THE EFFECT OF PERCEPTUAL WEIGHTING OF BINAURAL CUES ON PERCEIVED LOCATION

by

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The effect of perceptual weighting of binaural cues on perceived location

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This project investigated how interaural timing and level differences (ITDs and ILDs, respectively) can affect the perceived location of a sound when either one cue was at zero degrees azimuth (midline) and the other was not, or when they both were at non-zero azimuthal locations. Six subjects, including one with severe to profound hearing loss, participated in this study. Several cue combinations were tested, including conditions in which one cue was fixed (at either 30, 60, or 90 degrees) and the other was varied to be between 0 and 60 away from the fixed cue. It was hypothesized that non-zero cues would be weighted more heavily when the other cue was located at zero; whereas, when both cues were at non-zero locations it was hypothesized that both cues would be weighted more evenly, especially when they lie on either side of midline, in which case it was hypothesized that the perceived location would be between the cues presented. Results showed that both the normal hearing listeners and the listener with severe hearing loss have similar patterns. The results ultimately did not support all hypotheses, and different patterns were seen when comparing the three main conditions wherein the reference cue was located at 30, 60, or 90 degrees azimuth.

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PREFACE

Without the assistance and knowledge from the following people and organizations, this project would not have been possible. My deepest gratitude is given to the following:

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1.0 INTRODUCTION

Lord Rayleigh first reported the idea of binaural hearing in 1907. Since this discovery over a century ago, researchers have delved much further into his idea and as a result our understanding of the hearing mechanism has expanded greatly, and the cues for localization in the plane of azimuth have received a great deal of study. The two cues used to localize a sound source are interaural time differences and interaural level differences (ITDs and ILDs, respectively). ITDs relate to how much sooner a sound reaches the nearer ear compared to the farther ear when a sound source is to one side of the head. On the other hand, interaural level differences are present because the sound source is louder in the near ear than the farther ear. There have also been numerous studies looking more deeply into the cues themselves and how they are processed. For example, there are several competing hypotheses for the processing of time disparities (Breebaart et al., 2001a; Dietz et al., 2007; Harper & McAlpine, 2004; Jeffress, 1948; McAlpine & Grothe, 2003).

Given the prevalence of hearing loss in society, the use of both hearing aids and cochlear implants (CIs) is common. Although hearing restoration is often successful, one problem that remains is the lack of localization and lateralization acuity in individuals with cochlear implants. This relates to them having difficulties externally locating a sound source (localization) and internally perceiving the location of a sound (lateralization). As of yet, CI users still have difficulties with lateralizing a sound source, and there continue to be large performance differences between them and normal hearing subjects in their respective abilities to locate a sound. This discrepancy is largely due to the fact that normal hearing listeners have binaural processing that computes these differences for accurate lateralization; whereas, cochlear implants must have these differences encoded artificially to determine the location, and these differences are determined through time-intensity trading ratios. These ratios have been researched over the past several decades to understand the binaural process and how it relates to sound source localization and lateralization. To date, these ratios and the studies that investigate similar processes mainly rely on placing the ITD at midline with the ILD out in the periphery. These studies and the ratios collected from them are pertinent to cochlear implants and their processing. Currently, ILDs are more robust than ITDs in CI processing, but interaural differences are always present. One perspective on the binaural processing of sounds in CIs is that the ILD can help determine the spatial location, while the ITD is interpreted as if it is a midline when a sound source is in the periphery. This current study aimed to investigate this topic further by introducing signals with conflicting cues at different locations to determine if these altered ratios can affect lateralization. These conflicting cues included some combinations with one binaural cue at zero and the other in the periphery, while other combinations had both cues at non-zero locations.

1.1 BACKGROUND

1.1.1 Issues with cochlear implant processing

Cochlear implants have proven to be an incredible mechanism to restore hearing, one that often allows those who were profoundly deaf to recognize and perceive speech to an extent that allows them to hold conversations with others. Despite this feat, there have been several tradeoffs in order for this technology to complete the tasks at hand. One of the main trade-offs is realized in the lack of localization and lateralization abilities for those who use these devices (Grantham, Ashmead, Ricketts, Labadie & Haynes, 2008). Normal hearing listeners are able to localize sound due to binaural hearing, which allows them to compute the difference between the two ears when a sound is off to one side of the head. As mentioned previously, the two cues used in localizing a sound are interaural time and interaural level differences. As of now, cochlear implant users only robustly receive ILDs; whereas, ITDs are not reliably delivered, and are thus presumably either near zero or some other value. This is partially due to processing issues, as cochlear implants are not yet linked to one another. This means they cannot tune into each other's input and synchronously deliver a difference in timing to the perceptual system for processing. In order to be more well-informed so that we can better combat this issue, numerous studies have been conducted to find a binaural trading ratio that allows us to integrate ITDs and ILDs from the signal to create a unique location in the horizontal and lateral planes. Data collected from these studies have then been utilized in new processing techniques aimed at assisting cochlear implant users in locating sound sources.

1.1.2 Issues with previous literature

One main limitation regarding previous literature of lateralization sensitivity and trading ratios is that most look at one interaural cue at a time. For example, they will only study the effects of ITDs on a certain behavior or perceived location. All the while, the other cue (in this case the ILD) is simply ignored and considered not present, when in fact it is still present in the signal, indicating a position of 0 degrees azimuth. This configuration, in which the two binaural cues provide conflicting information, can be potentially problematic because it may lead to a perceptual location that is different than what the experimenter expects. Although conflicting binaural cues are often overlooked, they have been studied extensively in other contexts. To date, most studies that have done so had the goal of describing the ratio of interaural cues necessary for a perceived midline location. These ratios are then used as a means of creating stimuli with specific lateralization markers so that a given ratio can be related to a certain position in the plane of azimuth. One concern with these studies is the reliability and validity of the ratios acquired when focusing on one cue for adjustment. There is also the potentially unjustified use of these ratios for sounds across the entire lateralization plane when they were acquired through centering all test stimuli to midline.

There are several ways to study the contributions of each cue to the perception of a sound source along the mid-sagittal plane with time-intensity trading ratios, including: matching, scaling and centering (Raffin, Lilly, & Thornton, 1976). Of these, centering is the most used technique and involves one stimulus being presented to the listener with an ILD advantage. The subject must then alter the ITD of a stimulus on the contralateral side until the auditory image is perceived to be at midline laterally. The centering method in this case would yield the binaural trading ratio in terms of change in time over change in intensity (Raffin et al., 1976). One major issue with this technique, which Raffin, et al. (1976) acknowledges, is that studies that use this have a large amount of variability in their results—most subjects claim to hear two auditory images, while others state they only hear one, which may or may not be accurate because it is difficult for naive listeners to understand and describe what they are hearing in complex listening situations like these; in that case, those listeners who claim to hear one auditory image may only be focusing one auditory image to the center. Trahiotis and Kappauf (1978), further criticized previous studies that used this technique, citing that several of them, regardless of which cue was used as the reference cue, had contradicting results. In fact, depending upon which cue was adjusted in the test stimulus to achieve midline, the ratio was different. This was seen through the adjustments made by subjects, wherein their adjustments tended to have a slight bias "toward the [cue] which the standard had on the stimulus dimensions [that] was being adjusted" (Trahiotis & Kappauf, 1978, pp. 1043). For example, if the stimulus was being adjusted by intensity, then listeners adjusted the stimulus towards the location dictated by the intensity in the standard (aka reference). These results illustrated an effect similar to the shift-back effect, the issues of which will be discussed in the next section.

1.2 TONES AND THE SHIFT-BACK EFFECT

1.2.1 Adaptor tones

The presence of adaptor or reference tones, and an inflated weight of the to-be-adjusted cue all relate to an incomplete time-intensity trade, which involves listeners inaccurately judging the amount of an interaural cue necessary to centralize an auditory image to midline (where the reference tone is). To study the effect of adaptor tones on lateralization judgments, Phillips, Carmichael and Hall (2006) had participants lateralize tones of either 260 or 570 Hz before and after the presence of an adaptor tone that alternated with positive and negative values of the adapting cues that related to the same amount to the left and right of midline (ranging from strongly left to strongly right of midline). They found that an ILD of 12 dB created a displacement of ~ 101 msec in the judgment of laterality based on ITD; whereas, an ITD adaptor tone created a mean displacement of 2.9 dB on the ILD laterality judgment. Thus, an adapting stimulus carrying one cue has an effect on the lateralization of a test stimulus carrying the other cue, which in turn alters the ratio given in the output.

1.2.2 Reference tones and the shift-back effect

1.2.2.1 Reference tones

As for reference tones and the enlarged weight of the to-be-adjusted cue, some argue that it is mostly the latter that creates an incomplete trade, as the shift-back effect occurs even without a reference tone (Lang & Buchner, 2008). The shift-back effect, which is one way in which incomplete time-intensity trading functions are created, is a phenomenon in which listeners place a heavier weight on the cue that is adjusted from the periphery to midline, resulting in a ratio that gives a location that is off center and in the direction of the test stimulus. For example, if subjects are required to adjust the ILD to create an image that is perceived at midline (with or without a reference cue), the ILD that they give creates an image that is off-center and closer to the side the ILD in the test stimulus is located. This has been observed in several studies. For example, Lang and Buchner (2008) gathered empirical data on this phenomenon by having participants partake in a two-phase experiment. The first phase required subjects to compensate for one cue by adjusting the other to lateralize a sound to midline. This was then followed by a 'lateralization phase' where the ratios picked by the participants in the first phase were presented to them to see where the new image was perceived. A shift-back effect was seen, as each target presented in the lateralization phase was perceived closer to where the to-be-adjusted cue was in the first phase. Thus, the chosen ratio reflected an underestimated amount needed to compensate for the preset cue.

1.2.2.2 In addition to the shift-back effect

Despite the evidence that the shift-back effect and an incomplete trading occur without a reference tone, Ignaz, Lang and Buchner (2014) found that regardless of what cue was the preset one or if there was a reference tone present, a shift-back effect occurred; furthermore, when a reference tone was present, the effect was greater and the trade was even more incomplete. These results suggest that a reference tone and an increased weighting of the to-be-adjusted cue work in conjunction with one another when creating the shift-back effect. Ignaz et al. (2014) also illustrated that a reference tone doesn't necessarily act as a reliable anchor for judging midline, a point with which Lang and Buchner (2009) agree, as they found that subjects could identify midline without a reference tone. This leads to a notion that when finding a time-intensity trading ratio, the method of centering may not be the best choice, especially when used in conjunction with a reference tone that can alter the perception of a stimulus' location as well as the perception of midline.

1.3 ISSUES WITHIN THE CUES THEMSELVES

Despite the technological advancements that have taken place over the last few decades, cochlear implants still do not have the ability to encode the two binaural cues in an equivalent manner. Thus, not all localization cues are robustly available to cochlear implant users. When these are coupled with discrepancies within the cues themselves, ratios are jeopardized farther, which is evidenced in data collected from some of the studies below.

1.3.1 Inconsistency depending on cue used as reference

As mentioned previously, the ITD for a given stimulus and its reference can potentially affect the localization and lateralization of a sound source. This mostly occurs when the two have varying ITDs that can create multiple images being "viewed" by the listener. These ITD differences and their "images" can also be affected by what sound pressure level the stimuli are presented at. In fact, when studying this variance with speech-like stimuli, Raffin et al. (1976) concluded that up until 2.25 msec only one image is 'seen' by subjects, and that for ITDs beyond that (2.5 and 2.75 msec were tested) multiple images are ‘seen’ at 55 dB HL or above. Over all, this leads to the notion that the time-intensity trading ratio must decrease with each raise in level in order for a stimulus to be perceived at midline with some level of confidence. Yost, Tanis, Nielson, and Bergert (1975), also corroborate these findings in a slightly different manner through their focus on determining what amount of ILD was needed to produce an image of an equivalent location to the preset ITD. Results concluded that as the preset ITD increased, the amount of ILD necessary for balanced images decreased, relating to images being more difficult to separate as ITDs increased (Yost et al., 1975). Due to the variability of outcomes, it is hard to determine how the lateral location is related to both ITDs and ILDs, but there is the feasible idea that ITDs incrementally change with each level change, and this can possibly determine location (Yost et al., 1975).

1.3.2 Within the cues

Besides the previously stated issues, there are other issues with the centering method and its reliability in determining a ratio for time and intensity trading as well. First, it has been shown in the literature that the ratio depends upon which cue is being adjusted (Dekio-Hotta & Kaga, 2006; Hafter & Carrier, 1972; Lang & Buchner, 2009; Ruotolo, Stern, & Colburn, 1979). An asymmetry exists, in that a preset ILD is typically compensated for with an ITD in a linear way; whereas, a fixed ITD with an adjusted ILD showed that an ITD could be compensated for by and average of 6 dB (Dekio-Hotta & Kaga, 2006). Studies conducted by Lang and Buchner (2008; 2009) found similar results when studying both broadband stimuli and a 500Hz tone. Results illustrated that a preset

ITD had a significant effect on amount of ILD needed in control trials and that the shift-back effect was present for both types of stimuli.

One the other hand, ILDs have demonstrated a slight dominance in lateralization as well as in time-intensity trading. Aronoff, Yoon, Freed, Vermiglio, Pal and Soli (2010), illustrated that the same effect is seen for bilateral cochlear implant users, wherein ILDs are the main cue for localization, with ITDs playing a secondary role, if any. This was concluded as the ITD-only condition in Aronoff, et al.'s (2010) study was the worst condition, whereas the ILD-only and ITD + ILD conditions were better and had no significant difference. Furthermore, for a preset ILD, a previous experiment had shown that in some cases, no amount of ITD would be enough to compensate for certain ILDs, leading Lang and Buchner (2008) to include "not enough" as a response, which amounted to about 7.7% of all trials. Of these, a preset ILD of +/- 7.5 dB accounted for 73.8% of 'not enough' responses. The authors found that the percentage of 'not enough' responses decreased as the preset ILD moved closer to 0 dB/ midline. These data corroborate the aforementioned study in that a predetermined ILD has a significant effect on the ITD chosen to align the auditory image to midline. Ruotolo et al.'s (1979) research also validates the findings of these studies. In their study, subjects were presented with a 500 Hz tone that had a designated positive time delay (+t) and an intensity (-a), as well as another tone of the same frequency but with opposing values of the cues in the first tone (as in: -t and +a) (Ruotolo et al, 1979). It is important to note that a positive value corresponded with a position closer to the right ear. Their results validate those of the previously mentioned study, seen in the inability of some participants to perceive a single auditory image to lateralize to midline when listening to low-frequency tones. They concluded that this was due to an incomplete trading of the interaural time and intensity information (Ruotolo et al, 1979).

These results provide further evidence for the disconfirmation of centering as a valid means of obtaining a trading ratio, as they suggest that compensating for an ITD and compensating for an ILD are not perceptually equivalent. Thus, when a researcher is using conflicting cues, it is important to understand which cue was used as the preset cue. One aim of the current study was to compare ratios calculated by a preset ITD versus a preset ILD to see if ratios for various locations are similar when considering preset ITDs in comparison to preset ILDs. In the case that they provide similar ratios, researchers will have validation that either ratio can be used for a given location; if the ratios are contradictory, then further studies will be needed to determine which ratio or preset cue is used to establish the location for a given stimulus.

Further issues lie within the cues themselves. There have been reports that intensity can affect the arrival time of neuronal input (Grothe & Park, 1995) as well as reports of listeners having a nonuniform temporal weighting of interaural time differences (Stecker & Bibee, 2014). Both of these can create an abundance of issues before those of reference tones, adaptor tones, cue weighting and preset tones even begin. Grothe and Park's (1995) study concluded that an increase in the amount of intensity presented to the inhibited ear altered the ITD function, quite possibly due to the shortened arrival time at the inhibited ear. Furthermore, this phenomenon was shown in every auditory cell tested, providing agreement with Raffin et al. (1976) that presentation levels can affect ITDs at numerous frequencies. As for ITDs themselves, when looking at 500 Hz tones, Stecker and Bibee (2014) observed that subjects differed in their overall sensitivity to the temporal weights of ITDs. Despite this, all subjects shared three characteristics: (1) thresholds improved gradually with increasing duration, especially with a continuous stimulus; (2) the rate of threshold improvement over duration was significantly less than expected for uniform temporal weighting of ITDs; and (3) thresholds were best with onset cues and worst when only offset cues were present. These findings are also seen in reports with 500 Hz narrowband noise (Houtgast & Plomp, 1968) and high frequency impulse trains (Hafter & Dye, 1983), suggesting this lack of uniformity in the temporal weighting of ITDs is not dependent upon the regularity or frequency of the stimulus; rather, the temporal weighting of ITDs is most salient with onset cues. Thus, in the case that onset cues are missing, the ability for listeners to detect location based upon ITDs is less reliable, as they are already unable to weigh the temporal information of these cues in a uniform manner. As mentioned previously, these can then be further affected by the presentation levels of the stimuli, as witnessed in Grothe and Park's (1995) study, which suggested that intensity changes can alter the arrival time of neuronal input during binaural stimulation.

1.3.2.1 Phase

Although the time-intensity trading function is usually tested by counterbalancing intensity with a value of time for an image to be perceived in the center of the head, Young (1976) tested what the effects of phase were for this phenomenon. This was done by studying different increments of phase (between 0- 360 degrees) at various frequencies (200 Hz, 400 Hz, 600 Hz, 1000 Hz and 2000 Hz) with the subject altering the intensity to have the auditory image lateralize to midline (Young, 1976). The shifts in phase had a similar pattern with slightly varying magnitude over time. The overall pattern illustrated that a 0-90 degree phase shift required a lowering of intensity, then 90-180 degree shifts rose back toward the original amount, while180-270 degrees out-of-phase necessitated a rise in intensity and then 270- 360 degrees out-of-phase gradually went back to the origin; for the lowest three frequencies the amounts were about the same, but for 1000 Hz there was a slight loss in magnitude of change and for 2000 Hz there was essentially no effect (Young, 1976). These results led to the conclusion that low frequencies require both ITDs and ILDs for lateralization and phase is encoded at these frequencies; whereas, at higher frequencies, lateralization doesn't require both cues, or phase is not always encoded.

2.0 THE PRESENT STUDY

The current study is novel in that it provides conflicting cues to a listener, rather than asking them to centralize a cue or discriminate if a sound source is to the left or right of a reference cue. By doing so we aim to provide empirical data that give a glimpse into how conflicting cues may affect sound source localization processing in normal hearing listeners as well as one listener with severe to profound hearing loss. The results of the current study have implications for bilateral CI users as well, because the devices deliver a relatively accurate representation of ILDs, but not ITDs, a binaural configuration similar in some ways to that used presently.

Through the implementation of a different technique, one in which conflicting cues are presented to a listener who then judges a lateralized position, we desired to gather empirical data that consider both cues in lateralization processing, rather than focusing one towards the reference cue that is at midline to find a ratio for zero degrees azimuth. These data provided support that illustrates the ignorance of the other cue to be unjustifiable as some conditions demonstrated an uneven weighting of the cues. Furthermore, we studied how this potential uneven weighting may vary across different azimuthal locations, which will provide a clearer image of lateralization across the entire lateral plane, rather than generalizing results based upon stimuli centralized to midline. Lastly, as witnessed by previous studies (Trahiotis & Kappauf, 1978), ratios are highly dependent upon which cue is lateralized and if there is a reference tone. In turn, we aimed to see how ratios gathered from different locations may vary depending upon which cue is closer to midline.

2.1 HYPOTHESES

1. It is hypothesized that non-zero cues will be weighted more heavily when the other cue is at or near midline.

2. When both are at non-zero locations the cues will be weighted more evenly, especially when they are on either side of midline. In the latter, it is hypothesized that the perceived location will be in the middle of the cues presented (ie. An ITD at 30 degrees and an ILD at -30 degrees will result in the perceived location close to 0 degrees azimuth.)

3.0 METHODS

3.1 SUBJECTS

A total of 6 participants took part in this study. They were all students at the University of Pittsburgh ranging in age from 20 to 35 years old. Five participants, one of which was the investigator, had normal audiometric thresholds above 20 dB HL at each octave and half octave from 125 to 8000 Hz. The last participant, referred to as "NS", had an asymmetrical sensorineural hearing loss that has been present since birth. The hearing loss was found around one-and-a-half years of age, which is also when he was fitted with hearing aids. At the time of participation, hearing loss was severe on his right side and severe-to-profound on his left side. This study was approved by the University of Pittsburgh's Internal Review Board, and participants were compensated with either course credit or a wage of $10 per hour for their assistance.

3.2 STIMULI AND CONDITIONS

All stimuli were generated using the Python programming language (Python Software Foundation, 2015). The locations used for each reference and stimulus cue within the stimuli were created by transposing head-related transfer functions collected from a KEMAR™ mannequin (Gardner & Martin, 1995) onto a noise and then finding the ITDs and ILDs associated with the certain locations tested in the experiment.

All stimuli and reference tones were presented through circumaural headphones. A trial consisted of two sequential 300-ms 500-Hz monotic reference tones (one in the left ear and one in the right) followed by a 300-ms broadband Gaussian noise stimulus. The reference tones were to provide subjects with an idea of the most lateral positions possible. The noise stimulus was presented with varying ITD and ILD cues. All subjects sat inside a sound-proof booth with a monitor, headphones, and a response dial while data was collected on a computer outside of the booth.

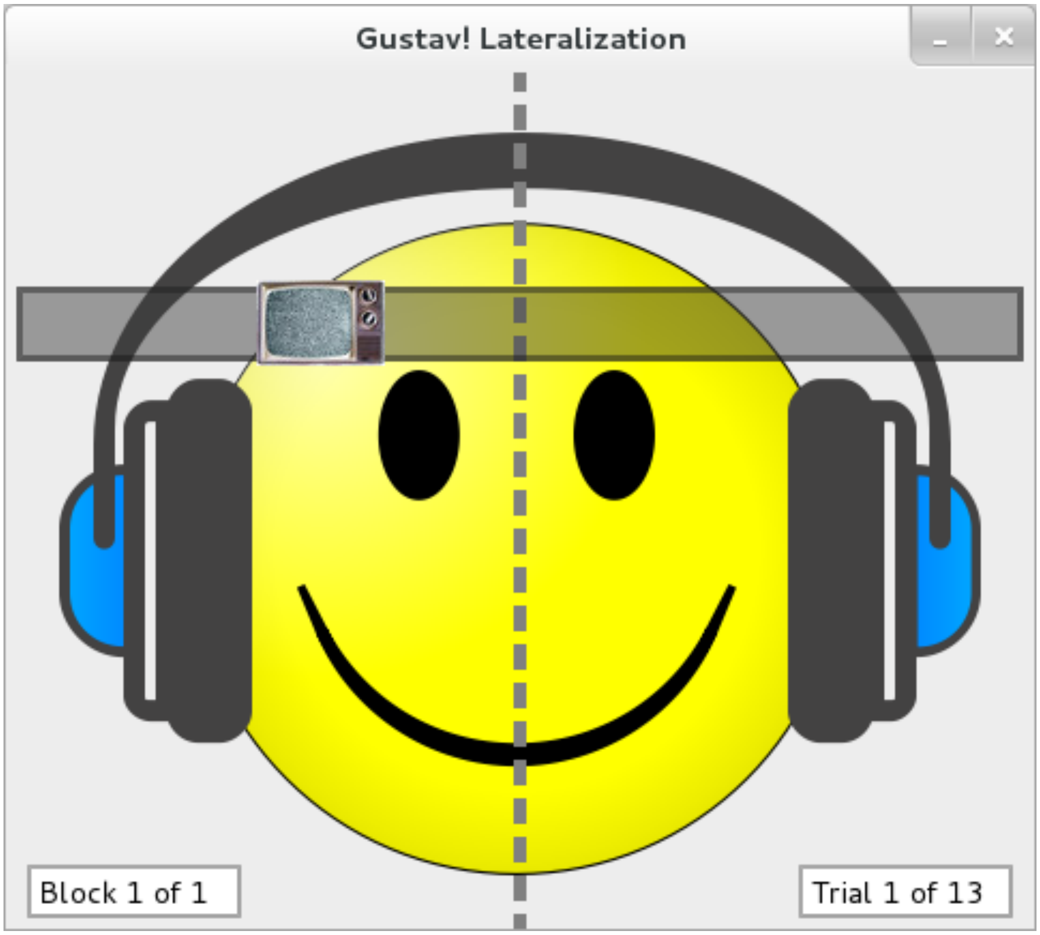
The reference cue did not change during a block of trials, and was located at either 30, 60, or 90 degrees azimuth (to the right). The stimulus cue changed from trial to trial, from between 60 and 0 degrees to the left of the reference in 5 degree steps. For example, if the reference cue azimuth was 30 degrees for a run, the stimulus azimuth during that run was between -30 and +30 degrees. Each stimulus azimuth was presented once and was not repeated in a block; thus, there were 13 trials per block and two blocks per condition. In one of the blocks, the ITD cue was the reference (and the ILD was the stimulus cue), and in the other block, the ILD was the reference (and thus, the ITD was the stimulus cue).

3.3 PROCEDURES

The entire experiment consists of 18 blocks, each with 13 trials. Subjects completed each block three times each, and an average was computed across the three perceived locations for each stimulus cue azimuth that was presented. The average time to complete one run of 18 blocks was 30 minutes, giving the average total of 1.5 hours of participation per subject.

After having a hearing screening collected, subjects were educated briefly on the study and how to respond after a stimulus was played. Each trial began with two reference tones that defined -90 and 90 degrees azimuth (the periphery) followed by the noise stimulus. A computer monitor in the booth showed a picture of a head with a loudspeaker icon that moved from the left ear to the right ear when a dial was turned (see Figure 1 below). Subjects used the dial to indicate the perceived lateral position of the stimulus, and then pressed a button to enter their response. The recording of their response then initiated the next trial. This was repeated for each trial until the subject completed the 18 blocks for that session.

Error bars are present to show any variance amongst normal hearing subjects for each condition. They represent the standard error of the mean. No error bars are shown for the hearing impaired listener's data, as there is only one subject in this listening group.



Supplement 1. Response Configuration. Image of the head with a loudspeaker icon that subjects used to record lateralization judgments. A dial that was connected to the computer could be turned, which then corresponded to a left- right movement of the loudspeaker on the bar across the head. The dashed line indicates where midline would be, and the edges of the bar correspond to the furthest left and right a sound could be lateralized.

4.0 RESULTS

4.1 NORMAL HEARING SUBJECTS

4.1.1 Non-zero azimuth conditions

4.1.1.1 Reference cue at 30 degrees

4.1.1.1.1 ITD as reference cue

In this condition, the reference cue was at 30 degrees azimuth and the stimulus cue was between -30 and 30 degrees azimuth. The left panel of Figure 1 illustrates the mean perceived lateral location as a function of changes in ILD, when the ITD was designated the reference cue and the ILD was the stimulus cue. The solid black line denotes the position of the stimulus cue, which was varied between -30 and 30 degrees azimuth, or between 60 and 0 degrees to the left of the reference cue. In the left panel of Fig. 1, the data show that the perceived location is slightly between the reference and stimulus cues, with an apparent bias toward the stimulus cue.

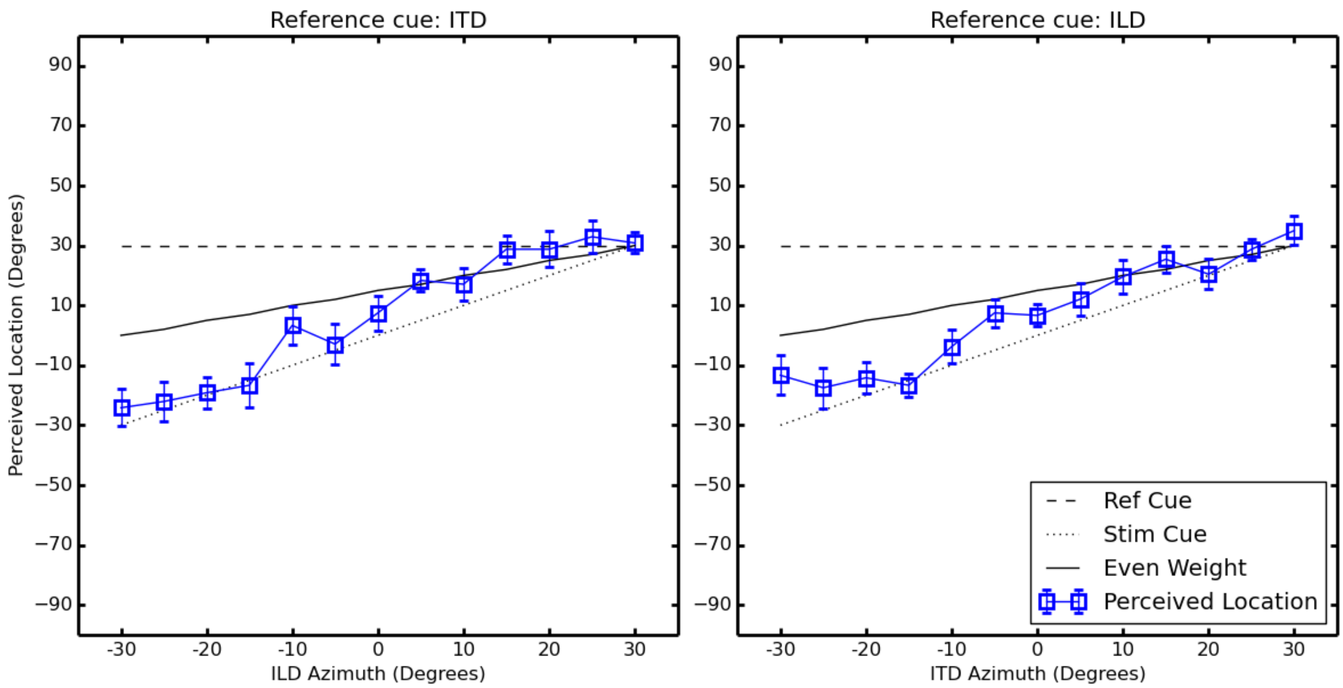


Figure 1. Averaged data for reference cue at 30. All data shown are the mean locations perceived per stimulus-reference combination collected from all five normal hearing subjects over their three separate sessions. Error bars are present to show any variability in performance between subjects.

4.1.1.1.2 ILD as reference cue

The right panel of Fig. 1 illustrates a similar pattern. For this condition, the ILD was the reference cue placed at 30 degrees azimuth while the ITD stimulus cue was varied within the same parameters of azimuth. Once again, there was a bias amongst listeners to lateralize the sound source towards the stimulus cue. Despite switching the reference and stimulus cue, this uneven weighting was also typically around -10 degrees azimuth, rather than midline, which would have indicated an even weighting of the cues.

4.1.1.1.3 *Summary*

These results present some support for our hypothesis, but ultimately disprove the overlying concept that was presented in the introduction. Overall, subjects did show similar patterns between the ITD versus ILD as reference cue conditions, but the data ultimately disprove the hypothesis that there would be an even weighting of the reference and stimulus cue. The implications of this outcome will be addressed in the discussion section.

4.1.1.2 Reference cue at 90 degrees

4.1.1.2.1 ITD as reference cue

In this condition, 90 degrees azimuth served as the reference cue's location, while the stimulus cue was randomly varied between 30 and 90 degrees azimuth over trials. The left panel of Figure 2 is a pictorial representation of the data gathered for the sub-condition where the ITD was the reference cue and the ILD served as the stimulus cue. As with the above figures, the black line denotes the stimulus cue's location, and the blue line represents the averaged data. These data show interesting results that differ from the previous conditions. As seen in the left panel, listeners heavily favor the reference ITD cue, as witnessed by the blue line appearing above 45 degrees azimuth, which would be midway between the cues. Furthermore, the function is relatively flat throughout, indicating that no change in the stimulus cue, which is the ILD cue, would relate to a change in the perceived location. These provide evidence that, in this condition, the ILD doesn't play an integral role in determining the location of the sound source, at least when it serves as the stimulus cue. This function then changes past 50 degrees azimuth. Once it reaches this point, listeners are unable to lateralize the sound source past 50 degrees azimuth, shown by the almost flat blue line.

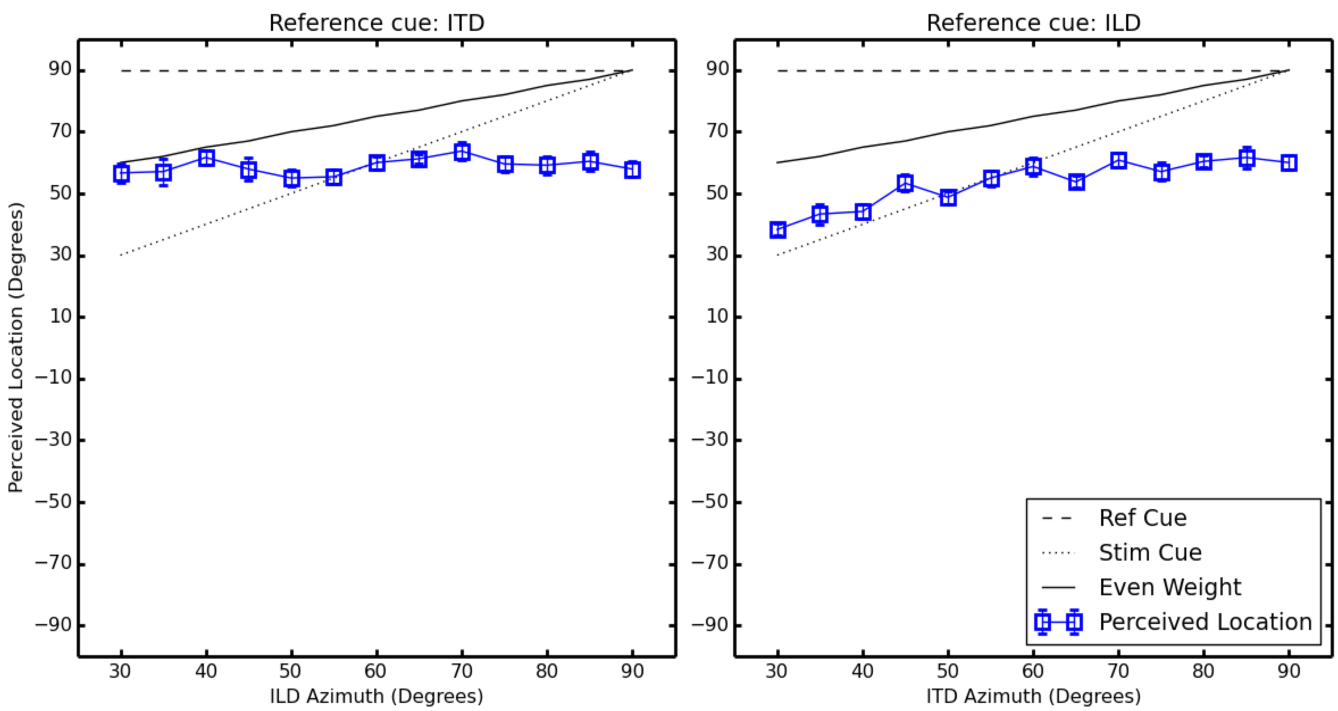


Figure 2. Averaged data for reference cue at 90. All data shown are the mean locations perceived per stimulus-reference combination collected from all five normal hearing subjects over their three separate sessions. Error bars are present to show any variability in performance between subjects.

4.1.1.2.2 ILD as reference cue

The results of the current subcondition, where the ILD was the reference cue and the ITD served as the stimulus cue, are seen in the right panel of Figure 2. Listeners all showed similar patterns amongst each other. Here, another uneven weighting is seen, albeit in a different manner than would be expected from the previous results. Subjects no longer demonstrated a preference for the reference ITD cue as with before; instead, the data indicate that listeners attend to the ITD cue until the 50-degree mark once again. This is shown in the position of the blue line being closer to the ITD, which was located between 30 and 90 degrees. As with before, once the stimulus cue reaches 50 degrees azimuth, listeners showed an inability to lateralize a sound source, demonstrated in the function flattening out past this point.

4.1.1.2.3 Summary

These results demonstrate that, unlike what was hypothesized, when a sound source has conflicting binaural cues that present a sound in the periphery subjects are unable to lateralize a sound source near the middle of both cues. Instead, they rely mainly on the ITD cue for lateralization in the periphery. Furthermore, subjects were unable to lateralize sound sources past 50 degrees azimuth. Results of this condition are important for research involving the weighting cues, as well as for cochlear implant processing, which will be considered further in the discussion section.

4.1.2. Reference cue at 60 degrees

4.1.2.1 ITD as reference cue

With respect to azimuthal location, 60 degrees marked the position of the reference cue in this condition, while the stimulus cue was randomly varied from 0-60 degrees azimuth from trial to trial. The data for the subcondition in which the ITD was placed at 60 degrees and the ILD originated at 0 are seen in the left panel of Figure 3. Overall, there was a mostly even weighting of the cues, with a slightly uneven weighting in the data collected when the stimulus cue was located closer to midline. Subjects appeared to show a less uneven weighting in this condition than the -30 and 30 condition in the cases where the stimulus was near zero.

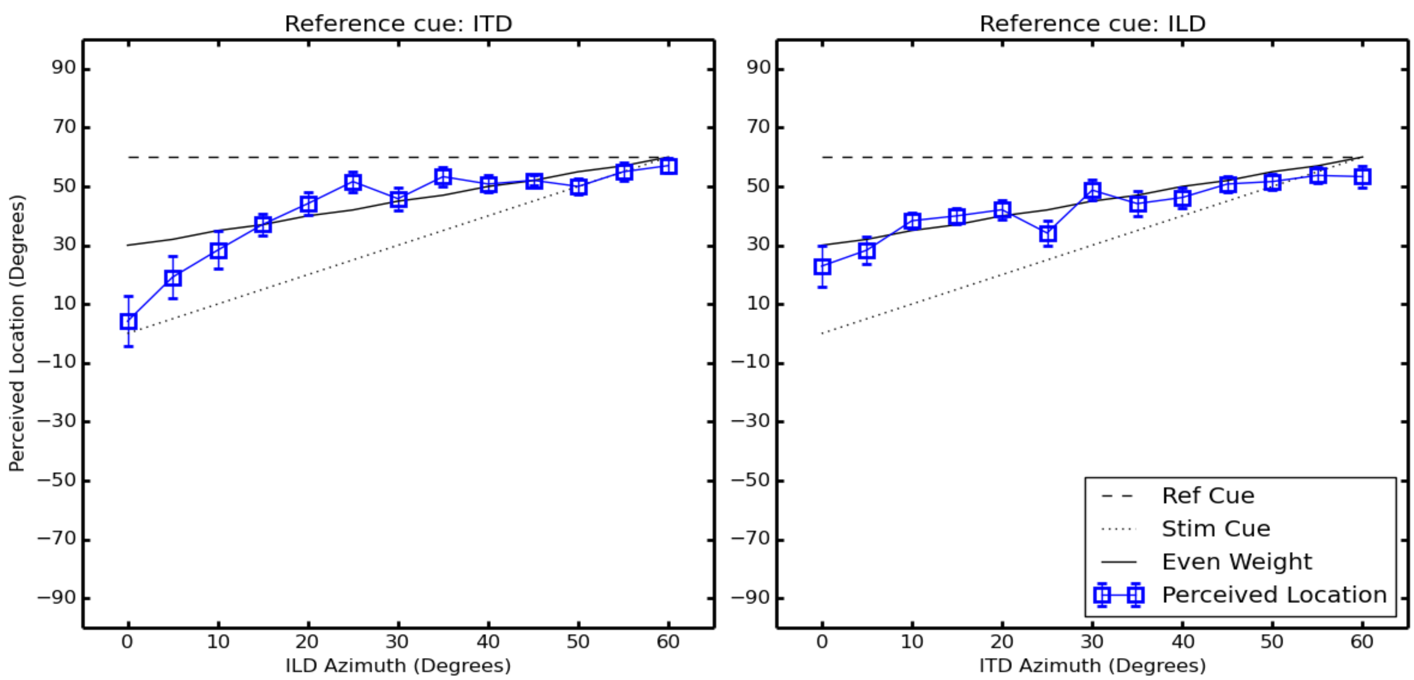


Figure 3. Averaged data for reference cue at 60. All data shown are the mean locations perceived per stimulus-reference combination collected from all five normal hearing subjects over their three separate sessions. Error bars are present to show any variability in performance between subjects.

4.1.2.2. ILD as reference cue

Data from this condition are similar to those when the ITD was the reference cue. Generally, there is an even weighting across stimulus cue locations. When the stimulus cue is near midline, there is a slight uneven weighting, but it is negligible when looking at overall results.

4.1.2.3. Summary

These results demonstrate a lack of support for our first hypothesis, in which the sound source's location was believed to be lateralized closer to the reference cue at 60 degrees. This outcome has implications for current ratios that have been obtained and used in current research, which will be discussed later.

4.2 RESULTS OF SUBJECT "NS"

Given that the sixth subject had an asymmetrical severe-to-profound hearing loss, results were expected to be different than those of the normal hearing subjects. As illustrated in Figures 4 through 6, this assumption was unwarranted. NS's data are noisy, but a similar pattern of results was found overall when compared to the normal hearing subjects' data. Fig.4 shows the data for the -30 and 30 condition, which demonstrate a slight preference for the stimulus cue. As shown in Figure 6, the 0 and 60 degree conditions also have a relatively even weighting of the cues for determining the perceived location of a sound.

Lastly, NS also favored the ITD cue in both of the conditions in which the reference cue is at 90 degrees and the stimulus cue is at 30 degrees azimuth, shown in Figure 5. This subject also showed a cut-off point around 50 degrees azimuth in this condition, which relates to an inability to lateralize a sound source past this point.

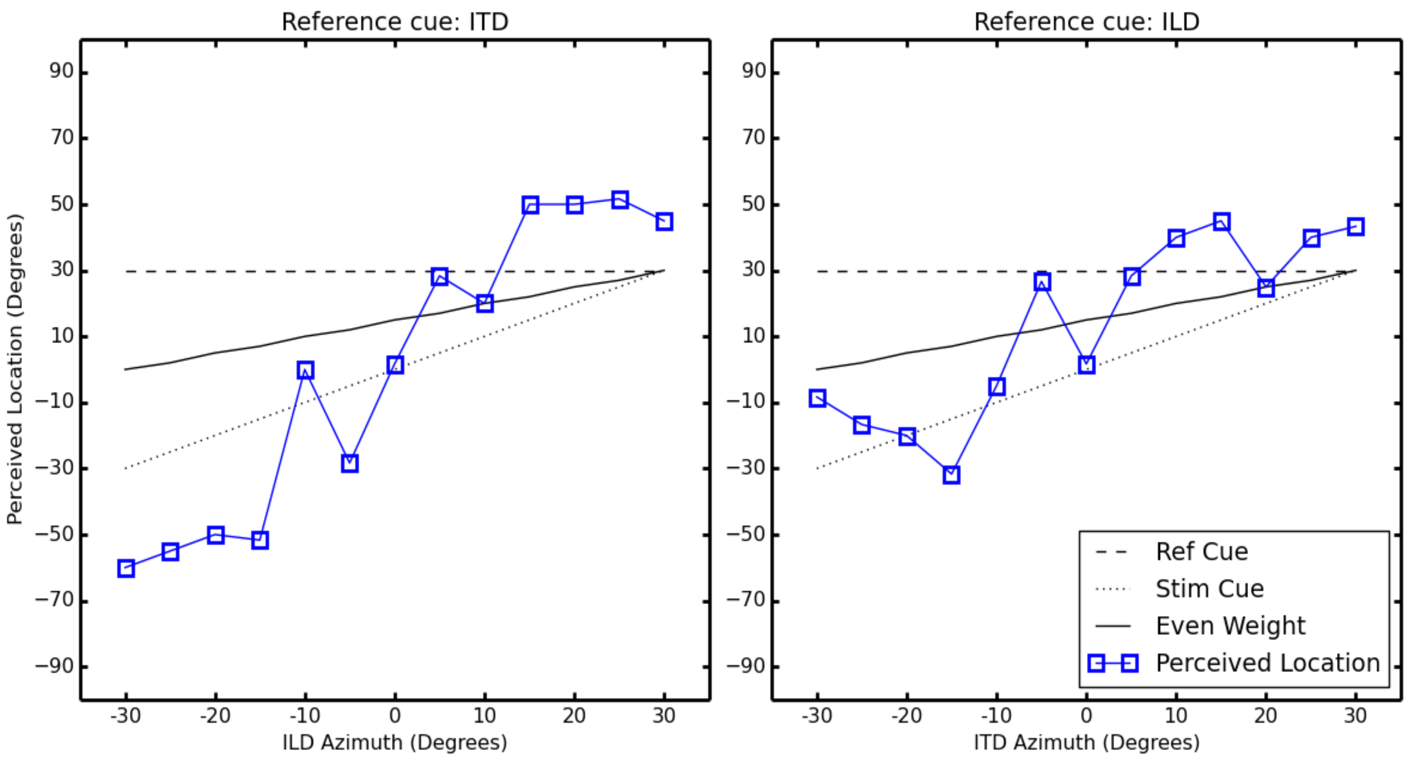


Figure 4. Results for NS with reference cue at 30. These data are the averaged responses from 3 sessions.

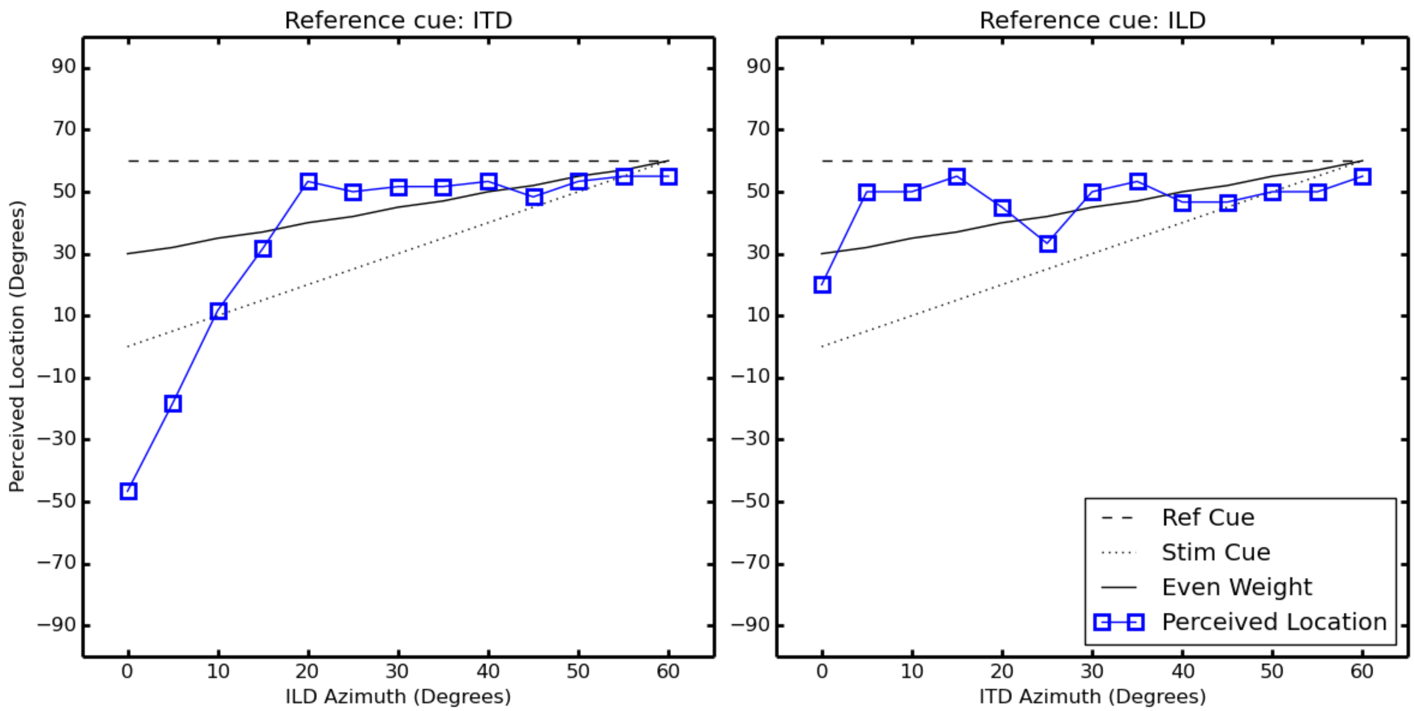


Figure 5. Results for NS with reference cue at 90. These data are the averaged responses from 3 sessions.

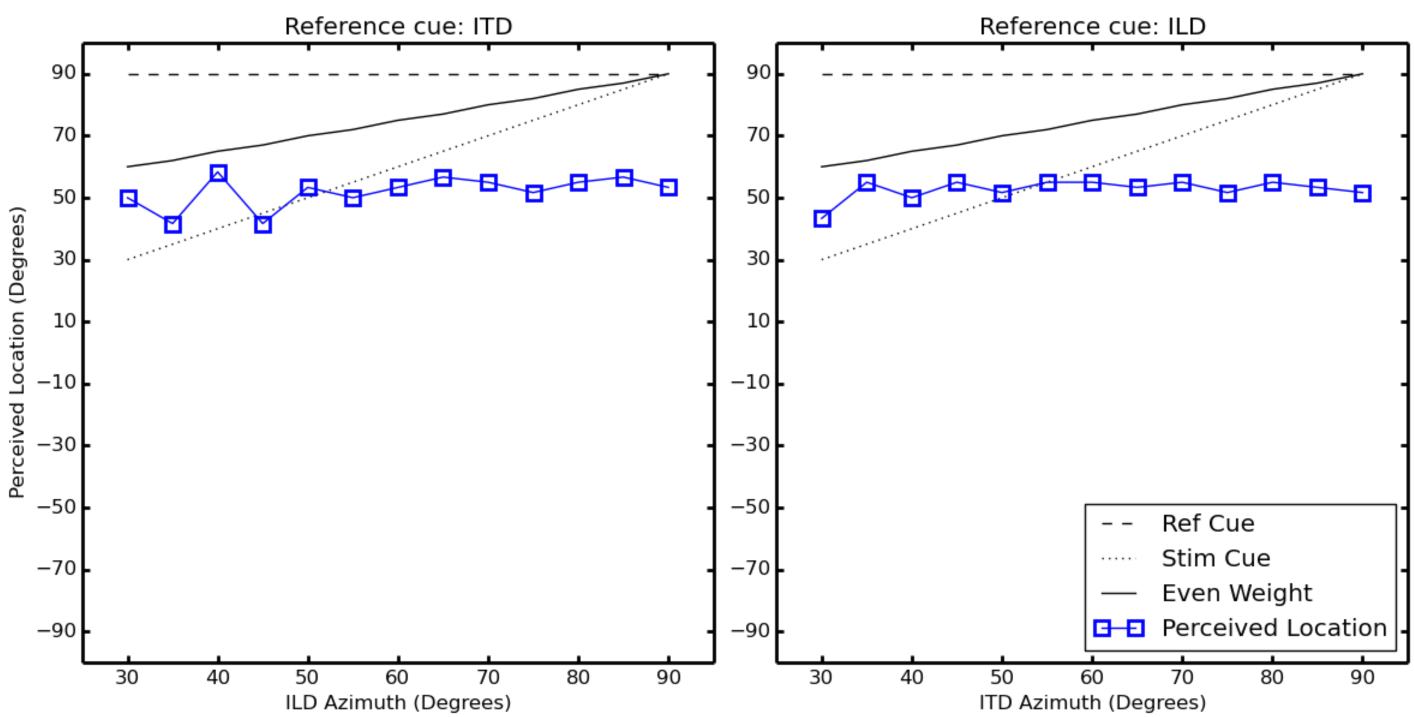


Figure 6. Results for NS with reference cue at 60. These data are the averaged responses from 3 sessions.

5.0 DISCUSSION

It is amazing that cochlear implant technology has allowed those with major hearing loss to not only recognize sounds but to understand speech. With this said, there are several key issues that have led to limitations in processing, such that it is difficult for CI users to fully benefit from the devices. One such example is the struggle that cochlear implant users present in understanding speech when there is noise present, as well as their difficulty with sound source localization and lateralization. The issues they present with processing the location of a sound source are mostly due to the fact that normal hearing listeners have binaural processing, which integrates the interaural differences present in a signal to establish its spatial location. On the other hand, CI processing only allows for ILDs to be delivered robustly to a listener, and all interaural differences, which are determined through time-intensity trading ratios, are encoded artificially to determine the location. These ratios have been studied for some time, with the aim of gaining more understanding of the binaural process. These types of studies have particular relevance for CI processing, as the only cue delivered relatively accurately is the ILD, despite there always being a time and level difference between the ears, even when it is zero. Thus, one way to think about the binaural representation of many CI users is that when a sound source is off to one side of the head, the ILD accurately reflects that spatial location, while the ITD is zero. This possibility is what motivated the current study.

As mentioned previously, numerous items can affect trading ratios, and thus most ratios that have been calculated likely include some bias due to an uneven weighting of the to-be-adjusted cue. The current study took a novel approach, in which listeners simply recorded the perceived location of a sound source when conflicting cues were presented. Thus, no manual manipulation of a stimulus cue was done by listeners and outputs were their subjective perception of the location. This novel approach allowed for a new point-of-view that illustrated how these cues interact in creating a percept.

5.1 NORMAL HEARING SUBJECTS

5.1.1 Reference cue at 30 degrees

Conditions were conducted where both the ITD and the ILD were the reference cue for an equal amount of trials in order to see if this variance would affect perceived location, along with that of randomly varying the stimulus cues position between -30 and 30 degrees azimuth. As shown in both panels of Figure 1, where the left panel corresponds to conditions where the ITD is the reference cue and the right panel includes the data from the conditions with ILD as the reference, there are similar patterns. The data demonstrate that lateralization of a sound source isn't dependent upon which of the cues (ITD versus ILD) is the reference cue; rather, listeners demonstrated an uneven weighting that related to a preference for the stimulus cue over the reference cue. This is most prevalent in the graph, as the perceived location tends to be weighted more heavily toward the stimulus cue, regardless of which cue it was.

These results present some support for our hypothesis, but ultimately disprove the overlying concept that was presented in the introduction. It was hypothesized that listeners would show similar patterns in how they lateralize a sound source for both sub-conditions (ITD versus ILD as reference cue) when the reference and stimulus cue are both at non-zero locations and when they are equi-distant from midline. These data do illustrate similar patterns in both sub-conditions, in which subjects all lateralized each sound closer to the stimulus cue. The error bars that illustrate a miniscule amount of variability amongst listeners bolster the reliability of these results.

However, this slightly uneven weighting of the cues disproves our hypothesis that cues would be weighted evenly in this condition. If they were indeed weighed evenly when processing the lateral location of a sound source, then the subjects' results would have begun at 0 degrees azimuth and continued in a linear fashion in the middle of both cues as the stimulus cue changed over trials. This uneven weighting may be due to an increased attention to the changing cue, which in this case was in the stimulus cue. Subjects most likely became accustomed to the reference cue's location from trial to trial and then focused more on the stimulus cue. This coincides with similar effects seen in the centering method for creating trading ratios, where subjects place more emphasis on the to-be-adjusted cue when manipulating its ITD or ILD to create a midline location. (Ignaz et al., 2014; Lang & Buchner, 2008). Future studies will need to be done to gain more insight on this phenomenon without the interference of attention on the stimulus cue due to a change in its azimuthal location.

5.1.2 Reference cue at 90 degrees

Unlike the previous condition, where the reference cue was at 30 degrees azimuth, these data suggest a different pattern of results. Rather than showing a preference for the stimulus cue over the reference cue, subjects showed a large bias for the ITD cue up until about 50 degrees azimuth, where the function then flattens. As shown in the first panel, the perceived location has a bias for the ITD cue, which happens to be the reference cue in this condition. In the right panel, the perceived location is no longer weighted towards the reference (ILD) cue, but it favors the stimulus (ITD) cue. As with the previous condition, error bars showed that there was minimal variability between subjects.

These data do not support our second hypothesis, which was that subjects would show an even weighting of cues when lateralizing a sound with conflicting cues in the periphery. This unexpected outcome suggests that different processes might be in play when considering how listeners lateralize a sound near midline, versus toward the periphery. In this case, the ITD is the most robust cue for sounds originating in this area of the lateral plane. Not only do these data disprove our hypothesis, but they provide conflicting information in regards to past studies that have found the ILD to be the most robust cue for sound localization and lateralization (Aronoff et al, 2010). These new results suggest the opposite, and in the case of cochlear implant users, they provide a clearer picture as to why CI users have difficulty with lateralizing a sound. Given that cochlear implants do not transmit ITD information reliably, as the fine structure is omitted in their programming, users of the devices receive the ITDs reliably, which then affects lateralization in the periphery in respects to the results of this condition.

Furthermore, the lack of an ability to lateralize sound sources past 50 degrees azimuth has several implications. First, this inability might be due to the use of reference tones that potentially artificially compressed listeners' perceptual spaces. This implication will be discussed further in the Future Directions section. Second, these results might be able to explain the findings of a study conducted by Grantham et al (2008). In this study, which focused on localization, CI users had a mean RMS error score that was almost triple that of their normal hearing counterparts. Additionally, the normal hearing listeners had a linear localization function; whereas, the CI users had functions similar to those found in our present study, where the function flattens at 50 degrees azimuth (Grantham et al, 2008). Upon looking at the similarities between the CI users in Grantham et al's (2008) study and the present study, it can be postulated that this flattening at 50 degrees might be due to listeners not having personalized head-related transfer functions (as the current study had stimuli presented through headphones, so listeners did not have personalized HRTFs). Given that past studies have demonstrated that personalized HRTFs are necessary for localizing a sound source (Hartmann & Wittenberg, 1996), it appears as though CI users only have the ability to lateralize rather than localize a sound source.

To date, some techniques for encoding the ITD information in the temporal envelope and fine structure have been studied. For example, Majdak, Laback and Baumgartner (2006) illustrated that it is possible for bilateral CI users to benefit from transposing the ITD information not only into the temporal envelope but the fine structure as well when using low pulse rates. Despite studies like this illustrating the potential benefit of transmitting ITD information in other forms, CI technology does not currently rely on this. In order for improvements in CI user lateralization abilities to occur, cochlear implant processing technology still needs further advancements that allow users to obtain the ITD cues more robustly or for the devices to be linked to create a more binaural processing of the cues. Perhaps then CI users will be able to have better lateralization capabilities that resemble those of normal hearing listeners, especially in the case of the periphery.

5.1.3 Reference cue at 60 degrees

Overall, in these conditions listeners had a fairly even weighting of the reference and stimulus cue. Both data sets show a relatively even weighting of the two cues across the range of conditions. No preference was shown for one binaural cue over the other, similar to the 30 degree reference cue condition. As with the condition where 90 degrees was the location of the reference cue, subjects showed an inability to lateralize a sound past 50 degrees.

These data disprove our hypothesis, which stated that a cue near zero would be weighted less heavily, which was not observed. This outcome, in addition to those from the two previous conditions, provide conflicting information about how humans lateralize a sound source. When sounds have one cue that indicates that a source originates from 60 degrees azimuth while the other cue gives a location at or near midline, the data illustrate that we process both cues fairly evenly. This can affect trading ratios that have been obtained in other experiments thus far, as these data suggest that for sound sources in this area of the lateral plane cue weighting is not reliant on which cue is the reference cue, or if there is a change in the stimulus cue.

5.2 RESULTS OF SUBJECT “NS”

Although the data for this subject are noisy, they illustrate a pattern similar to those collected from the normal hearing subjects, which was unexpected given the extent of this listener’s hearing loss. NS also preferred the stimulus cue in the condition where the reference cue was at 30 degrees, giving way to an uneven weighting when determining the lateral position of the sound source. This subject, like the normal hearing subjects, also demonstrated a fairly even weighting of the cues when 60 degrees was the reference cue’s location. NS also demonstrated a robust bias for the ITD cue for lateralization in the periphery, with a cut-off point where the ability to lateralize a sound diminished around 50 degrees azimuth.

These results are promising, in that they demonstrate that those with severe hearing loss, similar to the degree of those with CIs, can have similar patterns for lateralization compared to normal hearing listeners. This can potentially be used in future studies to determine how likely it is that a cochlear implant user can demonstrate skills similar to those of normal hearing listeners; although, it is worth noting that unless previous hearing capabilities were kept intact in the process of implantation, then CI users may lack some of the skills necessary for a completely similar pattern.

5.3 LIMITATIONS AND CAUTIONS

Some limitations are worth noting in this study. First, results from this study cannot be directly compared to data collected from previous studies that employed other methods to create trading ratios. This is due to the novel and different method used in the present study, in which subjects were presented with discrepancies in the cues within the signal and then required to pinpoint a location, rather than instructing the listener to manipulate a cue to centralize a signal or simply state if a stimulus is to the right or left of a reference cue in the lateral plane.

Second, it is not best practice to generalize the results of one listener with severe hearing loss to the entire hearing impaired population. This is especially the case for generalizing results to CI users, as they have been shown to have large intersubject variability. A larger sample population, preferably ranging in level of hearing loss and use of hearing aids versus cochlear implants would be ideal for more generalizable data.

5.4 FUTURE DIRECTIONS

As mentioned, one future study could incorporate more participation that includes subjects with varying hearing loss. Although psychoacoustic studies generally utilize few subjects, in a case where subjects with a given disorder are known to demonstrate great variance, it would be beneficial to run the same study with several listeners under each level of hearing loss as well as different durations of loss and various etiologies. These would help provide a clearer picture as to how the length of Deafness, length of wearing hearing aids and how central versus peripheral losses can alter one's ability to lateralize a sound source. It would also be ideal to include some subjects with sequential and simultaneously implanted CIs to see if they show similar patterns and if the method of implantation can affect outcomes. We could then compare these results with one another and with normal hearing subjects.

Since the condition where the reference cue was at 30 degrees azimuth illustrated results that relied more on attention to movement of the stimulus cue, a change in methods might be ideal. One method that could be employed is switching the binaural of the reference and stimulus cue over trials within the same condition. For example, in the condition where the reference cue is at 30 degrees azimuth, half of the trials could consist of the reference cue being the ITD (and ILD as the stimulus cue, while the other half of the trials have the ILD serve as the reference cue and the ITD as the stimulus cue. Trials would then vary across the condition such that the listener doesn't become accustomed to one binaural cue being the reference cue and then focusing more on the stimulus binaural cue and its changes over trials.

Although it would not counteract the issue of attention, another method could be employed to obtain data on attention as a function of azimuth. To do so, a condition would entail having the reference cue remain stationary at midline while the stimulus cue varies in azimuth over location. In this case, the stimulus could be lateralized on the left or right side of midline and into the periphery in order to have a more complete "image" of how attention varies across azimuthal locations.

Lastly, the use of monotic reference tones to assist listeners in determining the most lateral positions that a sound could be perceived might have skewed the results obtained. The reasons for this are two-fold. First, there aren't many monotic tones in nature, so the use of these provided listeners with a reference that was unnatural. Second, and more importantly, by providing these unnatural tones to listeners in the periphery, their perceptual space might have been artificially compressed, thus giving one reason why listeners did not lateralize sound sources past 50 degrees azimuth. Future studies can rely on the use of diotic clicks to help provide listeners with a more natural reference that is presented equally in both ears. These clicks would then create a reference perceived at midline, which would then open up the perceptual space as well.

6.0 CONCLUSION

This study used a novel method for researching how listeners combine binaural cues and the impact that they have on sound source lateralization. In this method, subjects were instructed to select the location of a noise that was presented with conflicting interaural cues at a variety of locations in the lateral plane. This differs from previous studies, as those generally employed a method where subjects had to manipulate one of the cues to create a centralized image; although different locations of the adjusted cue were tested in these studies, subjects were only ever required to create an image located at midline. The present study differed in that subjects had some conditions where the location could be at midline, but many others in which it was somewhere in the periphery, which allows for a much more accurate analysis of binaural processes across the lateralization plane.

The data gathered showed similar patterns between normal hearing listeners and one that has severe-to-profound hearing loss. Both groups demonstrated similar patterns between the three main conditions where the reference cue was located at 30 degrees, 60 degrees or 90 degrees azimuth. In the 30-degree-reference condition, both groups showed a slight tendency to weight the stimulus cue more heavily, most likely due to paying attention to a change in the stimulus compared to the static reference cue. In the second set of conditions, where the reference cue was at 60 degrees, participants showed a mostly even weighting of the cues with an eventual flattening of the function around 50 degrees that related to an inability to lateralize sounds past this point. Lastly, when the reference cue was at 90 degrees, subjects demonstrated that the ITD was the more robust cue, regardless of whether it was the reference or stimulus cue. These results have implications on the current time-intensity trading ratios used in experiments and CI processing, as each location tested showed different patterns in regards to how we combine these binaural cues to lateralize a sound source.

REFERENCES

Aronoff, J.M., Yoon, Y.S., Freed, D.J., Vermiglio, A.J., Pal, I., & Soli, S.D. (2010). "The use of interaural time and level difference cues by bilateral cochlear implant users," *Journal of the Acoustical Society of America,* 127 (3), EL87-92. doi: 10.1121/1.3298451.

Breebaart, J., van de Par, S., & Kohlrausch, A. (2001a). "Binaural processing model based on contralateral inhibition. I. Model structure," *Journal of the Acoustical Society of America,* 110, 1074-1088. doi: 10.1121/1.1383297.

Dekio-Hotta, S., & Kaga, K. (2006). "Comparative study of fixed time versus intensity trade and fixed intensity versus time trade tests in sound lateralization," *Auris Nasus Larynx,* 33 (3), 265-269. doi:10.1016/j.anl.2005.11.016

Dietz, M., Ewert, S.D., Hohmann, V., & Kollmeier, B. (2008). "Coding of temporally fluctuating interaural timing disparities in a binaural processing model based on phase differences," *Brain Research*, 1220, 234-245. doi:10.1016/j.brainres.2007.09.026.

Gardner W.G., & Martin K.D. (1995). "HRTF measurements of a KEMAR," *Journal of the Acoustical Society of America,*97, 3907–3908. http://dx.doi.org/10.1121/1.412407.

Grantham, D.W., Ashmead, D.H., Ricketts, T.A., Labadie, R.F., & Haynes, D.S. (2008). "Interaural time and level difference thresholds for acoustically presented signals in post-lingually deafened adults fitted with bilateral cochlear implants using CIS+ processing," *Ear and Hearing,* 29 (1), 33-44. doi: 10.1097/AUD.0b013e31815d636f

Grothe, B., & Park, T.J. (1995). "Time can be traded for intensity in the lower auditory system," *Naturwissenschaften,* 82, 521-523. doi: 10.1007/s001140050226

Hafter, E.R. (1977). "Lateralization model and the role of time-intensity trading in binaural masking: Can the data be explained by a time-only hypothesis?," *Journal of the Acoustical Society of America,* 62(3)633-5. doi: 10.1121/1.381565

Hafter, E.R., & Dye, R. H. J., (1983). "Detection of interaural differences of time in trains of high-frequency clicks as a function of interclick interval and number," *Jorunal of the Acoustical Society of America,* 73, 644-651. doi: 10.1121/1.388956

Hafter, E.R., & Carrier, S.C. (1972). "Binaural interaction in low-frequency stimuli: The inability to trade time and intensity completely," *Journal of the Acoustical Society of America,* 51(6), 1852-1862. doi: 10.1121/1.1913044

Hartmann, W.M., & Wittenberg, A. (1996). “On the externalization of sound images,” *Journal of the Acoustical Society of America*, 99 (6), 3678-3688. doi: 10.1121/1.414965

Harper, N. S. & McApline, D. (2004). “Optimal neural population coding of an auditory spatial cue,” *Nature*, 430, 682-686. doi:10.1038/nature02768.

Houtgast, T., & Plomp, T. (1968). “Lateralization threshold of a signal in noise,” *Journal of the Acoustical Society of America*, 44, 807-812. doi: 10.1121/1.1911178

Ignaz, A., Lang, A.G., & Buchner, A. (2014). “The impact of reference tones on the adjustment of interaural cues,” *Journal of the Acoustical Society of America* 135 (4) 1986-1992. http://dx.doi.org/10.1121/1.4867361

Jeffress, L. A. (1948). “A place theory of sound localization,” *Journal of Comparative and Physiological Psychology*, 41 (1), 35-39. http://dx.doi.org/10.1037/h0061495.

Lang, A-G., & Buchner, A. (2008). “Relative influence of interaural time and intensity differences on lateralization is modulated by attention to one or the other cue,” *Journal of the Acoustical Society of America*, 124(5), 3120-3131. doi: 10.1121/1.3212927

Lang, A-G., & Buchner, A. (2009). “Relative influence of interaural time and intensity difference on lateralization is modulated by attention to one or the other cue: 500-Hz sine tones,” *Journal of the Acoustical Society of America,* 126 (5), 2536-2542. doi: 10.1121/1.3212927

Majdak, P., Laback, B., & Baumgartner, W.D. (2006). “Effects of interaural time differences in fine structure and envelope on lateral discrimination in electric hearing,”*Journal of the Acoustical Society of America,* 120 (4), 2190-2201. doi: 10.1121/1.2258390

McAlpine, D. & Grothe, B. (2003). “Sound localization and delay lines—do mammals fit the model?,” *Trends in Neuroscience*, 26, 347-350. doi:10.1016/S0166-2236(03)00140-1.

Phillips, D.P., Carmichael, M.E., & Hall, S. E. (2006). “Interaction in the perceptual processing of interaural time and level differences,” *Hearing Research,* 211, 96-102. doi:10.1016/j.heares.2005.10.005.

Python Software Foundation. Python Language Reference, version 2.7. Available at http://www.python.org.

Raffin, M.J., Lilly, D.J., & Thornton, A.R. (1976). "Time-Intensity trade for speech: A temporal speech-stenger effect," *Journal of Speech and Hearing Research,* 19(4) 749-66. doi:10.1044/jshr.1904.749.

Rayleigh, L. (1907). "On our perception of sound direction," *Philosophy Magazine,* 13, 214-232. doi: 10.1080/14786440709463595.

Ruotolo, B.R., Stern Jr., R.M., & Colburn, H.S. (1979). "Discrimination of symmetric time-intensity traded binaural stimuli," *Journal of the Acoustical Society of America*, 66, 1733-1737. doi**:** 10.1121/1.383646.

Stecker, G.C., & Bibee, J.M. (2014). "Nonuniform temporal weighting of interaural time differences in 500 Hz tones," *Journal of the Acoustical Society of America,* 135 (6), 3541-3547. doi: 10.1121/1.4876179.

Trahiotis, C. & Kappauf, W.E. (1978)."Regression interpretation of differences in time-intensity trading ratios obtained in studies of laterality using the method of adjustment," *Journal of the Acoustical Society of America,* 64(4), 1041-1047. doi: 10.1121/1.382087

Yost, W.A., Tanis, D.C., Nielson, D.W., & Bergert, B. (1975). "Interaural time vs interaural intensity in a lateralization paradigm," *Perception & Psychoacoustics*, 18(6), 433-440. doi: 10.3758/BF03204117

Young, L. L. Jr. (1976). “Time- Intensity Trading Fucntions for Selected Pure Tones,” *Journal of Speech and Hearing Research,* 19(1), 55-67. doi:10.1044/jshr.1901.55.