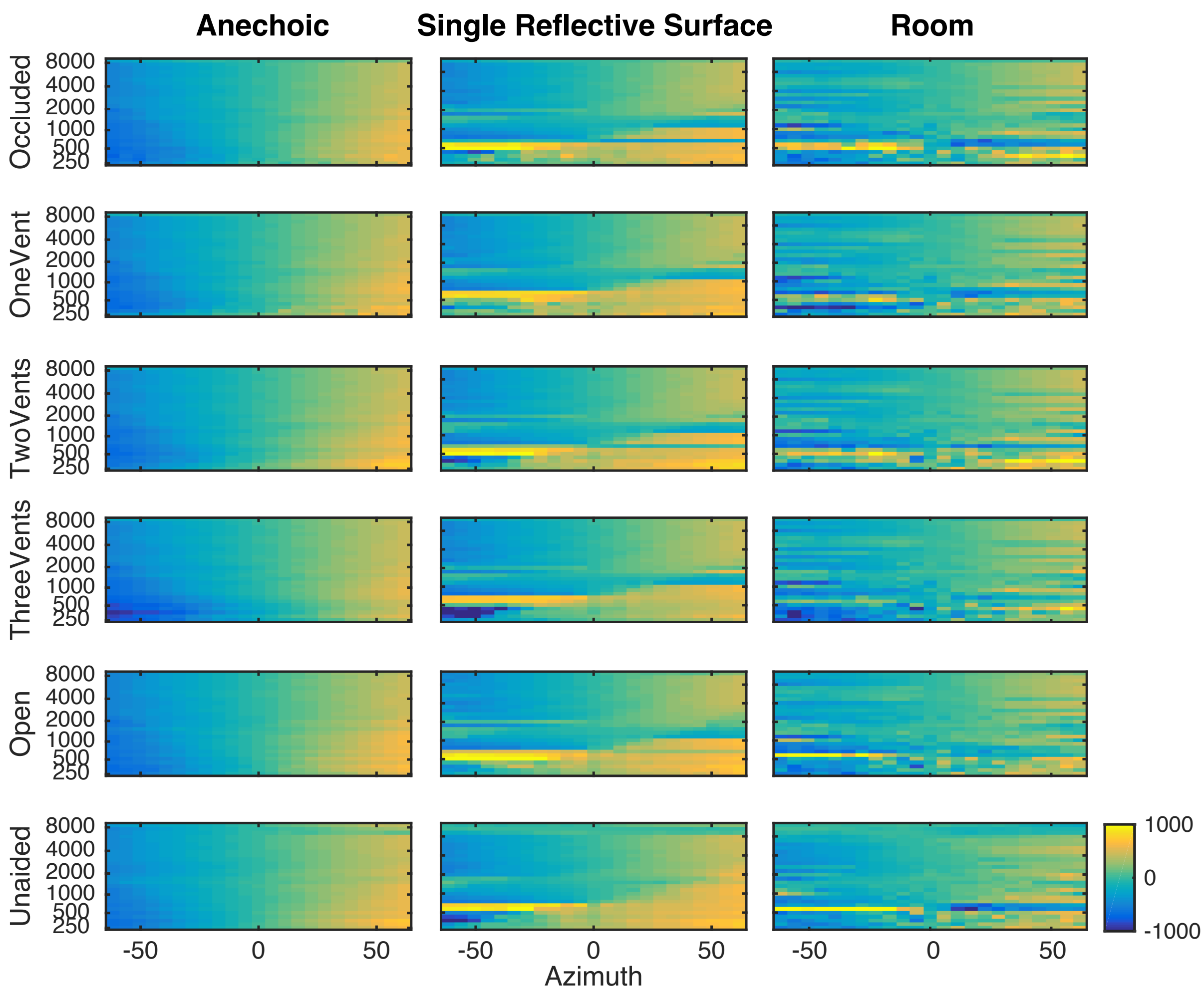


Figure 9. Color plots display normalized ITD for KEMAR. Columns represent three room conditions and rows represent six aided conditions. ITD values plotted in the same manner as Figure 8.

Effect of hearing aid venting is less clear. This is especially apparent for recordings on KEMAR where venting was slowly gaged using comply tips with increasing amounts of venting (Figure 9). The occluded hearing aid condition appears to have larger ITD values than open-fit and unaided in anechoic for individual listeners. For example, Figure 8 shows data for listener 1403. Other individual differences are available in Appendix B displaying ITD color plots for the other nine participants. For listener 1403, spread of low-frequency distortions are apparent across a larger range of channels for occluded versus open-fit and unaided. These differences are somewhat individual, but other participants show similar patterns. For KEMAR, in the occluded room condition, ITD distortions also appear greater than other aided conditions (Figure 9), but again these findings are not consistent across all listeners (Appendix B).

3.2 ILD Results

Similar to ITD, color plots for Figures 10 and 11 now represent measured ILD. Here, negative values representing leftward ILD (dB) and positive values indicating rightward ILD. Generally, ILD is stronger in higher frequencies and is reduced with increasing reverberation (anechoic → SRS → room). These findings are consistent across all research participants (Figure 10, Appendix C) and for KEMAR (Figure 11). Comparing ITD and ILD in the presence of reverberation, low-frequency channels, where ITD distortions occur, ILD cues are not in agreement. Thus, opposing ITD and ILD cues are apparent in the presence of reverberation.

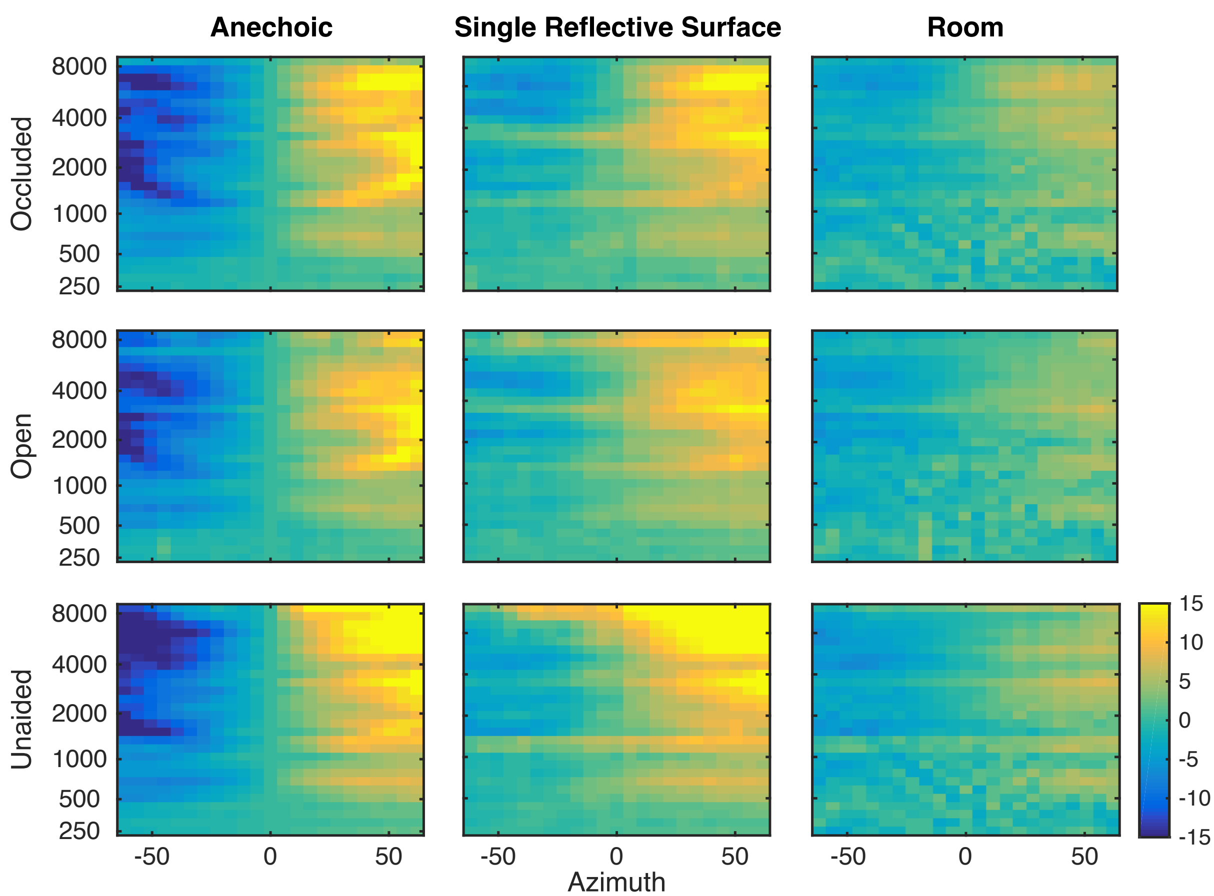


Figure 10. Color plots display normalized ILD for listener 1403. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.

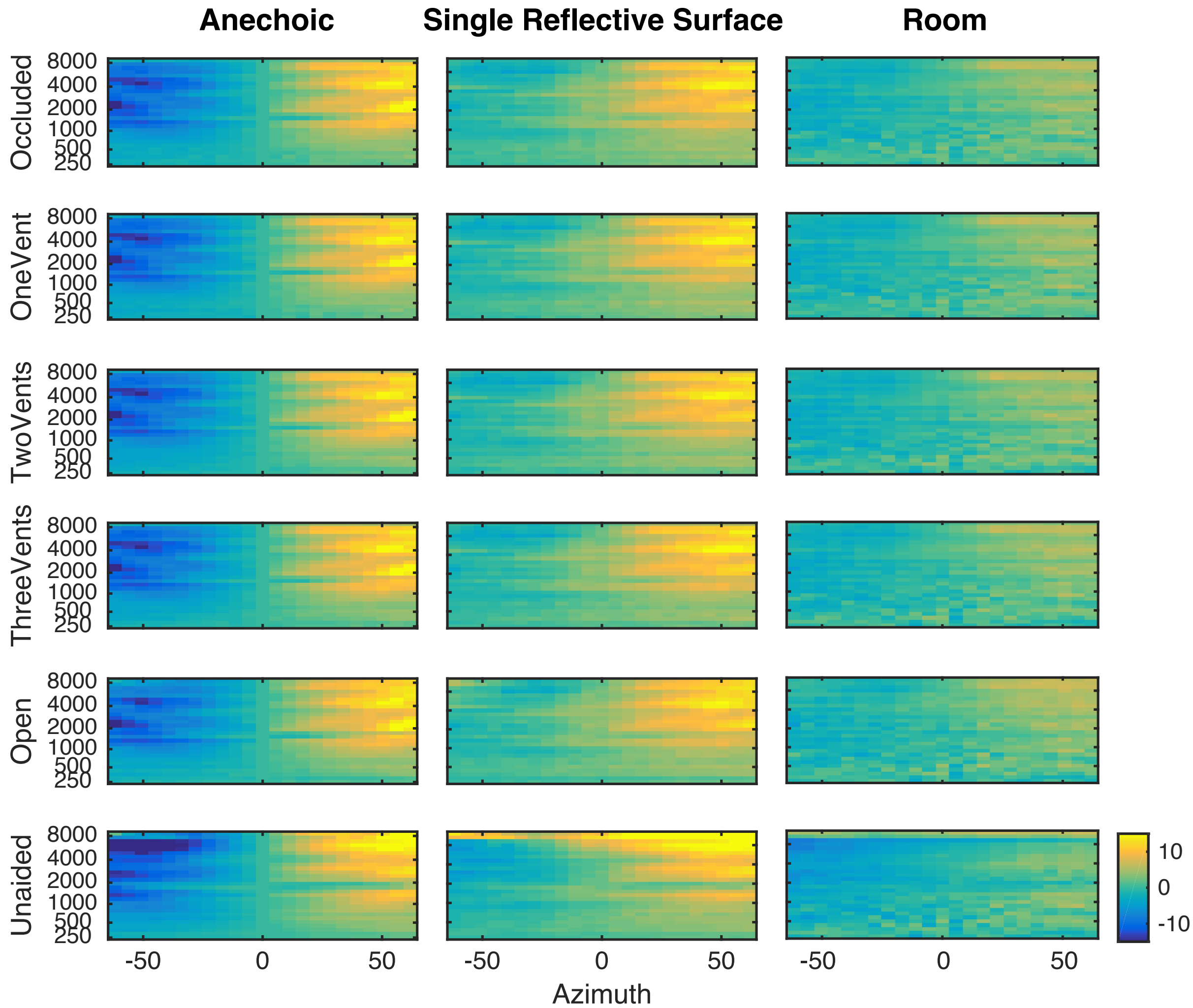


Figure 11. Color plots display normalized ILD for KEMAR. Panel layout is identical to Figure 9. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.

Similar to ITD, findings across aided conditions are less clear. For Anechoic and SRS conditions, high-frequency ILD appears stronger in unaided versus occluded and open-fit hearing aid conditions for most participants (Figure 10, Appendix C). In the room condition, this pattern across hearing aids is less apparent. ILD appears to be consistently reduced across all aided conditions for the simulated room. These patterns are potentially consistent with KEMAR (Figure 11), but less apparent. Unremarkable differences are seen for recordings on KEMAR with increased hearing aid venting.

3.3 Discussion

Consistent with the literature, presence of reverberation causes ITD to become erratic and reduces ILD cues (Rakerd and Hartman 1985, Shinn-Cunningham et al. 2005). Low-frequency ITD distortions are likely a product of virtual wall locations, and would likely shift in frequency with different simulated reverberation parameters. Also, while some listeners show some spectral differences for interaural cue distortions across aided conditions, others do not. This was especially apparent in the anechoic condition (Appendix B and C). If interaural cue distortions were to be caused by hearing aids, it must be because of something other than an interaction of acoustic (sound available through venting) and processed sound. This suggests that hearing aid venting is likely not the cause of interaural cue distortions, but rather features such as wide-dynamic range compression (Wiggins and Seeber 2011) and directional microphones (Picou et al. 2014) may be the cause of spatial deficits from amplification. Differences in ILD between unaided and aided conditions are likely due to spectral differences caused by BTE microphone location.

A limitation for interaural cue estimation was that the full duration of acoustic recordings were used to estimate ITD and ILD cues. Young normal hearing listeners may be better at weighting earlier portions of sound to estimate location. However, with increased reverberation and when wearing hearing aids, responses (shown below) were biased by later reflections. Thus, due to temporal aspects of listening in reverberation and temporal weighting of interaural cues for clinical populations, we believe analyzing the full duration of the waveform is a good approach to estimating interaural cues.

Sound Localization

Chapter 4 - Methodology

4.1 General Methods

4.1.1 Research participants

Listeners who participated in the binaural acoustic recordings (section 2.1.1) were then evaluated behaviorally. All procedures, including recruitment, consenting, and testing of human subjects, were approved by Vanderbilt University Institutional Review Board and non-lab members were compensated $15/hour for their time.

4.1.2 Stimuli

Across all room and aided conditions, four stimulus types were used in the sound localization experiment: Broadband (BB) noise, 500, 4000, and 500+4000 Hz narrowband noises. All noise types were 500 ms in duration. Ramp duration was 5 ms for BB noise and 10 ms for narrowband noises. Broadband noise was generated using a Gaussian white noise in the same way as BB noise from acoustic recordings. Narrowband noises were filtered to have a 1/6-octave bandwidth with 500 or 4000 Hz as the center frequency. When 500 and 4000 Hz were combined (500+4000 Hz stimulus), the narrowband noises were presented simultaneously. For BB noise, intensity was again set to -20 average binaural level (dB re: 1 volt peak) for hearing aid conditions, and -10 dB unaided. For 500, 4000, and 500+4000 Hz, levels were adjusted using across-ear average real-ear measurements, displayed in Appendix A. For each listener, correction factors were used to ensure equal intensity level across stimulus and aided conditions.

Broadband noise is known to be easier to localize due to energy across a broad frequency spectrum. Here, BB was used as a baseline to compare to a low-frequency band (typically used to code ITD), a high-frequency band (typically used to code ILD), and a combination of low plus high frequencies. Frequencies chosen were based off of the recordings that showed low-frequency distortions and reduced high frequency cues in reverberation.

4.1.3 Setup and arrangement

Set-up for sound localization was similar to acoustic recordings. Specifically, room conditions (anechoic, single virtual wall, simulated room), target speaker locations (±61º azimuth), hearing aid type (Siemens Motion 700 BTEs), and hearing aid settings (Appendix A) remained the same as acoustic recordings (see chapter 2). Hearing aid venting conditions evaluated here match those from human-subject acoustic recordings (occluded, open-fit, unaided). Thus, nine room x hearing aid conditions were evaluated across four stimulus types for 23 speaker locations in the Bill Wilkerson Center's anechoic chamber at Vanderbilt University.

4.1.4 Stimulus presentation and listener's task

The four stimulus types (BB, 500, 4000, 500+4000 Hz) were presented to the listeners in a randomized order and listeners indicated their responses on an iPad. To track head location, a Polhemus head tracker was mounted to a plastic adjustable headband. Responses were tracked on an iPad that was connected via USB to the test computer and acted as an external monitor. Sounds would not play until listeners were facing speaker one (0º azimuth) for three seconds.

Evaluation of sound localization performance across aided, room and stimulus conditions, was accomplished by having listeners seated in a chair located at the center of the 64-speaker array ring wearing a head-tracking device and hearing aids for 2/3 of the testing. At the beginning of a test block, they were instructed to face towards speaker one (0º azimuth) and touch anywhere on the response touch screen when ready to begin. During stimulus presentation, listeners were trained to keep their heads stationary for the full duration of the sound. Eye movements were allowed and encouraged during stimulus presentation, and the next trial would begin after their head orientation returned to the "home" position, or the location where their head was to begin a test block. They were cued on the touch screen with large red blocks which direction to move their heads to reach "home" position and monitored by audio and video from the control room. Re-instruction was accomplished, as needed during training, prior to evaluating experimental test blocks.

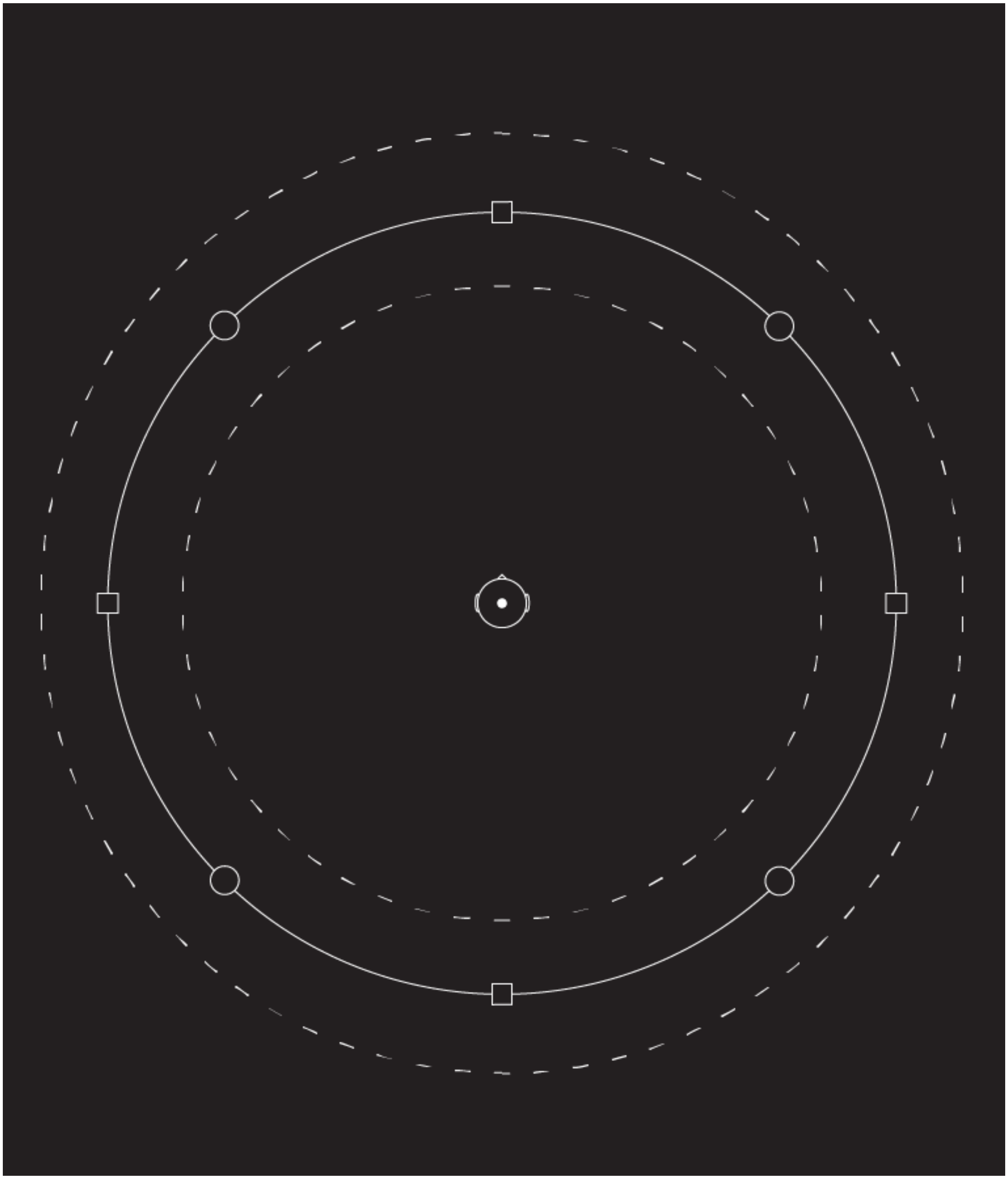


Figure 12. Response graphical user interface (GUI) used for sound localization experiment. GUI acted as an external monitor on an iPad connected via USB in the anechoic chamber. Listeners were instructed to respond with a finger touch where they perceived the sound to originate.

Training consisted of two practice blocks using broadband stimuli, for unaided, anechoic and simulated reverberation conditions. All participants were successfully trained at the localization task by the end of two practice blocks. Orientation of the response screen (Figure 12) was described to the listeners as if they were looking down from the ceiling in the anechoic chamber. The circle in the center represents the listener, the solid line the array of speakers and the dashed lines represent distance. They were informed that distance would not be analyzed, but rather, where they perceived the target speaker location. The square in front represents speaker one at 0º, circles at ±45º and squares to side ±90º. Instructions emphasized that eight speakers were located between each marker on the response screen and precise responses were encourage. They were also given an option to respond behind if that is where they perceived the target location. For instances where targets appeared diffuse and/or appearing above the speaker array, participants were encouraged to "indicate a location that corresponds best to your perceived location." For diffuse, this may be at the "center" of the sound, and for sounds perceived as above, they were instructed to "make a line down to the speaker array and indicate that speaker location."

A test block consists of two repetitions for each 23-speaker locations ranging from ±61º; 46 trials total. Each test block was approximately 7 minutes in length and no more than 4 test blocks were completed prior to taking a break.

4.2 Analytical Methods

For each stimulus type, nine aid x room conditions will be displayed by group means using the following analytical methods. Individual data for each analysis are available in Appendix D.

4.2.1 Localization error

Localization accuracy, or the degree of error for each trial, was calculated using root mean square (RMS) error across all speakers. Specific localization error calculation is shown in Equation 2. Here, the error term is the squared sum of differences between response azimuth in degree ($\theta_{Response}$) and target azimuth (θ_{Target}) for all trials (t) within one test condition (total trials = N), squared. To obtain RMSerror, the square root was calculated by dividing localization error by n, representing all 23-target locations, for each independent variable.

$$RMSerror = \sqrt{\frac{\sum_{t=1}^{N}(\theta Target - \theta Response)^2}{N}} \qquad (2)$$

As with the other analytical methods, localization error will be used to compare performance across room, aid, and stimulus conditions.

4.2.2 Localization gain (slope)

Another way to describe listeners' accuracy across test conditions is by observing localization gain, or slope, from the linear fit to the data. Linear regression analyses were computed for each test condition (stimulus x aid x room) to describe target and response azimuths using equation 3. β_0 represents the y-intercept, β_1 represents the slope and ε is the error term.

$$\theta Response = \beta_0 + \beta_1 \theta Target + \varepsilon \qquad (3)$$

A slope of, or near, 1.0 indicates that listeners' responses match target locations. Compression of responses, observed by behavioral responses biased to the front of the listener, was expressed through localization gain values less than 1.0. Similarly, expansion of responses, or indicating speaker location was more lateral to the target, are indicative of values greater than 1.0.

4.2.3 Localization Variance (R^2)

Similar to localization gain, localization variance uses R^2 values from correlation to describe the fit of responses across test conditions. The residual error, or 1-R^2, reflects both fixed and random errors. Thus, different than localization error or localization slope, localization variance describes randomness in the response. Using a linear regression model, R^2 was evaluated for observed response azimuth compared to predicted target azimuth including a column of ones as a constant. While R^2 is, by definition, a statistical measure of how close the observed data are fit to the regression line, here, the R^2 value will be used parametrically to evaluate fit in localization ability across test conditions.

4.2.4 Front-back reversals

Testing in an anechoic space can be deceptive for the auditory system. Specifically, when a room lacks reflective surfaces and reverberation, interaural cues from a horizontal plane are identical whether they are in front or behind the listener. For example, sounds directly in front and behind ideally have 0 ITD and 0 ILD. The only way to differentiate these two locations in an anechoic room is to use spectral cues from the pinna. When evaluating sounds in the vertical plane, interaural cues are supplemented by high-frequency spectral cues, but when testing solely in the horizontal plane, sounds in the front may be mistaken with those directly behind. This phenomenon would likely occur more frequently if pinna cues were removed or altered, such as by wearing BTE hearing aids.

For localization error, gain and variance analyses, all listener responses from behind were assumed to be front-back reversals, and were reflected to indicate azimuth values within -90º to +90º. Number of front-back reversals was recorded for each listener across test conditions and used to determine percentage of front-back confusion rate per test condition. When displaying individual data in scatter plot figures, corrected responses will be displayed in a different color.

4.3 Statistical Analyses

4.3.1 Factorial Analysis of Variance (ANOVA) model

Sound localization ability was measured for three independent variables. Factorial analysis of variance (ANOVA) was evaluated in Matlab (Mathworks Inc.). Analytical methods were predicted by three factors:

1. Stimulus (BB, 500, 4000, 500+4000 Hz)
2. Aided condition (Occluded, Open-fit, Unaided) and
3. Room condition (Anechoic, SRS, Room)

Deviations from the mean (μ), calculated for each analytical method (see section 6.2) are observed for stimulus (α), aided condition (β), and room condition (γ). Additionally, interactions are measured for each pair of factors ($\alpha\beta$, $\alpha\gamma$, $\beta\gamma$), and for all three factors ($\alpha\beta\gamma$) using the model below:

$$y_{ijk}=\mu+\alpha_i+\beta_j+\gamma_k+(\alpha\beta)_{ij}+(\alpha\gamma)_{ik}+(\beta\gamma)_{jk}+(\alpha\beta\gamma)_{ijk} \qquad (4)$$

4.3.2 Paired t-tests analysis

The above ANOVA model evaluates main effects and interactions for the three independent measures: stimulus, aided condition and room condition. Specific contrasts for each analytical method were evaluated using paired t-tests, appropriate for experiments where participants completed all test conditions. A paired t-test contains a difference in means in the numerator ($\overline{d}$) between the two dependent variables, thus it is possible for the t-statistic to be a negative number. The denominator is the square root for the ratio of variance (s^2) and number of participants (n) resulting in a t-statistic for n-1 degrees of freedom:

$$t = \frac{\overline{d}}{\sqrt{s^2/n}} \qquad (5)$$

Chapter 5 - Results

Guided by factorial ANOVA results, significant main effects and interactions for each analytical method are reviewed below. Further, pairwise comparisons were made to contrast independent variables (stimulus, aided condition, room condition). Statistically significant results for the ANOVA analysis are present in the text below; paired t-test results, for each analytical method, are available in Appendix E. Bonferroni correction for multiple comparisons were not utilized. For this reason, conservative significant criteria ($p \leq 0.01$) were used for uncorrected p-values, displayed in bold font in Appendix E.

5.1 Localization Error

Mean RMS error for ten listeners across 23 target speakers are illustrated in Figure 13. Results of the factorial ANOVA show significant main effects for each independent variable: stimulus $F(3,356) = 39.34$, $p<0.01$, aided condition $F(2,357) = 30.75$, $p<0.01$, and room condition $F(2,357) = 12.32$, $p<0.01$. Additionally, a significant interaction of stimulus and aided condition was observed: stimulus x aid $F(6,353) = 2.23$, $p=.04$. Guided by these results, paired t-tests (Appendix E) and mean data displayed (Figure 13) for specific contrasts across independent variables are discussed below.

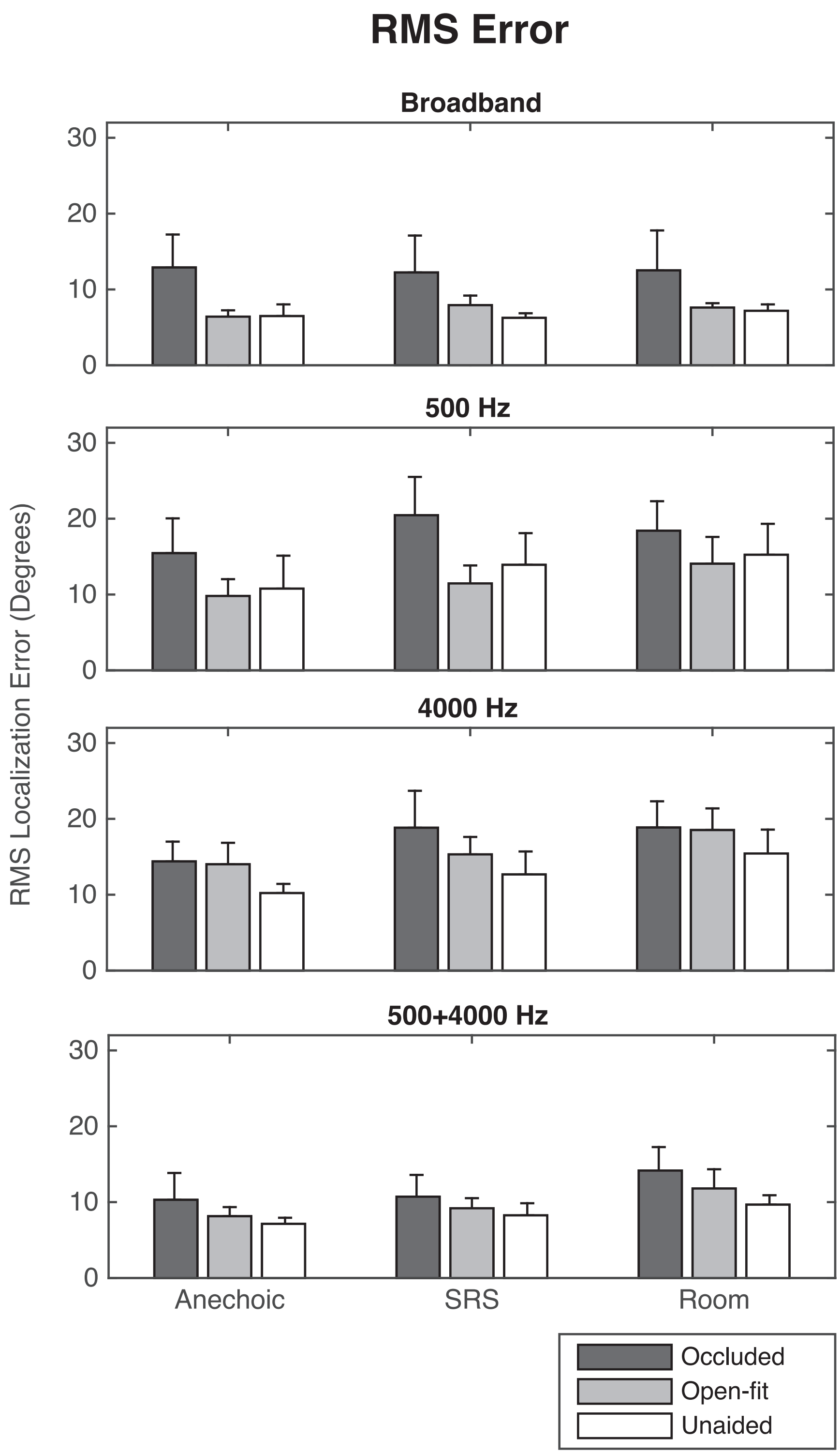


Figure 13. Panels represent RMS localization error for each stimulus type. Bars plot mean performance and standard error for each hearing aid condition (dark grey = occluded, light grey = open-fit, white = unaided). Each panel contains performance for three room conditions (anechoic left, single-reflective surface middle, room right).

5.1.1 Stimulus

The most apparent difference across stimulus conditions is decreased RMS error for broadband stimuli (BB & 500+4000Hz) compared to narrowband (500 & 4000 Hz). Broadband stimuli show similar degree of error until presented in the room condition, containing the greatest amount of reverberation, where BB had fewer errors than 500+4000 Hz.

Comparing narrowband stimuli, 500 & 4000 Hz show greater localization errors than 500+4000 Hz. One exception to this was 500 Hz and 500+4000 Hz had similar error rates when the ear canal is open (open-fit and unaided conditions).

5.1.2 Aided condition

Localization error was greatest for the occluded hearing aid condition. Across all room conditions, listeners showed greater degree of errors for occluded versus open-fit hearing aids when listening to low-frequency narrowband (NB) noise (500 Hz). Conversely, performance localizing high frequency NB stimulus (4000 Hz) was poorer for occluded versus unaided conditions across all room conditions. In fact, for both aided conditions, localization error rate was worse than unaided across all room conditions when localizing high-frequency NB noise.

5.1.3 Room condition

With increasing amounts of reverberation, localization error increased (Anechoic < SRS < Room). This trend is generally observed across all conditions, however, not all are statistically significant.

Increased errors are observed for simulated room compared to anechoic when localizing 4000 Hz and 500+4000 Hz stimuli across all aided conditions. By adding a single reflection, SRS showed greater error compared to anechoic at 4000 Hz when listeners were wearing hearing aids.

5.1.4 Interactions

Significant difference Tables in Appendix E are consistent with interactions of stimulus and aided ANOVA results. For instance, narrowband stimuli (500 & 4000 Hz) are significantly different only for open-fit hearing aids, suggesting a stimulus x aid interaction. Also, statistically significant differences were observed across stimuli for occluded hearing aid conditions compared to open-fit and unaided. Thus differences for occluded hearing aids could contribute to an interaction across stimulus conditions.

5.2 Localization Gain

Mean localization gain values for each independent variable are presented as bar plots in Figure 14. Results from the factorial ANOVA show significant main effects of: stimulus $F(3,356) = 44.73$, $p<0.01$, aid $F(2,357) = 6.27$, $p<0.01$, and room $F(2,357) = 6.76$, $p<0.01$. Additionally, a significant interaction was found for stimulus and aided conditions: stimulus x aid $F(6, 353) = 2.95$, $p<0.01$. Specific differences for paired t-tests are described in Appendix E and discussed below.

5.2.1 Stimulus

General observations from Figure 14 are that 500 Hz stimuli display expanded responses, 4000 Hz compressed responses, and broadband stimuli (BB & 500+4000 Hz) are mostly accurate (slope = 1). Paired t-tests *not* showing significant differences were BB versus 500 Hz, across all room conditions, for occluded and open-fit hearing aids. Additionally, broadband stimuli (BB & 500+4000 Hz) were *not* different for open-ear canal conditions (open-fit and unaided) across all rooms.

5.2.2 Aided condition

The most consistent significant differences across aided conditions were observed with a broadband stimulus. Occluded hearing aids were significantly different from both open-fit and unaided conditions across all rooms when listeners localized broadband noise. Additionally, there was less compression at 4000 Hz in the presence of reverberation (SRS & room) when listeners were localizing without hearing aids (slope for open-fit & occluded < unaided).

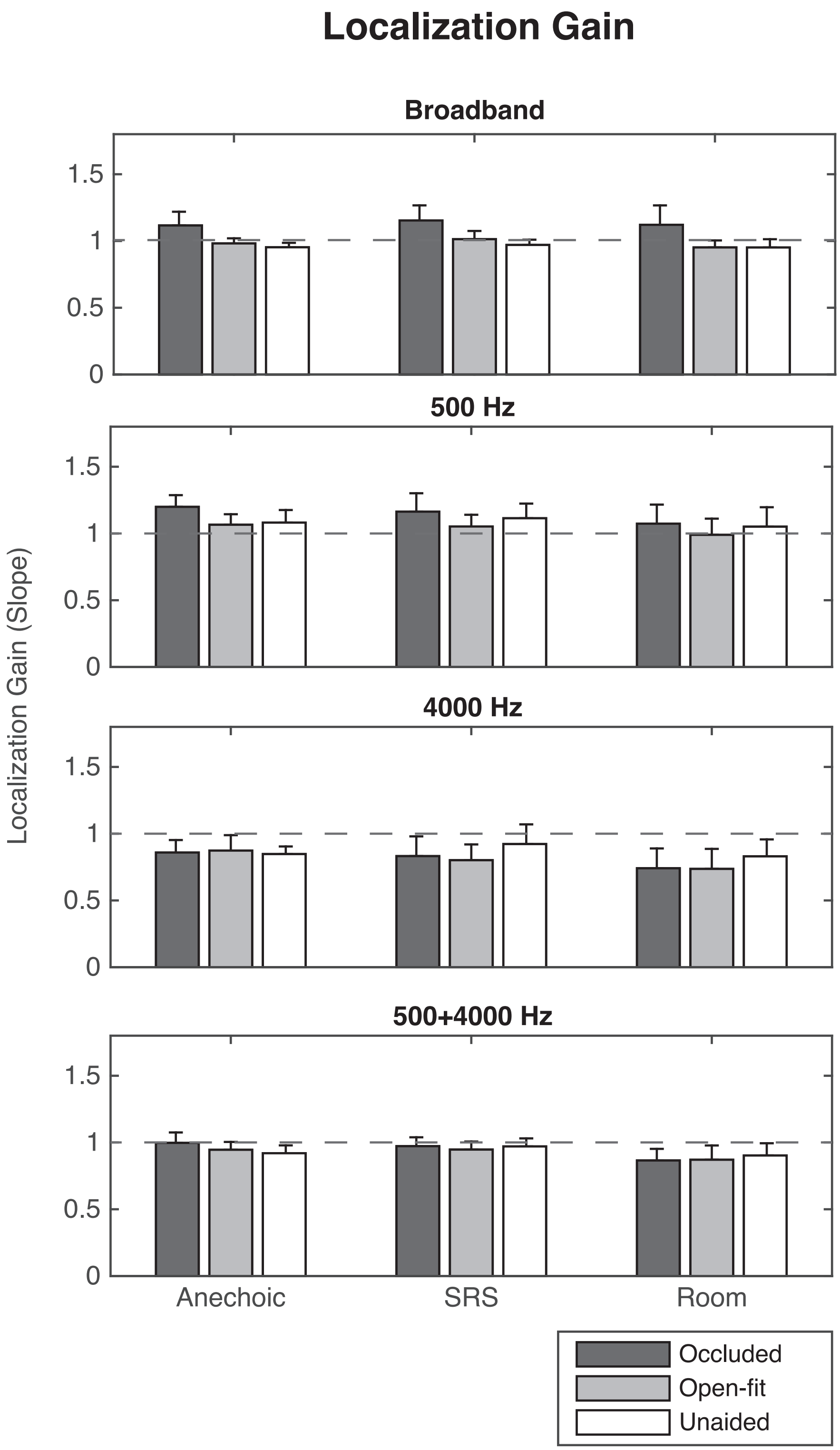


Figure 14. Panels plot localization gain by stimulus condition. Bars plot mean performance and standard error for each hearing aid condition (dark grey = occluded, light grey = open-fit, white = unaided). Each panel contains performance for three room conditions (anechoic left, single-reflective surface middle, room right). Dashed line represents a slope of 1, indicative of perfect performance.

5.2.3 Room condition

Statistically significant differences were observed for the independent variable room at both factorial ANOVA and paired t-test levels, however, results of the t-test did not reveal many consistent trends across room conditions. One notable difference was observed for the 4000 Hz stimulus. Specifically, mean performance in the simulated room when wearing hearing aids (occluded and open-fit) was significantly compressed compared to performance in anechoic. Other differences (Appendix E) appear somewhat random.

5.2.4 Interactions

Generally, 500+4000 Hz gain was accurate (slope = 1.0) except in the simulated room condition. Broadband, open ear canal conditions (open-fit & unaided) were also accurate while occluded gain was expanded. These results likely drove an interaction effect for stimulus and aided conditions.

5.3 Localization Variance (R^2)

Generally, R^2 values were high overall. However, as observed in Figure 15, there is enough variability in R^2 values to make parametric comparisons across independent measures. Using factorial ANOVA, significant main effects were observed for: stimulus $F(3,356) = 62.82$, $p<0.01$, aid $F(2,357) = 30.27$, $p<0.01$and room conditions $F(2,357) = 16.3$, $p<0.01$. Additionally, there were significant interactions for: stimulus x aid $F(6,353) = 3.17$, $p<0.01$and stimulus x room $F(6,353) = 3.5$, $p<0.01$.

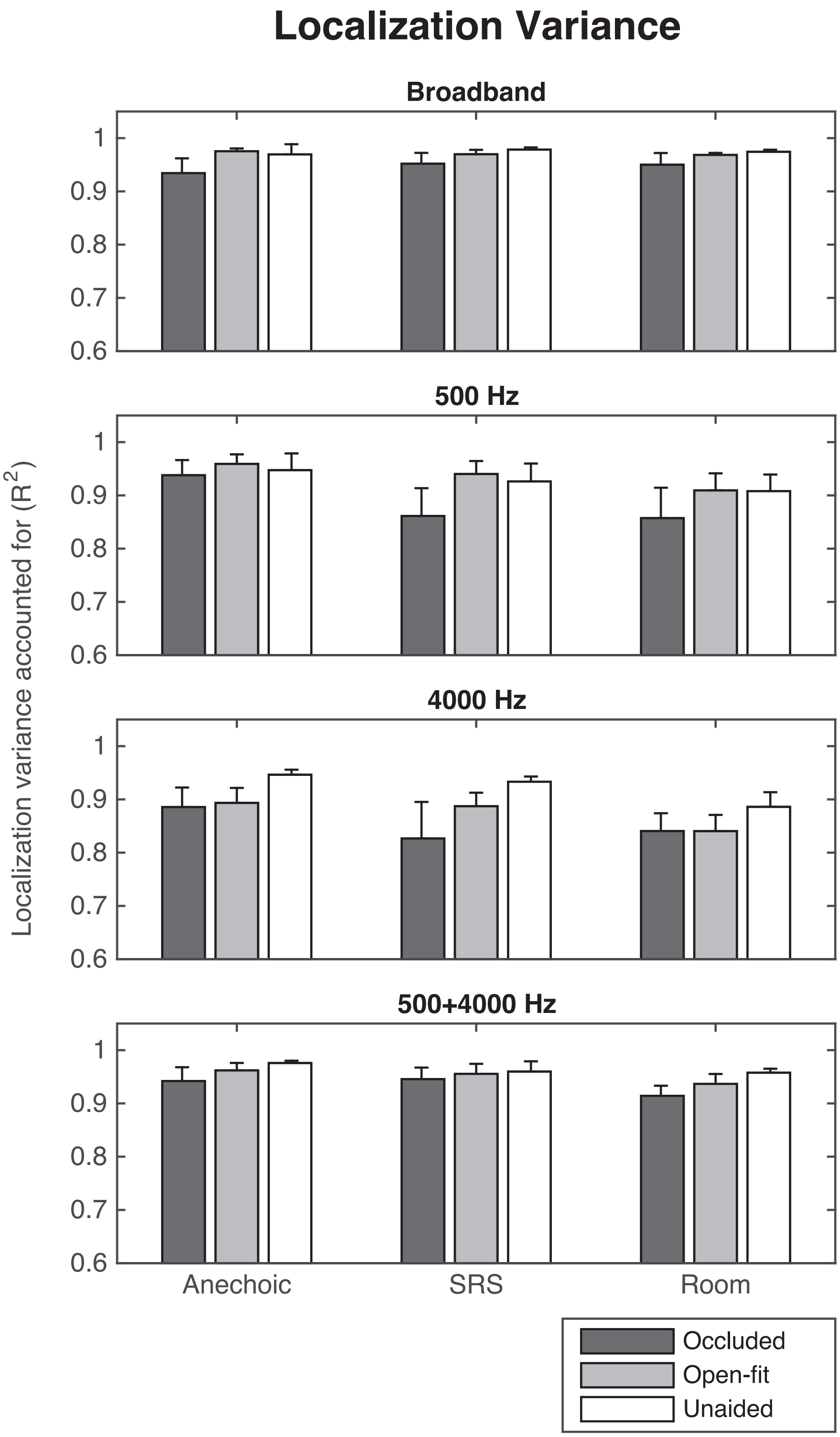


Figure 15. Bars plot localization variance as indicated by R^2. Bars plot mean performance and standard error for each hearing aid condition (dark grey = occluded, light grey = open-fit, white = unaided). Each panel contains performance for three room conditions (anechoic left, single-reflective surface middle, room right).

5.3.1 Stimulus

The clearest observations across stimulus condition were that broadband (BB & 500+4000 Hz) noises showed better fit than narrowband. Specifically, R^2 values were significantly lower for 4000 Hz compared to broadband across all room and aid conditions. Similarly, 500 Hz showed better fit than broadband conditions for occluded hearing aid in the presence of reverberation (SRS & room). Other, somewhat random differences for stimulus can be observed in Appendix E.

5.3.2 Aided condition

Generally, differences across aided conditions follow the trend occluded < open-fit < unaided for R^2 values. Statistically, occluded and open-fit hearing aids only differ for some conditions (BB anechoic, 500 Hz SRS) and aided versus unaided have clear statistical differences. The clearest findings for fit across aided condition were for 4000 Hz where across all rooms, greater R^2 values were found for unaided versus aided (open-fit and occluded). Similarly, most broadband conditions showed the same trend of greater R^2 values for unaided compared to aided. The only statistically significant difference in fit at 500 Hz was for SRS when comparing occluded hearing aids to open ear canal conditions (open-fit & unaided).

5.3.3 Room condition

The main story for room condition was greater fits were observed with increasing amounts of reflections (anechoic < SRS < simulated room). The most significant results appeared at the extremes (anechoic versus simulated room), but there were several significant differences at each level (Appendix E). Specifically, greater fit was seen across all aided conditions for narrowband noises (500 and 4000 Hz). Additionally, greater fit was observed for 500+4000 Hz with aided conditions (occluded and open-fit).

5.3.4 Interactions

According to the factorial ANOVA, both aid and room conditions interacted with the stimulus condition. The observable room interaction was likely due to narrowband noises having significantly worse fit than broadband. Interactions with the aided conditions, in general, were due to differences in the occluded hearing aid condition where R^2 values were significantly lower for the occluded conditions when stimuli were narrowband. No significant interactions were observed for room x aid or room x aid x stimulus.

5.4 Front-back confusions

The story for front-back confusions is much simpler than the other three analytical methods. Here, significant main effects were seen for: stimulus $F(3,356) = 11.45$, $p<0.01$and aid $F(2,357) = 4.02$, $p=.02$. There were no effects of room, thus, front-back confusions rate was similar across room conditions, and there were no significant interactions across independent variables.

5.4.1 Stimulus

Broadband and 500 Hz stimuli consistently showed front-back confusions for several listeners (Figure 16). While some confusions were present for 4000 Hz and 500+4000Hz, the majority of confusions were for BB and 500 Hz. For paired t-test analyses, the *only* statistically significant difference, with a less strict significance value ($p\leq0.05$) observed was for 500 Hz versus 500+4000 Hz in the occluded, simulated room condition, suggesting a reduction in front-back confusion for 500 Hz when played simultaneously with 4000 Hz.

5.4.2 Aided condition

While there were some trends in the paired t-test across aided conditions, there were no significant effects when comparing means, as suggested by the ANOVA model. This result was likely driven by the differences in occluded hearing aid condition when localizing broadband noise, were only a couple subjects had large amounts of front-back confusions.

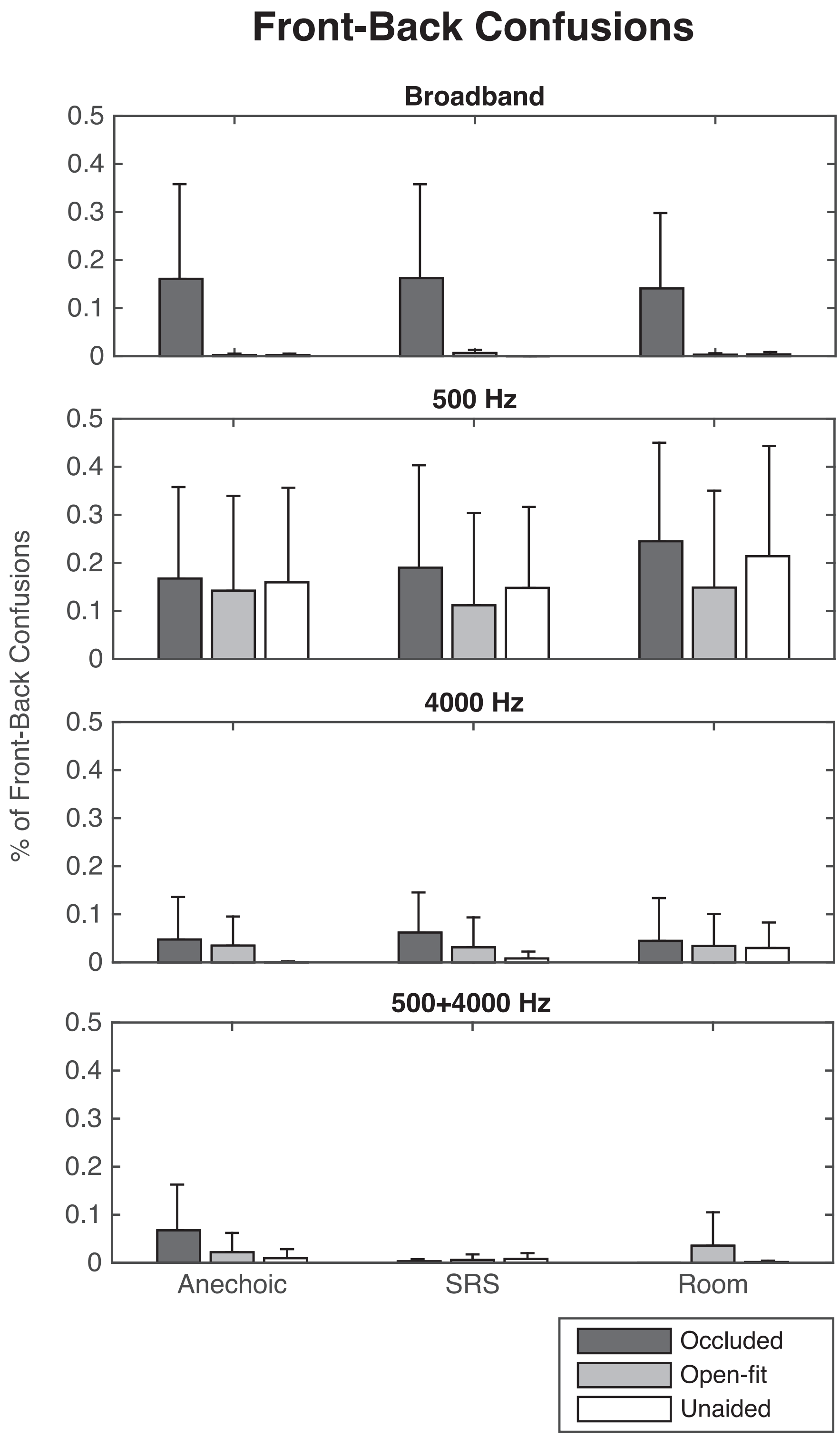


Figure 16. Bars plot percentage of front back confusions. Bars plot mean performance and standard error for each hearing aid condition (dark grey = occluded, light grey = open-fit, white = unaided). Each panel contains performance for three room conditions (anechoic left, single-reflective surface middle, room right).

Chapter 6 - Discussion

Effects of stimulus, hearing aid venting, and reverberation are evaluated for each analytical method, if applicable, below.

6.1 Effect of stimulus

Generally, results show sound localization accuracy to be better for broadband stimuli (BB, 500+4000 Hz) compared to narrowband stimuli (500, 4000 Hz). Considering the broad spectrum of sound available for BB and 500+4000 Hz, this finding makes logical sense.

6.1.1 Localization Error

Across all aided and room conditions, performance for 500 Hz and 4000 Hz alone were poorer than when presented simultaneously (500+4000 Hz). This finding differs from previous work in the literature. Ihlefeld and Shinn-Cunningham (2011) had conducted a similar experiment with simulated reverberation over headphones using 750 and 6000 Hz octave band noises. Their results showed RMS error pattern of 6000 Hz < 750+6000 Hz < 750 Hz. While testing in anechoic, here, ability to localize 500 Hz was similar to 500+4000 Hz when listeners' ear canals were open (open-fit and unaided). Otherwise, narrowband performance was similar for 500 and 4000 Hz, and consistently worse in terms of RMS error for 500+4000 Hz. Ihlefeld and Shinn-Cunningham (2011) concluded, in line with greater weighting of ITD, that listeners did not alter perceptual weighting of cues in reverberation and were harmed when low- and high-frequency noises were played simultaneously versus high-frequency alone. This was not observed here.

Disagreement between these two studies may be due to several methodological differences. First, Ihlefeld and Shinn-Cunningham (2011) tested over headphones, as opposed to free-field, and used non-individualized head-related transfer functions (HRTF) by collected BRIR on KEMAR. It could be argued that listening with BTE hearing aids in the occluded condition would give a similar error pattern, as several research participants reported that this condition sounded above or inside their head. The altered cues with occluded hearing aids is likely due to BTE microphone placement and loss of pinna cues, but even for the occluded hearing aid condition, error patterns across stimuli persisted (500 & 4000 Hz < 500+4000 Hz). Second, there were differences in stimulus duration and bandwidth across studies. Here, we tested 1/6-octave noise at 500ms duration compared to 250ms octave band noise. With increased bandwidth, there are more chances of additional spectral distortions in reverberation that could interact and cause confusion, especially for low frequencies. As shown with acoustic recordings above, ITD cues measured for neighboring low frequencies carried opposing directional cues. Opposing cue information could cause diffuse or erratic sound localization. Third, differences in room size and reverberation. In our reverberant condition, the simulated room was approximately the size of a classroom (5m left/right, 6.67m in front, 3.33m behind, no floor or ceiling) with a T60 reverberation time ~300ms. Ihlefeld and Shinn-Cunningham's (2011) BRIR's were recorded in an office 3.3m width, 5.8m length, 2.6m height.

In terms of cue weighting, our findings suggest listeners used low-frequency cues until reflections are added (SRS and simulated room), as 500 and 500+4000 Hz results were similar for simple scenes such as listening unaided in an anechoic condition. Ihlefeld and Shinn-Cunningham did not observe this finding for 750 Hz and 750+6000 Hz. In compromised listening situations, such as in reverberation or with occluded hearing aids, our listeners utilized available high-frequency cues to perform better than 500 Hz alone. Increased localization error for simultaneous presentation of 500+4000 Hz compared to 4000 Hz, was not observed.

Though it was not statistically significant, at the individual level, a few subjects performed slightly better at 4000 Hz in the occluded condition compared to 500 Hz, and one performed nearly better for 4000 Hz compared to 500+4000 Hz. While this slight trend of narrowband noise results for a few listeners matched Ihlefeld and Shinn-Cunningham's findings, results did not hold when the two noises were presented simultaneously.

6.1.2 Localization Gain

Mean results for localization gain, displayed in Figure 14, showed expanded responses for 500 Hz, compressed for 4000 Hz, and were mostly accurate for broadband stimuli. To further evaluate these findings, scatter plots for individual listeners across aided and room conditions were displayed in Figures 17 (500 Hz) and 18 (4000 Hz). While most condition evaluated with BB stimuli had slopes near 1.0, the occluded hearing aid condition showed expanded slopes for

BB across all rooms. Notably, BB and 500 Hz stimuli contained more front-back confusions than the other stimuli.

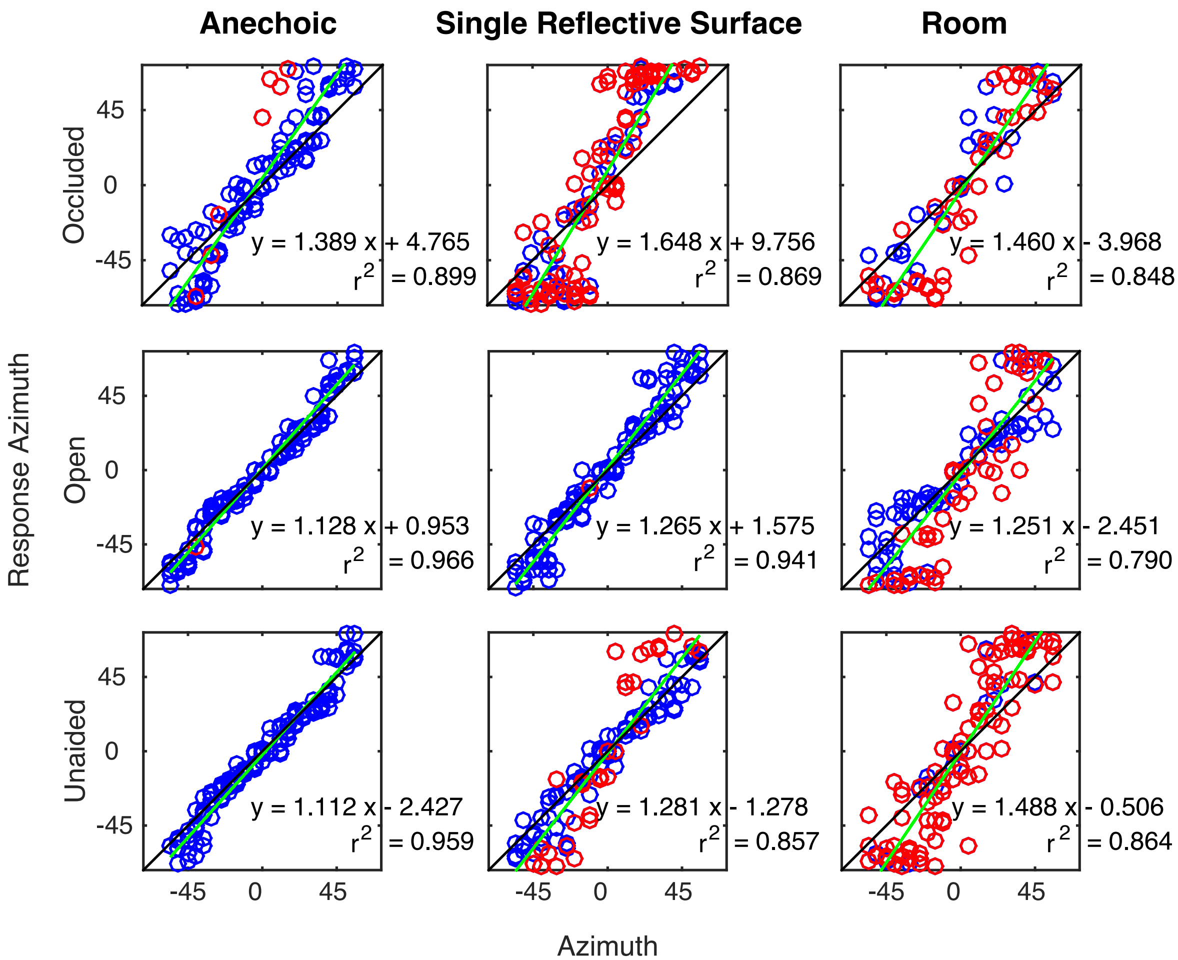


Figure 17. Sound localization responses for listener 1603 at 500 Hz narrowband noise. Y-axis represents response azimuth and x-axis target azimuth. Columns plots room conditions and rows aided conditions. Green line represents linear fit to the data with equation and R^2 displayed for each subplot. Blue circles represent individual trials for each 23-target locations. Red circles represent responses for resolved front-back confusions. Note expanded responses for occluded hearing aids and simulated room.

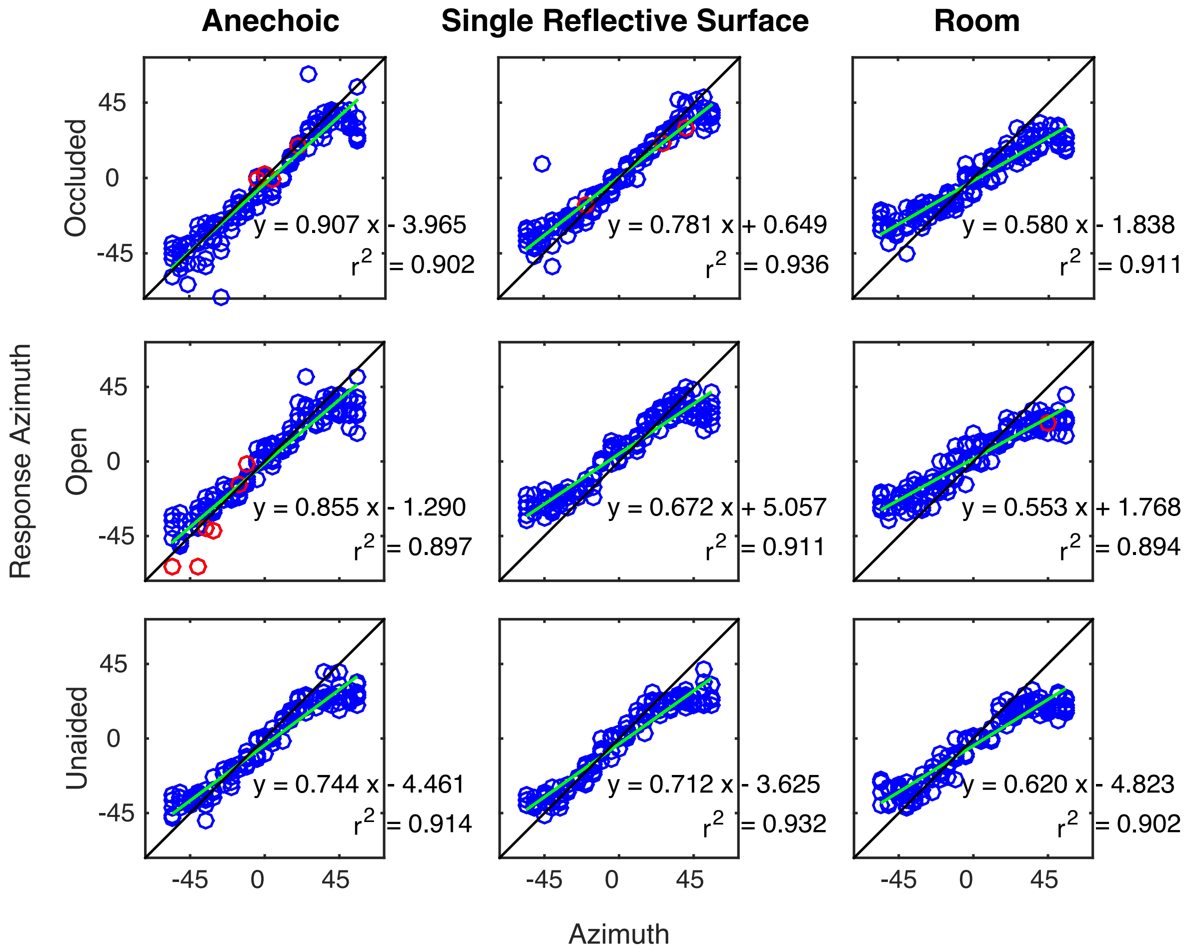


Figure 18. Sound localization responses for listener 1402 at 4000 Hz narrowband noise. Y-axis represents response azimuth and x-axis target azimuth. Columns plots room conditions and rows aided conditions. Green line represents linear fit to the data with equation and R^2 displayed for each subplot. Blue circles represent individual trials for each 23-target locations. Red circles represent responses for resolved front-back confusions. Note compressed responses and minimal front-back confusions.

One explanation for observable gain expansion (slope > 1.0) could be increased front-back confusions. For a few listeners, front-back confusions were observed at a high rate when localizing BB and/or 500 Hz. Subjectively, when indicating responses behind the listener, a greater degree error may occur. Increased errors may be due to listener’s inability to locate the speaker directly with their eyes prior to responding. For instance, data from a couple research participants’ when listening to broadband noise with occluded hearing aids are displayed in Figures 19 and 20. In Figure 19, few to no reversals were observed for listener 1406 compared to listener 1603 (Figure 20) who almost exclusively localized sounds to be behind. Generally, both listeners are really good at the task, but there are noticeably greater amounts of errors for listener 1603, with front-back confusions, resulting in expanded gain.

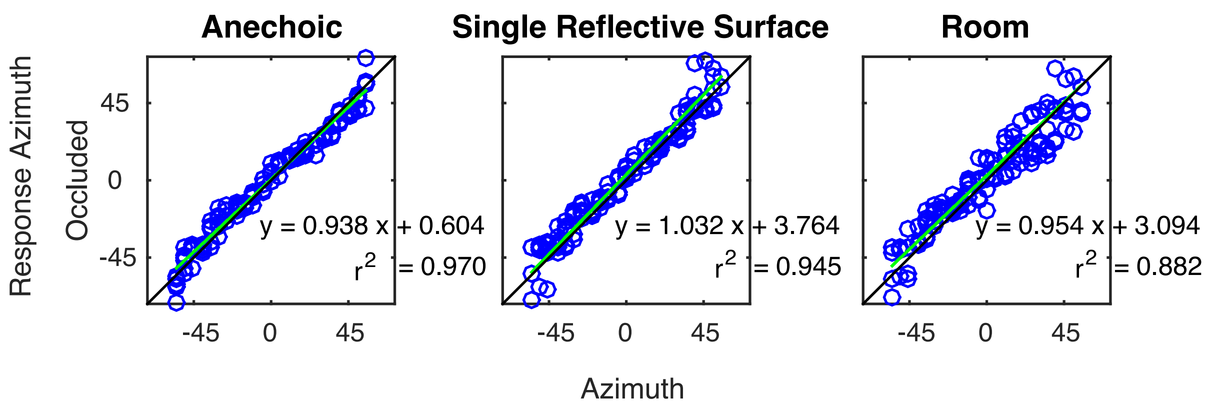


Figure 19. Sound localization responses for listener 1406. Responses for broadband noise with occluded hearing aids across room conditions (columns). Data are presented in the same manner as Figures 17 and 18.

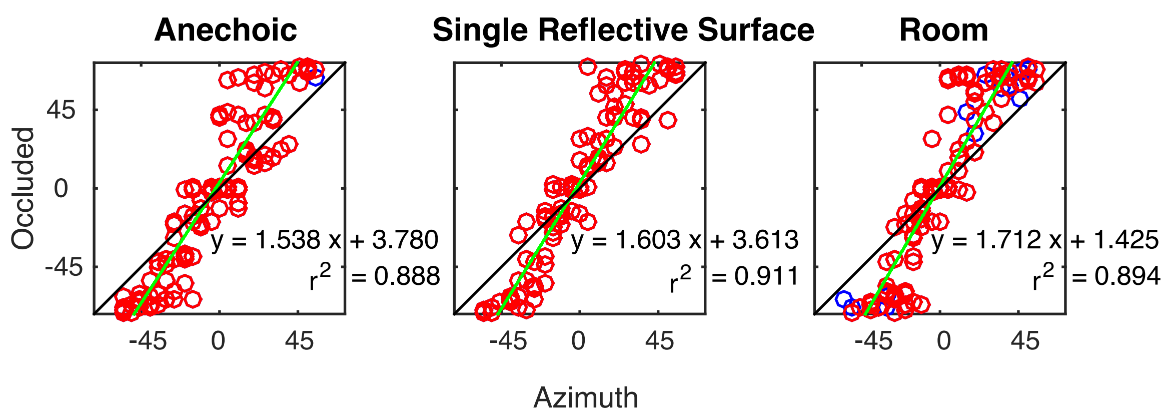


Figure 20. Sound localization responses for listener 1603. Responses for broadband noise with occluded hearing aids across room conditions (columns). Note differences in slope and variability for listener with front-back confusions, compared to Figure 19, plotting data for a listener with no front-back confusions.

6.1.3 Localization Variance

In the presence of reverberation, here produced by simulating a classroom size room, localization variance was significantly less at 500 Hz compared to BB and 500+4000 Hz with occluding hearing aids. Thus, when the low-frequency acoustic cues are inhibited, such as by occluding the ear canal with a foam tip and spectral cues are altered by presenting sound via microphones located on top of the pinna, these changes cause greater difficulty localizing low-frequency narrowband noise. For example, occluded hearing aid responses for listener 1501 are displayed in Figures 21 and 22 for 500 Hz and 500+4000 Hz, respectively. This listener only had front-back confusions at 500 Hz, while others had confusions for BB as well. For BB stimulus, Figure 23, responses had visually better fit, again arguing that responses listeners indicate for targets perceived behind tend to be less accurate in degree azimuth than those made for speakers in front.

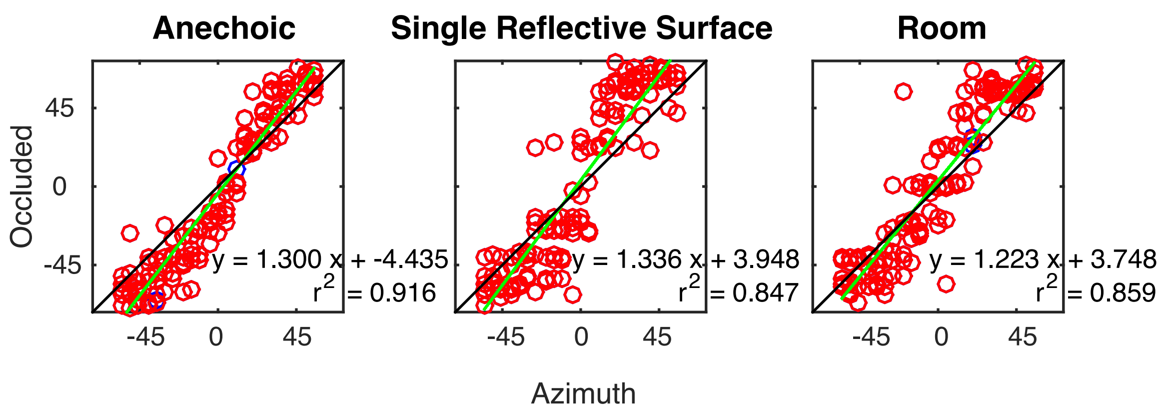


Figure 21. Localization responses for listener 1501 at 500 Hz. Similar to Figure 20, note variability and expanded slope for conditions when large amounts of front-back reversals are present.

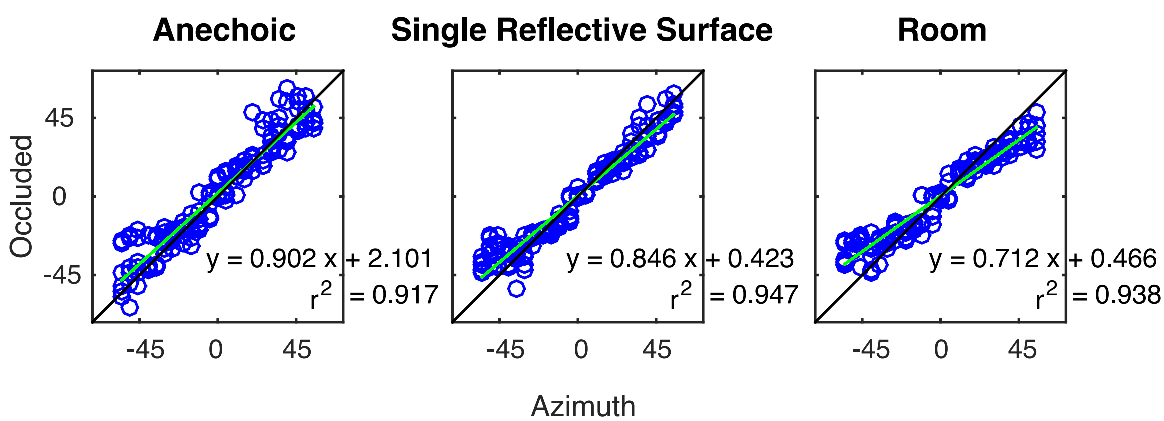


Figure 22. Performance for listener 1501 at 500+4000 Hz. Layout is the same as Figure 21. Note decreased variance and front-back reversals were eliminated when 4000 Hz was added.

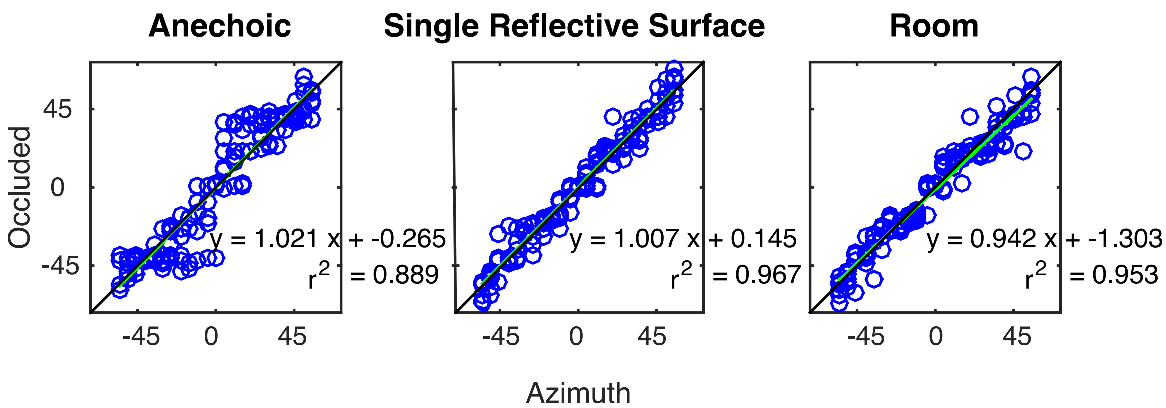


Figure 23. Listener 1501's sound localization performance for broadband stimulus. Layout matches Figures 21 and 22.

Generally, narrowband noises had lower R^2 values, indicating worse fit, than BB and 500+4000 Hz. This is especially true for 4000 Hz aided conditions (Figure 15). As noted in the acoustic recordings session, 4000 Hz aided conditions showed decreased ILD, especially in simulated reverberant conditions. The acoustical findings are likely contributing to expansion of 500 Hz and compression at 4000 Hz responses.

6.1.4 Front-back confusions

The *only* significant difference across all independent variables for front-back confusions was for a stimulus condition. Specifically, there was a significant reduction in front-back errors for 500 Hz when 4000 Hz was added. While 500+4000 Hz consistently showed reduction across all aided and room conditions, the only paired t-test resulting in a significant difference was for occluded hearing aids in the simulated room condition. These results cannot be entirely explained by additional high-frequency information, as BB occluded condition consistently caused some listeners to localize targets almost entirely from behind. The one constant factor in all of these conditions is that they involve occluded hearing aids, where errors can be explained by listeners lack of individualized HRTFs due to BTE microphone location and occluding the ear canal with a foam insert. The overall lack of significance for observable differences seen in Figure 16 may be due to individual differences. Appendix D shows mean individual data for all participants. Only a few individuals had front-back confusions for 500 Hz and BB, and those individuals were not always the same. When front-back confusions did occur, patterns for reporting confusions were either observed for all or nearly all trials in a particular condition or occurred sparingly at only a few degree angles. These large differences in front-back observation across listeners, with only 3 to 4 listeners reporting confusions, likely contributed to the lack of statistically significant differences across independent variables.

6.2 Effect of aided condition

Features on modern hearing aids are known to alter binaural cues. Wiggins and Seeber (2011) previously demonstrated wide-dynamic range compression caused reduced ILD, and Picou et al. (2014) showed that strong directional microphone technology eliminated binaural cues by presenting stimuli diotically when enabled. Picou et al. were evaluating the most extreme positions in their study by using an occluding foam comply tip, as used here in the occluded hearing aid condition. Venting through hearing aid coupling, such as open domes, allow for low-frequency acoustic information (typical for coding ITD), which was not accounted for in their results. Ihlefeld and Shinn-Cunningham's (2011) results combining low- and high-frequency noise bands suggest that erratic ITD cues from low-frequency noise can actually harm localization ability; Picou et al. were not evaluating for low-frequency interference, but rather for reduced localization ability with microphone directionality. For these reasons, all hearing aid features known to alter interaural cues were disabled, as well as some features that have not been specifically evaluated (i.e. feedback suppression, noise reduction). Spectral differences were of great interest in this research. Thus, aided conditions (occluded, open-fit, unaided) were chosen to emphasize the extremes.

Listeners have been shown to improve localization ability with altered spectral cues over a period of 5-10 days (Hofman et al. 1998, Carlile 2014). Here, listeners were naive to the altered spectral cues, but did spend at least 14 hours over 7 or 8 sessions performing sound localization task across the three aided conditions presented in random order. It is unclear whether any effects of training were observed, as it was not an objective for this research.

6.2.1 Localization Error

The greatest degree of error, as measured by RMS error across all speaker locations, was for occluded hearing aids. As suggested above, this is likely due to BTE microphone location and plugging the ear canal eliminating all acoustic spectral cues. It is unclear whether these findings would differ for experienced hearing aid users fit with BTE hearing aids, who are used to altered spectral cues. However, unless hearing loss is severe to profound, most hearing aid patients will have some venting in their earmolds or through open-fit coupling. Here, results show that occluded hearing aids had greater localization errors than open-fit hearing aids at 500 Hz across all room conditions. A likely explanation for this finding could be due to availability of low-frequency energy through the open-fit coupling.

There were also differences in aided (occluded and open-fit) versus unaided at 4000 Hz for occluded hearing aids across all rooms and most rooms for open-fit. These differences for high frequencies are, again, likely due to microphone location. Thus, most errors occurring across aided conditions can be explained by altered spectral cues rather than weighting of ITD and ILD for young normal hearing listeners naive to hearing aids. Perhaps these errors could be resolved with acclimatization (Hofman et al. 1998, Carlile 2014). A longitudinal study observing young normal hearing listeners acclimatized to low-gain hearing aids may be of interest, but more likely, experienced hearing aid users would be the preferred population.

6.2.2 Localization Gain

Localization gain, or slope, is mostly near normal for BB stimulus. The occluded hearing aid condition, however, is significantly expanded (slope > 1) across all rooms in comparison to aided conditions with an open ear canal (open-fit and unaided). The likely explanation for this finding is due to available low-frequency acoustic information. Also, similar to localization accuracy, localization gain is significantly more compressed for aided (occluded and open-fit) versus unaided at 4000 Hz in the presence of reverberation (SRS and simulated room). As shown by Shinn-Cunningham 2005 and acoustic recordings reported above, ILD cues coded by high frequencies are significantly reduced in reverberation. Behaviorally, this translates to localizing lateral sounds to be more in front of the listener. Essentially, when ILD is reduced by reverberation and listeners are presented sounds via BTE microphones eliminating pinna cues, listener responses show increased amounts of compression that is not relieved by open-fit coupling. While open-fit hearing aids allow for access to acoustic cues, higher frequencies (i.e. 4000 Hz) appear inaccessible acoustically.

6.2.3 Localization Variance

Localization variance as accounted for by R^2, generally follows the pattern occluded < open-fit < unaided. However, occluded and open-fit conditions only differ for BB and 500 Hz stimuli in anechoic and SRS. It should be noted, as mentioned previously, these two stimulus conditions have a high rate of front-back confusions for some listeners. While effects are not significant, variability may be in part due to reduced localization accuracy in degree azimuth response, as listeners show some difficulty accurately describing azimuthal angle for sounds perceived behind them. Also, across all room conditions 4000 Hz aided (occluded and open-fit) differ from unaided. As mentioned in the previous section, these differences are likely explained by BTE microphone location and inability to access high frequency acoustic cues through open-fit coupling.

6.3 Effect of room condition

Alteration of interaural cues due to reverberation has been observed most simplistically by Rakerd and Hartmann (1985) using a single reflective surface (SRS) and in a more complex environment by Shinn-Cunningham (2005) who measured BRIR for KEMAR in a typical office-sized room. Results from these experiments and acoustic recordings reported above, found that in the presence of reflective surfaces, ITD becomes erratic or diffuse and ILD is diminished. If measured right next to a wall, comb-filtering can occur in the low-frequencies (Shinn-Cunningham 2005), however, this is not directly relevant to this data-set as listeners were seated in the center of a circle array of speakers.

Another factor influencing performance could be temporal processing ability. An advantage young normal hearing listeners have is they excel at weighting early portions of sounds. In any acoustic scene, the direct sound carries appropriate interaural cues, which are quickly diminished or distorted by early reflections. Aged and hearing-impaired listeners tend to perform worse in reverberation. This may be due to weighting longer durations of sounds compared to young normal hearing listeners. It is likely that clinical populations will perform much worse in simulated room conditions if they weight direct and reflected, acoustic and processed sounds while wearing open-fit hearing aids.

6.3.1 Localization Error

In line with alteration of cues with increasing reverberation (Rakerd and Hartman 1985, Shinn-Cunningham 2005), localization error, as measured by RMS error in degrees across all 23 target locations, increases with increased number of reflections: anechoic < SRS < simulated room. These findings are consistent with reduced ILD and erratic ITD, as shown by the acoustic recordings above. Specifically, across all aided conditions, there is a significant difference between anechoic and simulated room for 4000 Hz and 500+4000 Hz. It is somewhat odd that this difference with added reverberation does not occur for 500 Hz and BB, but keep in mind that these stimuli contained large amounts front-back confusions which may have decreased percentage of variability as accounted for by R^2 and increased RMS error for some individuals.

6.3.2 Localization Gain

At 4000 Hz, localization gain is further compressed, as shown by reduced slope, for simulated room compared to anechoic when listeners performed the localization task wearing hearing aids. While reverberation has been shown to reduce ILD, this results shows that BTE microphone location further disrupts localization of high-frequency noise. Thus, both reverberation and reduced spectral information may be causing differences in localization gain at 4000 Hz.

6.3.3 Localization Variance

Similar to localization error, variability as measured by R^2 is reduced with increasing reverberation: anechoic > SRS > simulated room. Specifically, R^2 is reduced when listeners localize narrowband noises across all aided conditions. Simply, this could be explained by reduced spectral content for narrowband stimuli, and increased variability as interaural cues are diminished or distorted with increased reverberation. Additionally, R^2 is reduced for 500+4000 Hz across all aided conditions when comparing anechoic and simulated room. The fact that these results were significant across all aided conditions, including unaided, suggests that increased variability at 4000 Hz is due to reduced ILD cues and erratic ITD at 500 Hz in rooms rather than alterations from hearing aids.

ITD/ILD Trading Ratios – interaural cue weighting across room and hearing aid conditions

Chapter 7 - Interaural cue weighting for narrowband noises

7.1 Methodology

Collecting real-ear measurements and behavioral data in the same environments is advantageous, as those data can be correlated with one another to address interaural cue weighting across independent variables. Here, 500 and 4000 Hz narrowband noises will be compared to measured ITD and ILD at 508 and 3905 Hz respectively. Additionally, 500+4000 Hz will be compared to interaural cues from both frequency bands. Note slight discrepancies in frequency for acoustic recordings and behavioral measures are due to constraints of the binaural cross-correlation model (section 2.3.1).

Trading ratio analyses were accomplished in several steps. First, from the binaural cross-correlation model, ITD and ILD data for 508 and 3905 Hz across all azimuths were extrapolated from the larger data set of 28 frequency channels. For example, to compare measured ITD and ILD cues visually, normalized cue values are plotted for a 500 Hz anechoic occluded condition in Figure 24, second panel. ITD is displayed on the left y-axis and ILD on the right. In the anechoic condition, the two cues mostly agree and code left interaural cues for leftward sounds and right for rightward. Figure 25 (second panel), displays an example of an opposing cue condition for 500 Hz occluded in a simulated room where ITD is erratic and coding opposing cues and ILD is diminished. The top panel for both figures displays behavioral responses across azimuth.

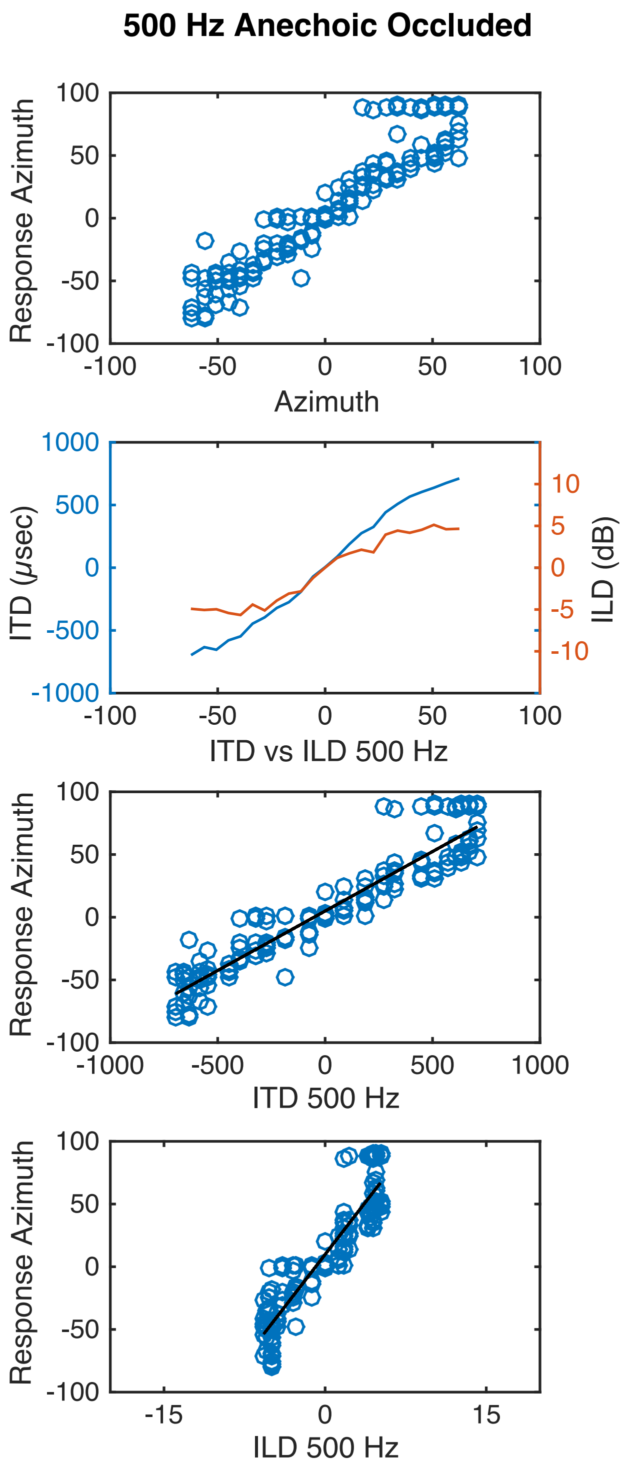


Figure 24. Data for listener 1402 at 500 Hz in anechoic with occluded hearing aids. Top figure plots response azimuth (y-axis) against target azimuth (x-axis) as seen previously. Second panel plots measured ITD (blue) and ILD (red) for 508 Hz frequency channel, as measured during acoustic recordings. Lower panels plot responses azimuth (y-axes) against measured ITD and ILD (x-axes). Linear regressions lines comparing measured ITD and ILD represent black line on lower panels. Measured trading ratio for this condition is 117 µsec/dB.

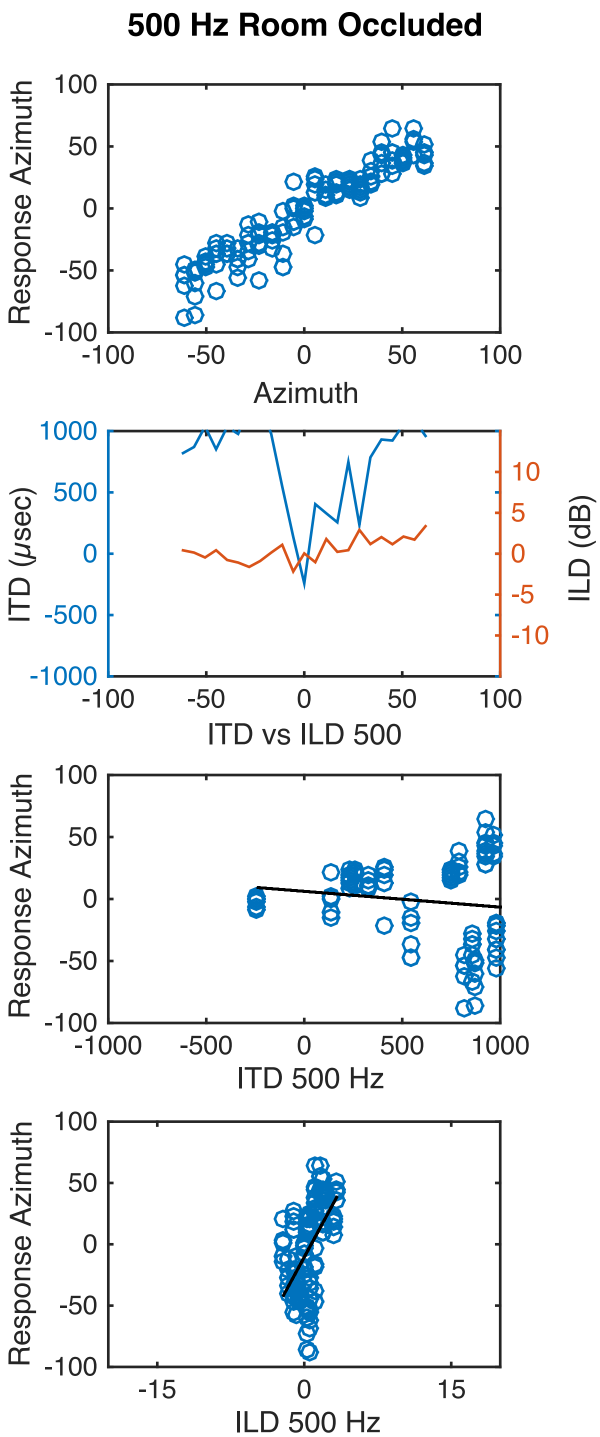


Figure 25. Data for listener 1402 at 500 Hz in simulated room with occluded hearing aids. Layout is the same as Figure 24. Measured trading ratio for this condition is -1155.5 μsec/dB.

Next, measured interaural cues (x-axis) are plotted against behavioral responses (y-axis). Thus, Figures 24 and 25 display ITD (third panel) and ILD (fourth panel) against degree azimuth of behavioral responses, here, for a 500 Hz stimulus compared to measured 508 Hz ITD and ILD cues. From here, multiple linear regression analysis is used to evaluate behavioral responses as predicted by measured ITD and ILD. Specifically, regression coefficients (slope and intercept) were collected by regressing behavioral data to measured interaural data (β_1 = slope) and a dummy variable of ones (β_2 = intercept). These regression lines were used to fit data for panels three and four for Figures 24 and 25. At this point in the trading ratio analyses, β_1 for ITD and ILD separately may be used to describe changes in ITD and ILD across speaker azimuth.

Finally, the ratio of ILD and ITD slopes (β_1ILD / β_1ITD) were evaluated for time-intensity trading ratio (TR) to describe data by changes in µsec/dB across azimuth. These values are listed in Table 3. For the two examples shown in Figures 24 and 25, notably, if the measured ITD and ILD are monotonic, the TR is expressed as a positive number. If ITD and ILD cues are in opposition, the TR is a negative number. The size of the trading ratio increases as ITD becomes erratic and can be largely decreased if ILD is small, or diminished.

7.2 Results

As seen in Table 3, for the most ideal setting (anechoic, unaided) TRs for 500 Hz range from 98 to 170 µsec/dB, and 31 to 41 µsec/dB at 4000 Hz. In comparison to the literature, large and small trading ratio values were greater than 250µsec and around 40 µsec, respectively.

For a complex scene, such as occluded hearing aid in the simulated room condition, TR values range from -1156 to 294 µsec/dB for 500 Hz and 22 to 82 µsec/dB for 4000 Hz. Four of the ten participants had negative TRs at 500 Hz for occluded hearing aids in the simulated room condition. No negative values were seen at 4000 Hz across all conditions. This is likely because ITD values were small at 4000 Hz, and were never inversely related to ILD cues at this frequency. Since 500+4000 Hz stimulus takes into factor both frequency channels, the same participants with negative TRs for 500 Hz were present for 500+4000 Hz.

Subject ID	Stimulus	Occluded						Open-fit						Unaided					
		Anechoic		SRS		Room		Anechoic		SRS		Room		Anechoic		SRS		Room	
		.5k	4k	.5k	4k	.5k	4k	.5k	4k	.5k	4k	.5k	4k	.5k	4k	.5k	4k	.5k	4k
0507	500	99.9		168.6		188.5		116.7		190.9		177.8		105.0		116.4		-339.6	
	4000		34.6		49.9		82.7		36.3		54.7		80.4		32.5		49.6		77.0
	500+4000	100.0	33.9	168.8	48.1	184.0	80.3	116.6	35.5	191.3	52.6	188.2	77.3	105.2	31.8	118.2	46.9	-326.9	73.9
0509	500	140.5		-444.4		-441.6		133.7		323.7		180.8		138.8		276.1		198.4	
	4000		54.8		89.7		48.7		50.6		78.1		70.6		33.5		47.1		73.7
	500+4000	141.1	52.8	-377.2	81.3	-422.7	46.4	133.8	48.7	324.6	74.7	180.6	69.1	138.5	33.2	275.7	45.7	211.5	72.1
1402	500	117.0		134.1		-1155.5		119.8		255.9		450.0		112.4		95.7		173.3	
	4000		35.1		48.7		22.6		39.3		59.0		30.1		34.6		52.5		90.1
	500+4000	116.6	34.6	134.8	48.0	-1258.4	22.8	119.2	39.2	254.5	57.6	488.2	30.4	112.4	33.8	94.3	51.6	182.8	86.6
1403	500	124.3		-192.1		152.1		141.6		154.5		275.9		119.3		202.6		208.5	
	4000		34.8		45.3		35.6		32.5		46.8		62.8		37.5		56.8		83.9
	500+4000	124.3	34.0	-192.4	43.5	167.6	34.5	141.5	31.5	157.7	43.2	268.4	62.2	119.3	37.3	203.8	56.3	219.1	81.7
1404	500	141.0		135.6		117.3		171.9		590.0		243.6		125.4		279.6		223.8	
	4000		43.7		59.8		55.7		44.2		61.3		56.7		32.6		46.9		78.0
	500+4000	140.0	43.3	137.4	57.5	113.4	55.4	171.1	43.5	581.7	58.9	256.3	56.6	123.9	32.1	286.9	45.1	242.6	76.1
1406	500	163.7		420.3		153.8		172.6		194.8		-189.0		113.9		156.4		-303.1	
	4000		48.7		76.6		52.3		44.7		67.0		82.2		32.8		49.5		79.5
	500+4000	162.9	48.4	408.5	75.7	173.1	52.5	172.6	44.2	202.6	66.8	-203.5	81.8	113.8	32.4	157.1	49.4	-325.5	78.1
1501	500	246.9		272.3		-214.0		274.9		437.5		144.3		169.5		279.5		142.4	
	4000		42.4		68.8		31.7		44.0		49.6		54.8		41.4		60.7		84.8
	500+4000	245.6	40.6	251.7	62.7	-208.8	31.2	281.7	44.4	412.9	47.6	140.8	55.1	167.6	41.2	285.3	60.3	167.4	83.6
1503	500	156.4		-171.2		231.7		139.2		168.9		-283.7		120.7		94.7		-572.2	
	4000		41.0		67.2		58.0		45.7		65.3		67.7		30.9		47.2		80.5
	500+4000	156.9	40.6	-163.2	67.5	295.5	55.7	139.8	45.0	168.9	63.5	-279.5	65.0	120.7	30.8	94.5	46.6	-532.4	80.4
1603	500	129.2		-127.1		-366.1		142.6		-159.0		-306.0		114.1		-137.6		189.9	
	4000		44.5		60.9		33.1		50.9		66.9		98.9		33.8		55.0		90.5
	500+4000	129.4	44.0	-143.9	59.8	-302.6	31.5	142.0	46.1	-161.0	60.3	-346.2	95.7	114.3	33.6	-146.7	54.6	200.2	89.9
1617	500	108.5		-130.3		294.2		118.7		-140.0		-310.2		98.4		-107.4		-595.5	
	4000		38.2		65.3		29.3		43.2		66.5		50.0		36.6		57.2		65.3
	500+4000	110.0	35.2	-130.2	61.0	276.8	28.3	119.9	40.3	-138.9	61.8	-317.9	48.9	98.9	36.6	-113.9	57.1	-542.5	66.4

Table 3. Trading ratios calculated by taking the ratio of ILD and ITD slopes (β_1ILD / β_1ITD). All values in the table represent dB/µsec trading ratios. Calculations are displayed for each of the ten listeners (first column) and stimulus conditions (second column) for aided and room conditions (displayed in rows 1 & 2).

7.3 Discussion

Rakerd and Hartmann (1985) evaluated time-intensity trading ratios (TR) for each of their 8 target speakers. We used a similar method here, but rather than comparing coefficients for each speaker location, coefficients for linear fit were used to obtain µsec/dB ratios. Having TRs across azimuth allows for comparison across independent variables: stimulus, aided condition, room condition. However, the values obtained through this method do not match the range of values measured by Rakerd and Hartmann (1985). Comparing our results to some classic TR experiments conducted over headphones, 4000 Hz TR values match nicely with the small TRs, but 500 Hz TRs are quite erratic. However, for some individuals and test conditions, 500 Hz TRs match nicely with large TRs previously reported in the literature.

An apparent limitation here is the inability to directly compare our results to previous trading ratio experiments due to methodological differences. Most classic TR experiments controlled interaural cues values over headphones. Here, ITD and ILD will vary slightly with head movements, which can alter cues across trials and conditions. In testing human subjects, such occurrences will occur, even when attempting to control by use of a head tracker and close monitoring by experimenter through closed loop video. To limit these differences that may occur across trials, acoustic recordings should be made for each trial. This approach, however, decreases listener comfort by having probe-tubes in their ears throughout entire length of testing, and increases testing and data processing time.

For the one notably similar approach in the literature, Rakerd and Hartman (1985) used a similar method as described above, but their TRs were calculated for each individual speaker location for 500 Hz tones in an anechoic chamber with a single-reflective surface. This difference in calculation makes it difficult to compare our SRS condition to their results. A benefit to the approach used here, if further testing is evaluated for different clinical populations, such as aging and hearing impairment, these TRs could be compared across populations. Also, TRs vary across aided, room and stimulus conditions, which can all be compared here (Table 3).

Lastly, another limitation, but also potential benefit, is use of virtual rooms. Virtual walls are not necessarily realistic, and can predictably distort interaural cues. However, use of individualized HRTFs and presenting sounds over headphones has its limitations as well. Testing research participants while wearing hearing aids allows for micro-movements. Even if individualized HRTFs are measured for headphone experiments, the slight spectral cues available through micro-movements in free-field testing are unavailable, and thus, it is unrealistic to test over headphones. As with most clinical research experiment designs, there is always a balance of attempting to control the environment and get close to real-world experiences. Here, we chose to control the room and use real hearing aids.

Chapter 8 - Conclusions

To summarize, performance for sound localization across room condition generally followed the pattern anechoic > SRS > simulated room. Results across aided and stimulus conditions were slightly more complex. Mostly broadband stimuli (BB and 500+4000 Hz) were better than narrowband, and performance for low and high frequencies were similar. These findings, however, interacted with aided condition. Generally, if the ear canal was open (unaided and open-fit hearing aid), performance for low frequencies improved. Conversely, while wearing BTE hearing aids (occluded and open-fit), performance for high frequencies decreased. Lastly, performance across aided conditions mostly followed the pattern unaided > open-fit > occluded. Occluded was especially difficult for some listeners for BB and 500 Hz, but these findings may be biased by front-back confusions. Differences across aided conditions are likely due to BTE microphone placement and altering spectral cues normally available by the pinna rather than processing alone. Thus, binaural cue distortion from hearing aids is likely related to advanced hearing aid features rather than interference from multipath acoustics.

Sound localization performance for this young normal hearing group was good overall, especially for broadband stimuli. Listeners were able to approximately locate each 23-target speaker (separated by 5.625º) by indicating on an iPad using the interface displayed in Figure 12. This degree of accuracy in ideal settings, such as unaided anechoic, ensures accurate explanations for more difficult conditions.

Consistent with the literature, acoustic recordings measured for ten research participants and an acoustic manikin showed erratic ITD across frequency and reduced ILD with increased reverberation. Specifically, some low-frequency bands showed opposing ITD cues for both single-reflective surface and simulated room conditions. Less consistent were effects of multipath acoustics for recordings made with occluded and open-fit linear hearing aids. Notably, localization performance was worse for the occluded hearing aid condition, especially when evaluated in the simulated room. However, acoustic recordings appear to have similar distortions across all aided conditions presented in the simulated rooms. The amount of ITD distortions may be greater for occluded hearing aids compared to open-fit or unaided, but the magnitude of ILD appears consistent across conditions. Despite the distorted interaural cues showing in the acoustic recordings, young normal hearing listeners performed quite well. We hypothesized that the acoustic + processed sound from open-fit hearing aids may cause difficulty with sound localization. Based off our results, we conclude that young normal hearing individuals did not have greater difficulty localizing sounds with open-fit hearing aids. In fact, performance was both similar to unaided results, or to occluded hearing aid results depending on the stimulus, and occluded hearing aids were consistently the most difficult condition. Given that young normal hearing listeners performed well, next step would be to recruit older normal hearing and hearing impaired individuals to evaluate for aging and hearing impairment. Open-fit hearing aids still could be detrimental to populations with impaired temporal processing ability.

Interpretation of trading ratio values was less clear. Results are difficult to compare to previous trading ratio literature due to methodological differences. However, large and small trading ratio values were seen for low and high narrowband frequencies, consistent with classic literature outlined above. The greatest benefit for this trading ratio approach was for comparison across room, hearing aid, and stimulus conditions here, and for aged and hearing-impaired populations in the future.

While differences in localization performance across aided and room conditions did occur, the large acoustical distortions measured in rooms did not severely disrupt young normal hearing listeners overall accuracy. Additionally, compressed responses at high frequencies and expanded responses at low frequencies when wearing hearing aids are likely explained by microphone placement and occluded earmolds. Thus, the interaction of acoustic and processed sounds in rooms alone did not hurt young normal hearing listeners overall localization performance. It will be interesting to evaluate clinical populations in the future and whether some individuals with hearing impairment a) perform worse with open-fit coupling and b) if those results can be predicted by measured in-ear interaural cues.

Appendix

Appendix A

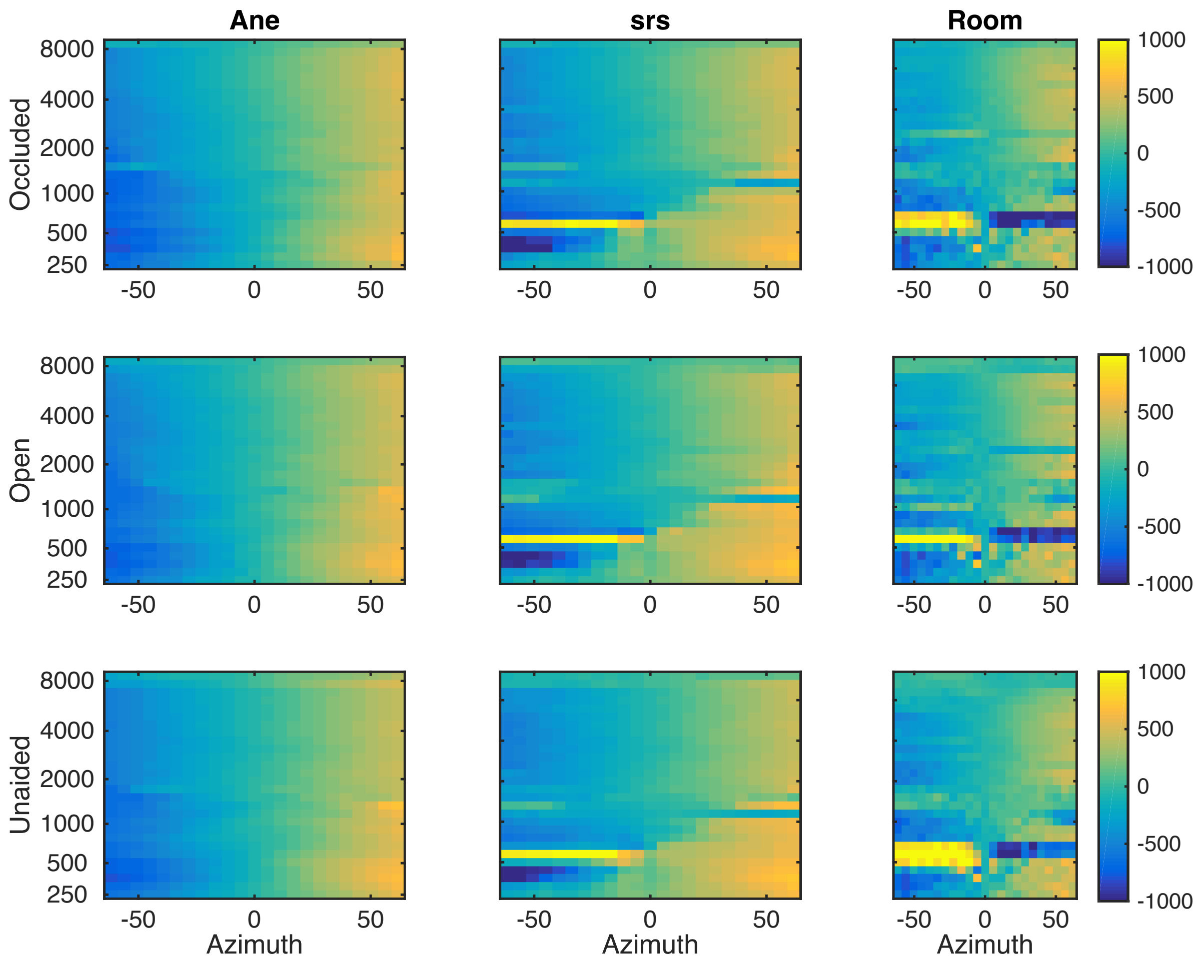
		250		500		1000		2000		3000		4000		6000	
		R	L	R	L	R	L	R	L	R	L	R	L	R	L
0507	Occluded	55	57	59	60	58	67	79	75	64	69	64	67	50	57
	Open	55	55	56	57	50	59	78	74	67	70	65	65	49	52
	Unaided	55	56	56	56	50	48	58	56	58	58	55	55	48	49
0509	Occluded	60	61	68	66	61	61	80	85	68	70	61	65	59	56
	Open	56	56	59	59	57	57	87	87	76	71	70	65	44	46
	Unaided	56	55	58	57	49	50	57	57	61	60	55	52	44	41
1402	Occluded	58	58	64	64	67	62	74	80	64	63	67	69	49	53
	Open	56	56	58	58	57	54	75	82	64	61	66	65	42	48
	Unaided	55	56	57	58	52	52	60	65	49	52	50	54	42	40
1403	Occluded	55	59	60	63	60	57	78	77	60	55	63	62	45	48
	Open	54	57	58	56	52	47	75	73	62	53	59	59	46	45
	Unaided	54	56	56	56	48	46	59	60	55	47	49	51	48	46
1404	Occluded	61	62	67	66	61	66	77	76	66	61	72	68	52	50
	Open	55	58	58	58	55	55	74	73	69	63	67	66	42	40
	Unaided	56	57	58	58	51	50	54	56	59	56	52	57	42	41
1406	Occluded	61	60	65	64	61	59	81	78	65	60	67	65	53	49
	Open	55	57	56	57	53	52	77	78	67	68	69	67	49	51
	Unaided	55	57	56	57	51	50	61	61	60	57	57	58	48	43
1501	Occluded	56	56	61	58	59	59	74	75	72	59	53	55	55	50
	Open	55	57	57	55	52	52	77	79	77	69	63	60	45	40
	Unaided	55	56	56	55	50	50	62	64	63	60	51	48	43	41
1503	Occluded	58	59	64	64	60	61	83	84	77	70	55	57	47	46
	Open	55	58	58	58	55	51	75	77	82	70	60	61	45	49
	Unaided	55	57	56	57	51	51	64	63	67	64	50	49	47	53
1603	Occluded	60	61	65	66	63	63	78	80	61	63	62	61	46	51
	Open	56	58	56	57	52	52	76	78	65	68	64	63	44	44
	Unaided	55	58	55	56	48	49	58	56	56	55	52	51	42	41
1617	Occluded	58	59	64	65	58	57	83	84	60	58	61	57	53	48
	Open	55	57	57	56	52	50	82	82	64	61	61	57	47	43
	Unaided	54	56	56	56	48	48	63	64	55	54	50	49	42	42

Real-ear Measurement - Speechmap @ 65 dB (table heading spanning all frequency columns)

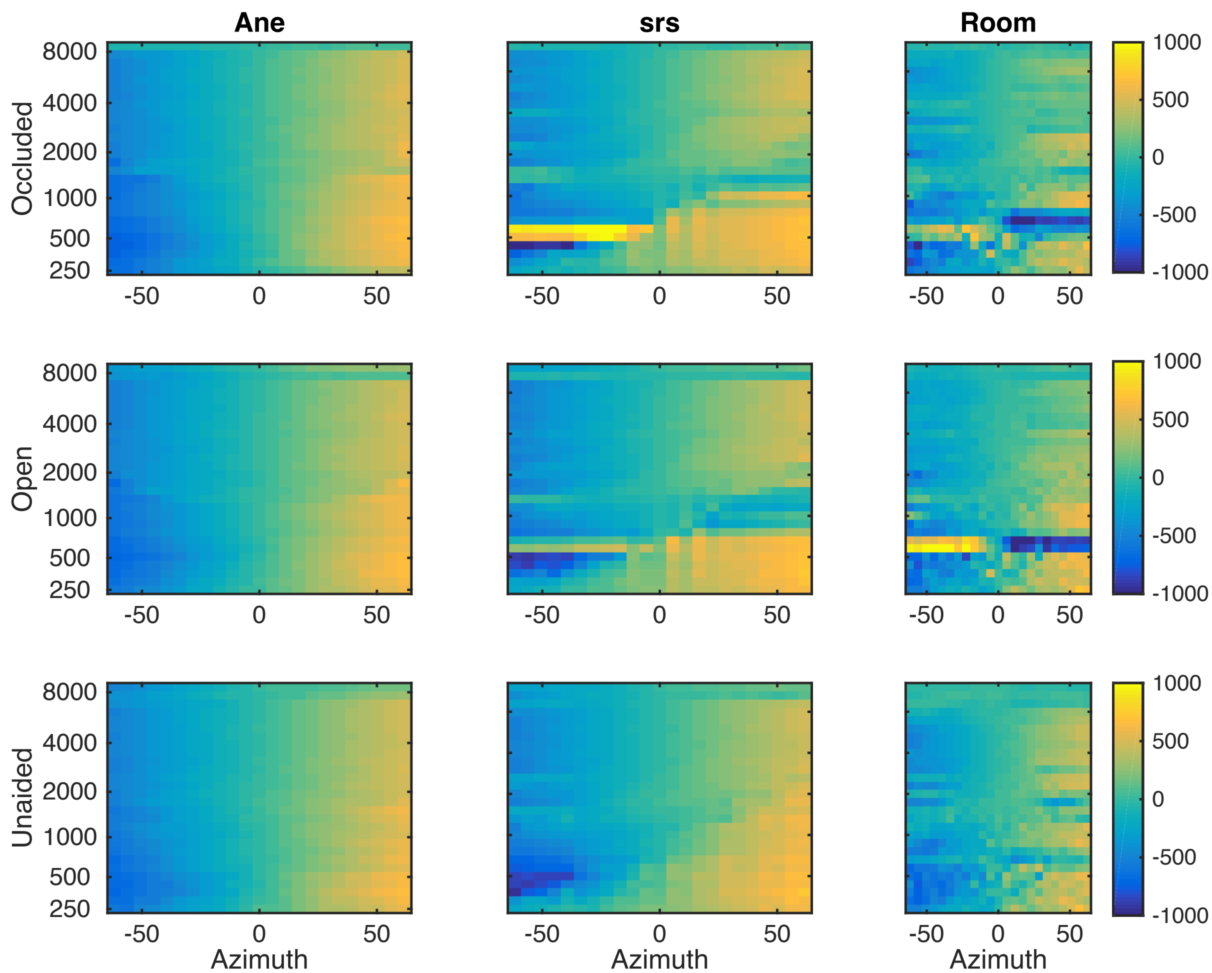
Appendix A. Hearing aid outputs measured with Audioscan's Verifit system using speechmap program at 65dB. Listeners were excluded if measurements at 500 and 4000 Hz were greater than 5 dB different. Values were used to equalize levels during behavioral data collection.

Appendix B.

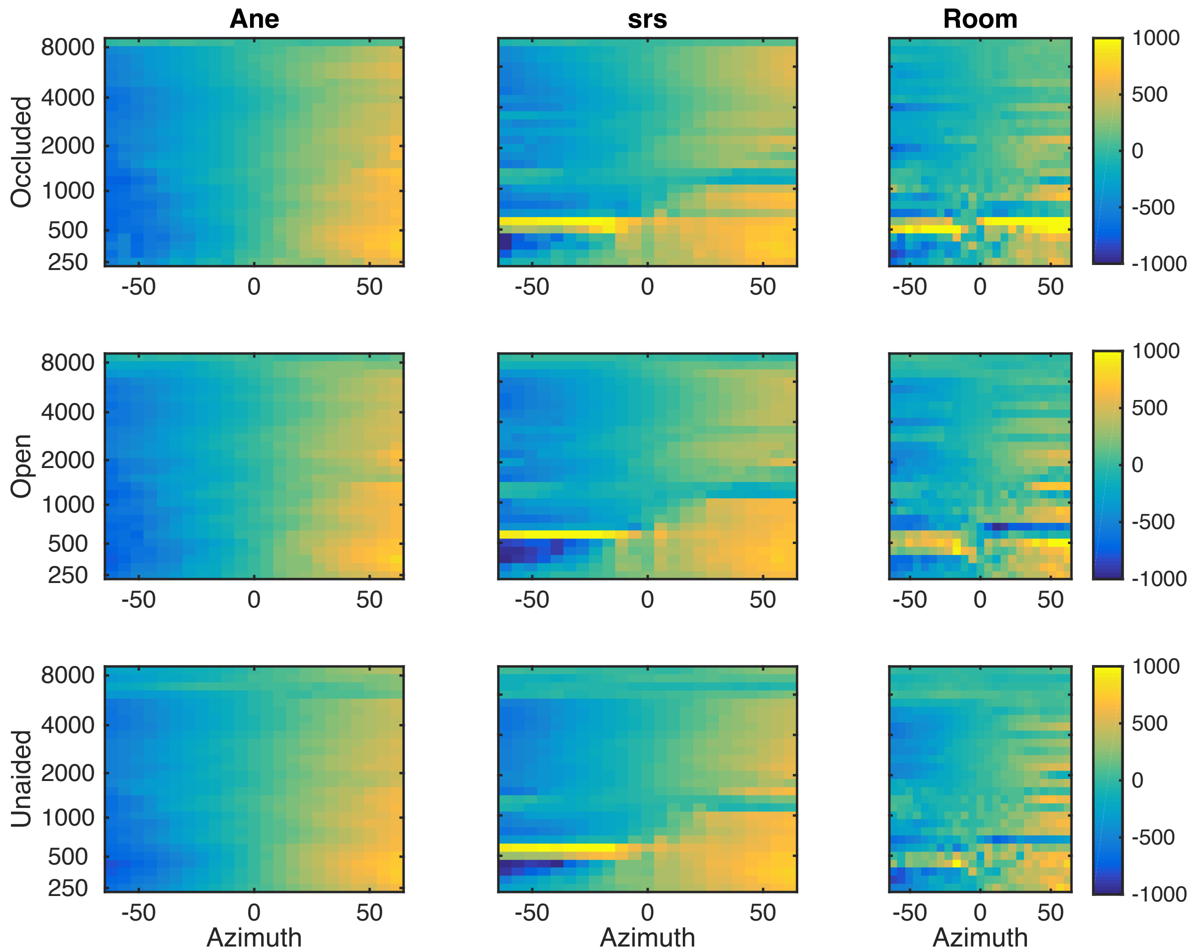
Color plots for individual listeners' normalized ITD:



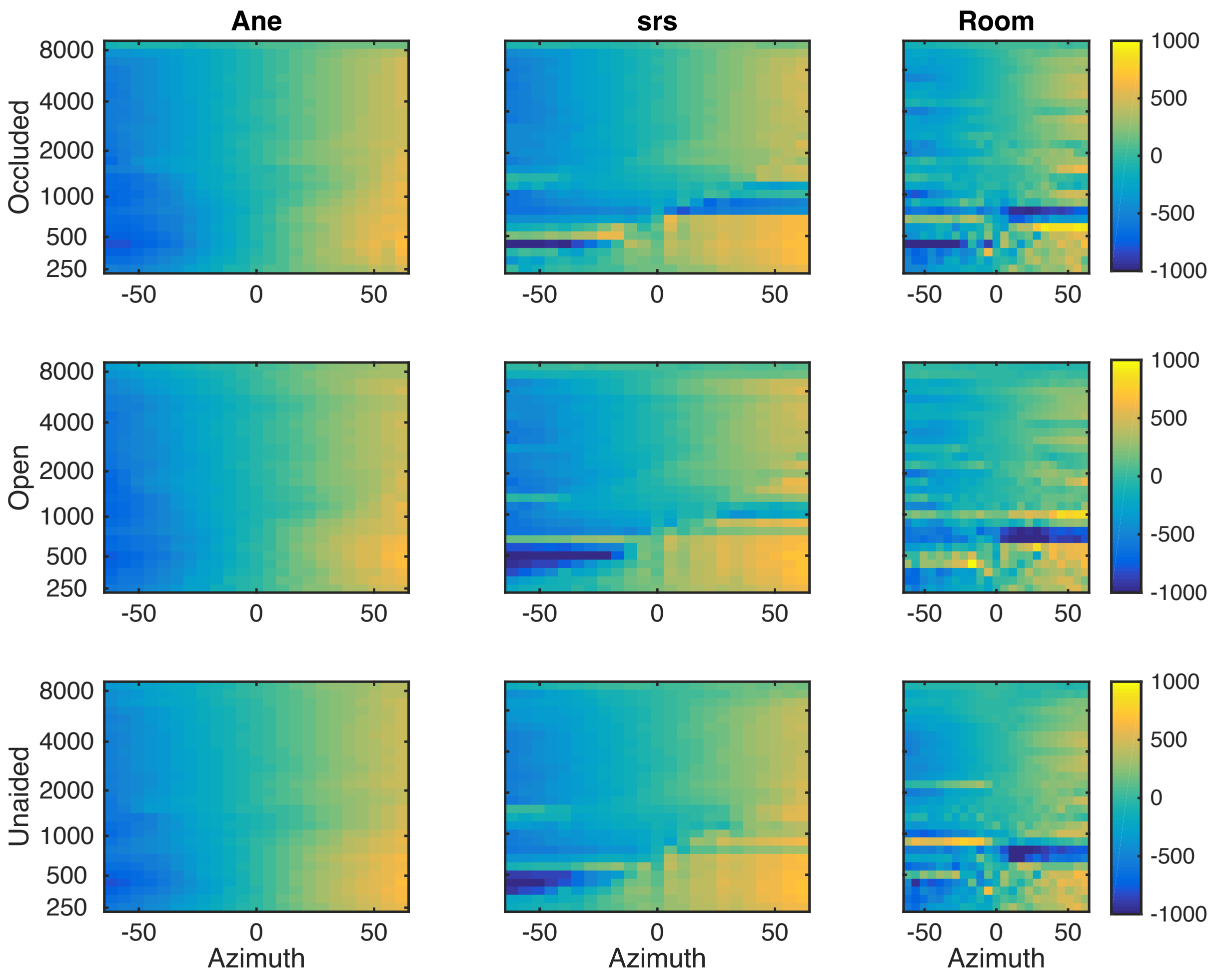
Color plots display normalized ITD for listener 0507. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



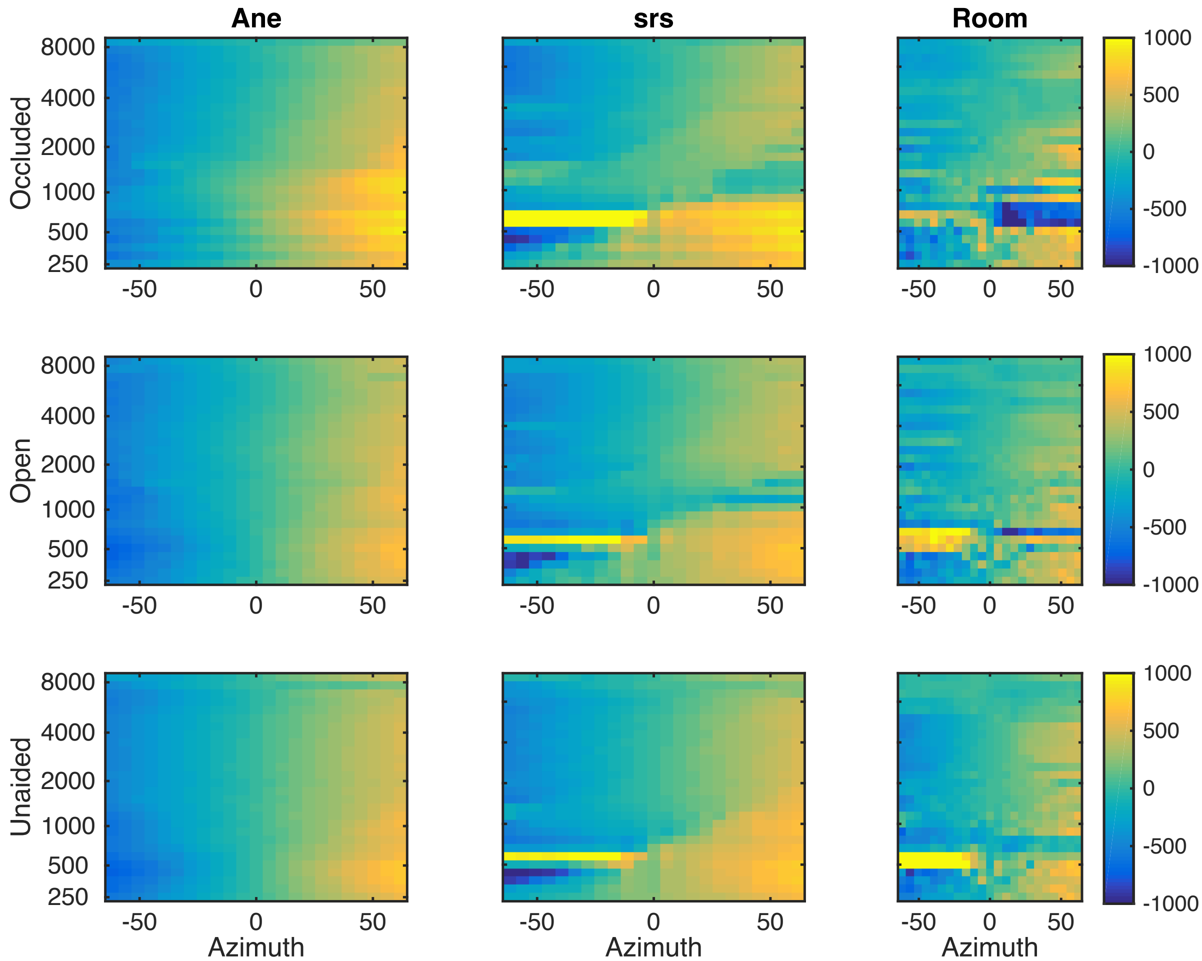
Color plots display normalized ITD for listener 0509. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



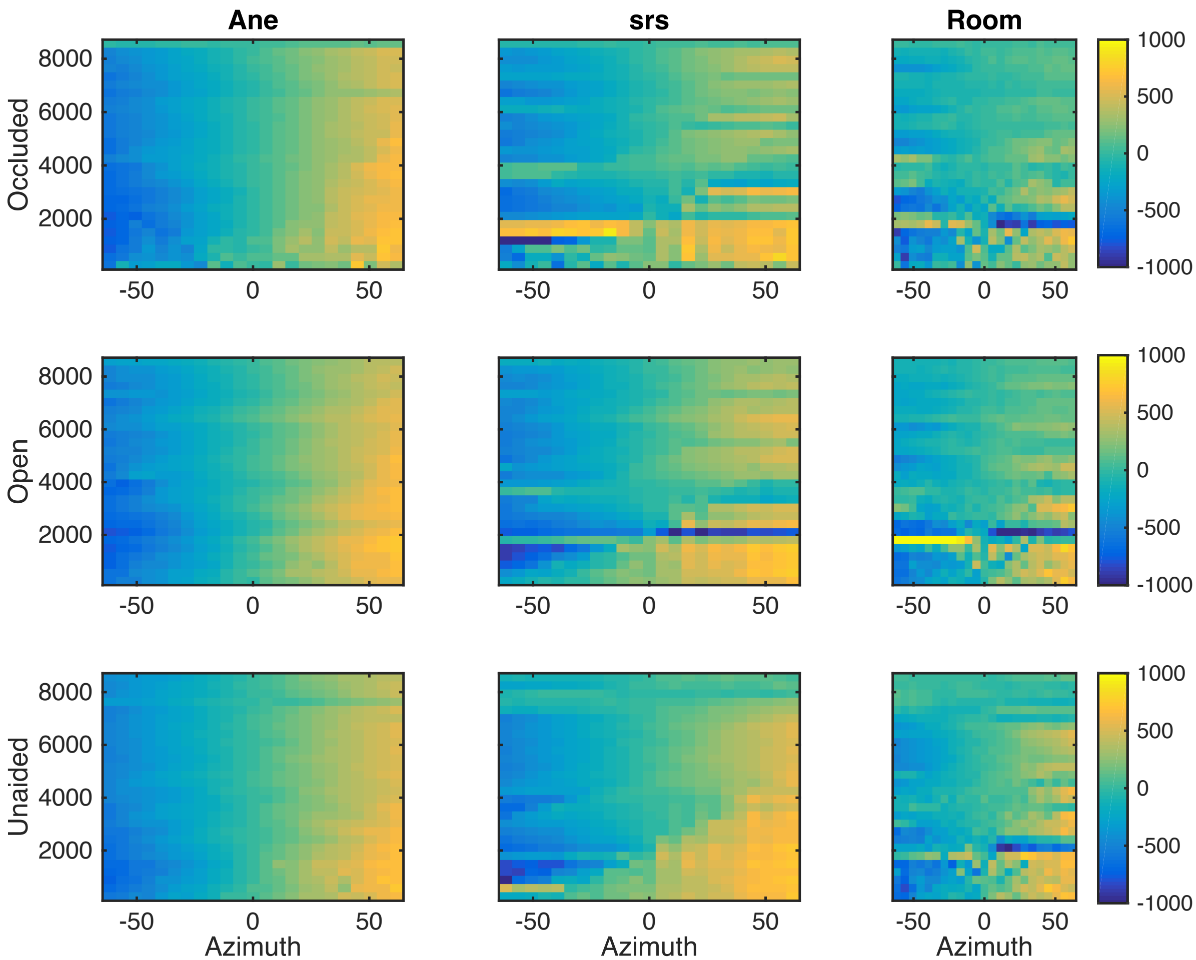
Color plots display normalized ITD for listener 1402. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



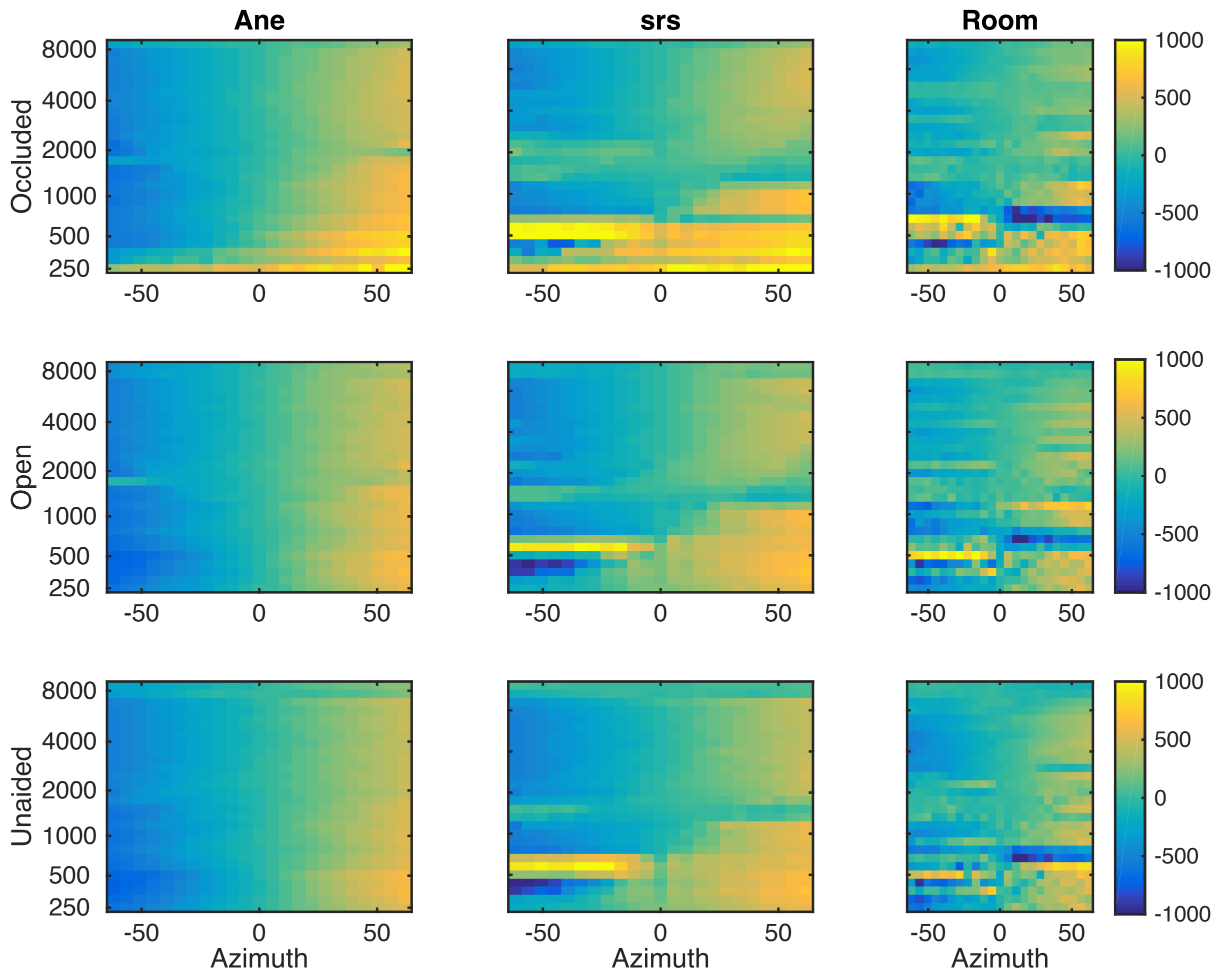
Color plots display normalized ITD for listener 1404. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



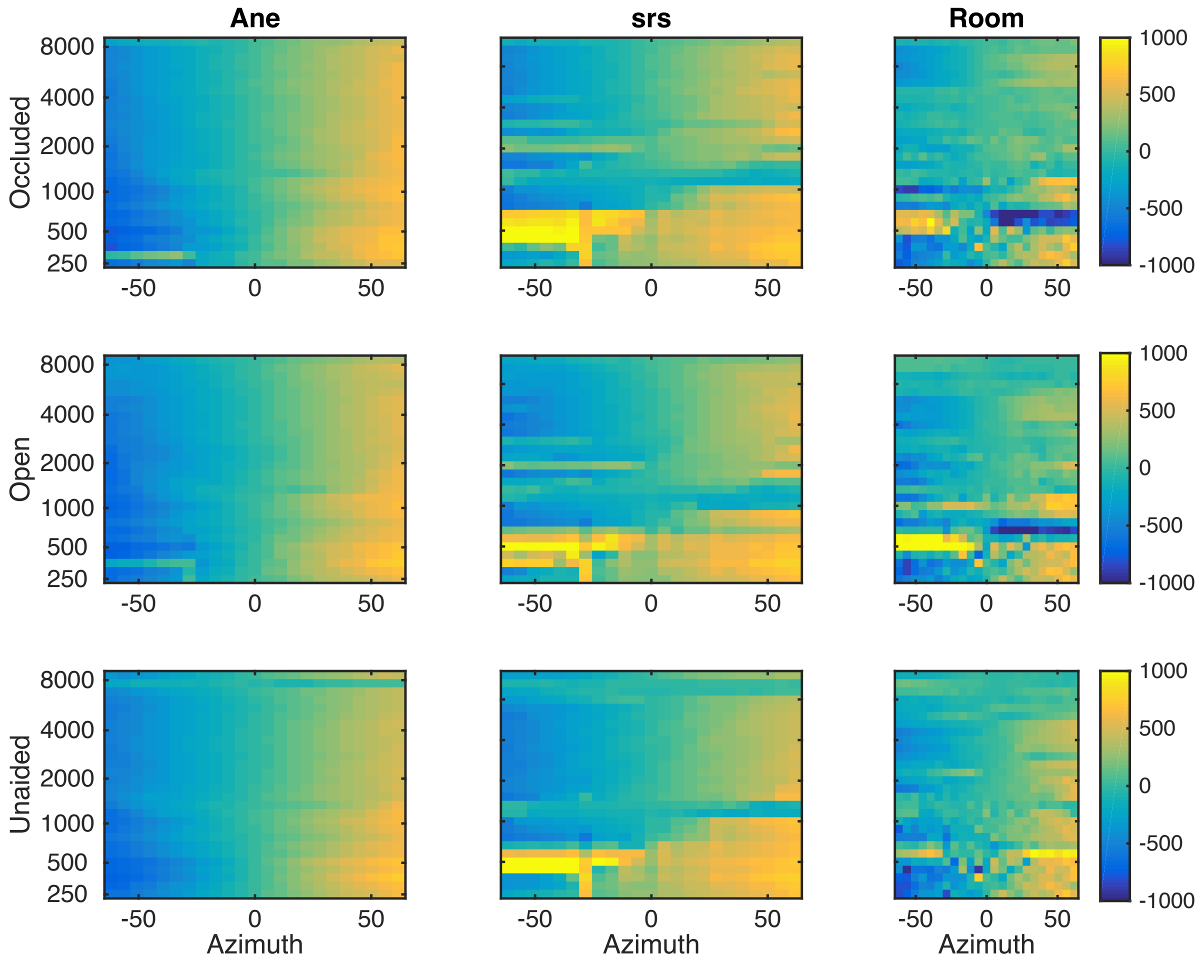
Color plots display normalized ITD for listener 1406. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



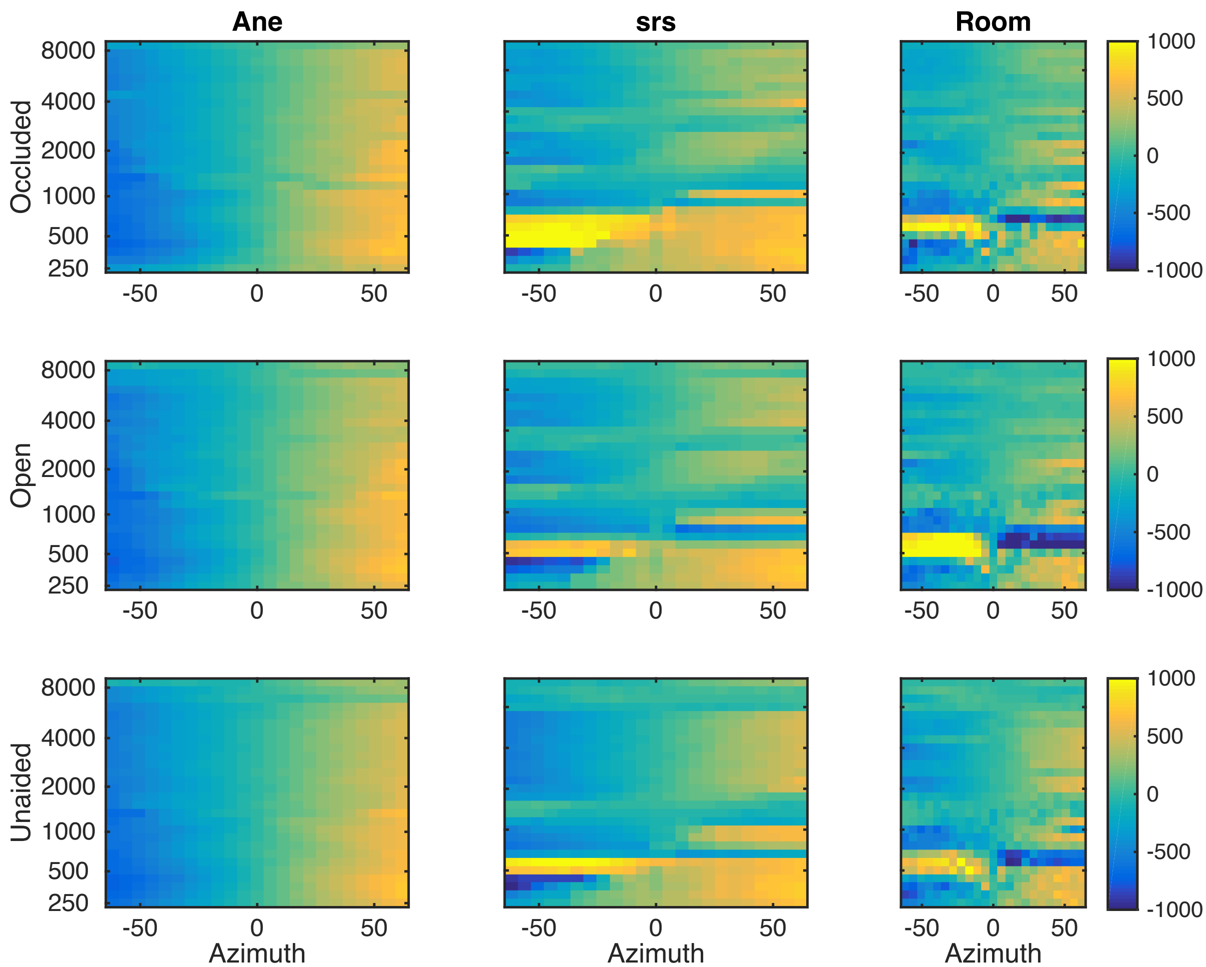
Color plots display normalized ITD for listener 1501. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



Color plots display normalized ITD for listener 1503. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



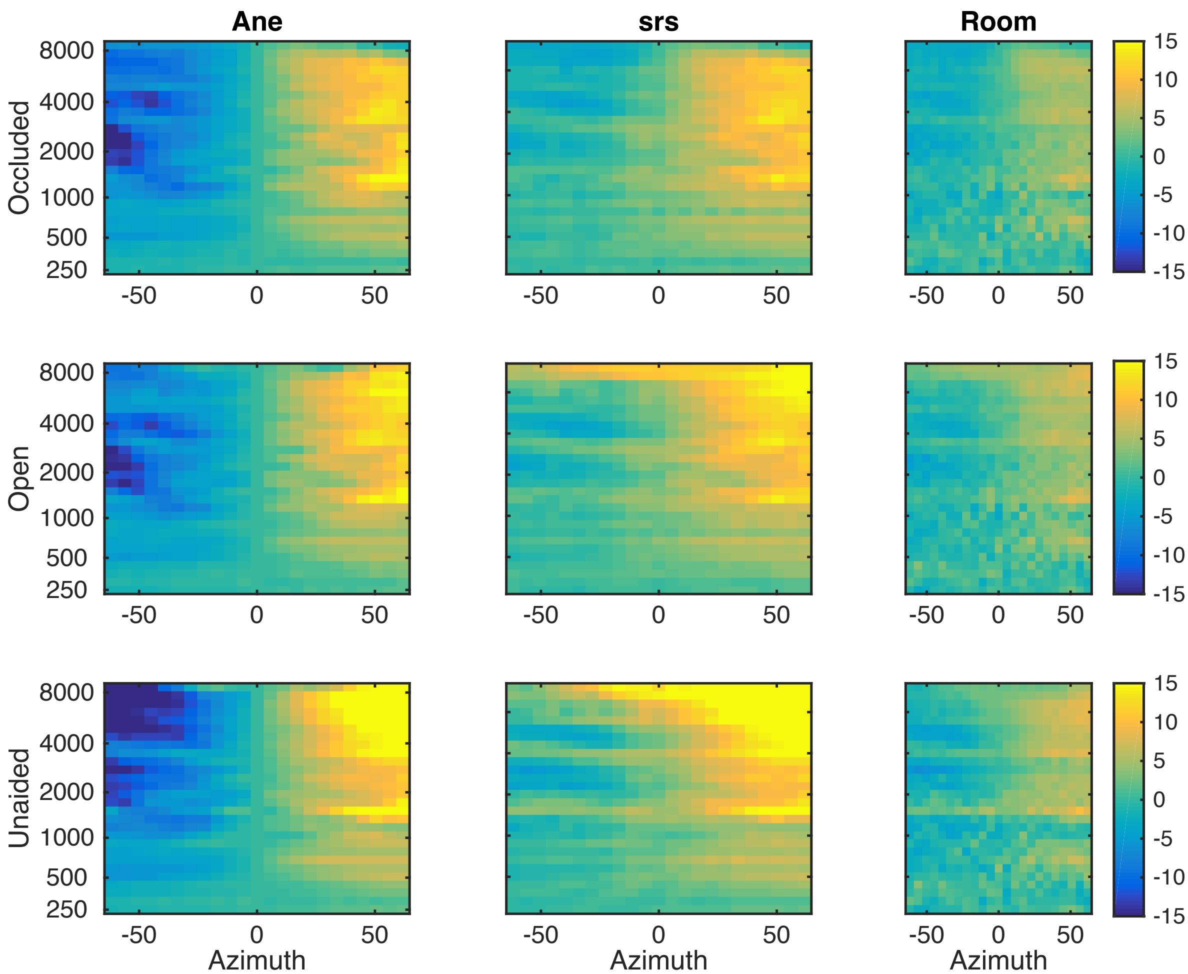
Color plots display normalized ITD for listener 1603. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.



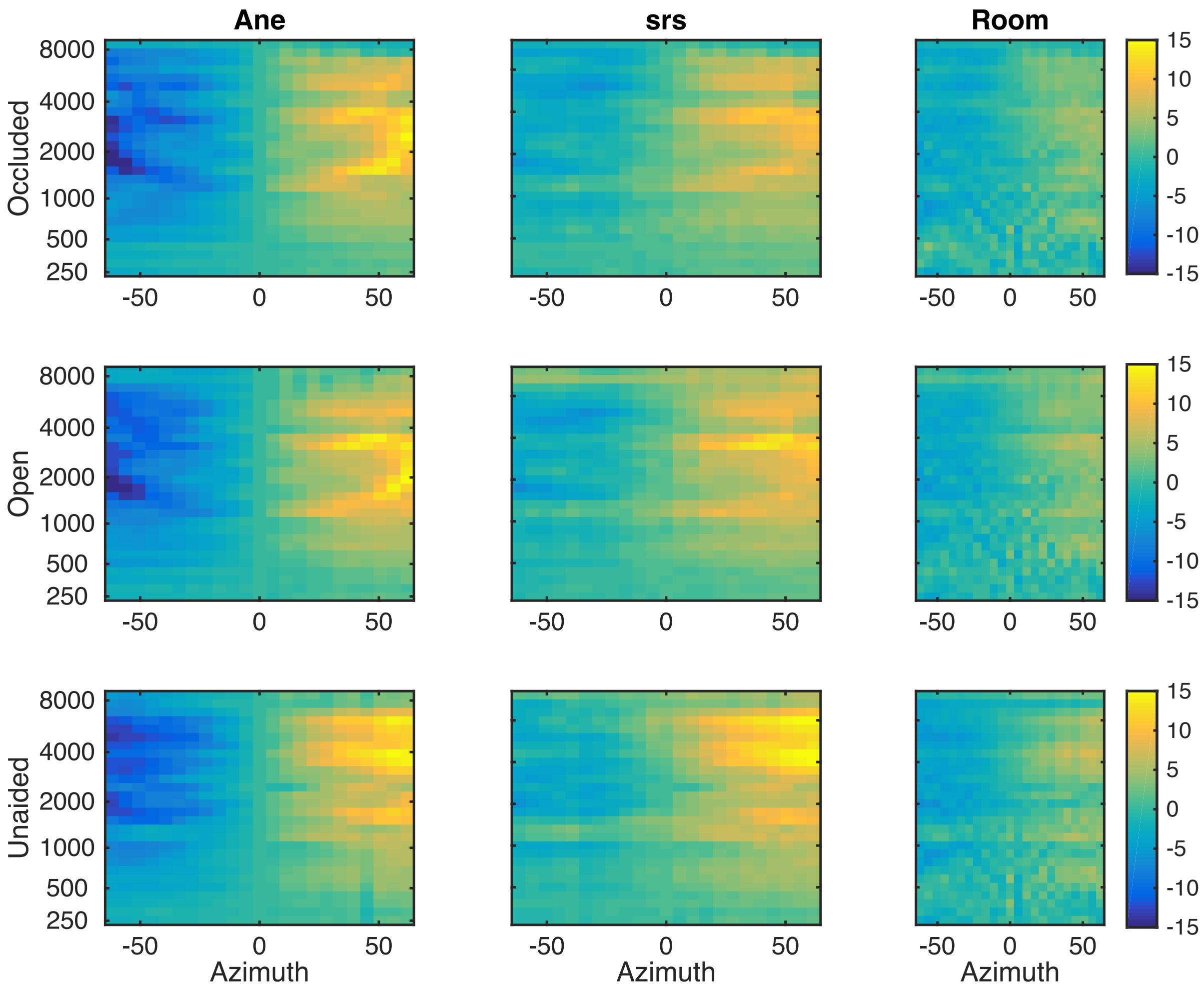
Color plots display normalized ITD for listener 1617. Panel layout is identical to Figures 8. ITD is represented by color, with yellows indicating rightward ILD and blues leftward.

Appendix C.

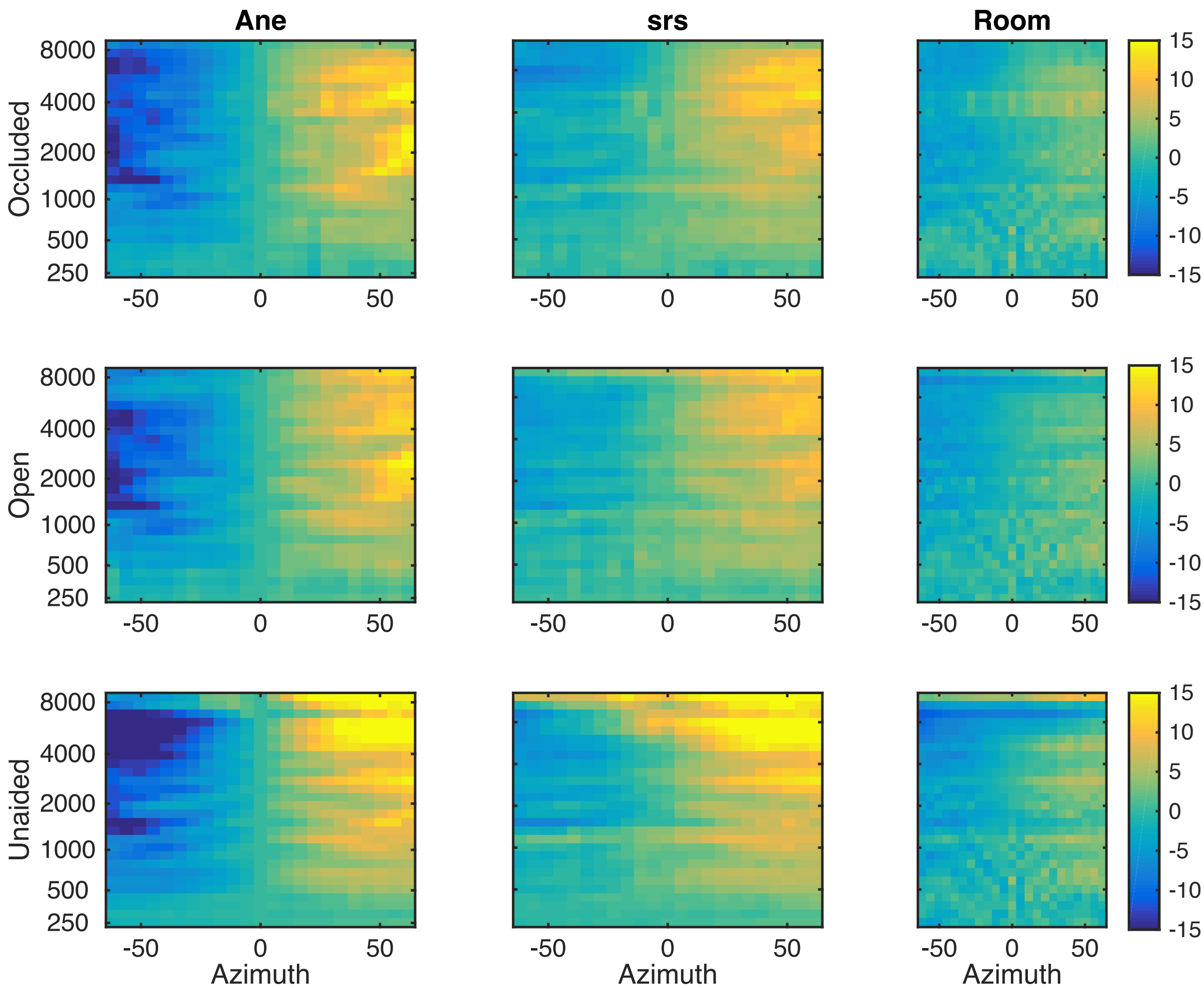
Color plots for individual listeners' normalized ILD:



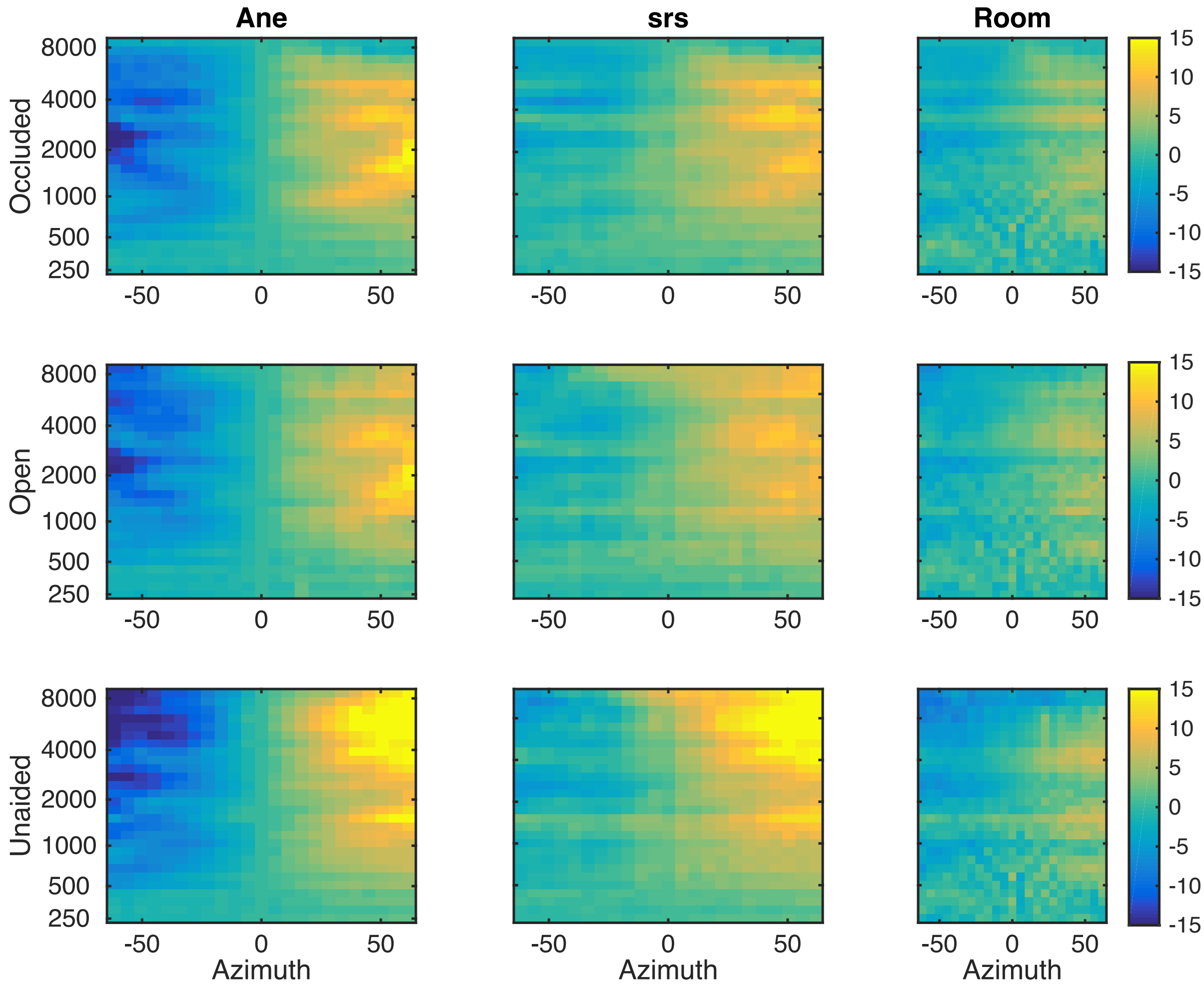
Color plots display normalized ILD for listener 0507. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



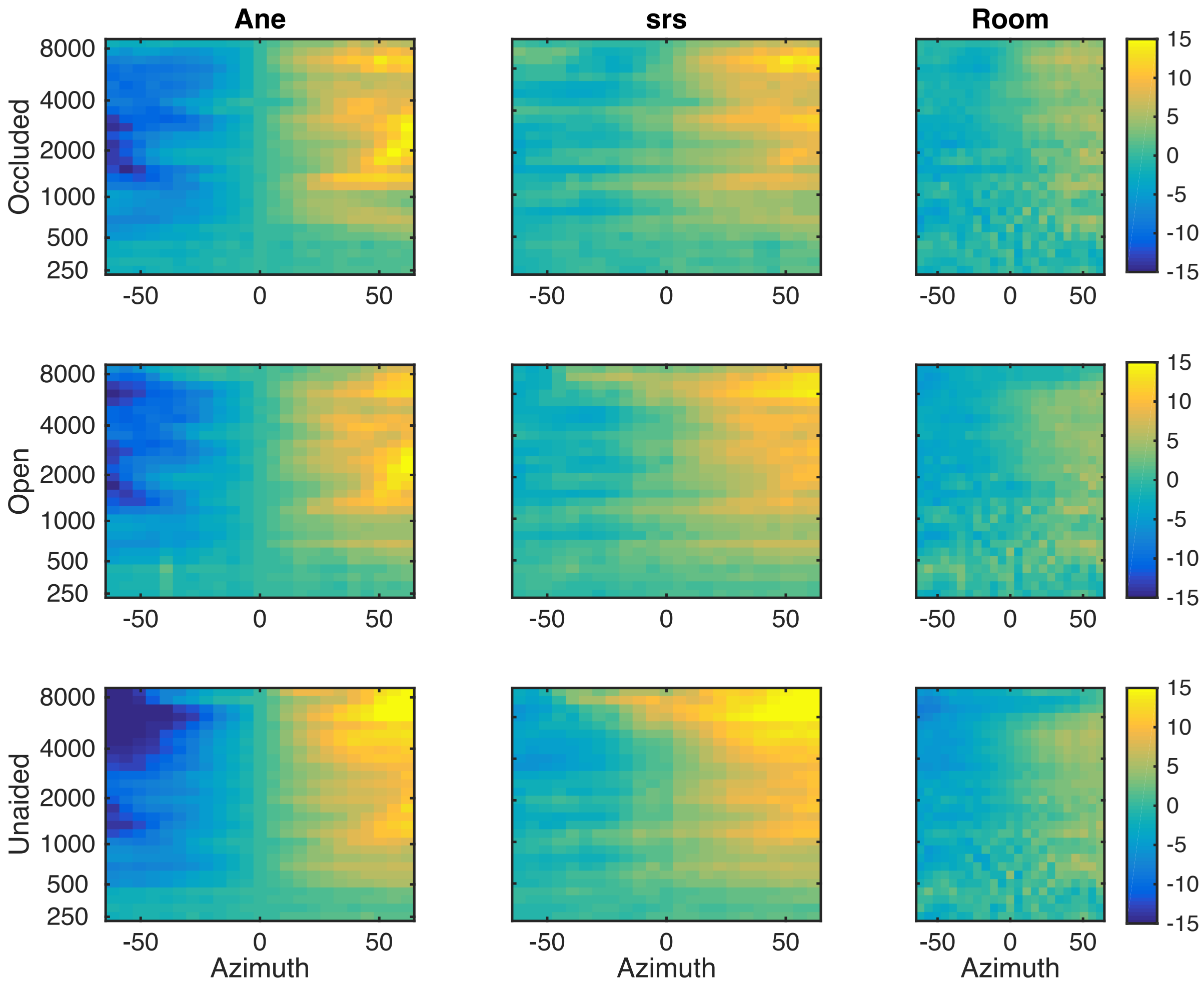
Color plots display normalized ILD for listener 0509. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



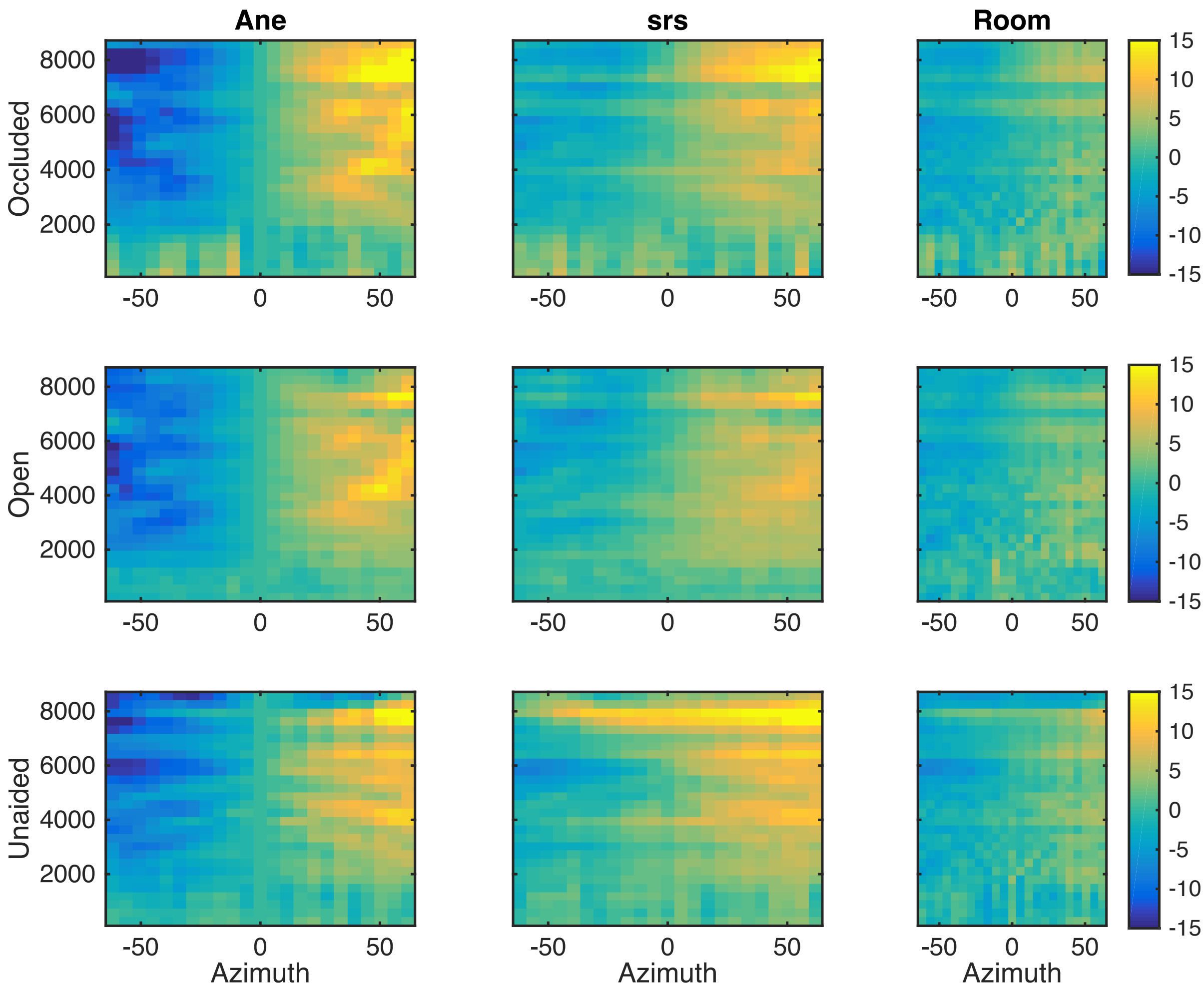
Color plots display normalized ILD for listener 1402. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



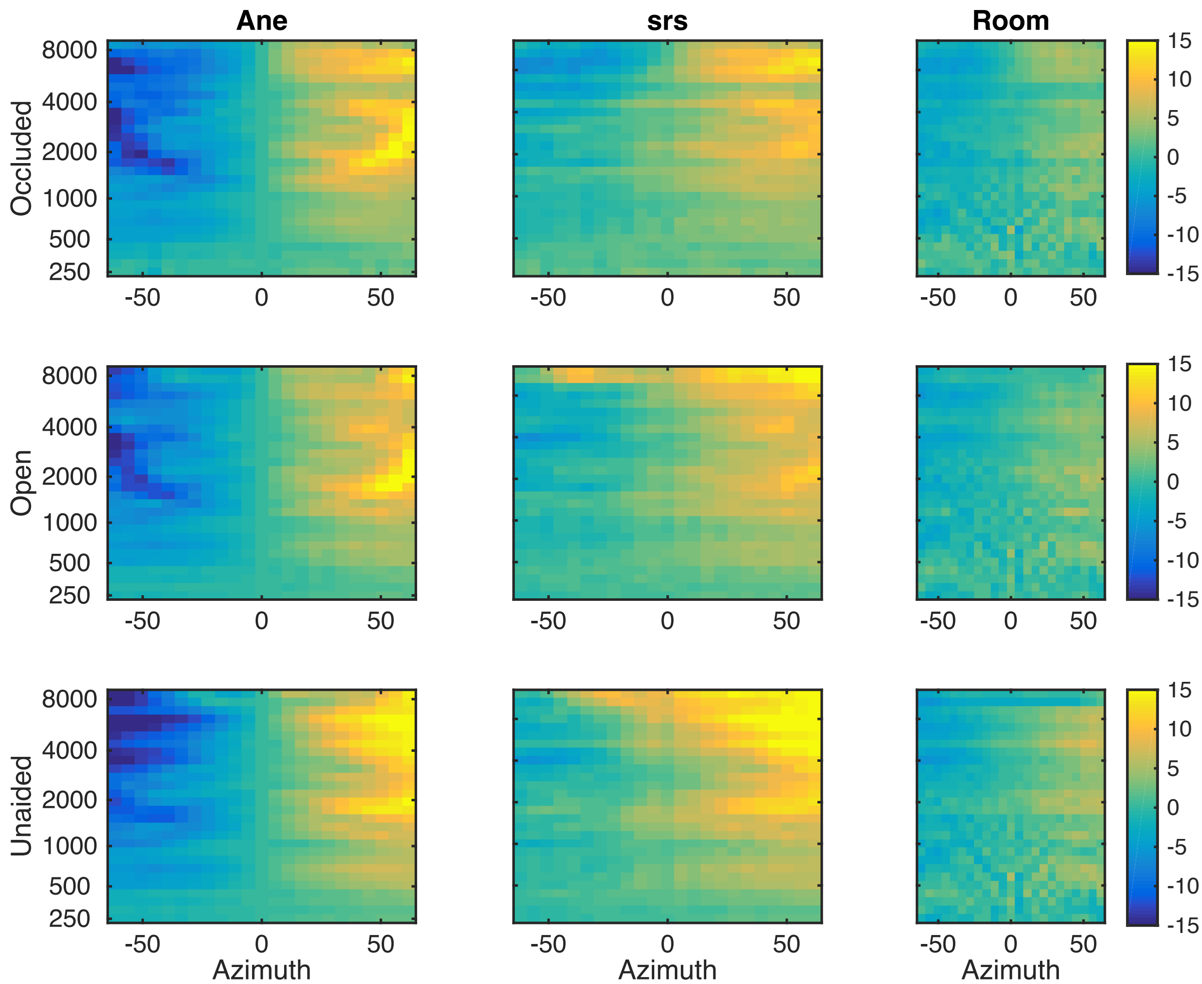
Color plots display normalized ILD for listener 1404. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



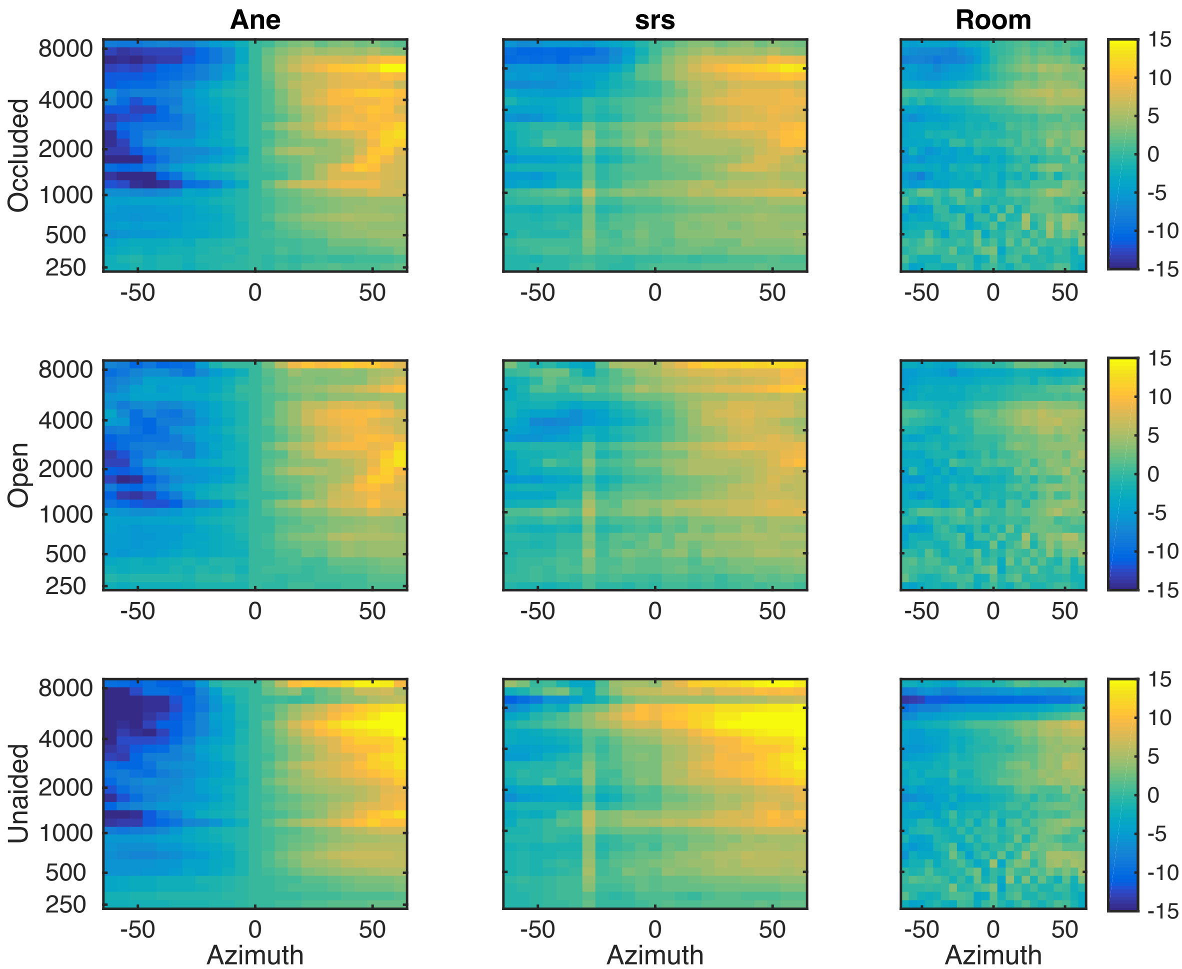
Color plots display normalized ILD for listener 1406. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



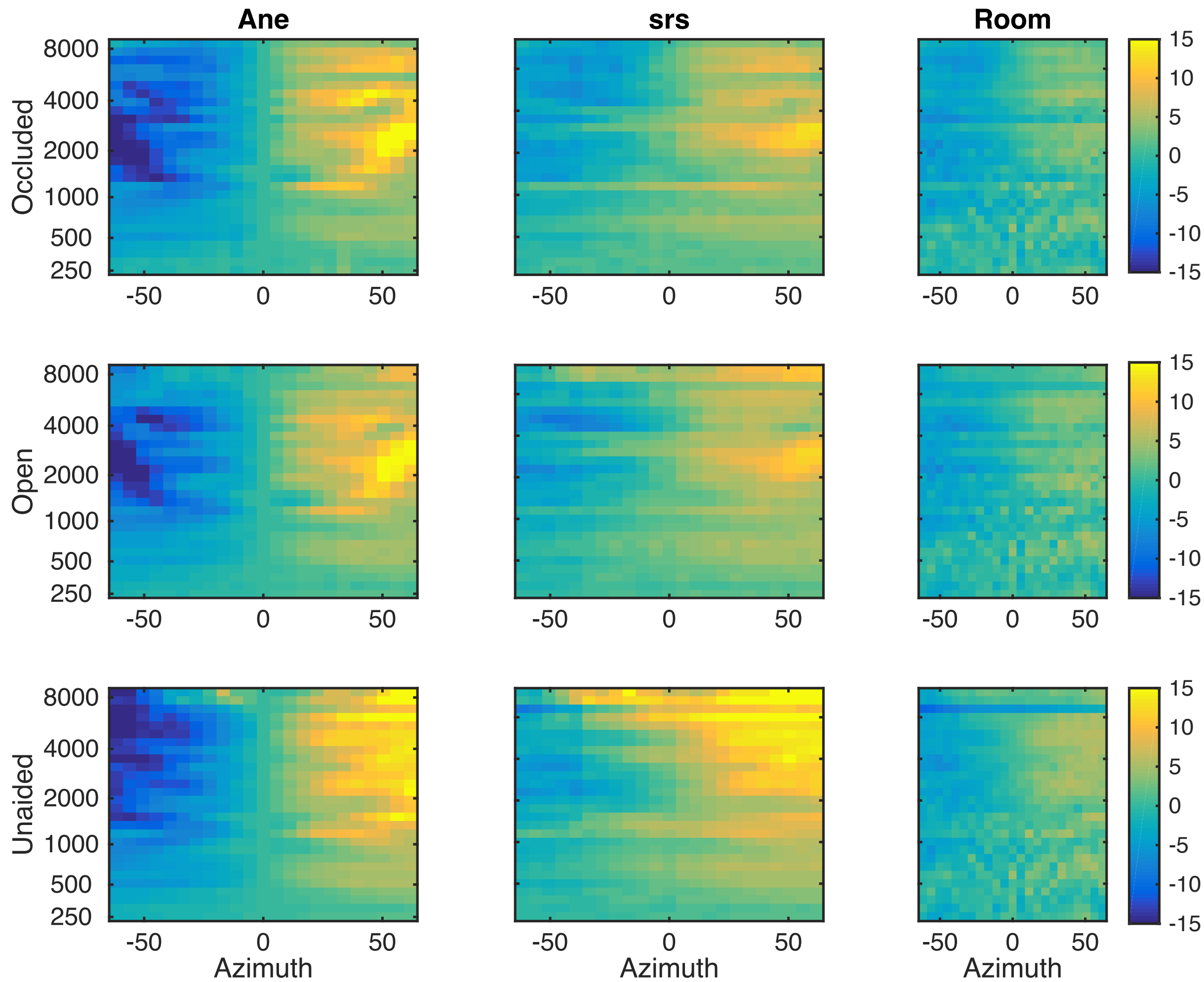
Color plots display normalized ILD for listener 1501. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



Color plots display normalized ILD for listener 1503. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



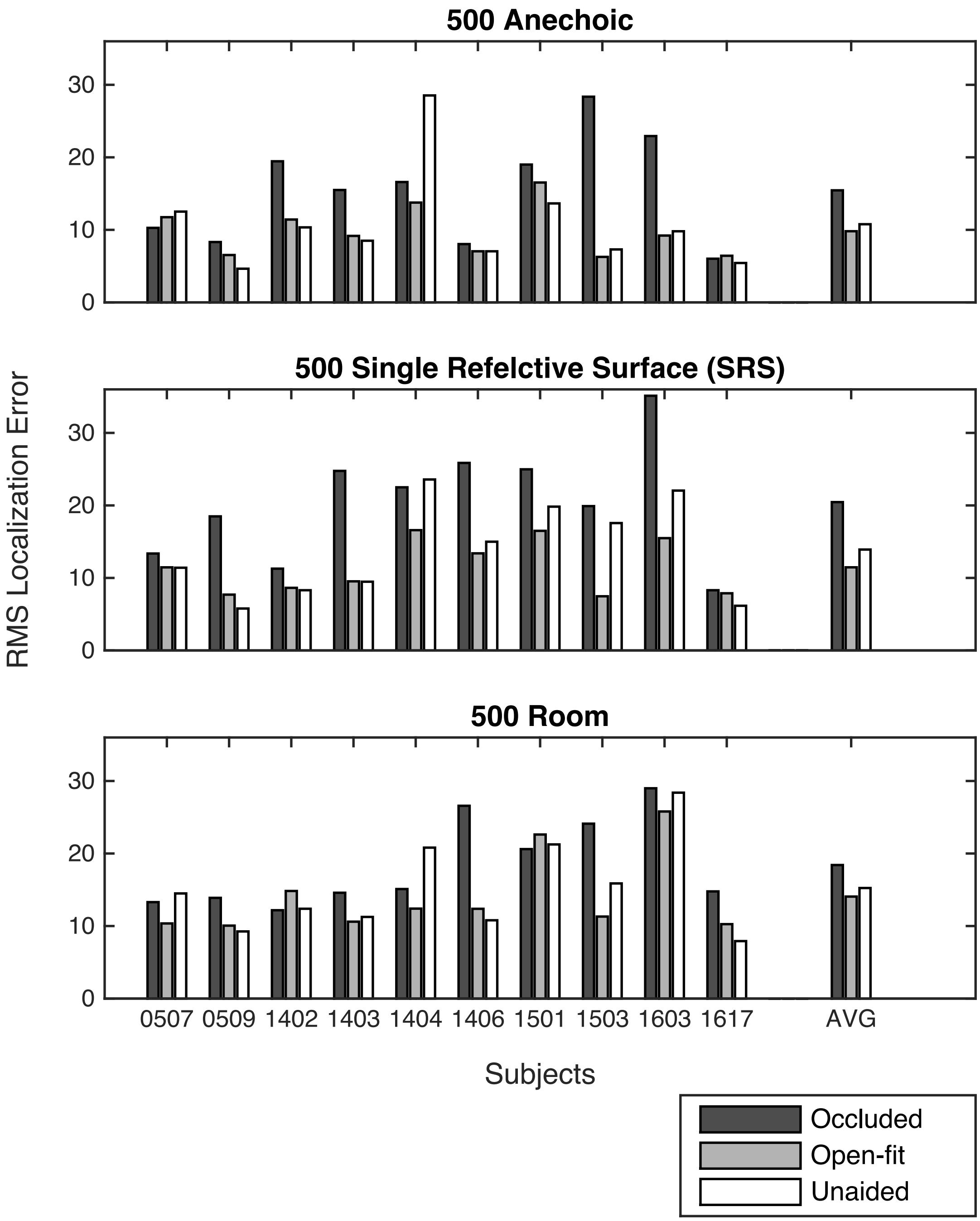
Color plots display normalized ILD for listener 1603. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.



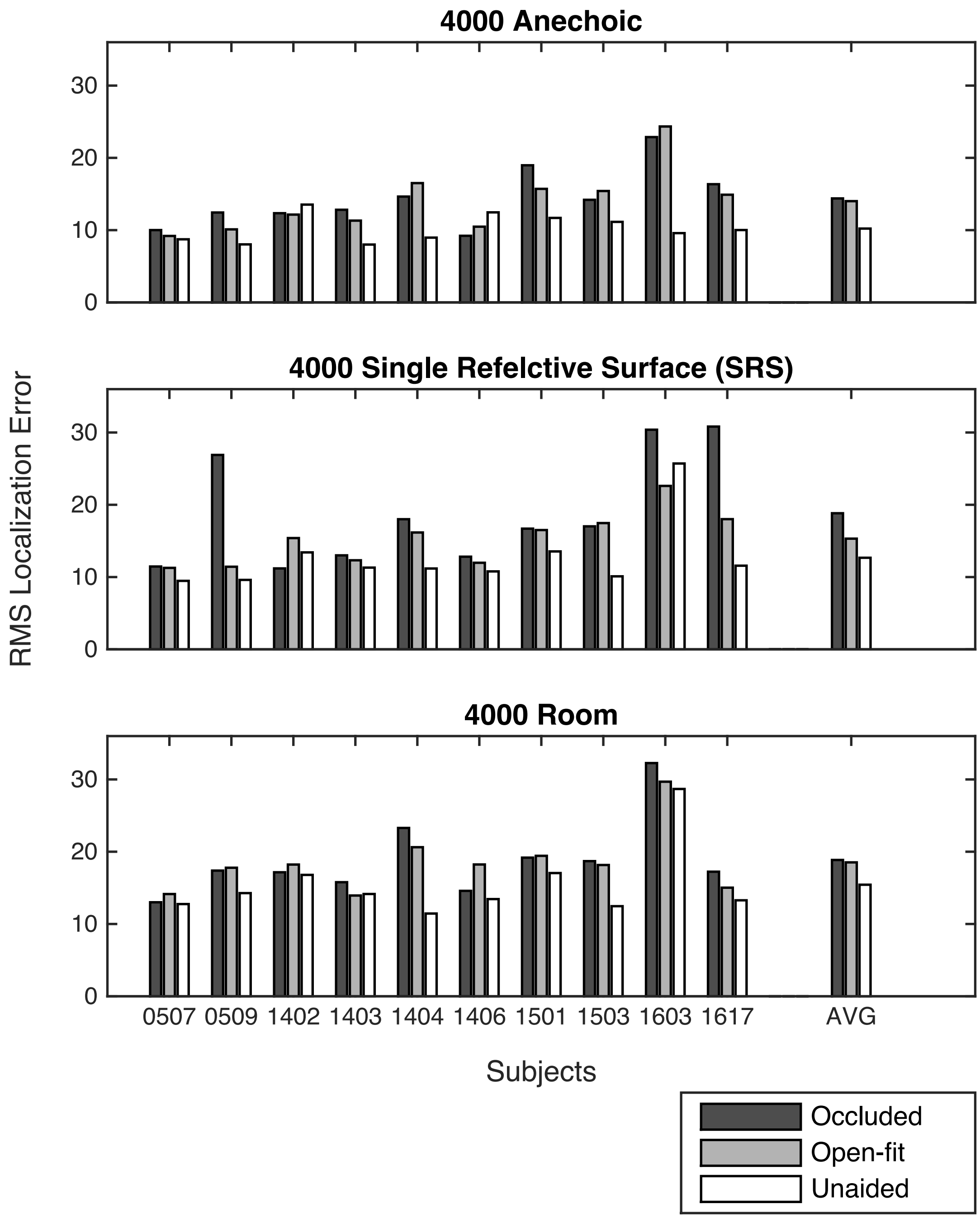
Color plots display normalized ILD for listener 1617. Panel layout is identical to Figures 8. ILD is represented by color, with yellows indicating rightward ILD and blues leftward.

Appendix D.

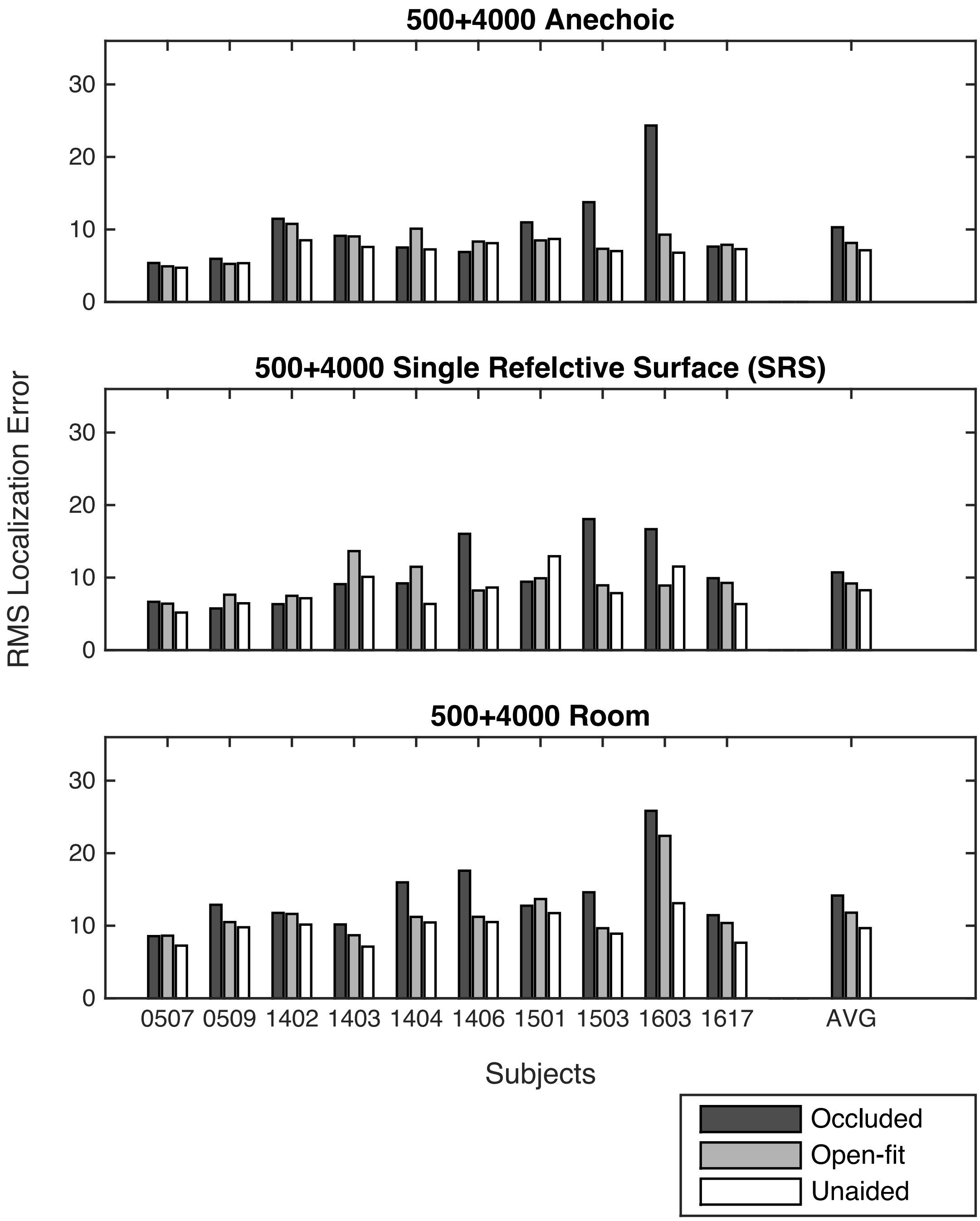
Individual data bar plots across all analytical methods:



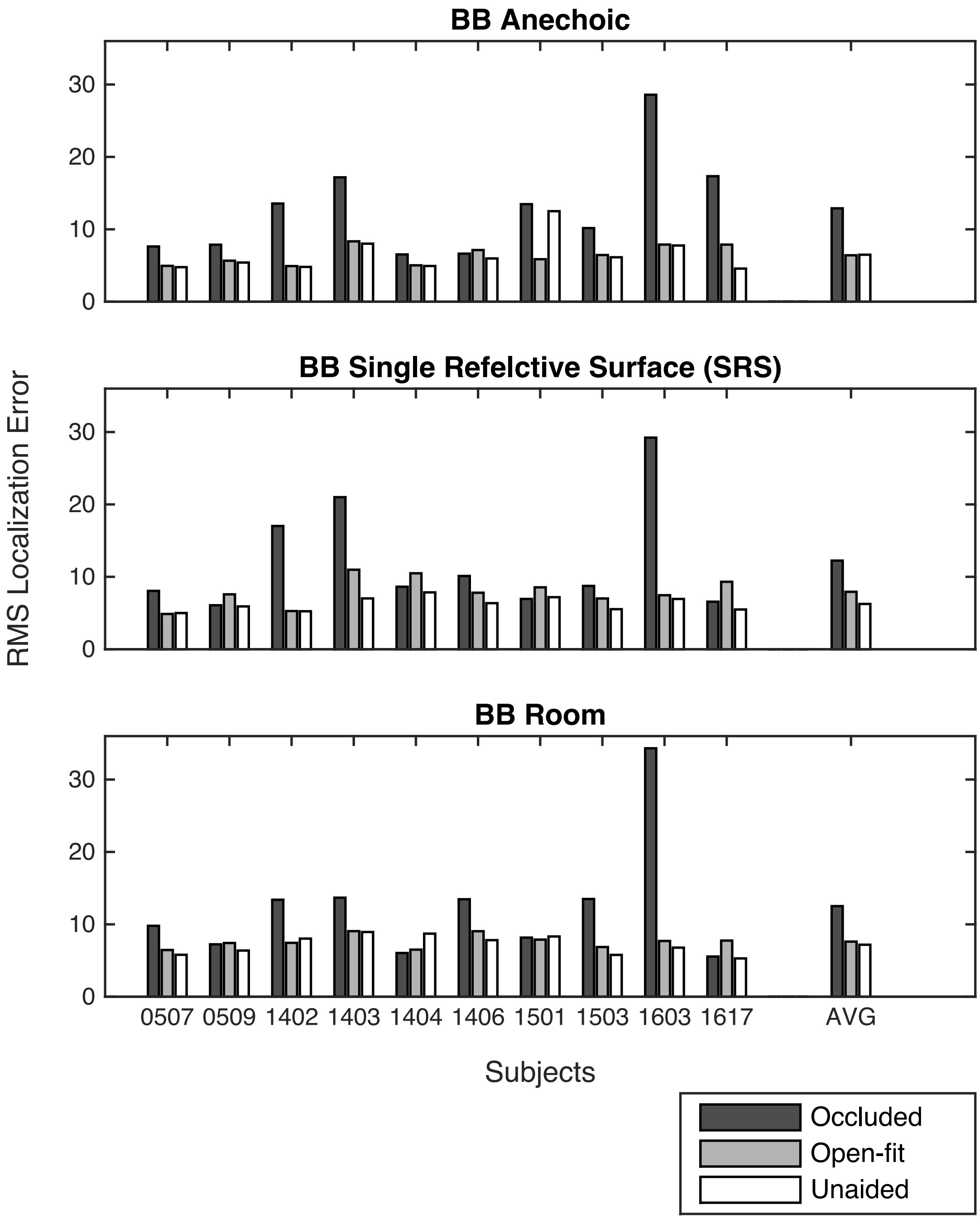
Bars plot mean data for each listener and the average across listeners. Localization error plotted for 500 Hz plotted by room (panels) and aided (bars) conditions.



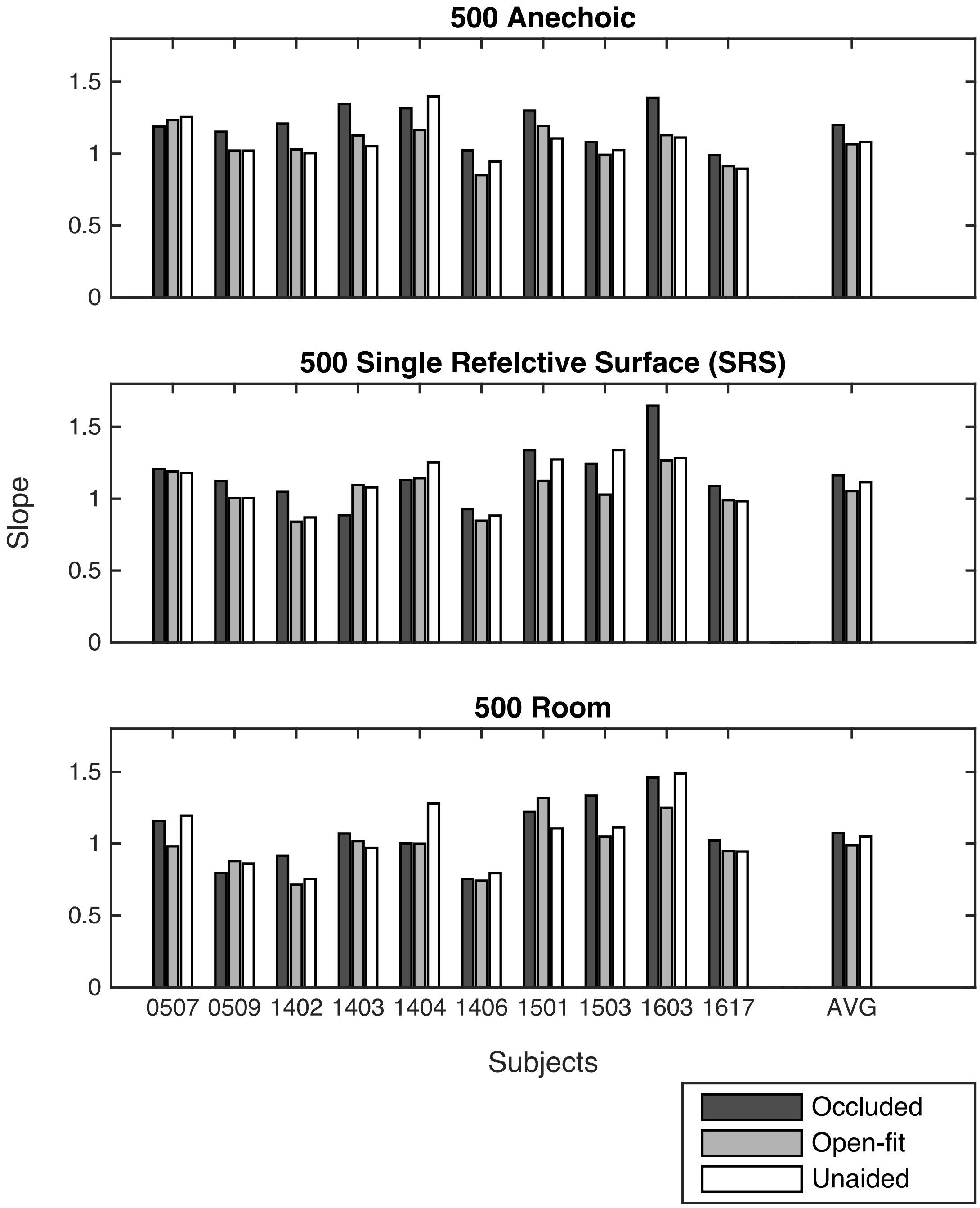
Bars plot mean data for each listener and the average across listeners. Localization error plotted for 4000 Hz plotted by room (panels) and aided (bars) conditions.



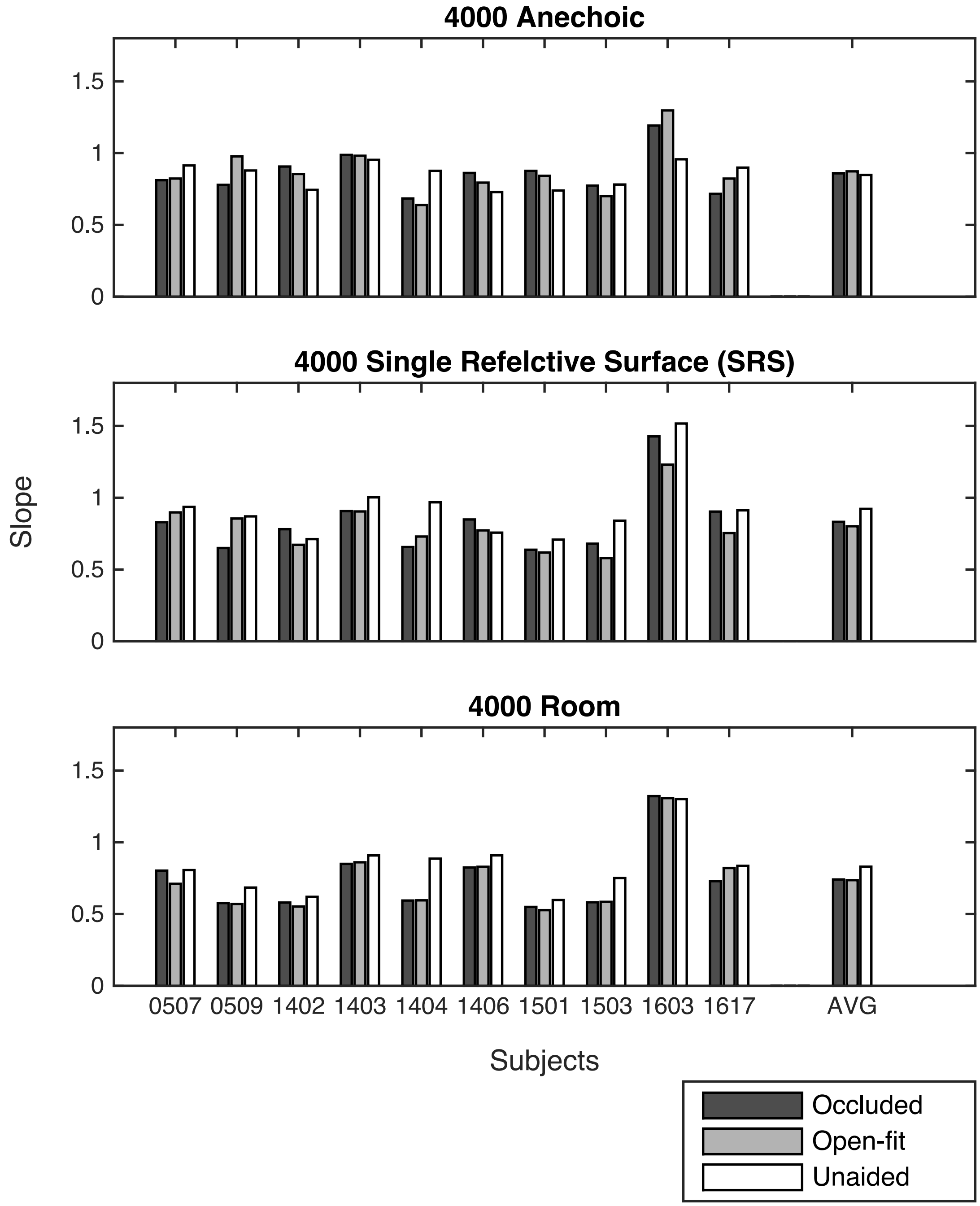
Bars plot mean data for each listener and the average across listeners. Localization error plotted for 500+4000 Hz plotted by room (panels) and aided (bars) conditions.



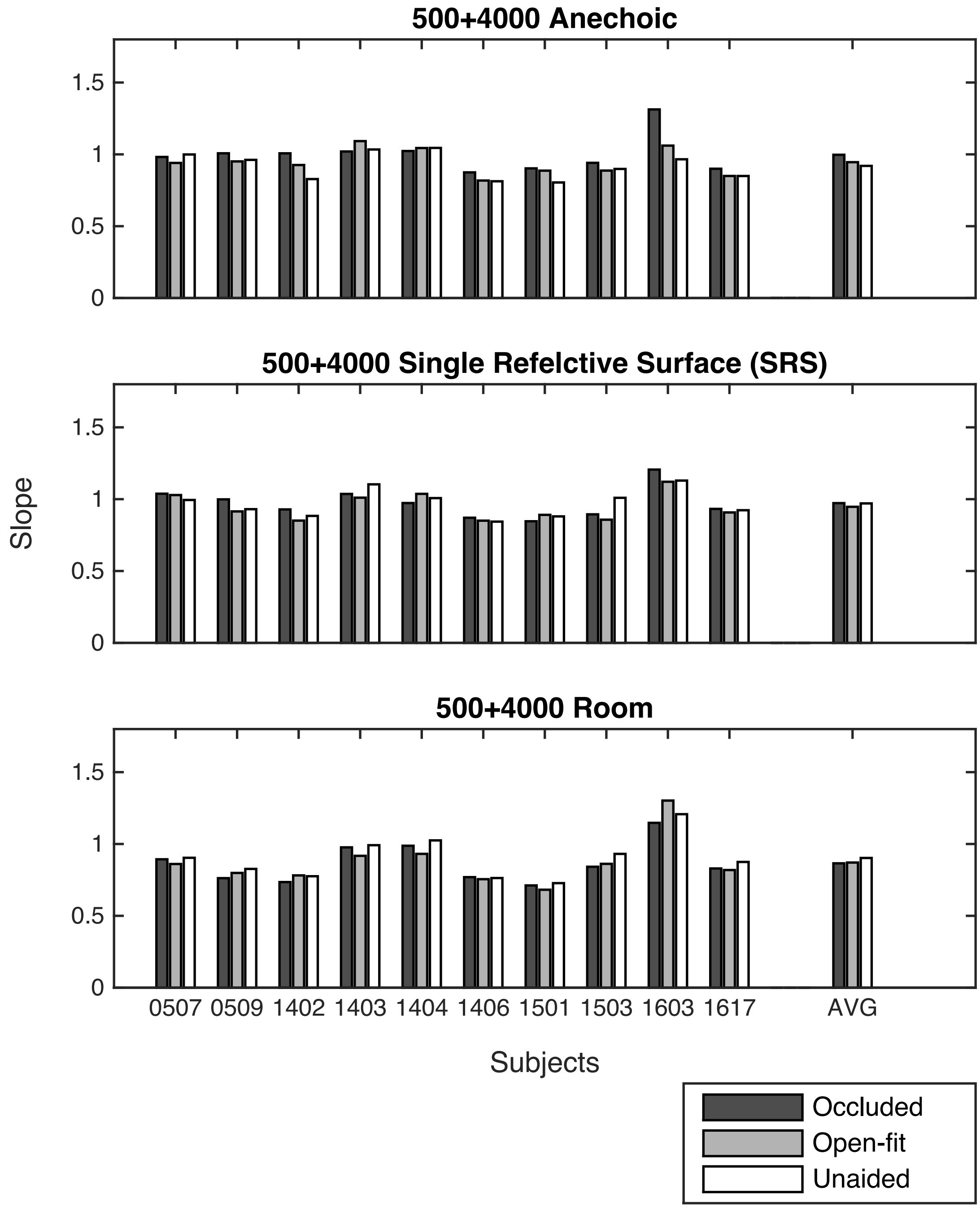
Bars plot mean data for each listener and the average across listeners. Localization error plotted for BB noise plotted by room (panels) and aided (bars) conditions.



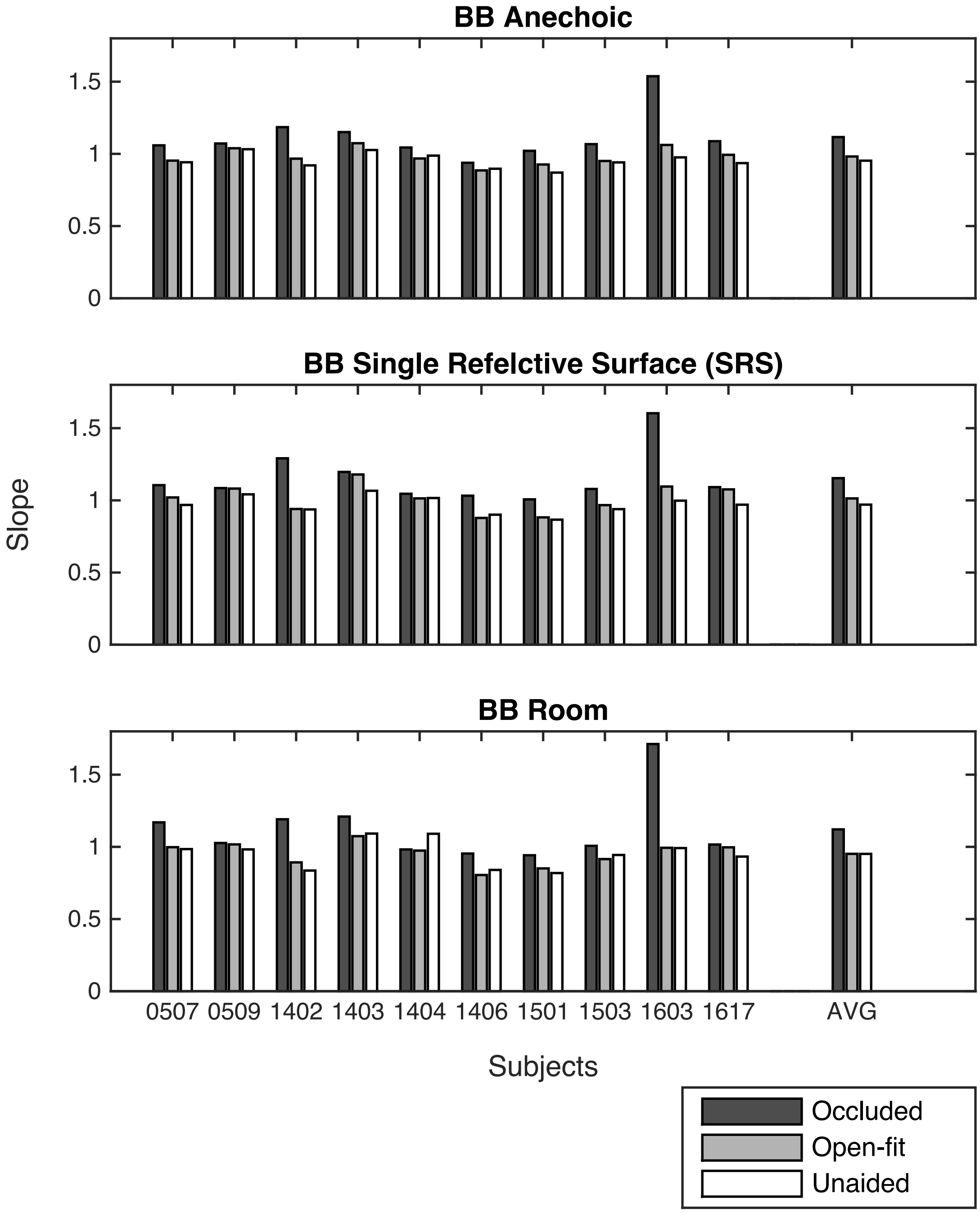
Bars plot mean data for each listener and the average across listeners. Localization gain plotted for 500 Hz plotted by room (panels) and aided (bars) conditions.



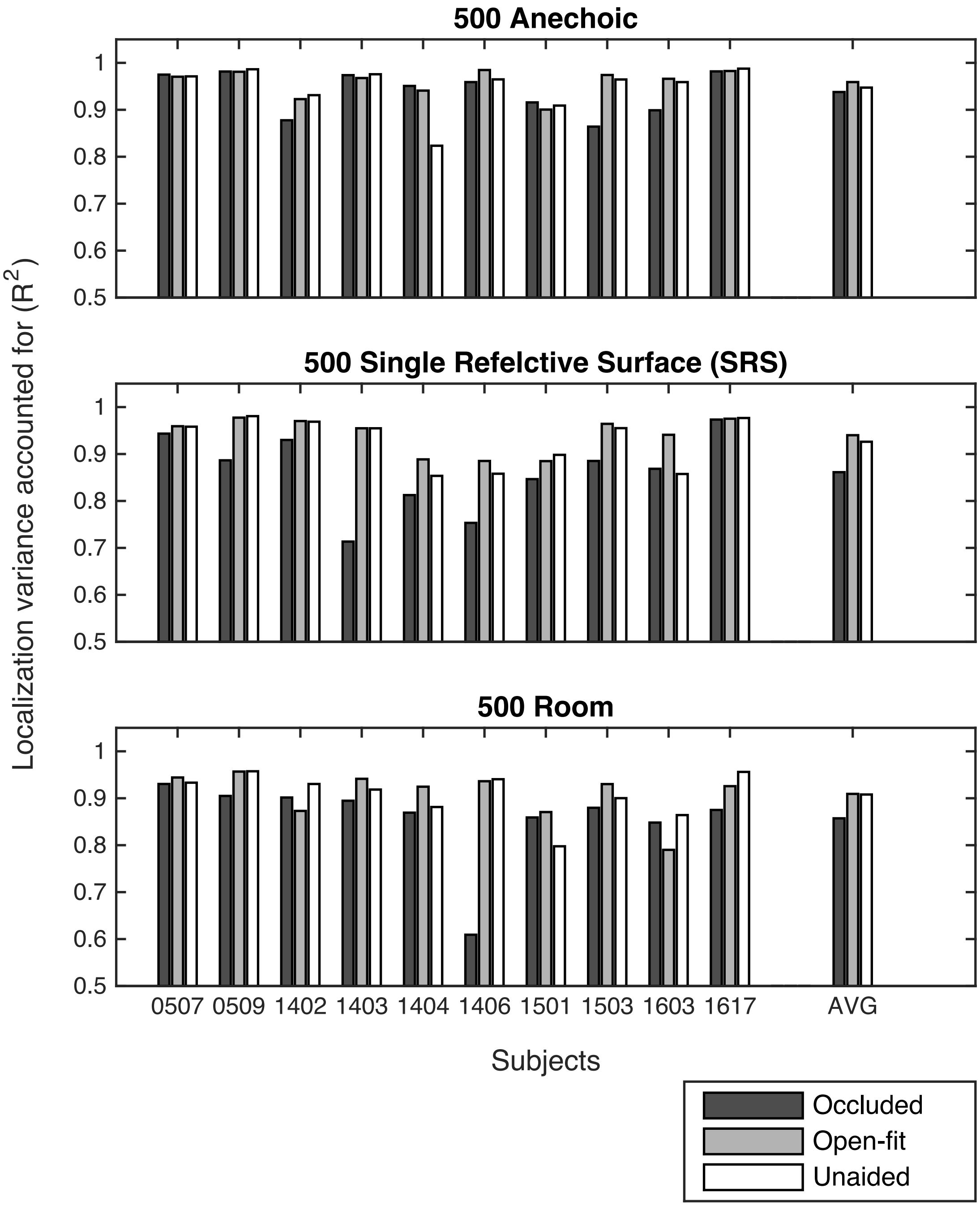
Bars plot mean data for each listener and the average across listeners. Localization gain plotted for 4000 Hz plotted by room (panels) and aided (bars) conditions.



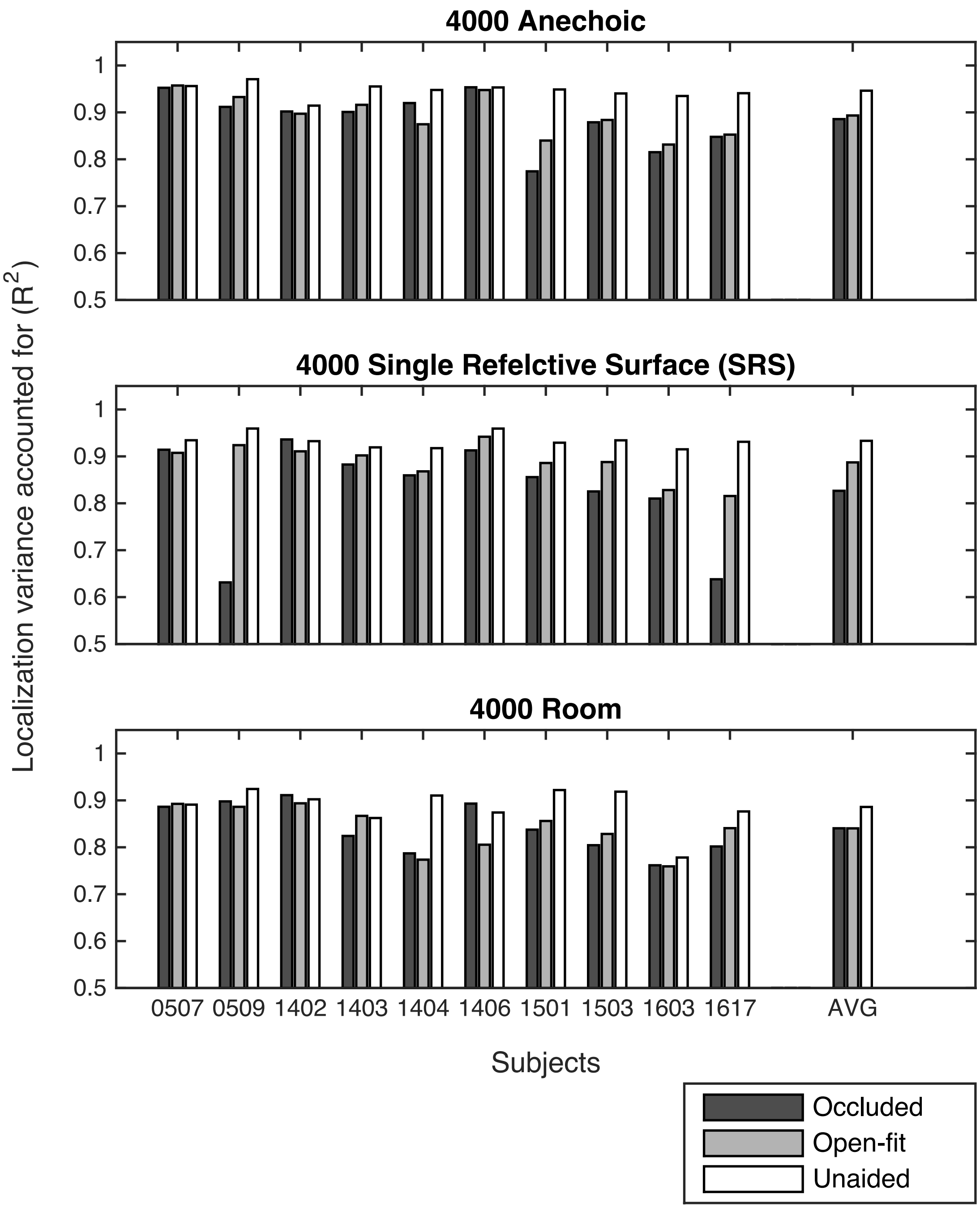
Bars plot mean data for each listener and the average across listeners. Localization gain plotted for 500+4000 Hz plotted by room (panels) and aided (bars) conditions.



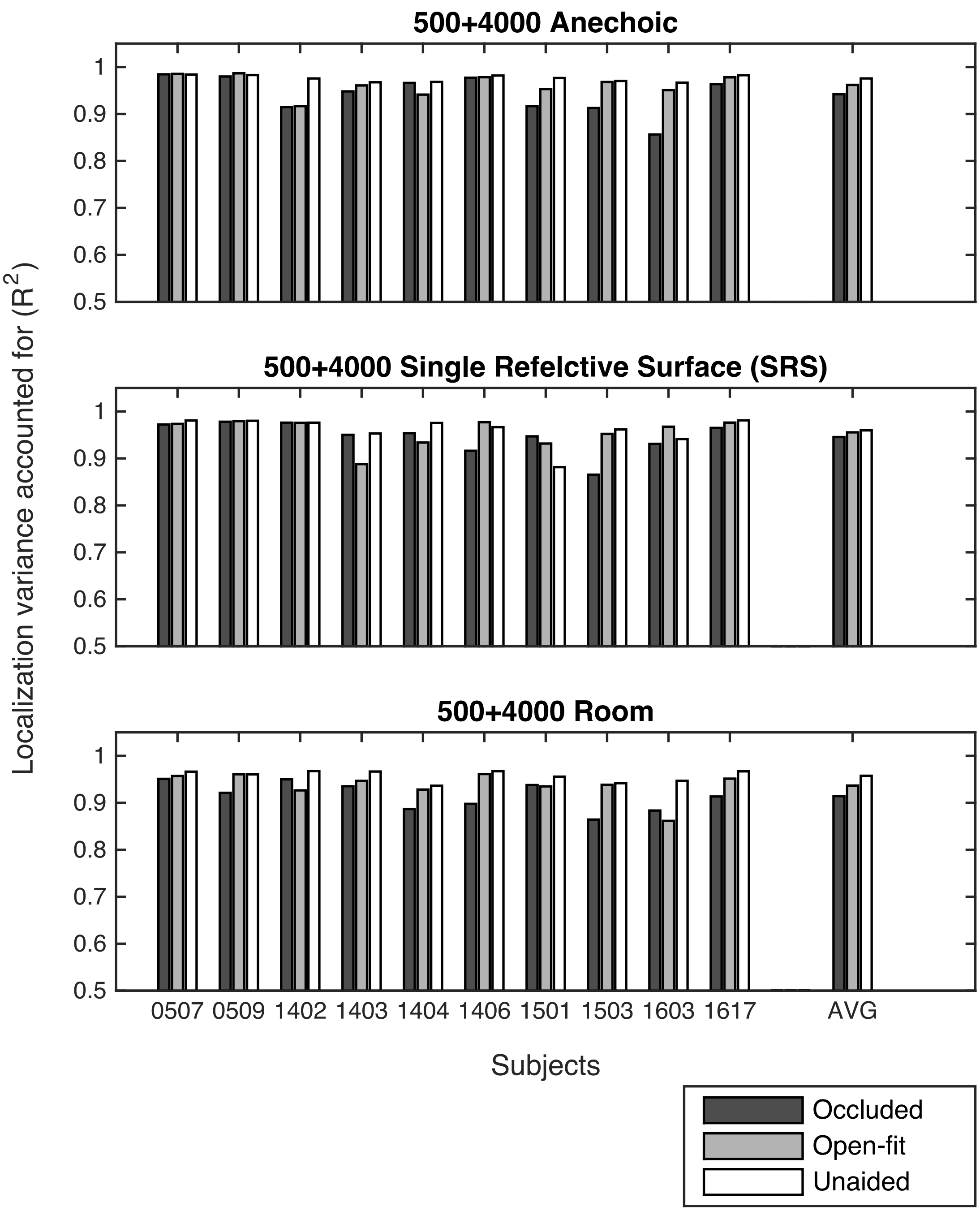
Bars plot mean data for each listener and the average across listeners. Localization gain plotted for BB noise plotted by room (panels) and aided (bars) conditions.



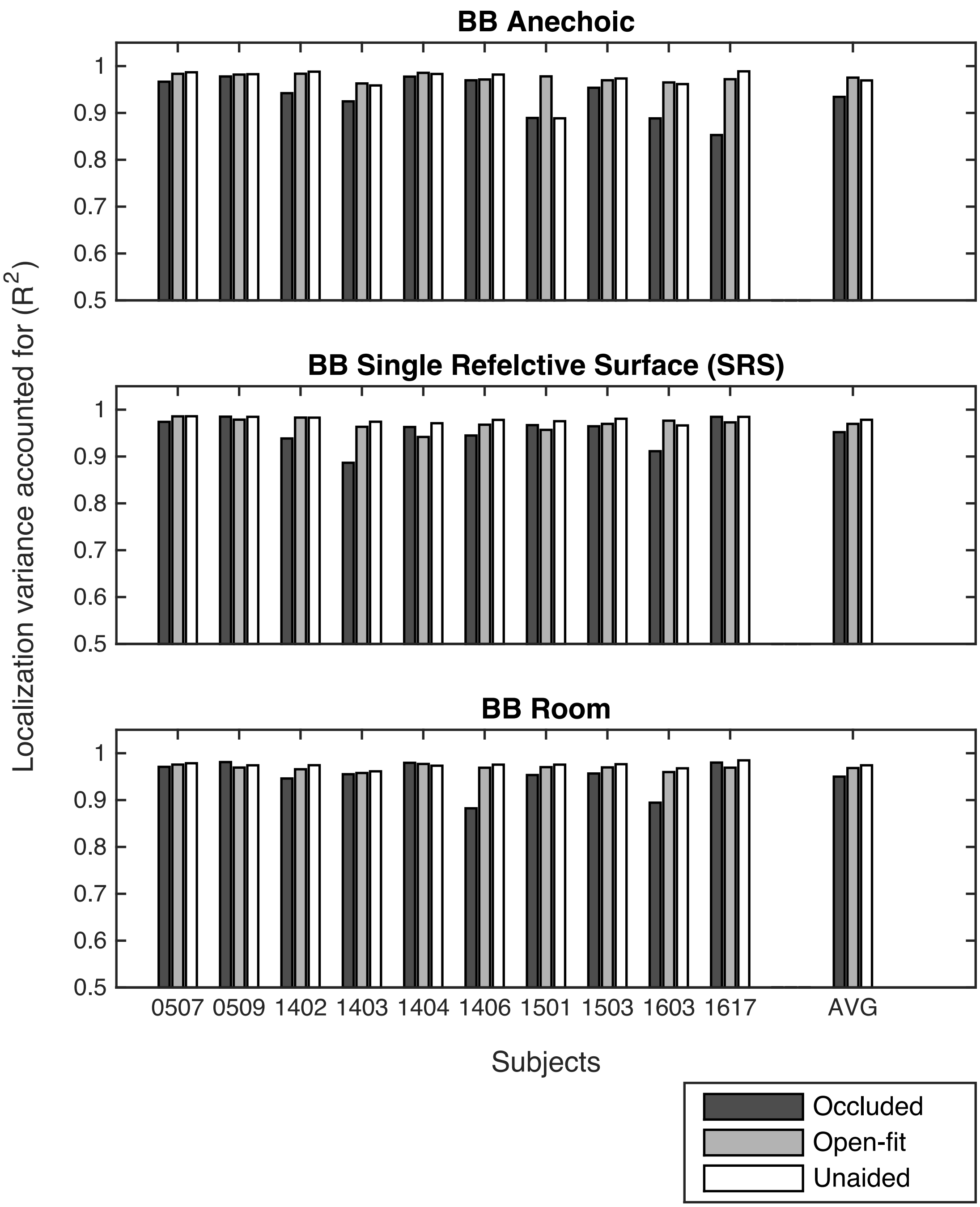
Bars plot mean data for each listener and the average across listeners. Localization variance plotted for 500 Hz plotted by room (panels) and aided (bars) conditions.



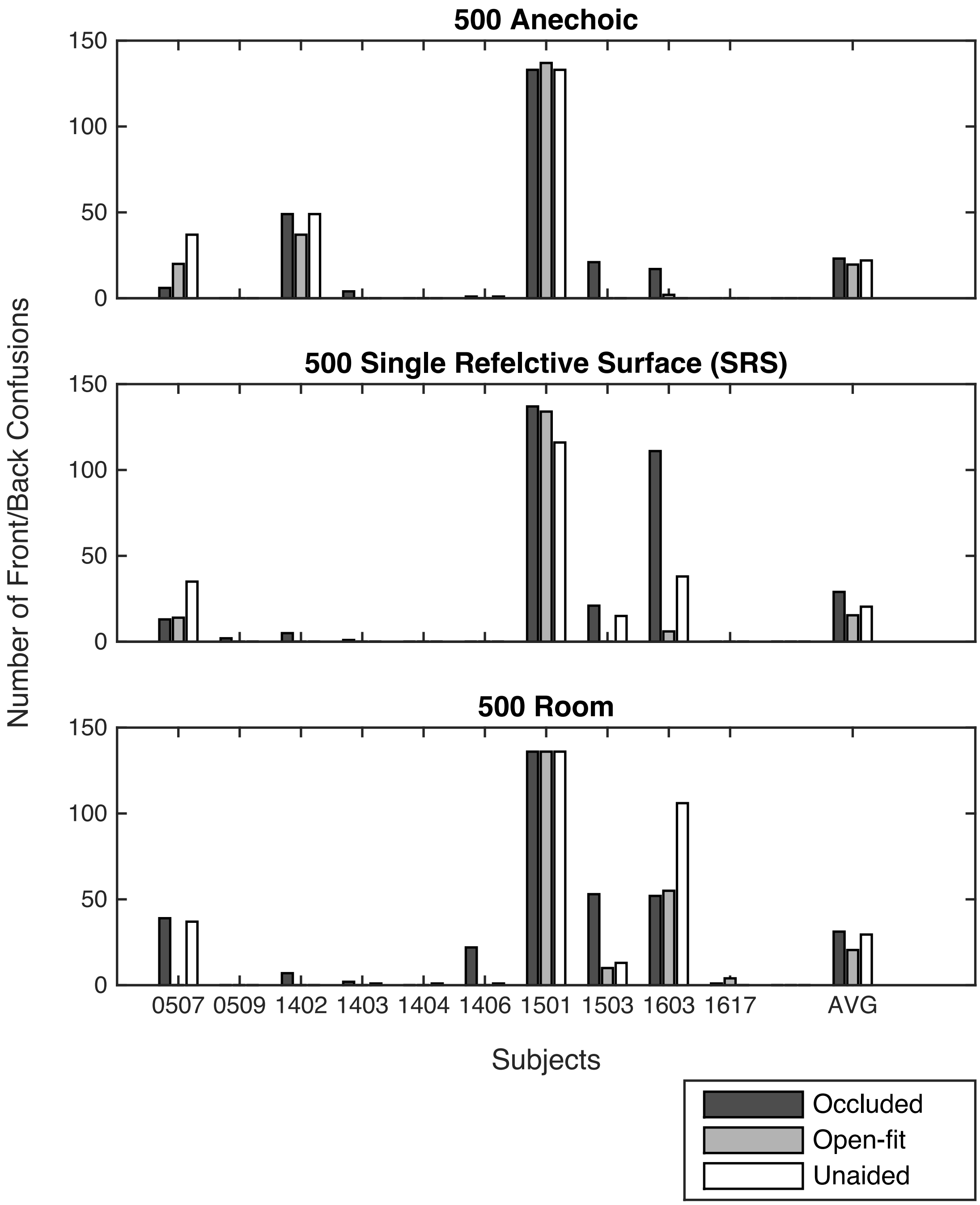
Bars plot mean data for each listener and the average across listeners. Localization variance plotted for 4000 Hz plotted by room (panels) and aided (bars) conditions.



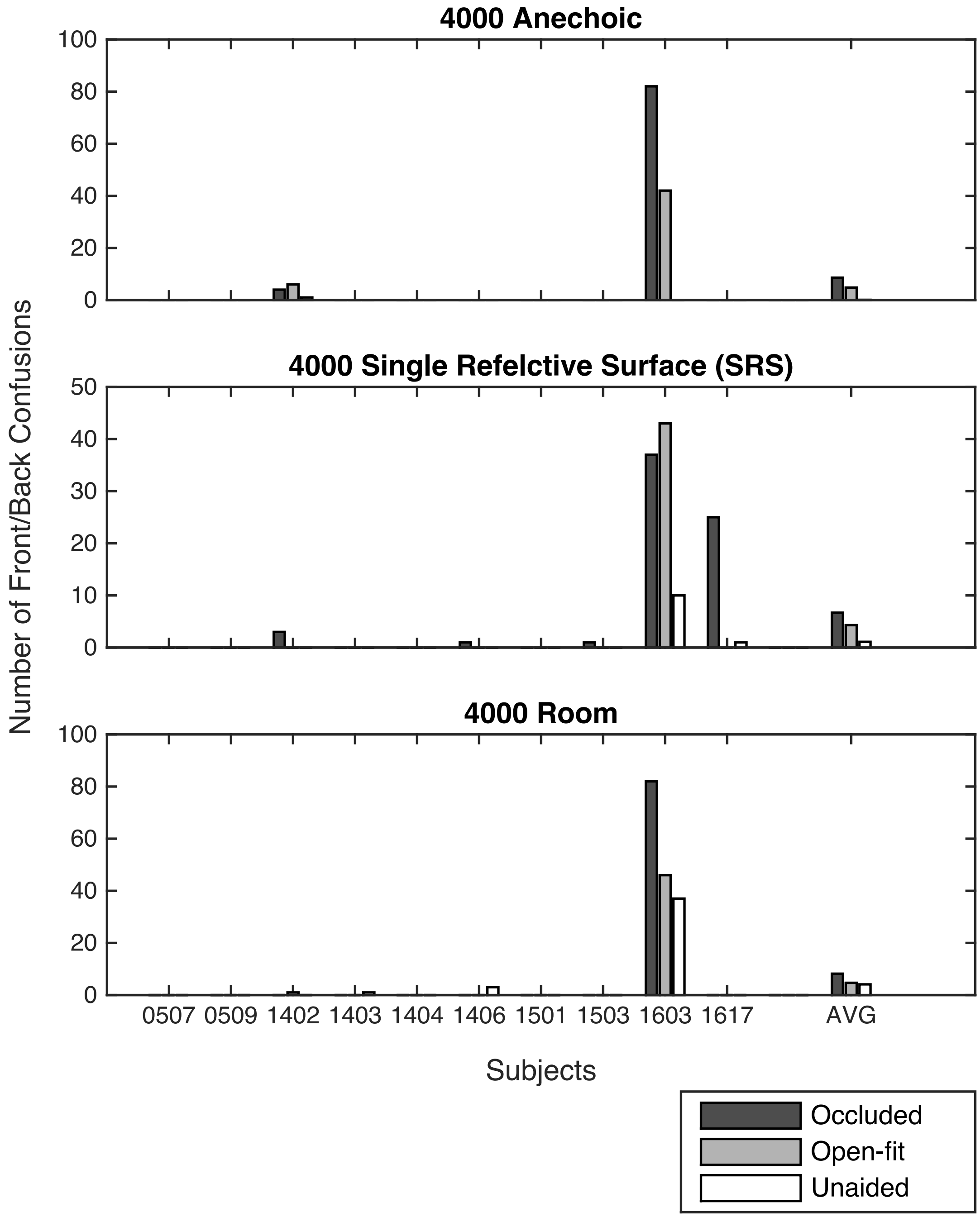
Bars plot mean data for each listener and the average across listeners. Localization variance plotted for 500+4000 Hz plotted by room (panels) and aided (bars) conditions.



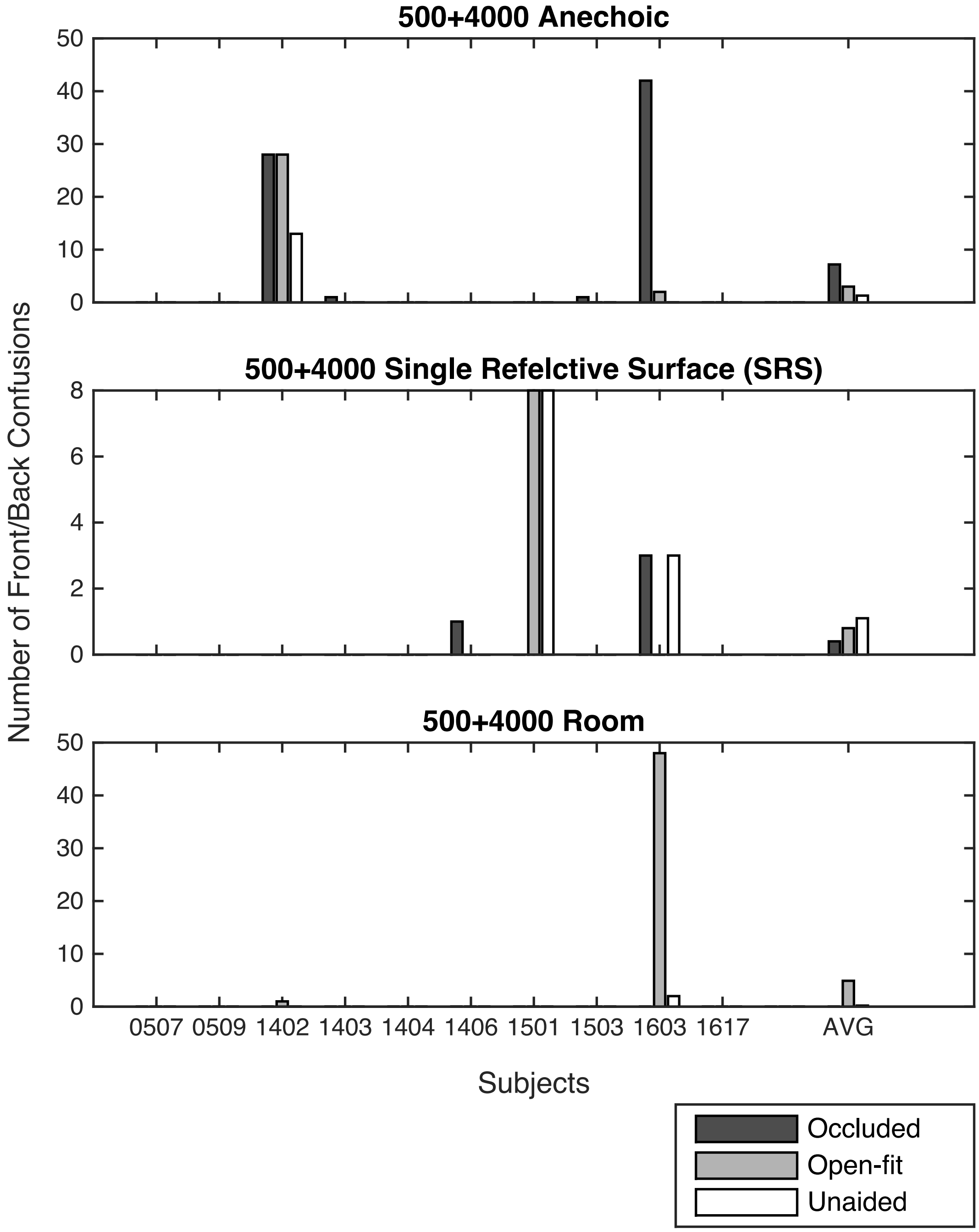
Bars plot mean data for each listener and the average across listeners. Localization variance plotted for BB noise plotted by room (panels) and aided (bars) conditions.



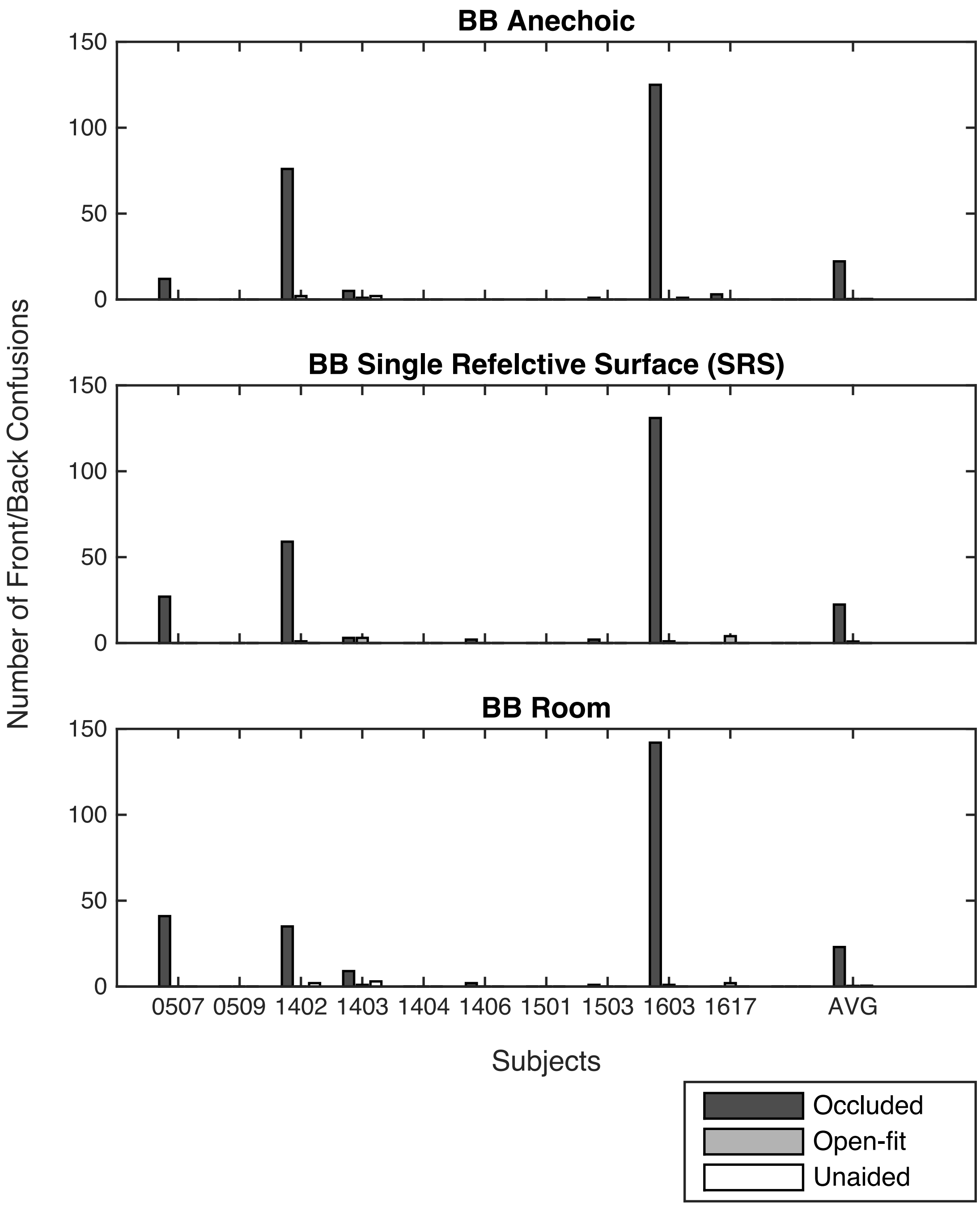
Bars plot mean data for each listener and the average across listeners. Front-back confusions plotted for 500 Hz plotted by room (panels) and aided (bars) conditions.



Bars plot mean data for each listener and the average across listeners. Front-back confusion plotted for 4000 Hz plotted by room (panels) and aided (bars) conditions.



Bars plot mean data for each listener and the average across listeners. Front-back confusions plotted for 500+4000 Hz plotted by room (panels) and aided (bars) conditions.



Bars plot mean data for each listener and the average across listeners. Front-back confusions plotted for BB noise plotted by room (panels) and aided (bars) conditions.

Appendix E.

T-test tables for each analytical methods compared by stimulus, aid, and room conditions:

	Occluded		
	Anechoic	SRS	Room
BBvs500	-0.98 (0.35)	**-3.55 (0.01)**	**-3.01 (0.01)**
BBvs4000	-1.06 (0.32)	-2.02 (0.07)	**-3.38 (0.01)**
BBvs500+4000	2.06 (0.07)	0.63 (0.55)	-0.96 (0.36)
500vs4000	0.52 (0.62)	0.49 (0.63)	-0.25 (0.81)
500vs500+4000	**3.18 (0.01)**	**4.68 (0.00)**	**3.73 (0.00)**
4000vs500+4000	**3.70 (0.00)**	**3.10 (0.01)**	**5.14 (0.00)**
	Open		
	Anechoic	SRS	Room
BBvs500	**-2.48 (0.03)**	**-2.93 (0.02)**	**-3.66 (0.01)**
BBvs4000	**-5.67 (0.00)**	**-5.87 (0.00)**	**-7.38 (0.00)**
BBvs500+4000	**-2.53 (0.03)**	**-4.39 (0.00)**	**-3.27 (0.01)**
500vs4000	**-2.51 (0.03)**	**-2.77 (0.02)**	**-4.36 (0.00)**
500vs500+4000	1.56 (0.15)	1.85 (0.10)	**2.71 (0.02)**
4000vs500+4000	**4.65 (0.00)**	**4.84 (0.00)**	**14.27 (0.00)**
	Unaided		
	Anechoic	SRS	Room
BBvs500	-1.87 (0.09)	**-4.03 (0.00)**	**-4.05 (0.00)**
BBvs4000	**-4.03 (0.00)**	**-4.43 (0.00)**	**-5.08 (0.00)**
BBvs500+4000	-0.93 (0.38)	**-2.96 (0.02)**	**-3.86 (0.00)**
500vs4000	0.24 (0.81)	0.64 (0.54)	-0.12 (0.90)
500vs500+4000	1.68 (0.13)	**3.05 (0.01)**	**3.39 (0.01)**
4000vs500+4000	**7.16 (0.00)**	**3.59 (0.01)**	**4.69 (0.00)**

Localization error t-statistics and p-values for paired stimulus t-tests across aided and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Anechoic	SRS	Room
Occluded vs Open	**3.36 (0.01)**	1.72 (0.12)	1.89 (0.09)
Open vs Unaided	-0.10 (0.93)	**3.72 (0.00)**	1.06 (0.32)
Occluded vs Unaided	**3.12 (0.01)**	2.52 (0.03)	2.00 (0.08)
	500 Hz		
	Anechoic	SRS	Room
Occluded vs Open	2.43 (0.04)	**4.54 (0.00)**	2.54 (0.03)
Open vs Unaided	-0.61 (0.56)	-1.87 (0.09)	-1.03 (0.33)
Occluded vs Unaided	1.65 (0.13)	**3.55 (0.01)**	1.65 (0.13)
	4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	0.67 (0.52)	1.75 (0.11)	0.52 (0.62)
Open vs Unaided	2.49 (0.03)	2.77 (0.02)	**3.50 (0.01)**
Occluded vs Unaided	2.84 (0.02)	2.81 (0.02)	**3.12 (0.01)**
	500 + 4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	1.33 (0.22)	0.99 (0.35)	**3.06 (0.01)**
Open vs Unaided	2.76 (0.02)	1.16 (0.28)	2.60 (0.03)
Occluded vs Unaided	1.83 (0.10)	1.83 (0.10)	**4.03 (0.00)**

Localization error t-statistics for aided conditions across stimulus and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Occluded	Open	Unaided
Anechoic vs SRS	0.44 (0.67)	-2.74 (0.02)	0.35 (0.73)
SRS vs Room	-0.22 (0.83)	0.55 (0.60)	**-3.14 (0.01)**
Anechoic vs Room	0.22 (0.83)	**-4.04 (0.00)**	-0.98 (0.35)
	500 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	-1.90 (0.09)	-1.83 (0.10)	-1.75 (0.11)
SRS vs Room	1.21 (0.26)	-1.94 (0.08)	-1.28 (0.23)
Anechoic vs Room	-1.27 (0.23)	-2.66 (0.03)	-2.13 (0.06)
	4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	-2.36 (0.04)	-2.73 (0.02)	-1.54 (0.16)
SRS vs Room	-0.01 (0.99)	**-3.34 (0.01)**	**-7.44 (0.00)**
Anechoic vs Room	**-4.79 (0.00)**	**-6.02 (0.00)**	**-3.17 (0.01)**
	500 + 4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	-0.28 (0.79)	-1.63 (0.14)	-1.68 (0.13)
SRS vs Room	-2.93 (0.02)	-1.78 (0.11)	-2.11 (0.06)
Anechoic vs Room	**-3.38 (0.01)**	**-3.06 (0.01)**	**-4.15 (0.00)**

Localization error t-statistics for room condition across stimulus and aided conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Occluded		
	Anechoic	SRS	Room
BBvs500	-1.84 (0.10)	-0.16 (0.88)	0.70 (0.50)
BBvs4000	**8.19 (0.00)**	**8.72 (0.00)**	**9.90 (0.00)**
BBvs500+4000	**5.88 (0.00)**	**5.07 (0.00)**	**5.13 (0.00)**
500vs4000	**8.21 (0.00)**	**4.65 (0.00)**	**4.35 (0.00)**
500vs500+4000	**6.06 (0.00)**	**3.18 (0.01)**	**3.49 (0.01)**
4000vs500+4000	**-4.28 (0.00)**	-2.69 (0.03)	-2.52 (0.03)
	Open		
	Anechoic	SRS	Room
BBvs500	-2.12 (0.06)	-0.95 (0.37)	-0.61 (0.56)
BBvs4000	2.33 (0.05)	**4.52 (0.00)**	**3.00 (0.01)**
BBvs500+4000	1.88 (0.09)	2.52 (0.03)	1.71 (0.12)
500vs4000	2.96 (0.02)	**4.95 (0.00)**	**3.09 (0.01)**
500vs500+4000	**3.81 (0.00)**	**4.39 (0.00)**	1.88 (0.09)
4000vs500+4000	-1.40 (0.19)	**-3.70 (0.00)**	**-3.13 (0.01)**
	Unaided		
	Anechoic	SRS	Room
BBvs500	-2.76 (0.02)	-2.47 (0.04)	-1.54 (0.16)
BBvs4000	**5.41 (0.00)**	0.73 (0.49)	2.13 (0.06)
BBvs500+4000	1.81 (0.10)	-0.01 (1.00)	1.54 (0.16)
500vs4000	**4.93 (0.00)**	2.67 (0.03)	**3.70 (0.00)**
500vs500+4000	**4.56 (0.00)**	**3.17 (0.01)**	**3.21 (0.01)**
4000vs500+4000	**-3.92 (0.00)**	-0.93 (0.38)	-2.09 (0.07)

Localization gain t-statistics and p-values for paired stimulus t-tests across aided and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Anechoic	SRS	Room
Occluded vs Open	**3.28 (0.01)**	2.69 (0.02)	2.52 (0.03)
Open vs Unaided	2.66 (0.03)	2.82 (0.02)	0.03 (0.98)
Occluded vs Unaided	**3.34 (0.01)**	**3.37 (0.01)**	2.38 (0.04)
	500 Hz		
	Anechoic	SRS	Room
Occluded vs Open	**4.98 (0.00)**	2.19 (0.06)	2.04 (0.07)
Open vs Unaided	-0.55 (0.60)	-1.90 (0.09)	-1.30 (0.22)
Occluded vs Unaided	2.88 (0.02)	0.97 (0.36)	0.50 (0.63)
	4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	-0.50 (0.63)	0.80 (0.44)	0.34 (0.74)
Open vs Unaided	0.52 (0.61)	**-3.51 (0.01)**	**-3.52 (0.01)**
Occluded vs Unaided	0.24 (0.81)	-2.32 (0.05)	**-3.14 (0.01)**
	500 + 4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	1.95 (0.08)	1.60 (0.14)	-0.27 (0.79)
Open vs Unaided	1.51 (0.16)	-1.29 (0.23)	-1.87 (0.09)
Occluded vs Unaided	2.17 (0.06)	0.10 (0.92)	**-4.05 (0.00)**

Localization gain t-statistics for aided conditions across stimulus and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Occluded	Open	Unaided
Anechoic vs SRS	-2.88 (0.02)	-2.09 (0.07)	**-3.65 (0.01)**
SRS vs Room	1.48 (0.17)	**6.88 (0.00)**	1.17 (0.27)
Anechoic vs Room	-0.18 (0.86)	2.19 (0.06)	0.08 (0.94)
	500 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	0.56 (0.59)	0.47 (0.65)	-0.69 (0.51)
SRS vs Room	1.97 (0.08)	1.76 (0.11)	1.63 (0.14)
Anechoic vs Room	1.94 (0.08)	1.56 (0.15)	0.55 (0.60)
	4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	0.59 (0.57)	2.27 (0.05)	-1.36 (0.21)
SRS vs Room	**4.97 (0.00)**	1.72 (0.12)	2.98 (0.02)
Anechoic vs Room	2.52 (0.03)	2.84 (0.02)	0.33 (0.75)
	500 + 4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	1.50 (0.17)	-0.08 (0.94)	-2.54 (0.03)
SRS vs Room	**4.60 (0.00)**	2.26 (0.05)	**3.15 (0.01)**
Anechoic vs Room	**5.03 (0.00)**	1.87 (0.09)	0.52 (0.62)

Localization gain t-statistics for room condition across stimulus and aided conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Occluded		
	Anechoic	SRS	Room
BBvs500	-0.19 (0.85)	**4.27 (0.00)**	**4.31 (0.00)**
BBvs4000	**4.42 (0.00)**	**3.12 (0.01)**	**5.49 (0.00)**
BBvs500+4000	-0.57 (0.58)	0.47 (0.65)	2.91 (0.02)
500vs4000	2.85 (0.02)	0.69 (0.51)	0.48 (0.64)
500vs500+4000	-0.47 (0.65)	**-3.33 (0.01)**	-2.12 (0.06)
4000vs500+4000	**-4.29 (0.00)**	**-3.15 (0.01)**	**-5.64 (0.00)**
	Open		
	Anechoic	SRS	Room
BBvs500	1.58 (0.15)	**3.06 (0.01)**	**3.86 (0.00)**
BBvs4000	**5.98 (0.00)**	**6.46 (0.00)**	**8.36 (0.00)**
BBvs500+4000	1.70 (0.12)	1.88 (0.09)	**3.68 (0.01)**
500vs4000	**5.06 (0.00)**	2.83 (0.02)	**4.16 (0.00)**
500vs500+4000	-0.47 (0.65)	-1.16 (0.28)	**-3.31 (0.01)**
4000vs500+4000	**-5.44 (0.00)**	**-4.35 (0.00)**	**-7.88 (0.00)**
	Unaided		
	Anechoic	SRS	Room
BBvs500	1.32 (0.22)	**3.43 (0.01)**	**4.35 (0.00)**
BBvs4000	2.09 (0.07)	**11.34 (0.00)**	**6.74 (0.00)**
BBvs500+4000	-0.68 (0.51)	2.11 (0.06)	**4.16 (0.00)**
500vs4000	0.07 (0.95)	-0.43 (0.68)	1.09 (0.30)
500vs500+4000	-1.90 (0.09)	-2.09 (0.07)	**-3.55 (0.01)**
4000vs500+4000	**-6.51 (0.00)**	-2.78 (0.02)	**-5.00 (0.00)**

Localization variability t-statistics and p-values for paired stimulus t-tests across aided and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Anechoic	SRS	Room
Occluded vs Open	**-3.20 (0.01)**	-1.64 (0.14)	-1.79 (0.11)
Open vs Unaided	0.63 (0.54)	-2.56 (0.03)	**-3.77 (0.00)**
Occluded vs Unaided	-2.65 (0.03)	-2.93 (0.02)	-2.29 (0.05)
	500 Hz		
	Anechoic	SRS	Room
Occluded vs Open	-1.64 (0.14)	**-3.63 (0.01)**	-1.58 (0.15)
Open vs Unaided	0.97 (0.36)	1.55 (0.16)	0.09 (0.93)
Occluded vs Unaided	-0.50 (0.63)	-2.84 (0.02)	-1.53 (0.16)
	4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	-0.88 (0.40)	-1.94 (0.08)	0.01 (0.99)
Open vs Unaided	**-4.21 (0.00)**	**-4.54 (0.00)**	**-3.21 (0.01)**
Occluded vs Unaided	**-3.44 (0.01)**	-2.98 (0.02)	-2.83 (0.02)
	500 + 4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	-1.86 (0.10)	-0.74 (0.48)	-2.10 (0.07)
Open vs Unaided	-2.30 (0.05)	-0.42 (0.69)	-2.59 (0.03)
Occluded vs Unaided	-2.89 (0.02)	-1.10 (0.30)	**-6.04 (0.00)**

Localization variability t-statistics for aided conditions across stimulus and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Occluded	Open	Unaided
Anechoic vs SRS	-1.10 (0.30)	1.16 (0.28)	-1.00 (0.34)
SRS vs Room	0.19 (0.85)	0.25 (0.81)	2.42 (0.04)
Anechoic vs Room	-0.92 (0.38)	**4.21 (0.00)**	-0.52 (0.61)
	500 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	2.43 (0.04)	1.60 (0.14)	1.40 (0.20)
SRS vs Room	0.15 (0.89)	1.65 (0.13)	1.17 (0.27)
Anechoic vs Room	2.47 (0.04)	**3.40 (0.01)**	2.60 (0.03)
	4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	1.73 (0.12)	0.75 (0.47)	2.54 (0.03)
SRS vs Room	-0.40 (0.70)	**3.26 (0.01)**	**3.75 (0.01)**
Anechoic vs Room	2.66 (0.03)	**3.58 (0.01)**	**4.47 (0.00)**
	500 + 4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	-0.26 (0.80)	0.63 (0.55)	1.73 (0.12)
SRS vs Room	**4.41 (0.00)**	1.44 (0.18)	0.22 (0.83)
Anechoic vs Room	2.04 (0.07)	**3.16 (0.01)**	**6.27 (0.00)**

Localization variability t-statistics for room condition across stimulus and aided conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Occluded		
	Anechoic	SRS	Room
BBvs500	-0.05 (0.96)	-0.42 (0.68)	-0.45 (0.66)
BBvs4000	1.76 (0.11)	1.43 (0.19)	2.12 (0.06)
BBvs500+4000	1.69 (0.13)	1.66 (0.13)	1.63 (0.14)
500vs4000	0.92 (0.38)	1.48 (0.17)	1.58 (0.15)
500vs500+4000	1.17 (0.27)	1.79 (0.11)	**2.32 (0.05)**
4000vs500+4000	0.29 (0.78)	1.60 (0.14)	1.00 (0.34)
	Open		
	Anechoic	SRS	Room
BBvs500	-1.42 (0.19)	-1.08 (0.31)	-1.44 (0.18)
BBvs4000	-1.07 (0.31)	-0.79 (0.45)	-0.95 (0.37)
BBvs500+4000	-1.04 (0.33)	0.10 (0.92)	-0.95 (0.37)
500vs4000	1.00 (0.34)	0.78 (0.46)	1.18 (0.27)
500vs500+4000	1.23 (0.25)	1.17 (0.27)	1.16 (0.28)
4000vs500+4000	0.38 (0.71)	0.78 (0.45)	-1.00 (0.34)
	Unaided		
	Anechoic	SRS	Room
BBvs500	-1.59 (0.15)	-1.75 (0.11)	-1.82 (0.10)
BBvs4000	0.80 (0.44)	-1.11 (0.30)	-0.96 (0.36)
BBvs500+4000	-0.74 (0.48)	-1.34 (0.21)	0.71 (0.50)
500vs4000	1.61 (0.14)	1.67 (0.13)	1.78 (0.11)
500vs500+4000	1.55 (0.16)	1.78 (0.11)	1.86 (0.10)
4000vs500+4000	-1.00 (0.34)	0.00 (1.00)	1.12 (0.29)

Front-back confusion t-statistics and p-values for paired stimulus t-tests across aided and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val). Note – only one significant difference for less strict significance criteria.

	Broadband		
	Anechoic	SRS	Room
Occluded vs Open	1.62 (0.14)	1.59 (0.15)	1.61 (0.14)
Open vs Unaided	0.00 (1.00)	1.96 (0.08)	-0.26 (0.80)
Occluded vs Unaided	1.62 (0.14)	1.66 (0.13)	1.59 (0.15)
	500 Hz		
	Anechoic	SRS	Room
Occluded vs Open	1.10 (0.30)	1.31 (0.22)	1.93 (0.09)
Open vs Unaided	-1.14 (0.28)	-1.13 (0.29)	-1.51 (0.16)
Occluded vs Unaided	0.25 (0.81)	1.09 (0.30)	0.23 (0.82)
	4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	0.94 (0.37)	0.92 (0.38)	0.97 (0.36)
Open vs Unaided	1.13 (0.29)	0.97 (0.36)	0.61 (0.56)
Occluded vs Unaided	1.04 (0.33)	1.68 (0.13)	0.90 (0.39)
	500 + 4000 Hz		
	Anechoic	SRS	Room
Occluded vs Open	1.06 (0.32)	-0.45 (0.67)	-1.02 (0.33)
Open vs Unaided	1.14 (0.28)	-1.00 (0.34)	1.02 (0.33)
Occluded vs Unaided	1.38 (0.20)	-0.86 (0.41)	-1.00 (0.34)

Front-back confusion t-statistics for aided conditions across stimulus and room conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

	Broadband		
	Occluded	Open	Unaided
Anechoic vs SRS	-0.08 (0.94)	-1.33 (0.22)	1.41 (0.19)
SRS vs Room	-0.19 (0.86)	1.86 (0.10)	-1.46 (0.18)
Anechoic vs Room	-0.14 (0.89)	-0.32 (0.76)	-0.80 (0.44)
	500 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	-0.55 (0.60)	1.13 (0.29)	0.23 (0.82)
SRS vs Room	-0.28 (0.79)	-0.98 (0.35)	-1.33 (0.22)
Anechoic vs Room	-1.10 (0.30)	-0.12 (0.90)	-0.62 (0.55)
	4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	0.35 (0.73)	0.81 (0.44)	-0.99 (0.35)
SRS vs Room	-0.28 (0.79)	-1.31 (0.22)	-1.12 (0.29)
Anechoic vs Room	1.00 (0.34)	0.15 (0.89)	-1.09 (0.31)
	500 + 4000 Hz		
	Occluded	Open	Unaided
Anechoic vs SRS	1.50 (0.17)	0.74 (0.48)	0.12 (0.91)
SRS vs Room	1.31 (0.22)	-0.83 (0.43)	1.13 (0.29)
Anechoic vs Room	1.52 (0.16)	-0.34 (0.74)	0.82 (0.43)

Front-back confusion t-statistics for room condition across stimulus and aided conditions. Significant differences displayed with bold font. Format of cells: tstat (p-val).

REFERENCES

Ahlstrom, J.B., Horwitz, A.R., Dubno, J.R. (2014). "Spatial separation benefit for unaided and aided listening," Ear Hear, 35(1): 72-85.

Byrne D., Noble W., Glauerdt B. (1996). "Effects of earmold type on ability to locate sounds when wearing aids," Ear Hear. 17(3): 218-228.

Byrne D., Noble W. (1998). "Optimizing sound localization with hearing aids." Trends in Amp. 3(2): 51-73.

Byrne D., Sinclair S., Noble W. (1998). "Open earmold fittings for improving aided auditory localization for sensorineural hearing losses with good high-frequency hearing," Ear Hear. 19(1): 62-71.

Carette, E., Van den Bogaert, T., Laureyns, M., Wouters, J. (2014). "Left-right and front-back spatial hearing with multiple directional microphone configurations in modern hearing aids," J. Am. Acad. Audiol 25(9): 791-803.

Carlile, S. (2014). "The plastic ear and perceptual relearning in auditory spatial perception," Front. Neurosci. 8:237. doi: 10.3389/fnins.2014.00237

David, E.E., Guttman, N., van Bergeijk, W.A. (1959). Binaural interaction of high-frequency complex stimuli. J. Acoust. Soc. Am. 31(6): 774-782.

Deatherage, B. H. and Hirsh, I. J. (1959). "Auditory localization of clicks," J. Acoust. Soc. Am. 31(4): 486-492.

Devore S., Ihlefeld A., Hancock K., Shinn-Cunningham B., and Dulgutte B. (2009). "Accurate sound localization in reverberant environments is mediated by robust encoding of spatial cues in the auditory midbrain," Neuron. 62(1): 123-134.

Feddersen, W.E., Sandel, T.T., Teas, D.C., Jeffress, L.A. (1957). Localization of high-frequency tones. J. Acoust. Soc. Am. 29 (9): 988-991.

Hafter, E. R. and Jeffress, L. A. (1968). “Two-image lateralization of tones and clicks,” J. Acoust. Soc. Am. 44(2): 563-569.

Hartmann W.M. (1983). “Localization of sound in rooms,” J. Acoust. Soc. Am. 74(5): 1380-1391.

Hausler, R., Colburn, S., Marr, E. (1983). “Sound localization in subjects with impaired hearing: Spatial-discrimination and interaural-discrimination tests,” Acta Oto-Laryngol. Suppl 400: 1-62.

Helfer, K. S., Wilber, L. A. (1990). “Hearing loss, aging, and speech perception in reverberation and noise,” J. Speech Hear. Res. 33(1): 149-155.

Helfer, K. S. (1992). “Aging and the binaural advantage in reverberation and noise,” J. Speech Hear. Res. 35: 1394-1401.

Hofman, P.M., Van Riswick, J.G.A., Van Opstal, A.J. (1998). “Relearning sound localization with new ears,” Nature Neurosci. 1(5): 417-421.

Ihlefeld A., and Shinn-Cunningham B.G. (2011). “Effect of source spectrum on sound localization in an everyday reverberant room,” J. Acoust. Soc. Am. 130(1): 324-333.

Irving S., and Moore D.R. (2011). “Training sound localization in normal hearing listeners with and without a unilateral ear plug,” Hear. Res. 280: 100-108.

Kopčo N., and Shinn-Cunningham B.G. (2011). “Effect of stimulus spectrum on distance perception for nearby sources,” J. Acoust. Soc. Am. 130(3): 1530-1541.

Moushegian, G., Jeffress, L.A. (1959). Role of interaural time and intensity differences in the lateralization of low-frequency tones. J. Acoust. Soc. Am. 31(11): 1441-1445.

Noble W., Sinclair S., Byrne D. (1998). "Improved in aided sound localization with open earmolds: observations in people with high-frequency hearing loss." J. Am. Acad. Audiol. 9:25-34.

Picou E.M., Aspell E., and Ricketts T.A. (2014). "Potential benefits and limitations of three types of directional processing in hearing aids," Ear Hear. 35(3): 339-52.

Rakerd B., and Hartmann W.M. (1985). "Localization of sound in rooms, II: The effects of a single reflective surface," J. Acoust. Soc. Am. 78(2): 524-533.

Shaxby, J.G., Gage, F.H. (1932). The localization of sounds in the median plane: an experimental investigation of the physical processes concerned. Med. Res. Counc. (Brit.) Spec. Rep. Ser. 166: 1-32.

Shinn-Cunningham B.G. (2000). "Learning reverberation: Considerations for spatial auditory displays," Proc. of the 2000 Int. Conf. on Aud. Disp. 126-134.

Shinn-Cunningham B.G., Kopčo N., and Martin T.J. (2005). "Localizing nearby sound sources in a classroom: Binaural room impulse responses," J. Acoust. Soc. Am. 117(5): 3100-3115.

Stecker G.C., and Hafter E.R. (2002). "Temporal weighting in sound localization," J. Acoust. Soc. Am. 112(3 Pt. 1): 1046-1057.

Van den Bogaert, T., Klasen, T., Moonen, M., Van Deun, L., Wouters, J. (2006). "Horizontal localization with bilateral hearing aids: Without is better than with," J. Acoust. Soc. Am. 119(1): 515-526.

Whitworth, R. H. and Jeffress, L. A. (1961). “Time vs intensity in the localization of tones,” J. Acoust. Soc. Am. 33(7): 925-929.

Wiggins I.M., and Seeber B.U. (2011). “Dynamic-range compression affects the lateral position of sounds,” J. Acoust. Soc. Am. 130(6): 3939-53.