The effects of target spectrum, noise, and reverberation on auditory cue weighting in sound localization

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science  
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THE EFFECTS OF TARGET SPECTRUM, NOISE, AND REVERBERATION ON AUDITORY CUE WEIGHTING IN SOUND LOCALIZATION

(Thesis Format: Monograph)

by

Tran Nguyen

Graduate Program in Health and Rehabilitation Science

A thesis submitted in partial fulfillment of the requirements for the degree of a Master of Science

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Abstract

Sound localization in the horizontal plane depends on interaural time difference (ITD) and interaural level difference (ILD) cues, which are both available in wideband sounds. Previous studies have directly measured listener weighting of those cues only under quiet, anechoic conditions, but not in the presence of noise and reverberation, which can degrade both ITD and ILD. This study examined the effects of changes in target spectral profile, background noise, and reverberation on sound localization performance and cue weighting strategies. Listeners reported locations of targets that were presented over headphones in virtual auditory space. ITD and ILD were manipulated by attenuating or delaying the sound at one ear, and their weighting was computed by comparing the listener’s localization response bias to the imposed cue bias. Results suggest that ITD dominates for any wideband target in quiet conditions, but that listeners increase their weighting of ILD in more adverse listening conditions.

Keywords

sound localization, auditory cue weighting, interaural time difference, interaural level difference, auditory system, binaural system, background noise, reverberation
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Chapter 1

1 Introduction

Most sound localization studies in the past have used quiet and thus unrealistic environments. However, this study will examine sound localization in both noisy and reverberant conditions, and the different strategies human listeners use, compared to sound localization in quiet conditions.

It has been shown in several sound localization studies that interaural time difference (ITD) cues and interaural level difference (ILD) cues both provide information to the listener for sound localization in the horizontal plane. We are interested in the weightings listeners give these cues when both are available. Few studies in the past have examined how listeners weight these two auditory cues in the quiet environment and none have directly examined how listeners weight these cues in noisy and reverberant environments.

Previous studies have shown that the ITDs are the dominant interaural cue in quiet environments (Wightman & Kistler, 1992; Macpherson & Middlebrooks, 2002), but we wish to determine whether the ITD will continue to be the dominant auditory cue in more realistic environments with background noise and reverberation.

Previous studies have suggested that when noise is introduced into the environment, causing interaural de-correlation of the signal, listeners will focus on other auditory cues instead of continuing to use the ITD cues (Good & Gilkey, 1996; Lorenzi et al, 1999). The purpose of this study is to establish exactly how listeners will re-weight their ITD and ILD auditory cues when the signal becomes less reliable and whether their re-weighting is appropriate to maintain accurate localization performance.
This thesis section examines the previous research done on different auditory cues used during sound localization, the weighting of auditory cues, and sound localization performance and auditory cue weighting in quiet, noisy and reverberant environments.

1.1 **Interaural time difference (ITD) cue**

In 1907 Lord Rayleigh discovered the role that interaural difference cues play in sound localization, and stated that there are two main auditory cues that listeners use to localize sounds (Rayleigh, 1907). The first cue is called the interaural time difference cue (ITD); depending on the location of the source, the sound wave will arrive at one ear before it arrives at the other as illustrated in Figure 1. The auditory system can then determine the location of the sound source based on at which ear the sound first arrived and by how much (Middlebrooks & Green, 1991). For example, if a sound were played on the right side of the listener, the sound wave would arrive at the right ear before the left ear; thus, the listener would determine that the sound was on the right side. The ITD cues can be carried both by the detailed fine structure information of low-frequency sound as well as by the amplitude envelope fluctuation of high-frequency sounds (Zwislocki & Feldman, 1956; Bernstein & Trahiotis, 1994).

The ITD works more effectively with low-frequency pure tones because at higher frequencies the ITD cues are more ambiguous to the listeners and less detectable. This is due to the fact that it becomes harder for the human brain to detect the differences in time at higher frequencies. Studies have shown that at 800 Hz the cues start to become ambiguous, and at 1300Hz the cues are completely undetectable (Zwislocki & Feldman, 1956).
ITDs are also available in high-frequency envelopes, however just noticeable differences are high relative to the low-frequency fine structure ITDs. In addition, the perceived degree of lateralization is often lower for the high-frequency envelope ITDs compared to the low-frequency fine structure ITDs as well (Zwislocki & Feldman, 1956; Bernstein & Trahiotis, 1994).

![Figure 1. A graphical representation of an interaural time difference (ITD) cue. When an acoustic signal reaches the closer ear before the more distant ear then an ITD cue occurs. Source locations farther from the midline produce larger ITDs (Stern, 2006).](image)

### 1.2 Interaural level difference (ILD) cue

The second cue is called the interaural level difference cue (ILD), which occurs when a sound is presented on either side of the head and an acoustic shadow is created when the waveform interacts with the head before arriving at the furthest ear (Yost, 2007). The amount of shadowing that is created depends upon both the position of the listener’s head and the wavelength of the sound. ILD is larger for higher frequencies because the wavelengths are shorter and the listener’s head casts a shadow when the waves interact with the head. In comparison, at lower frequencies the sound waves are larger than the
head and therefore it does not cast an effective sound wave shadow. Figure 2 below shows the interaural level difference cue for a low-frequency tone (200 Hz) compared to a high frequency tone (6000 Hz). When the high frequencies interact with the head of the listener an acoustic shadow is cast, however this does not occur for low frequencies (Middlebrooks & Green, 1991). Therefore, we can use the head shadow effect to aid in sound localization at higher frequencies (Middlebrooks & Green, 1991).

**Figure 2.** A graphical representation of an interaural level difference (ILD) cue. Part A shows the ILD of a low frequency sound (200Hz) and Part B shows the ILD of a high frequency sound (6000Hz) (Gulick, 1989).
1.3 Spectral cues

When sound sources are located on the median plane such as vertically or in a front or back direction, they may produce the same ITD and ILD values even if they are coming from different places, which make it hard to localize the sound source. Sounds coming from this region are said to be coming from the “cone of confusion” because the listener cannot localize the sound using their interaural cues alone (Shinn-Cunningham et al, 1999; Middlebrooks & Green, 1991).

Batteau thought there were direction-dependent reflections within the pinnae and we now recognize that the reflections produce direction-dependent frequency-domain filtering by the pinna, ie. spectral cues (Middlebrooks & Green, 1991; Batteau, 1967; Hebrank & Wright, 1974). These are referred to as monaural cues, however we know that spectral information from both ears is combined, therefore the information we receive is not strictly monaural (Macpherson & Sabin, 2007)

1.4 Methods of measuring cue weighting

In a wideband stimulus that includes a combination of both low and high frequencies, all the auditory cues are available to the listener.

Previous time/intensity trade-off experiments compared the influence of both cues, but done with non-externalized stimuli lacking HRTFs. A trade-off ratio is measured by a subject listening to stimuli over headphones in which the ITD is biased towards one side and the ILD is biased towards the opposite side. The listener then has to adjust the auditory cues accordingly to make the sound centered (Moushegian & Jeffress, 1959).
Results show that the trade-off ratio (in $\mu$s/dB) for low-frequency stimuli is lower than for high-frequency stimuli. This suggests that ITD is more effective compared to ILD at low frequencies (Harris, 1960).

1.5 Localization in quiet conditions

Previous studies have consistently shown that sound localization performance in quiet conditions is more accurate than sound localization in any other conditions. This is because there is no interference from background noise or reverberation to interaurally de-correlate the signal of the target stimuli (Good & Gilkey, 1996; Lorenzi et al, 1998), which would interfere with ITD, or to add energy at both ears, which would reduce ILDs.

Sound localization can be split into three different dimensions: front/back, left/right and up/down. Sound localization in the front/back dimension has been shown to be less accurate than in the up/down or left/right dimensions. This is because when we are localizing sounds in the left/right dimension the direction of sound relative to the median plane allows all the auditory cues available to us (ITD, ILD and spectral cues), whereas sound localization in the front/back dimension is mainly done with only fine spectral cues (Good & Gilkey, 1996).

The Duplex Theory of Localization considers both the ILD and ILD auditory cues and is a basis for many localization studies. The theory was originally developed by Lord Rayleigh in the early 1900s and stated that due to the ITD and ILD cues, accurate sound localization is possible in the horizontal plane (Rayleigh, 1907). For low-frequency stimuli, the ITD cues are primarily available to the listener and for high-frequency stimuli
the ILD cues are primarily available to the listener. Therefore for wideband stimuli, both ITD and ILD auditory cues are available to the listener. Previous studies have shown that low-frequency ITDs are the dominant cues for broadband sounds and that ILD are the dominant cues for localizing high-frequency sounds (Macpherson & Middlebrooks; 2002). This was demonstrated in the Macpherson and Middlebrooks study where listeners gave low weighting to ITD cues for high pass stimuli and high weighting to ITD cues for low pass stimuli. For wideband conditions, which included both low pass and high pass stimuli, the ITD weighting was either greater than or equal to that of the ILD weighting (Macpherson & Middlebrooks, 2002). These results were similar to Wightman & Kistler’s (1992), which showed that in all conditions in which the low frequency ITD cues conflict with other auditory cues, the sound source direction is largely determined by the ITD cue (Wightman & Kistler, 1992).

1.6 Sound localization with varying target bandwidths

We want to determine when we are localizing sounds, even under quiet conditions, how target bandwidth affects our localization performance. Yost et al (2013) explored this idea in a study on sound source localization of filtered noises and on whether ITD and/or ILD processing differently affected the localization performance of the listeners. The target was either a low-, mid-, or high- frequency 200-ms, 2-octave sound. The results from this study show that the sound localization performances of listeners are approximately the same for each filter condition. This means that sound localization is not differently affected by which interaural cue (ITD or ILD) a listener uses for sound localization for broadband signals (Yost et al, 2013).
A second study also done by Yost aimed to investigate the sound localization performance of listeners as a function of the stimulus bandwidth (Yost, 2013). The results from this study identified that sound localization accuracy of listeners depends on the stimulus bandwidths and for narrow bandwidths performance depends on the center frequency. As the stimulus bandwidths become increasingly narrow, performance becomes worst and for narrow bandwidths, localization performance is the best for pure tones of low frequencies, worse for mid frequencies and intermediate for higher frequencies. Therefore, if the bandwidth of a target sound source is less than two octaves wide, the listener’s sound localization accuracy is dependent on whether their ILD or ITD cues are used most. However, if the bandwidth of a target sound source is at least two octaves wide then the listener’s localization performance is not affected by which cues are used (Yost, 2013).

1.7 Localization in noisy conditions

Most of the information we have acquired about a human’s ability to localize sounds has been obtained in quiet conditions with minimal reflections, reverberation, or background noise. However, listeners’ localization of sounds with additional background noise is different from localization in quiet conditions because there are competing auditory stimuli that dilute the direct signal and distort the ITD and ILD cues. The introduction of noise during sound localization has been shown to have negative effects on the accuracy of the listener’s responses. The noise causes the interaural de-correlation of the stimulus signal, so the ITD is less reliable and harder for the listener to detect (Kolarik & Culling 2009). In addition, noise will also reduce the ILD and affect the spectral cues as well. In
order to examine the effects of noise on sound localization we must study how listeners respond to localizing targets in the presence of noise.

Previous studies have been conducted to determine whether listeners use the same auditory processes to localize sound sources in noisy conditions as they do in quiet conditions. Sound localization in noise is determined by three main factors: the signal to noise ratio (SNR), the spatial distribution of the maskers and the dimension that the listeners are localizing in (front/back, left/right and up/down).

A study by Abouchacra et al (1998) examined the localization of speech messages with competing background noise. Seventeen normal hearing listeners were asked to identify the phrase “where is this?” in quiet and noisy conditions. The noisy conditions included eleven different SNRs from -18 dB to +12 dB in 3 dB increments. The results showed that there was a linear relationship between increased localization performance and SNR increase.

However, it is not only the decreased SNR that affects a listener’s localization performance, it is also the location of the masker. This is shown in a study conducted by Good & Gilkey (1996) in which three subjects were asked to localize target sounds originating anywhere between -45 degrees and + 90 degrees in the horizontal azimuth as the SNR was manipulated. The localization performances of the listeners were examined for ten conditions, which consisted of a quiet condition and nine masked conditions with SNRs ranging from +15 to -13 dB, in relation to the subject’s masked detection threshold. The results for analysis were divided into left/right, front/back, and up/down dimensions. The final results of this study showed that localization performance of the
listeners was very accurate for the quiet conditions. The decrease in localization accuracy with reductions in the SNR varied in all three dimensions. The dimension least affected is the left/right dimension, whereas the front/back condition appears to be most affected and the up/down dimension was in between. Good & Gilkey argued that this is because localization in the left/right dimension is based on both the ITD and ILD cues, whereas localization in the front/back and up/down conditions is primarily based on the analysis of spectral cues. Therefore, since the left/right dimension depends on multiple auditory cues, then the performance in that dimension will degrade more slowly as the SNR decreases, compared to the front/back and up/down dimensions that only rely on one auditory cue (Good & Gilkey, 1998).

Another study, done by Lorenzi et al (1999), also examined the effects of masker location and sound localization performance. The study consisted of the listeners localizing an auditory target in the presence of a white noise masker at SNRs ranging from +18 to -9 dB. The auditory target was a wideband, high pass or low pass click train and was always presented in the presence of a masker noise. The listeners’ localization accuracy was unaffected by all masker locations and filtering until the SNR was reduced to 0 to -6 dB. In addition, Lorenzi et al’s results showed that if the masker is on either side of the listener (left or right) then localization tends to be poorer than if the masker was coming from directly ahead for all filtering conditions and SNRs (Lorenzi et al, 1999).

The results from Lorenzi et al’s (1999) study also demonstrated that the low-frequency ITD, the high-frequency ILD and spectral cues provided an accurate sound location in quiet conditions or when the masker was directly in front of the listener. However, when
the masker was presented to either side of the listener, the low-frequency ITD cues were less resistant to the masking noise in comparison to the high frequency ILDs. Lorenzi et al argued when more than one cue is present, listeners will base their localization on the cue that provides the most accurate sound source location (Lorenzi et al, 1999). Overall, the results of this study suggest that the listeners were able to appropriately weight the auditory cues and use the ones that were most beneficial. This is demonstrated in the finding that when both low- and high- frequency information was available, the listeners based their decision on the cues providing the most accurate estimation of the direction of the sound source, which in this case are the high frequency cues (Lorenzi et al, 1999).

Therefore, the results from these studies show that even though the weighting of the ITD cues is dominant for sound localization in quiet conditions, the ITD cues may not be the dominant cue in noisy conditions. Although we know that ITD cues aren’t always dominant in adverse listening conditions, we lack quantitative information about the weighting of the auditory cues in a noisy environment. Hence, more research is needed when it comes to measuring the weighting of the auditory cues in noisy conditions.

1.8 Localization in reverberant conditions

Not only is it important to examine sound localization in noise, it is crucial to study sound localization in reverberant conditions because the auditory processes used to localize sounds in reverberant conditions may differ from the auditory processes used to localize sounds in noisy and quiet conditions.
Reverberation has been shown to negatively affect sound localization performance because the reverberation distorts the ITD and ILD cues with its reflected energy. For ITDs, the reverberation decreases the interaural coherence of the target signal and thus decreases the reliability of ITD. For ILDs the reverberation tends to add energy to each ear causing the proportion of direct energy to be reduced, and this causes the ILD cues to become smaller and less reliable as well (Ihlefeld & Shinn-Cunningham, 2011).

Previous studies of sound localization in reverberation have shown that listeners overall perform better in anechoic conditions compared to reverberant conditions (Giguère & Abel, 1993; Ihlefeld & Shinn-Cunningham, 2011). However, even though it is harder for listeners to localize in reverberant conditions, it is still possible due to the precedence effect. The precedence effect describes the phenomenon in which the influence of reflected sounds is partially eliminated during the localization process and priority is given to the direct sound (Wallach et al, 1949; Hartmann, 1983). In a reverberant environment the sound travels in multiple directions and is also reflected off surfaces, therefore reaching the listeners’ ears through multiple paths. The first arriving waveforms dominate the perception of the sound source location. The early reflections of the direct sound are between 1-5 ms of the initial sound and are still perceptually fused with the direct sound. Therefore, we hear the direct sound and early reflections as one unit. However, if there is a large delay between the direct sound and reflections the sound is then heard as two separate sounds. Our auditory system must resolve which is the direct sound and which are the reflections (Yost, 1999). Direct measurements of the temporal weighting of ITD and ILD cues show that listeners weight ITD and ILD cues strongly at stimulus onset (Stecker et al, 2013) and during
rising portions of the amplitude envelope (Dietz et al, 2013). Unlike ITD, ILD cues are strongly weighted both at onset and at offset (Stecker et al, 2013). Therefore, in reverberation listeners benefit from onset weighting since the cues are more accurate at the stimulus onset and become more ambiguous during the steady state reverberation.

In addition to the precedence effect and the signal onset, sound localization performance in reverberation is also dependent on: target location, direct to reverberant ratio (DRR, which is the amount of direct sound waves compared to the amount of reflected sound waves), and reverberation time (Hartmann, 1983).

A study by Giguère & Abel (1993) assessed the effects of reverberation time (absorbent vs. reverberant room), stimulus rise/decay time (5 vs 200 ms) and speaker placement on the sound source localization performance of four individuals. The speaker array was either a lateral array with speakers positioned from the front to the back of the listener (0 degrees to 180 degrees), or a frontal array that had speakers positioned from the left to the right of the listeners (+90 degrees to -90 degrees). The final results of the study showed that listeners localize better in absorbent compared to reverberant conditions, the effect of the rise/decay time was not significant, and the sound localization performance of the listeners was strongly dependent on the speaker array. Listeners performed better in the frontal speaker array because the lateral array caused frequency dependent front/back confusions. Lastly, increasing the reverberation time resulted in an overall decrease in the accuracy of sound localization performance (Giguère & Abel, 1993).
Due to the fact that listeners use different processes to locate target sounds in reverberant conditions, previous studies have indirectly investigated which auditory cues listeners use when localizing a target sound in the presence of reverberation. Studies conducted by Ihlefeld & Shinn-Cunningham (2011) and Bharadwaj (2013) both showed that listeners do not always optimally weight their ITD and ILD auditory cues in reverberation.

In the first experiment, Ihlefeld & Shinn-Cunningham (2011) assessed how listeners localized narrowband bursts of noise centered at 750 Hz (ITD emphasis) and 6 kHz (ILD emphasis). In the second experiment, they examined performance when listeners localized sounds with both low- and high-frequency bursts presented simultaneously.

They wanted to assess whether listeners combined localization performance from both their ITD and ILD cues to achieve optimal accuracy. The results from the first experiment showed more accurate results for the high frequencies compared to low frequencies, suggesting that ILDs are less susceptible to the damaging effects of reverberation. In the second experiment, the results showed that listeners do not combine their localization performance from high- and low-frequency components to accurately localize sounds. Instead, combined low- and high-frequency stimuli resulted in less accurate localization performance compared to high-frequency noise, but equal to or better than low-frequency noise (Ihlefeld & Shinn-Cunningham, 2011).

A study by Bharadwaj et al (2013) consisted of a series of localization experiments using low-pass, high-pass and broadband speech in both anechoic and reverberant conditions. The objective was to assess the importance of high-frequency ILD cues and envelope ITD cues for spatial judgments in reverberant rooms. The results from this study showed
that the localization inaccuracy due to the addition of reverberation and the performance of the listeners is dependent on the target spectrum (wideband, low-pass of high-pass). The imposed reverberation was least disruptive with high pass speech and most disruptive with low-pass speech. High frequencies are less affected by the de-correlation from reverberation compared to low frequencies (Bharadwaj, 2013). Therefore, the results from the Ihlefeld & Shinn-Cunningham and Bharadwaj et al studies suggests that listeners continue to weigh ITD cues more heavily, even in adverse listening conditions when it is not advantageous to do so. This is because both studies illustrated that although high frequencies are more reliable in adverse conditions, the listeners will still weigh their ITD cues more heavily in comparison to their ILD cues.

Research has also tried to identify whether the fine structure or envelope ITD cues are more useful in reverberant settings. Previous studies show that the envelope ITDs are more susceptible to reverberation in comparison to the fine structure ITDs (Devore & Delgeutte, 2010; Rackerd & Hartmann, 2010; Monaghan et al, 2013).

Both the Monaghan et al (2013) and Rackerd & Hartmann (2010) studies looked at the effects of reverberation on ITD discrimination. These results suggest that much higher levels of binaural coherence are required to detect envelope ITD cues than fine structure ITD cues (Rackerd & Hartmann, 2010). Monaghan et al (2013) alternatively examined the discrimination thresholds for fine structure ITDs at low frequencies and envelope ITDs at high frequencies. The stimulus was either a low-frequency narrowband noise or the same noise transposed to a higher frequency. The results showed that the envelope ITD thresholds were significantly higher than the fine structure ITD thresholds, meaning
the effects of reverberation were more detrimental to the envelope ITD cues than the fine structure ITD cues. Therefore, both Monaghan et al (2013) and Rackerd & Hartmann (2010) showed similar findings that the envelope ITD cues are less resistant in reverberation compared to the fine structure ITD cues.

The Devore & Delgutte (2010) study was conducted from a neurophysiological perspective, and measured the directional sensitivity of single neurons in the inferior colliculus of rabbits. The results of this study showed that when both ITD and ILD cues were available in reverberation, the high-frequency ILDs provided better directional information than the ITDs. However, when only the ITDs were available, the low-frequency-sensitive cells with fine structure information maintained better directionality in reverberation compared to the high frequency ITD cues (Devore & Delgutte, 2010). Contrary to this finding and that of Monaghan et al (2013), a neurophysiological study conducted by Ruggles et al (2012) showed listeners’ fine structure ITD information was more disrupted by reverberation than were their envelope ITDs.

1.9 Conclusion

The results from the studies reviewed show that even though the weighting of the ITD cues is dominant for sound localization in quiet conditions, the ITD cues may not be the dominant cue in more adverse environments such as noisy or reverberant conditions. Although we know that ILD cues are more beneficial to listeners in adverse listening conditions, we do not know why the listeners continue to give a higher weighting to their ITD cues. Thus, more research is required when it comes to measuring the weighting of auditory cues in noisy and reverberant conditions.
Chapter 2

2 General Design and Methods

2.1 Objective

Most sound localization studies in the past have used quiet and thus unrealistic environments. In contrast, this study will examine sound localization in quiet, noisy and reverberant conditions and the different strategies human listeners use. The study will assess listeners’ weighting of low- and high-frequency localization cues in quiet conditions with a varying target spectrum, as well as in noisy and reverberant conditions. The purpose of this study is to establish how listeners will re-weight their ITD and ILD auditory cues when the signal becomes less reliable and the possible consequences of the re-weighting of cues, such as a decrease in their sound localization performance. In order to assess the listeners changing weighting of ITD and ILD cues in noisy and reverberant environments, we measured the weighting of the low- and high-frequency cues first in a quiet environment and then in noisy and reverberant environments.

The following is an outline of what we sought to examine:

1. Whether altering the balance of low and high frequency energy in wideband stimuli will affect listeners’ auditory cue weighting during sound localization.

2. Whether placing a masking noise at high or low frequencies will affect the auditory cue weighting during sound localization.

3. Whether placing reverberation at high or low frequencies will affect the auditory cue weighting during sound localization.
4. Whether having a low SNR or direct to reverberant ratio (DRR) impacts the auditory cue weighting during sound localization.

5. Whether the re-weighting of auditory cues in noisy and reverberant environments accounts for observed changes in localization performance.

2.2 Hypotheses

Evidence from previous literature and from the results of a pilot study allowed for predictions to be made about the sound localization performance of listeners in quiet, noisy and reverberant environments. We predicted the localization performance of listeners in quiet to be accurate, and in reverberant or noisy environments, that listeners will adapt their weighting of low- and high-frequency ITD and ILD cues to maximize their localization performance. Listeners will start using their ILD cues instead of their dominant ITD cues when the low frequencies are interaurally de-correlated. In contrast, listeners will start using their ITD cues instead of their ILD cues when the high-frequency ILDs are reduced by the presence of noise or reverberation. In quiet, the balance of low- and high-frequency energy in a wideband stimulus will influence ITD and ILD weighting.

The specific hypotheses for the study are as follows:

1. Sound localization will be accurate in quiet conditions with wideband target stimuli.

2. Increasing the target’s high-frequency energy will increase the ILD weight, and decreasing the high-frequency energy will reduce the ILD weight and increase the ITD weight.
3. When a masker is placed at lower frequencies, listeners will pay more attention to the ILD cues than the ITD cues. However, when the masker is placed at higher frequencies, listeners will pay more attention to the ITD cues than the ILD cues. Regardless of the frequency of the masker, a low SNR will have an adverse effect on the listeners’ sound localization accuracy.

4. When reverberation is disrupting the ITD cues, the listener will start paying more attention to the ILD cues and when the reverberation is masking the ILD cues, the listener will use their ITD cues.

5. The listeners’ localization performance will decrease with decreasing SNRs and DRRs.

Previous studies have shown that listeners give a higher weighting to ITD cues when the target sound consists of low frequencies and listeners give a higher weighting to ILD cues when the target sound consists of high frequencies. However, this is the first study to quantitatively measure auditory cue weighting with a wideband stimuli with altering low and high frequency content. It is also the first study to measure the auditory cue weighting of a listener with different target masker combinations at varying SNRs and DRRs. Thus, hypotheses 2, 3, and 4 are novel to this study.

2.3 Overview

This study consisted of three related experiments. The first experiment examined the effect of target spectral profile on listeners’ auditory cue weighting during sound localization in a quiet condition. The second experiment examined the listeners’ auditory cue weighting during sound localization in a noisy environment, and the third experiment
in a reverberant condition. This chapter describes the experimental methods common to all three experiments.

2.4 Participants

Sixteen normally hearing listeners (13 females, 2 males, age range= 21-28 years, mean age= 23 years) participated in the quiet condition of the experiment, eight (8 females, mean age=23 years) of those listeners went on to participate in the noisy condition, and seven (5 females, 2 males, mean age= 23 years) of those listeners went on to participate in the reverberant condition, as one participant withdrew from the latter part of the study. All the participants gave informed consent in accordance with ROMEO ethics at Western University. Participants were all recruited from Western University. All participants were compensated $15/an hour for their participation in the study.

G Power software (Erdfelder, Faul, & Buchner, 1996) was used to estimate the required sample size for the study. A large effect size (1.25) was estimated from a pilot data set by taking differences between the mean cue weighting coefficients in representative conditions and dividing by their pooled standard deviations. An alpha of 0.05 and a power of 0.8 were also used in the calculation. Based on that effect size, G Power computed that a total of 6 participants in each condition would be required to achieve the alpha and power that we desired for the study. However, to ensure the validity and reliability of the study and to allow for dropouts, we instead recruited eight subjects in each condition.

2.4.1 General Inclusion Criteria

Participants in this study had to be between the ages of 18-35, and to be able to pass an initial hearing screening to demonstrate normal hearing. The hearing screening consisted
of standard pure-tone audiometric testing and participants had to be able to demonstrate pure tone thresholds of 20 dB HL or less at octave frequencies between 125 and 8000 Hz. Participants also had to be able to perform an initial sound localization task prior to testing in which they demonstrated whether they were able to correctly identify the majority of target sound sources in a quiet environment.

2.4.2 Exclusion Criteria

Participants were ineligible to participate in the study if they demonstrated any of the following issues:

1. History of vestibular/balance disorders or dizziness, because the participant might be at risk during sound localization tests that involve head movement;

2. Lack of neck and/or back flexibility that might limit the ability of the participant to orient their head towards a sound source during sound localization tests;

3. Reporting of active external ear canal pathology and/or active middle ear dysfunction;

4. Current use of ototoxic medication;

5. Difficulty standing and/or sitting for extended periods of time, because sound localization tests were performed in these positions and were sometimes more than two hours in duration.

2.5 Apparatus and Materials

The experiment was conducted in the anechoic chamber, a darkened soundproof and echo-free room, at The National Centre for Audiology, University of Western Ontario.
The participants stood on a platform within a circle of loudspeakers in the center of the chamber. During the experiment they wore an electromagnetic tracker (Polhemus FASTRAK) mounted on their head, to track the position of their head in space in real time. The participants’ head-orienting responses regarding a sound source’s apparent location were recorded by pressing a button on a hand held device provided for them. The auditory stimuli used were presented by means of circumaural headphones (Beyerdynamic DT-990-Pro) using previously recorded individualized head related transfer functions (HRTFs). The target presentation and additional masking noise presented over headphones were required to simulate the sound source relative to the head in the quiet, noisy and reverberant condition.

2.6 HRTF Measurement

The measurements of ear directionality were performed on each research participant to acquire the individualized HRTFs necessary to generate accurate sounds to present to each listener over headphones in subsequent parts of the study. The measurements were created by inserting miniature omni-directional electret microphones (Knowles FG3629) into ear-plugs (ER1-14B, with tubing removed), which were then placed in the listeners’ ear canal. Participants were then instructed to stand motionless on a platform in the center of the anechoic chamber while maximum-length sequence (MLS) excitation signals (Rife & Vanderkooy, 1989) were played at a sampling rate of 48828 Hz via a RX6 realtime processor (Tucker Davis Technologies) from a circular array of 16 loudspeakers (Tannoy i5AW, amplified by CX18 amplifiers, QSC Audio) placed 22.5 degrees apart from one another. Foam was placed on the ground surrounding the listener to prevent any reflections that might interfere with the results of the experiment. The listeners were
equipped with a head mounted LED and electromagnetic tracker (Polhemus FASTRAK), and were asked to aim the light directly in front of them at 0 degrees azimuth. This was to help prevent head movement during the measurement. Each loudspeaker-to-ear HRTF impulse response was computed by deconvolving the MLS from the ear microphone signal recorded by the RX6. In order to correct for individual loudspeaker characteristics, each individual HRTF measurement was divided by the appropriate loudspeaker transfer function, which was previously measured with a reference microphone (Brue & Kjaer 4189) placed in the center of the array of loudspeakers. Any unwanted reflections in the impulse responses were removed after processing. Figure 3 shows an example left-right-pair of computed impulse responses. Headphone equalization filters were derived from impulse responses measured from the headphones to be used for localization stimulus presentation (Beyerdynamic DT-990-Pro) to the ear microphones.

Figure 3. An example of the impulse response obtained during HRTF measurements. The red impulse response represents the right ear, and the blue impulse response represents the left ear. The graph illustrates the impulse responses coming from the -90 degrees speaker positioned to the left of the listener. At -90 degrees the sound would reach the listener’s left ear before their right ear, thus the blue impulse response should occur earlier than the red impulse response. The x-axis shows time in samples at a rate of 48828 samples/s.
2.7 Target Stimuli

The target sounds and masker were all presented over headphones using the listeners’ individual HTRFs, after which the ITD or ILD bias was imposed. The target sounds were presented at 65 dB SPL in the quiet condition and at levels from 55 to 80 dB SPL in the noisy and reverberant conditions depending on SNR or DRR. The stimulus duration was 100 ms and the onset and offset ramps for the stimuli were 1 ms. For each target, 56 combinations of target location and imposed bias were presented. For 16 of these, no bias was imposed, and the locations corresponded to the 16 loudspeaker locations surrounding the listener spaced by 22.5 degrees. For each of the ten locations lying between -45 and +45 degrees in the front and between -135 and +135 degrees in the rear, the target was also presented with an ILD bias of +10 dB or -10 dB or an ITD bias of +300 µs or -300 µs. The target locations are illustrated in Figure 4.
Figure 4. An illustration of speaker and virtual target positions. The sounds were presented 360 degrees around the subject, at every 22.5 degrees. The HRTFs were measured from all 16 locations. Unbiased virtual targets were presented from all 16 locations, and ITD- and ILD-biased virtual targets were presented from the 10 locations indicated by the filled speaker symbols.

2.8 Auditory cue weighting measurement

The approach to ITD and ILD manipulation and weight computation was adapted from Macpherson & Middlebrooks (2002). Stimuli were 100-ms bursts of noise filtered by the left- and right-ear HRTFs for the desired location. ITD bias was implemented by delaying the signal in one ear or the other by 300 µs. Bias of the ILD auditory cue was established by increasing the sound’s volume by 5 dB in one ear and decreasing the volume in the other ear by 5 dB to produce an additional 10 dB difference between the two ears (Figure 5). The imposed ITD and ILD biases (10 dB and 300 µs) correspond to approximately the same amount of angle change for a wideband stimulus.

Listener weighting of the manipulated cues was determined by examining the resulting localization response biases. The bias response of the listener was computed by
comparing the localization response of the listener to the actual location of the stimulus as described below.

Figure 5. An illustration depicting the biased virtual auditory space stimulus generation, for both the ILD bias (left) and ITD bias (right). The right picture shows the imposed ILD bias with the sound attenuated at one ear and amplified at the other ear after going through the directional transfer function filters. The left picture shows the imposed ITD bias with the sound only delayed at one ear after going through the directional transfer function filters. Adapted from Macpherson & Middlebrooks (2001)

2.9 Presentation Procedure

Participants made multiple visits to the National Centre for Audiology (NCA) in Elborn College, Western University. The majority of the testing took place in the anechoic chamber and the other portion of the study took place in the soundproof booth in the Hearing Science Lab. During the first visit (30-60 minutes) the tasks involved in the study were explained to the participants, and it was ensured that they met the criteria for participation. This included administering a hearing test and obtaining information about age and any history of hearing, vision, balance, or flexibility problems. Participants that did not meet the eligibility criteria were not asked to participate in the
study. During each subsequent visit (each 1-1.5 hours long, up to 14 visits over several weeks based on participant and laboratory availability), participants were asked to participate in one or more of these types of activities: measurements of ear directionality and tests of sound localization. Participants were familiarized with each of the sound localization tasks prior to data collection in order to minimize learning effects. In the study, there are three experimental conditions: sound localization in quiet conditions, sound localization in noisy conditions and sound localization in reverberant conditions. The participants were expected to finish either the quiet condition and noisy condition, or the quiet condition and reverberant condition.

Participants were given training, practice and testing in the tasks that involved the localization of sound sources. Participants stood on a platform centered within a circle of loudspeakers located in the anechoic chamber at the NCA. Participants wore a cap that had a sensor to monitor the orientation of their head. Brief sounds were played at a comfortable volume from the headphones, and participants were asked to indicate the apparent position of the sound source. Participants were asked to point their nose toward the location of the target sound, then to press a response button on the hand held device given to them, which caused a computer to record the head position for every response. Each sequence of trials lasted for 8-12 minutes. In a 60-90-minute visit to the laboratory, participants would complete as many sequences of trials as possible with a rest period after every 1-3 sequences depending on their length. We then examined their localization error patterns and computed how the imposed ITD and ILD biases affected the participant’s performance in the quiet, noisy and reverberant conditions.
2.10 Analysis

Figure 6 depicts sound localization examples, for the wideband condition, of response azimuth versus target azimuth for subject L107. The x-axis is the target lateral angle (left/right angle disregarding front/back location) in degrees and the y-axis is the response lateral angle in degrees. The listener’s localization response to the target lateral angle was plotted in the scatterplot, and a line of best fit (Figure 6, red line) was then fit through the data. The y-intercept of this line represented the listener’ mean leftward or rightward response bias. The slope of this line, the lateral angle gain, represented the listener’s sensitivity to changes in target lateral angle, and for trials without imposed ITD or ILD bias, was taken as a metric of localization performance. Other localization performance metrics were the lateral angle scatter (the RMS deviation of individual responses from the regression line), and front/back percent correct (percentage of trials in which front/rear hemisphere was correctly identified regardless of other errors).

Values related to the listener’s weighting of a particular cue were computed by finding the regression coefficient between the applied cue bias values and the response shift values. A regression coefficient near zero will indicate that the applied cue bias had little effect (and therefore that the listener was not weighting that particular cue heavily), whereas a large regression coefficient would indicate a large effect of the bias and therefore a large perceptual weight on the biased cue. The graphs illustrate that the ILD bias caused larger response shifts (values in degrees in the top left of each panel) than did ITD bias for the target spectrum in this example.
Figure 6. Sound localization responses for listener L107 for a wideband noise stimulus in quiet with an imposed ITD (top panel) and ILD (bottom panel) bias. The x-axis is the target lateral angle (deg) and the y-axis is the response lateral angle (deg). Each circle symbol indicates the listener's response to one target sound, and the red line represents the line of best fit. The number in the upper left of each graph is y-intercept of the regression line, and represents the listener's response bias.

The listener’s weighting of ITD and ILD was determined from the relationship between the imposed cue biases and the resulting response biases. Figures 7 and 8 show the response biases of listener L107 as a function of imposed ITD bias and ILD bias for a wideband noise stimulus. The y-axis represents the amount in degrees that the listener’s responses shifted in response to the imposed bias and the x-axis represents the imposed ILD or ITD bias (in µs or dB).
Figure 7. The ITD response bias (top panel) graph for listener L107. The x-axis is the amount of imposed ITD bias (µs), the y-axis is the response bias of the listener (deg) and the red line is the line of best fit. The ITD bias slope in the bottom right corner indicates that the listener moves 0.049 degrees for every µs imposed.

Figure 8. The ILD response bias (top panel) graph for listener L107. The x-axis is the amount of imposed ILD bias (dB), the y-axis is the response bias of the listener (deg) and the red line is the line of best fit. The ILD bias slope in the bottom right corner indicates that the listener moves 0.89 degrees for every dB imposed.
2.11 Outline of testing sequence

The sequence of testing and number of subjects involved in the Quiet, Noisy, and Reverberant experiments are summarized in Table 1.

Table 1. The table illustrates the progression of the listeners in the study

<table>
<thead>
<tr>
<th>Session</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (16 subjects)</td>
<td>Screening, demographics, enrollment, demonstration, scheduling</td>
</tr>
<tr>
<td>2 (16 subjects)</td>
<td>Measurement of ear directionality (HRTFs) and practice sound localization tasks in free-field conditions</td>
</tr>
<tr>
<td>3 (16 subjects)</td>
<td>Practice sound localization task in virtual condition (over headphones using individualized HRTFs)</td>
</tr>
<tr>
<td>4-6 (16 subjects)</td>
<td>Sound localization in Quiet condition over headphones (3 repetitions)</td>
</tr>
<tr>
<td>7-12 (7 subjects in noisy condition) (8 subjects in reverberant condition)</td>
<td>Sound localization in Noisy condition over headphones (2 repetitions)</td>
</tr>
</tbody>
</table>

2.12 Conclusion

This chapter outlined the presentation procedure and weighting analysis used throughout the three different experiments. In Chapter 3 the weighting analysis was used to examine the influence of low- and high-frequency energy balance on cue weighting in wideband stimuli. In Chapter 4 the weighting analysis was used to examine the cue weighting in different SNRs and in Chapter 5 the weighting analysis was used to examine the cue weighting in different DRRs.
Chapter 3

3 Experiment I: Quiet - Effect of spectral profile on cue weighting and localization performance

3.1 Objective

The purpose of this study is to examine the effect of target spectrum on the listeners’ cue weighting and localization performance. Experiment I sought to assess several questions. First of all, whether altering the balance of low and high frequency energy on cue weighting in wideband stimuli will affect the auditory cue weighting of listeners during sound localization. Secondly, whether the sound localization performance of the listeners varies across the nine different spectra, and lastly, to examine the possible consequences of the re-weighting of auditory cues in noisy and reverberant environments.

3.2 Hypotheses

Based on the results from the Macpherson and Middlebrooks (2002) study, we developed the following hypotheses for sound localization of low and high frequency energy on cue weighting:

1. Sound localization will be accurate in quiet conditions with wideband target stimuli.
2. Increasing the high-frequency energy will increase the ILD weight and decrease the ITD weight.
3. Decreasing the high-frequency energy will reduce the ILD weight and increase the ITD weight.
3.3 **Methods**

In the quiet experiment we determined how weighting of ITD and ILD cues varied with the low- and high-frequency energy balance in wideband stimuli. As described in Chapter 2 (General Methods), listeners reported the apparent locations of targets that were presented over headphones using individual HRTF’s. ITD and ILD cues were manipulated by attenuating or delaying the sound at one ear (by up to 300μs or 10 dB). Listener weighting of the manipulated cues was determined by examining the relationship between then imposed cue biases and the resulting localization response biases. The response bias of the listener was computed by comparing the localization response of the listener to the actual location of the stimulus. In the quiet condition trials, a portion of the trials had an imposed ITD and ILD bias and a portion of the trials had no imposed bias.

3.4 **Stimuli**

The quiet condition used nine different stimulus spectra. Stimuli were 100-ms bursts of noise whose spectra were low-pass (LP), high-pass (HP), or flat from 0.5 to 2 kHz and from 4 to 16 kHz with a level difference between those low- and high-frequency ranges varying in 10-dB steps from -30 to +30 dB as shown in Figure 9. The wideband profiles will be referred to by the high-to-low level difference (“+30”, “-20”, etc.) except for the flat profile, which will be labeled WB.
The quiet condition used nine different spectra with a target level of 65 dB SPL. For each target spectrum, the 56 combinations of target location and imposed bias described in Chapter 2 were presented. Given the nine target spectra and 56 location/bias combinations, a complete set of stimuli consisted of 504 trials. The 504 trials were randomized and then broken down into 6 smaller blocks of 84 trials that were more manageable for the listener to complete during testing. Each block took approximately 7-9 minutes to complete, depending on the listener’s pace, and each block was repeated three times for a total of 18 blocks and 1512 trials. Listeners L101 and L108 completed only two repetitions of the stimulus set, while L113 and L116 each missed a single block of trials out of 18 total blocks in the quiet condition, which may have affected their results. Listeners L101 and L108 have large standard deviations in their individual ILD bias condition for the high-pass spectrum compared to

Figure 9. The nine different target spectral profiles used in the quiet condition. The y-axis corresponds to the relative level (dB) and the x-axis corresponds to the frequency (kHz) of the stimulus spectra. The ITD and ILD labels indicate that the most salient ITD cues are available at low frequencies and the most salient ILD cues are available at high frequencies.
the other listeners. In addition, listeners L108 and L116 have large standard deviations in their individual ITD bias condition for the wideband spectrum compared to the other listeners. (See Figures 12 and 13 below).

3.5 Results

The following graphs are: raw data examples of a representative subject in all conditions (Figures 10 and 11), the individual subject weighting functions in all conditions (Figures 12 and 13), and the mean weighting of the ITD and ILD cues across subjects (Figures 14 and 15).

In the scatterplots (Figures 10 and 11), the x-axis is the imposed bias and the y-axis is the listener’s response bias. In the ITD scatterplots (Figure 10), the middle scatterplots show accurate sound localization performance when there is no imposed bias. The listener responds to the imposed ITD bias for the spectral profiles containing low frequency information. In the ILD scatterplots (Figure 11), the middle scatterplots also show accurate sound localization performance when there is no imposed bias. The listener responds to the imposed ILD bias for the spectral slopes containing more high frequencies (+20, +30 and HP).
Figure 10. An example of subject L017’s sound localization scatterplot with an imposed ITD bias. The middle scatter plots have no imposed ITD bias, the scatter plots on the right have a +300 µs imposed bias to the right of the listener and the scatter plots on the left have a -300 µs imposed bias to the left of the listener. The x-axis is the target lateral angle (deg) and the y-axis is the response lateral angle (deg). The symbols, lines and numbers are similar to those in Figure 6.

The graphs in the middle section have no imposed bias, the graphs on the right have an imposed bias of +300 µs to the right of the listener and the graphs on the left have an imposed bias of -300 µs to the left of the listener. Each row of three panels corresponds to a single target spectrum increasing in high-to-low energy balance from LP to WB in the left group of panels and continuing from +10 to HP in the right group. Red lines are the linear fits to the target and response lateral angle data, and the values in the top left of each panel indicate the response bias values derived from the fit.
Figure 11. Sound localization with an imposed ILD bias in the quiet condition. Responses for subject L107. The middle scatter plots have no imposed ITD bias, the scatter plots on the right have a +300 µs imposed bias to the right of the listener and the scatter plots on the left have a -300 µs imposed bias to the left of the listener. The x-axis is the target lateral angle (deg) and the y-axis is the response lateral angle (deg).

The graphs in the middle section have no imposed bias, the graphs on the right have an imposed bias of +10dB to the right of the listener and the graphs on the left have an imposed bias of -10dB to the left of the listener.
3.5.1 Individual weighting functions

Figure 12 and 13 show the individual weighting patterns of subjects for the different spectral profiles. The ILD bias weighting function shows that listeners start to increase their ILD weighting as the amount of high frequencies increase. In comparison, the ITD bias weighting function shows that listeners’ ITD weighting is relatively constant until the low frequencies are completely removed in the high-pass condition.

Figure 12. Auditory cue weighting function of each subject in the quiet condition with an imposed ILD bias. The x-axis represents the nine different spectral profiles ranging from a low-pass spectrum containing only low frequencies to a high-pass spectrum containing only high frequencies. The y-axis represents the ILD bias slope.
Figure 13. Auditory cue weighting function of each subject in the quiet condition with an imposed ITD bias. The x-axis represents the nine different spectral profiles ranging from a low-pass spectrum containing only low frequencies to a high-pass spectrum containing only high frequencies. The y-axis represents the ITD bias slope.
3.5.2 Mean ILD and ITD weighting patterns

The general trend in the mean ILD weights (Figure 14) illustrates that as the amount of high frequency information is increased in the target spectra, the listeners start to increase the reliance or weighting of their ILD cues. The general trend of the mean ITD weights (Figure 15) shows that increasing the low-frequency content in the target sound does not cause an increase in the listeners weighting of the ITD cue.

Figures 14 and 15 include a right-hand y-axis indicating the “normalized weighting”. A value of 1 on this scale corresponds to the reciprocal of the mean slope of wideband ILD-versus-azimuth or ITD-versus-azimuth functions measured in the listeners’ HRTFs. This is the value of bias slope that would be expected if listeners fully weighted a single cue and disregarded the other. For target spectra from LP to +20, the normalized ITD weight is much higher than the ILD weight, thus it is reasonable to say that ITD dominates for those spectra.
Figure 14. The mean ILD weighting (bias slope) across listeners for each target spectral profile in the quiet condition. The x-axis consists of the nine different spectral profiles that are arranged from a low-pass spectrum with only low frequencies to a high-pass spectrum with only high frequencies. The y-axis represents the ILD bias slope. The normalized cue weighting on the right hand y-axis is the value of bias slope that would be expected if listeners fully weighted a single cue and disregarded the other.

Figure 15. The mean ITD weighting (bias slope) across listeners for each target spectral profile in the quiet condition. The x-axis consists of the nine different spectral profiles that are arranged from a low-pass spectrum with only low frequencies to a high-pass spectrum with only high frequencies. The y-axis represents the ITD bias slope. The normalized cue weighting on the right hand y-axis is the value of bias slope that would be expected if listeners fully weighted a single cue and disregarded the other.
To test the statistical significance of these trends, a one-way repeated measures ANOVA was conducted for ILD. The analysis indicated that there was a significant main effect of spectral profile on ILD weighting ($F (8,104)= 37.399, p= 0.000$). When post-hoc pairwise comparisons based on the 95% confidence interval were applied, the results demonstrated that there were multiple significant differences between the +30 slope condition and all the spectral slope conditions except for the high-pass condition and the +20 slope condition and the −30 slope condition. Overall, the results show that increasing the amount of high frequencies in the spectral profiles increases the listeners’ ILD cue weighting.

Table 2. The P-values of the significant differences between each of the spectrum for the imposed ILD bias condition.

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th>-30</th>
<th>-20</th>
<th>-10</th>
<th>WB</th>
<th>+10</th>
<th>+20</th>
</tr>
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<tr>
<td>+20</td>
<td>P=.003</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>+30</td>
<td>P=.000</td>
<td>P=.000</td>
<td>P=.000</td>
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<td>P=.001</td>
<td>P=.004</td>
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<tr>
<td>HP</td>
<td>P=.000</td>
<td>P=.001</td>
<td>P=.000</td>
<td>P=.000</td>
<td>P=.001</td>
<td>P=.000</td>
<td>P=.007</td>
</tr>
</tbody>
</table>

To test the statistical significance of these trends, a one-way repeated measures ANOVA was conducted for ITD. The analysis indicated that there was a significant main effect of spectral slopes on ITD weighting ($F (8,104)= 85.637, p=0.000$). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results demonstrated that there were multiple significant differences between the spectral slope conditions. The significant differences existed between the high-pass condition and all
the spectral slope profiles except for the +30 spectral slope condition. Overall, the final results show that emphasizing low frequencies does not change the ITD or ILD weighting. However, emphasizing higher frequencies increases the ILD weight and decreases the ITD weight.

Table 3. The P-values of the significant differences between each of the spectrum for the imposed ITD bias condition.

<table>
<thead>
<tr>
<th>LP</th>
<th>-30</th>
<th>-20</th>
<th>-10</th>
<th>WB</th>
<th>+10</th>
<th>+20</th>
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<tbody>
<tr>
<td>HP</td>
<td>P=.005</td>
<td>P=.000</td>
<td>P=.000</td>
<td>P=.000</td>
<td>P=.000</td>
<td>P=.000</td>
</tr>
</tbody>
</table>

3.5.3 Sound Localization Performance

The listeners’ sound localization performance was measured by the lateral angle gain, lateral scatter, and front/back percent-correct, as described in Chapter 2, and is plotted in Figure 16. The results show that the adjustment in the auditory cue weighting maintained the sound localization performance of the listeners across the nine different spectral profiles, and there were no significant main effects in the lateral angle gain. However, there was a significant main effect between the spectral slopes in the lateral scatter and front/ back percent correct condition. The low-pass slope had a lower front/back percent correct compared to the other spectral slopes. A possible explanation for this could be that the listeners did not have access to high-frequency spectral cues with the low-pass spectra, thus they were not able to resolve their front/ back confusions.
Figure 16. Sound localization performance measures in the quiet condition. The top bar graph is the mean lateral gain of all the listeners, the middle graph is the mean lateral scatter and the bottom graph is the front/back percent correct. The y-axis is the sound localization performance measure and the x-axis consists of the nine different spectral profiles.
The x-axis is the spectral profile and the y-axis in the first graph is the lateral gain of the listeners, the y-axis in the second graph is the lateral scatter of the listeners and y-axis in the bottom graph is the front/back percent correct.

To test the statistical significance of these trends a one-way, a repeated measures ANOVA was performed, which showed a significant main effect of spectral profile on lateral scatter (F (8, 120) = 2.39, p=0.0198) and on front/back percent correct (F (8, 120) = 21.09, p=0.000).

When post hoc comparisons based on the 95% confidence intervals were applied, the results showed a significant difference in the lateral scatter condition between the high-pass profile and the LP, -30, -20, -10 and WB profiles. There was also a significant difference between the -10 and WB spectra. Table 4 shows all the p-values for the lateral scatter condition. In the front/back percent correct measure there was a significant effect between the spectral slopes, however, when a post hoc analysis done with a Bonferroni correction factor was applied, it resulted in no significant differences between the spectral slopes.

Table 4. The P-values of significant differences between each of the spectrum for the lateral scatter sound localization measure.

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th>-30</th>
<th>-20</th>
<th>-10</th>
<th>WB</th>
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<tr>
<td>HP</td>
<td>p=0.0070</td>
<td>p=0.0235</td>
<td>p=0.466</td>
<td>p=0.0020</td>
<td>p=0.0244</td>
</tr>
<tr>
<td>-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>p=0.0244</td>
</tr>
</tbody>
</table>
3.6 Discussion

The low-pass, high-pass and wideband results are in accordance with the duplex theory of sound localization and with the findings of Macpherson & Middlebrooks (2002). The low-pass condition yielded a high ITD weighting and low ILD weighting. In comparison, the high-pass condition resulted in a high ILD weighting and a low ITD weighting and the wideband condition resulted mainly in a high ITD weighting.

The ILD bias condition findings were consistent with the proposed hypothesis. As the high-frequency energy in the wideband target stimuli increased, the listeners’ ILD weighting also increases. It was expected that listeners would increase their ILD weighting as the high frequency energy is increased because listener’s predominately use their ILD cues when localizing high frequency sounds.

However, the ITD bias condition findings were inconsistent with the proposed hypothesis because as the low-frequency energy in the wideband target stimuli is increased, the listeners’ ITD weighting did not change. It was expected that as the low-frequency energy in the wideband target stimuli is increased, the listeners would also increase their ITD weighting because listeners predominately use their ITD cues when localizing low frequency sounds.
The sound localization performance of the listeners across the nine different stimulus spectra was approximately equal. The results of this study show that the frequency of the target bandwidth does not affect the sound localization performance of the listeners if the target stimulus is 2-octave or higher. This finding related to Yost’s finding (Yost, 2013) which showed listeners had the same localization performance across low-pass, high-pass and wideband 200-ms, 2-octave target stimuli. The results of the Yost (2013) study show that the listeners’ sound localization isn’t affected by the frequency of the stimulus spectrum if the target stimulus is 2-octave or higher in bandwidth. The results of Experiment II are discussed in more detail in Chapter 6.
Chapter 4

4 Experiment II: Noise - Effect of target spectrum, noise spectrum, and SNR

4.1 Objective

The purpose of this experiment is to establish exactly how listeners will re-weight their ITD and ILD auditory cues when the signal becomes less reliable, and the possible consequences of the re-weighting of cues. In order to assess the listeners’ changing weighting of ITD and ILD cues in noisy environment, we measured the weighting of the low and high frequency cues in a noisy environment.

Experiment II sought to examine three questions. The first is whether placing the masker noise at high or low frequencies will affect the auditory cue weighting in sound localization. The second is whether having a low SNR will impact the auditory cue weighting during sound localization. The last question is to examine the possible consequences of the re-weighting of auditory cues, such as a decrease in the listeners’ sound localization performance.

4.2 Hypotheses

Based on the review of previous studies described in Chapter 1, we developed the following hypotheses:

1. When lower frequencies are masked, listeners will pay more attention to the ILD cues than the ITD cues. However, when the higher frequencies are masked, listeners will give more weighting to the ITD cues than the ILD cues. Regardless
of the spectrum of the masker, a low SNR will have an adverse effect on the listeners’ sound localization accuracy.

2. The listeners’ localization performance will decrease as the SNR decreases.

4.3 Methods

In the second experiment, in order to assess the listeners’ auditory cue weighting in a noisy environment, normally hearing listeners were asked to identify the location of target sound sources which were presented simultaneously with continuous background noise over headphones using their personalized HRTF’s. Five different combinations of target and masker spectra were each presented at varying SNRs. The target was masked at certain frequencies depending on the masker spectra.

4.3.1 Target and Masker Combinations

The first target/masker combination, WB/WB, was a wideband target (0.5-16 kHz) and a wideband masker noise (WB, 0.5-16 kHz). The wideband target and wideband masker spectra completely overlapped with one another, thus at a lower SNR both low- and high-frequency components of the target were equally masked, and both the low-frequency ITD cues and high-frequency ILD cues were affected by the masking noise. The second combination, WB/LP, was a wideband target (0.5-16 kHz) and a low pass masker noise (0.5-2 kHz), in which both the target noise and masker noise spectra started at 0.5 kHz. Because the masker spectrum ended at 2 kHz and the target spectrum extended to 16 kHz, the noise masked only the low-frequency portion of the target signal, and was
expected to interfere mostly with ITD cues. The third combination, WB/HP, was a wideband target (0.5-16 kHz) and a high pass masker noise (4.0-16 kHz). The target’s spectrum extended to 0.5 kHz but the masker noise extended only to 4 kHz, and both had a high-frequency cut-off at 16 kHz. Therefore, the noise masked only the high-frequency portion of the target signal and was expected to interfere mostly with ILD cues. The fourth combination, LP/LP was a low-pass target (0.5-2 kHz) and a low-pass masker noise (0.5-2 kHz), the target and masker spectra both started at 0.5 kHz and ended at 4 kHz therefore only the low frequencies were present. Thus, at a low SNR the listeners are expected to increase their low frequency ITD weighting. The last target/masker combination was a high pass target (4-16 kHz) and a high pass masker noise (4-16 kHz). Thus, at a low SNR the listeners are expected to increase their high frequency ILD weighting. To approximate a highly diffuse free-field noise situation and to avoid introducing salient ITD cues in the masker, independent (uncorrelated), continuous noise signals were added to the target signals at the left and right ears. The masker for each ear was also filtered by the listener’s location-averaged HRTF for that ear (diffuse-field average) and by the headphone equalization filter.
4.3.2 Filters

The wideband filter consists of frequencies between 0.5 to 16 kHz. When listeners are localizing a wideband target consisting of these frequencies they are expected to use both their low-frequency ITD cues and their high-frequency ILD cues. The high-pass filter consists of frequencies between 4 to 16 kHz. When listeners are localizing a high-pass target consisting of these frequencies they are mainly expected to use their high-frequency ILD cues. The low-pass filter consists of frequencies between 0.5 to 2 kHz. When listeners are localizing a low-pass target consisting of these frequencies they are mainly expected to use their low-frequency ITD cues.

4.3.3 SNR Calibration

The calibration of the signal-to noise ratio of the target and masker was based on measurements of the HRTF-filtered target signals and diffuse-field-filtered masker signals delivered to the headphones. The levels and spectra of the HRTF- filtered target signals varied significantly from location to location and somewhat from listener to listener. An SNR of 0 dB was therefore defined as the combination of target level and masker level that produced equal RMS levels measured over the masker bandwidth when averaged over six target locations (azimuths of -45, 0, +45, -135, 180, +135 degrees), five listeners (L101-L105), and both ears. Figure 20 shows, for the left and right ears of listener L101, the relative levels of the masker (black lines) and the target headphone
spectra (blue and pink lines) at 0-dB for those six target azimuths. Adjusting the target level, which was approximately 60 dB SPL in the 0-dB SNR conditions, varied SNR.

Figure 17. Spectra of HRTF-filtered target signals and diffuse-field-filtered masker signals for subject L101. The x-axis is the frequency (kHz) and the y-axis is the relative level (dB). An SNR of 0 dB was defined when averaged over locations, 5 listeners and both ears.
Figures 21 and 22 show examples of the target and masker spectra in the wideband / low pass condition. The wideband target is between (0.5 to 16 kHz) with a low-frequency masker (0.5 to 2 kHz). The purpose of the low frequency masker is to mask the listeners’ low- frequency ITD cues. The negative SNR means the target level is lower than the masker level over the masker bandwidth. The results from this target / masker combination are expected to have listeners use their ILD cues instead of their ITD cues. The positive SNR illustrated in Figure 22 means the target level is above the masker level. The results from this target / masker combination are expected to have listeners use their ILD cues instead of their ITD cues.
Figure 18. An example of a wideband target/low-pass masker target spectrum at a negative SNR. The x-axis is the frequency (kHz) and the y-axis is the amplitude. The wideband target extends from 0.5 to 16 kHz and the low-pass masker extends from 0.5 to 2 kHz, masking only the low frequencies. The masker appearing larger than the target spectrum represents a negative SNR.

Figure 19. An example of wideband target/low-pass masker target spectrum at a positive SNR. The x-axis is the frequency (kHz) and the y-axis is the amplitude. The wideband target extends from 0.5 to 16 kHz and the low-pass masker extends from 0.5 to 2 kHz, masking only the low frequencies. The masker appearing smaller than the target spectrum represents a positive SNR.
4.3.4 Stimuli

The wideband/low-pass and wideband/high-pass target masker combinations were presented at SNRs of +20, +10, 0, and -5 dB, but the wideband/wideband, low-pass/low-pass and high-pass/high-pass target masker combinations were only presented at SNRs of +20, +10, and 0 dB. This is because the target sound started to become inaudible at -5 dB SNR in the target masker combinations that overlapped one another completely in frequency. The target/masker combinations and SNRs used are summarized in Table 5. Each block of trials in Experiment II used a single target/masker combination and SNR, and consisted of the 56 location/bias combinations described in Chapter 2 (General Methods) presented in a randomized order. Listeners completed two repetitions for each of the combinations presented in Table 5 except for listener L113 who completed only one repetition for the low-pass/low-pass +10 SNR condition.

<table>
<thead>
<tr>
<th></th>
<th>WB/WB</th>
<th>WB/LP</th>
<th>WB/HP</th>
<th>LP/LP</th>
<th>HP/HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>+20 SNR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>+10 SNR</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
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</tr>
<tr>
<td>-5 SNR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

4.4 Results

Each individual’s raw data were analyzed to produce graphs for auditory cue weighting. First of all, example scatter plots illustrate how individual listeners’ responses were recorded and how the ITD and ILD bias were computed from their raw data. Then examples of the individual ITD and ILD weighting for all the subjects in the noisy
condition are presented to demonstrate the listeners’ different weighting patterns. Lastly, mean cue weighting and localization performance and statistical analyses are presented for each target/ masker combination.

4.4.1 Results for Wideband target/Wideband masker

In the wideband target/ wideband masker condition, listeners were presented with wideband target sounds in quiet or simultaneously with wideband noise at SNRs of +20, +10 and 0 dB SNR.

4.4.1.1 Raw Localization Response Examples

The responses of one listener in the imposed ITD bias condition (Figure 23) show that the subject has accurate responses in the no imposed ITD bias condition. The scatter plots on the right side have an imposed +300-µs ITD bias to the right at different SNRs. The plots show that as bias is implemented, the listeners shifted their responses to the right side (upwards on the y axis). The scatter plots on the left side have an imposed -300-µs ITD bias to the left at different SNRs. The plots show that as bias is implemented, the listeners shift their responses to the left (downwards on the y axis). The scatter plots of L113 are representative of the rest of the listeners in the noisy condition.

The responses of the listener in the imposed ILD bias condition (Figure 24) show that they have accurate responses in the no imposed ILD bias condition. The scatter plots on the right side have an imposed +10 dB bias to the right at different SNRs. The plots on the left side have an implemented ILD bias of -10dB. The results show when the ILD bias is implemented, the listeners do not shift their localization responses as much as they did in the imposed ITD bias condition. A possible explanation for this could be due to the fact that in the wideband target and high-pass masker condition, listeners are relying on
their low-frequency ITD cues to localize the target. Therefore, the imposed ITD bias
greatly impacted their localization responses however; their ILD bias did not since they
were not using their ILD cues to localize. The scatter plots of L113 are representative of
the rest of the listeners in the noisy condition.
Figure 20. Scatterplots for the wideband target/ wideband masker with an imposed ITD bias for subject L113. The middle scatterplots have no imposed bias, the scatterplots on the right have a +300 µs bias to the right side of the listener and the scatterplots on the left have a -300 µs bias to the left of the listener. The x-axis is the target lateral angle (deg) and the y-axis is the response lateral angle (deg).
Figure 21. Scatterplots for the wideband target/wideband masker with an imposed ILD bias for subject L113. The middle scatterplots have no imposed bias, the scatterplots on the right have a +10 decibel bias to the right side of the listener and the scatterplots on the left have a -10 decibel bias to the left of the listener. The x-axis is the target lateral angle (deg) and the y-axis is the response lateral angle (deg).
The scatter plots above show the raw data for subject L113 in the wideband target/wideband masker condition with an imposed ITD bias and imposed ILD bias. The graphs in the middle column have no imposed ITD bias and were presented at different SNRs (quiet, +20, +10, 0 and -5, one SNR per row). The x-axis on the graphs is the target lateral angle and the y-axis is the response lateral angle of the listener.

4.4.1.2 Individual weighting functions

Figures 25 and 26 show the individual ITD and ILD weighting patterns for the seven listeners in this condition. The x-axis shows the different SNRs (quiet, +20, +10, 0 and -5) and the y-axis shows the listeners’ weightings. The weighting patterns of all the listeners were similar in both the ITD and ILD conditions. The ITD bias condition showed that the listeners decreased their ITD weighting as the SNR decreased, whereas the ILD bias condition showed that the listeners increased their ILD weighting as the SNR decreased. Therefore, there appears to be a tradeoff between the weighting of the ITD and ILD cues. The auditory cue weighting patterns were similar across listeners in the other target masker conditions as well, so only the mean weighting data will be presented below.
Figure 22. Individual ITD auditory cue weighting functions in the wideband target/ wideband masker condition.
The individual weighting functions presented are for listeners L101, L103, L109, L110, L111 and L113. The x-axis represents the four different SNRs and the y-axis represents the ITD bias slope.

Figure 23. Individual ILD auditory cue weighting functions in the wideband target/ wideband masker condition.
The individual weighting functions presented are for listeners L101, L103, L109, L110, L111 and L113. The x-axis represents the four different SNRs and the y-axis represents the ILD bias slope.
4.4.1.3 Mean ITD and ILD Weights for Wideband target/Wideband Masker

The general trend of the ITD and ILD weighting graphs illustrate that the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues at high SNRs. However, when the SNR decreased and the target signal became less audible and the ITDs are more disrupted by the noise, the listeners began to give more preference to their ILD cues during sound localization. ITD and ILD weights were computed for each listener at each SNR, and the means across all 7 listeners are plotted in Figure 27 (ITD) and Figure 28 (ILD).
Figure 24. Mean ITD weight in the wideband target/wideband masker condition as a function of SNR. The x-axis represents the different SNRs and the y-axis represents the ITD bias slope.

Figure 25. Mean ILD weight in the wideband target/wideband masker condition as a function of SNR. The x-axis represents the different SNRs and the y-axis represents the ILD bias slope.
To test the statistical significance of these trends, one-way repeated measures ANOVAs were conducted. For ITD, the analysis indicated that there was a significant main effect of SNR on ITD weight ($F(3,18) = 19.942$, $p = 0.000$). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results showed multiple significant differences between the SNR conditions. There was a significant difference between the ITD weight at 0 dB SNR and all the other conditions (quiet, +20 dB SNR and +10 dB SNR). There was also a significant linear trend ($p=0.001$) between decreasing ITD weighting and decreasing SNR.

Table 6. The P-values of the significant differences between the ITD weights at different SNRs in the wideband target/wideband masker condition.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20 SNR</th>
<th>+10 SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0 SNR</strong></td>
<td>p=0.003</td>
<td>p=0.010</td>
<td>p=0.004</td>
</tr>
</tbody>
</table>

The one-way repeated measures ANOVA on ILD weights showed a significant effect of SNR on ILD weighting ($F(3, 18) = 24.129$, $p = 0.000$). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results showed multiple significant differences between the SNR conditions. There were significant differences between the 0-dB SNR and all the other conditions (quiet, +20 dB and +10 dB SNR). There was also a significant linear trend ($p=0.001$) between increasing ILD weighting and decreasing SNR.

Table 7. The P-values of the significant differences between the different SNRs in the wideband target/wideband masker condition with an imposed ILD bias.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20 SNR</th>
<th>+10 SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0 SNR</strong></td>
<td>p=0.008</td>
<td>P=0.004</td>
<td>P=0.041</td>
</tr>
</tbody>
</table>
In the wideband target, wideband masker condition, both the target and masker spectra extended from 0.5 to 16 kHz. The wideband target contained both low-frequency ITD cues and high-frequency ILD cues. Thus, the masker would mask both the ITD and ILD cues as well.

The proposed hypothesis stated that the listeners would start to decrease their ITD weighting when the listener’s low frequencies are de-correlated with the addition of a masker. The results are in accordance with the hypothesis because they show that listeners start to decrease their ITD weighting as the SNR decreases. In comparison, listeners start to increase their ILD weighting as the SNR decreases. This shows that the listeners have a trade off in their ITD and ILD weighting in order to maximize their localization performance in noisy environment.

4.4.1.4 Mean sound localization performance results for wideband target/wideband masker combination

To test the statistical significance of these trends, one-way repeated measure ANOVAs were conducted. For the sound localization performance metrics of lateral gain, lateral scatter and front/back confusion, the analysis indicated no significant main effect of SNR on sound localization performance as shown in Figure 29.
Figure 26. Mean sound localization performance measures for wideband target/ wideband masker condition.

The top graph represents the mean lateral gain results, the middle graph represents the mean lateral scatter results and he bottom graph represents the mean front/back percent correct results. The x-axis are the different SNRs and the y-axis is the sound localization performance measure.
Table 8. The P-values of the significant difference between the different SNRs in the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral gain</th>
<th>Lateral scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.2236</td>
<td>0.3218</td>
<td>0.3783</td>
</tr>
</tbody>
</table>

4.4.2 Results for Wideband target/ Low-pass masker

In the wideband target/ low-pass masker condition with an imposed ILD bias the listeners were presented with a wideband target sound simultaneously with low-pass noise for the SNRs of quiet, +20, +10, 0 and -5. ITD and ILD weights were computed for each listener at each SNR, and the means across all 7 listeners are plotted in Figure 30 (ITD) and Figure 31 (ILD).

4.4.2.1 Mean ITD and ILD Weights For Wideband Target/Low-pass Masker

The general trend of Figure 30 shows that when the SNR is high, listeners use primarily ITD cues when localizing the target sound source, however when the SNR decreased, the listeners slightly decreased their weighting of the ITD cues.
Figure 27. Mean ITD weight in the wideband target/wideband masker condition as a function of SNR.

Figure 28. Mean ILD weight in the wideband target/low-pass masker condition as a function of SNR.
To test the statistical significance of these trends, one-way repeated measures ANOVAs were conducted. For ITD, the analysis indicated that there was a significant main effect of SNR on ITD weight ($F(4, 24) = 6.297, p= 0.001$). However, after post hoc comparisons were done with a Bonferroni correction, the post-hoc pair-wise comparisons were not significant ($p>0.05$) but there was a significant linear trend ($p=0.008$) between the listeners’ decreasing ITD weighting and decreasing SNR.

**Table 9.** The P-values of the significant differences between the different SNRs in the wideband target/low-pass masker condition with an imposed ITD bias.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20 SNR</th>
<th>+10 SNR</th>
<th>0 SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5 SNR</td>
<td>P=0.007</td>
<td>P=0.033</td>
<td>P=0.021</td>
<td>P=0.042</td>
</tr>
<tr>
<td>Quiet</td>
<td></td>
<td></td>
<td></td>
<td>P=0.009</td>
</tr>
</tbody>
</table>

In the wideband target/ wideband masker condition with an imposed ILD bias listeners were presented with a wideband target sound simultaneously with low-pass noise for the SNRs of quiet, +20, +10, 0 and -5. The general trend of Figure 31 demonstrates that listeners give a low ILD weighting when localizing target sound in this condition and that decreasing the SNR does not change the weighting of the ILD cues. A repeated measure ANOVA showed a significant effect of SNR on ILD weighting in the data set ($F(4, 24) = 3.909, p=0.014$). However, after post hoc comparisons were done with a Bonferroni correction, the post-hoc pair-wise comparisons were not significant ($p>0.05$) but there was a significant linear trend ($p=0.038$) between the listeners’ increasing ILD weighting and decreasing SNR.
Table 10. The P-values of the significant differences between the different SNRs in the wideband target/low-pass masker condition with an imposed ILD bias.

<table>
<thead>
<tr>
<th></th>
<th>0 SNR</th>
<th>-5 SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>P=0.034</td>
<td>P=0.033</td>
</tr>
</tbody>
</table>

In the wideband target/ low-pass masker condition, the listeners are presented with wideband stimuli (0.5 to 16 kHz) that contain both the low frequency ITD cues and high frequency ILD cues. The low-pass masker is presented from 0.5 to 4 kHz and was meant to mask the low-frequency ITD cues of the listener. The proposed hypothesis was that listeners will heavily rely on their ITD cues, but when the masker masks the low frequency ITD cues listeners will start to use their ILD cues instead to localize the target sound. The results are in accordance with the hypothesis because the listeners start to decrease their weighting of ITD cues and increase their weighting of ILD cues as the SNR decreases. This suggests that the listeners have a tradeoff between the two auditory cues to maximize their localization performance in noisy environments.
4.4.2.2 Mean sound localization performance results for wideband target/low-pass masker combination

To test the statistical significance of these trends, one-way repeated measure ANOVAs were conducted. For the sound localization performance metrics of lateral gain, lateral scatter and front/back confusion, the analysis indicated no significant main effect of SNR on sound localization performance shown in Figure 32.

![Graphs showing mean lateral gain, mean lateral scatter, and mean front/back percent correct for different signal to noise ratios.]

Figure 29. Wideband target/low-pass masker sound localization performance measure graphs.
Table 11. The P-values of the significant differences between the different SNRs in the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral gain</th>
<th>Lateral scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.7505</td>
<td>0.4780</td>
<td>0.3331</td>
</tr>
</tbody>
</table>

4.4.3 Results for Wideband target/ High-pass masker

In the wideband target/ high-pass masker condition the listeners were presented with a wideband target sound simultaneously with high-pass noise for the SNRs of quiet, +20, +10, 0 and -5. ITD and ILD weights were computed for each listener at each SNR, and the means across all 7 listeners are plotted in Figure 33 (ITD) and Figure 34 (ILD).

4.4.3.1 Mean ITD and ILD Weights For Wideband target/ High-pass Masker

The general trend of Figures 33 and 34 show the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues during sound localization, but that there was little effect of SNR on cue weighting.
Figure 30. Mean ITD weight in the wideband target/ high-pass masker condition as a function of SNR.

Figure 31. Mean ILD weight in the wideband target/ high-pass masker condition as a function of SNR.
To test the statistical significance of these trends, one-way repeated measures ANOVAs was conducted. The ANOVA indicated that there were no significant main effects of SNR on ITD weight. (F (4, 24)=2.158, p=0.105). There were also no main effects observed between the SNRs in the ILD bias condition (F (4, 24)= 1.960, p=0.133).

4.4.3.2 Mean sound localization performance results for wideband target/high-pass masker combination

To test the statistical significance of these trends, one-way repeated measure ANOVAs were conducted. For the sound localization performance metrics of lateral gain, lateral scatter and front/back confusion, the analysis indicated no significant main effect of SNR on sound localization performance shown in Figure 35.
Figure 32. Wideband target/high-pass masker sound localization performance measure graphs.

Table 12. The P-values of the significant differences between the different SNRs in the lateral gain, lateral scatter and front/back confusion localization measures.
<table>
<thead>
<tr>
<th></th>
<th>Lateral gain</th>
<th>Lateral scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.5338</td>
<td>0.5154</td>
<td>0.3749</td>
</tr>
</tbody>
</table>

### 4.4.4 Results for Low-pass target/ Low-pass masker

In the low-pass target/ low-pass masker condition the listeners were presented with a low-pass target sound simultaneously with low-pass noise for the SNRs of quiet, +20, +10 and 0. ITD and ILD weights were computed for each listener at each SNR, and the means across all 7 listeners are plotted in Figure 36 (ITD) and Figure 37(ILD).

#### 4.4.4.1 Mean ITD and ILD Weights for Low-pass target/Low-pass Masker

The general trend of these graphs show that overall, listeners give a high weighting to their ITD cues and give low weighting to their ILD cues. However, as the SNR decreases and the target signal becomes more inaudible the listeners increase their ILD weighting.
Figure 33. Mean ITD weight in the low-pass target/low-pass masker condition as a function of SNR

Figure 34. Mean ILD weight in the low-pass target/low-pass masker condition as a function of SNR
To test the statistical significance of these trends, one-way repeated measures ANOVAs was conducted. For ITD, the analysis indicated that there was no significant main effect of SNR on ITD weight \((F (3, 18) = 1.148, p=0.357)\).

In comparison, the ANOVA showed significant differences in the ILD bias condition between the SNRs \((F (3, 18) = 17.332, p=0.000)\). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results showed multiple significant differences between the SNR conditions. There were significant differences between the 0 SNR condition and the quiet and +20 SNR condition. There were also a significant difference in the linear trend \((p=0.001)\) between the increasing ILD weighting and decreasing SNR.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20 SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 SNR</td>
<td>p= 0.009</td>
<td>p=0.005</td>
</tr>
</tbody>
</table>

Table 13. The P-values of significant differences among the different spectral slopes in the low-pass target/low-pass masker condition with an imposed ILD bias.

In the low-pass target/ low-pass masker condition both the target and masker were presented at 0.5-4 kHz. The listeners are expected to use their low-frequency ITD cues to localize the target sounds at these frequencies. The proposed hypothesis for this condition was that in accordance with the duplex theory of sound localization, listeners will weigh their ITD cues heavily at low frequencies. The results are in accordance with the hypothesis because in the ITD bias condition, listeners heavily rely on their ITD cues for all SNR conditions. However, in the ILD bias condition the listeners give a low weighting to their ILD cues, but start to increase their ILD weighting as the SNR
decreases. This suggests that the listeners rely on their ITD cues when localizing low-frequency target sounds, however when the target is more difficult to identify at lower SNRs they begin to use other auditory cues such as their ILD cues.

4.4.4.2 Mean sound localization performance results for low-pass target/low-pass masker combination

To test the statistical significance of these trends, one-way repeated measure ANOVAs were conducted. For the sound localization performance metrics of lateral gain, lateral scatter and front/back confusion, the analysis indicated no significant main effect of SNR on sound localization performance shown in Figure 38.
Figure 35. Low-pass target/low-pass masker sound localization performance measure graphs.
Table 14. P-values of the significant differences between the different SNRs in the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral gain</th>
<th>Lateral scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>p=0.8383</td>
<td>p=0.6908</td>
<td>p=0.7914</td>
</tr>
</tbody>
</table>

4.4.5 Results for High-pass target / High-pass masker

In the high-pass target/ high-pass masker condition the listeners were presented with a high-pass target sound simultaneously with high-pass noise for the SNRs of quiet, +20, +10 and 0 SNR. ITD and ILD weights were computed for each listener at each SNR, and the means across all 7 listeners are plotted in Figure 39 (ITD) and Figure 40 (ILD).

Sound localization tests were not conducted at -5 SNR because the targets were inaudible to the listeners.

4.4.5.1 Mean ITD and ILD Weights for High-pass target/High-pass masker

The general trend of this graph shows that the listeners do not pay much attention to the ITD cues in the high-pass condition, however as the SNR decreases the listeners weighting of ITD cues decreases even more.
Figure 36. Mean ITD weight in the high-pass target/ high-pass masker condition as a function of SNR

Figure 37. Mean ILD weight in the high-pass target/ high-pass masker condition as a function of SNR
To test the statistical significance of these trends, one-way repeated measures ANOVAs were conducted. For ITD, the analysis indicated that there was a significant main effect of SNR on ITD weight ($F (3, 18) = 18.965, p=0.000$). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results showed multiple significant differences between the SNR conditions. Significant differences exists between the quiet and +10 SNR and 0 SNR, as well as the +20 SNR and 0 SNR. There was also a significant difference in the linear trend ($p=0.000$) between the listeners decreasing ITD weighting and decreasing SNR. As the SNR starts to decrease and the target signal becomes less audible, the listeners start to decrease their ITD weighting.

Table 15. The P-values of the significant differences among the different spectral slopes in the high-pass target/ high-pass masker condition with an imposed ITD bias.

<table>
<thead>
<tr>
<th></th>
<th>+10 SNR</th>
<th>0 SNR</th>
<th>+20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>P= 0.012</td>
<td>P=0.000</td>
<td></td>
</tr>
<tr>
<td>0 SNR</td>
<td></td>
<td></td>
<td>P= 0.003</td>
</tr>
</tbody>
</table>

In the high-pass target/ high-pass masker condition with an imposed ITD bias listeners were presented with a high-pass target sound simultaneously with high-pass noise for the SNRs of quiet, +20, +10 and 0. Sound localization tests were not conducted at -5 SNR because the targets were inaudible to the listeners. The general trend in these graphs is that listeners give a low weighting to their ITD cues and a high weighting to their ILD cues.
The general trend in this graph shows that listeners weigh their ILD cues very high and the decreasing SNR does not have any effect on the weighting of the ILD cues. The one-way ANOVA shows no main effects observed between the SNRs (F (3, 18)=17.332, p=0.000).

In the high-pass target/ high-pass masker condition both the target and masker were presented from 4-16 kHz. At the higher frequencies the listeners are expected to use their high-frequency ILD cues to localize the target sound. The proposed hypothesis was that the listeners would heavily weight their ILD cues to localize the target sound and give a low weighting to their ITD cues. The hypothesis also stated that as the SNR decreased and the target sound became more inaudible, the listeners would switch their weighting to a different auditory cue. The results were in accordance with the hypothesis because the listeners gave a high weighting to the high frequency ILD cues and a low weighting to the low frequency ITD cues. However, only in the ITD bias condition did the listeners decrease their ITD weighting as the SNR decreased. The listeners did not change their ILD weighting as their SNRs decreased.

4.4.5.2 Mean sound localization performance results for high-pass target/high-pass masker combination

To test the statistical significance of these trends, one-way repeated measure ANOVAs were conducted. For the sound localization performance metrics of lateral gain, lateral scatter and front/back confusion, the analysis indicated no significant main effect of SNR on sound localization performance shown in Figure 41.
Figure 38. High-pass target/high-pass masker sound localization performance measure graphs.
Table 16. The P-values of the significant differences between the different SNRs in the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th>P value</th>
<th>Lateral gain</th>
<th>Lateral scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0216</td>
<td>0.0915</td>
<td>0.2216</td>
<td></td>
</tr>
</tbody>
</table>

In the lateral gain measure the initial repeated measures ANOVA p-value showed a significant difference in the data set (p<0.05). However, after post hoc comparisons were done with a bonferroni correction, the post-hoc pair-wise comparisons were not significant (p>0.05) but there was a significant linear trend (p=0.049) between the listeners’ decreasing SNR and their sound localization performance.

### 4.5 Conclusion

In Experiment II, we measured ITD and ILD weighting as a function of the target/masker combinations and SNR. The results show when low-frequency ITD cues were available, the addition of interfering noise at low frequencies resulted in a decrease in ITD weighting. However, as the SNR decreased there was an increase in ILD weighting even when the masking noise also affected the high frequency ILDs.

Over the range of SNRs tested, there was little effect of SNR on localization performance for most target/masker combos. These results are discussed in more detail in Chapter 6.
Chapter 5

5 Experiment III: Reverberation - Effect of target spectrum, reverberation spectrum, and DRR

5.1 Objective

The purpose of this experiment is to establish exactly how listeners weight their ITD and ILD auditory cues when the signal becomes less reliable. In order to assess the listeners changing weighting of ITD and ILD cues in a reverberant environment, we measured their weighting of low and high frequency cues in a reverberant condition.

Experiment III sought to examine three questions. The first question is whether placing the reverberation at high or low frequencies will affect the auditory cue weighting during sound localization. The second question is whether having a low direct to reverberant ratio (DRR) impacts the auditory cue weighting during sound localization. The last question is to examine the possible consequences of the re-weighting of auditory cues in noisy and reverberant environments, such as a decrease in sound localization performance.

5.2 Hypotheses

Based on the review of previous studies described in Chapter 1, we developed the following hypotheses:

1. When reverberation is disrupting the low-frequency ITD cues, the listener will increase the weighting of the ILD cues, and when reverberation is diluting the ILD cues, the listener will increase the weighting of low-frequency ITD cues.

2. In the wideband target/ wideband reverberation condition, when both auditory cues are available, listeners will increasing their ILD weighting because their ITD
cues will be more diluted in reverberation.

3. The listeners’ localization performance will decrease with decreasing direct to reverberant ratio (DRR).

5.3 Methods

In the third experiment, in order to assess the listeners’ auditory cue weighting in a reverberant environment, normally hearing listeners were asked to identify the apparent locations of the target sound sources which were presented with simulated reverberation over headphones using their personalized HRTFs. Similar to the five target/masker combinations used in Experiment II, Experiment III used five combinations of target and reverberation spectra, with varying direct to reverberant ratio (+20,+10, 0 and -5 dB DRR). In order to compare the target-masker combinations in the reverberant condition to the noisy condition, the same DRRs and SNRs values are used. These values have the same de-correlating effect because both provide similar ratios of target energy to de-correlated energy when the reverberation is in its steady state. The different target masker combinations are unrealistic in everyday listening environments; however they were expected to create similar de-correlating effects as real reverberation.

The first combination was a wideband target (0.5-16kHz) and wideband reverberation (0.5-16kHz), in which both the target signal and reverberation started at 0.5 kHz and ended at 16kHz which means the reverberation affected all frequencies of the target signal.

The wideband target and wideband reverberation condition completely overlap with one another, thus at a lower DRR both the low-pass ITD cues and high-pass ILD cues were affected. The second combination was a wideband target (0.5-16kHz) and a low pass
reverberation (0.5-4kHz), in which both the target and reverberation started at 0.5 kHz. However, the reverberation ended at 4 kHz and the target continued until 16 kHz therefore the reverberation masked the low frequency portion of the target signal. Thus, at a lower DRR, listeners were expected to pay less attention to their ITD cues and more attention to their ILD cues because the low frequencies were masked. The third combination was a wideband target (0.5-16kHz) and a high pass masker reverberation (4.0-16 kHz), in which the target started at 0.5 kHz and the reverberation did not start until 4 kHz, both ended at 16 kHz. Therefore, the reverberation masked the high frequency portion of the target signal. Thus, at a lower DRR, listeners were expected to pay less attention to their ILD cues and more attention to their ITD cues because the high frequencies are masked.

The fourth combination was a low-pass target (0.5-4kHz) and a low pass reverberation (0.5-4kHz), in which the target and masker both started at 0.5kHz and ended at 4 kHz therefore only the low frequencies were present. The last combination was a high pass masker (4-16 kHz) and a high pass reverberation (4-16 kHz), in which the target and masker both started at 4 kHz and ended at 16 kHz therefore only the high frequencies were present. The target and masker both started at 4 kHz and ended at 16 kHz therefore only the high frequencies were present.

5.3.1 Generation of artificial reverberation

The artificial reverberation was computed by taking a 0.5 second Gaussian noise signal (Fig 42, A) and multiplying it with an exponentially decaying envelope (panel B) to create the reverberation impulse response shown in panel C. Panel D is the 100-ms dry target signal or the direct auditory target, and E is the reverberation component alone,
which was the dry 100-ms target signal (D) convolved with the reverberation impulse response (C). Independent reverberation impulse responses were computed using uncorrelated noise samples (panel A) for the left and right ears.

This artificial reverberation does not reproduce the acoustics of a specific room, but it should have similar effects on ITD and ILD cues. Figure 42 is illustrates the generation of wideband reverberation. The Gaussian noise sample (A) is band limited to either 0.5-2kHz for a low-pass filter or 4-16 kHz for a high-pass filter, before the computation of the impulse response is applied. Similar to Experiment II, the reverberation signals were filtered by each listener’s diffuse-field-average HRTF and the headphone equalization filter. Figure 42 F and G show the direct and reverberation signals combined at DRRs of 0 and +10 dB, respectively. The DRR was changed by altering the relative level of the reverberant component, and it was defined and calibrated similarly to SNR in Experiment II based on measurements of headphone-signal levels averaged over target locations, listeners, and ears. Only the steady-state portion (50-100 ms) of the reverberation component was used in calibrating the DRR because the reverberation took approximately 50 ms to build up to its steady state.

The reverberation time (RT) of 500 ms was used in this study because it is the typical of a RT of an office-sized bare room and past sound localization studies have demonstrated that it was able to affect the listener’s sound localization ability. Ihlefeld & Shinn-Cunningham’s reverberation times, estimated from the left ear binaural room impulse
recordings for a source at 1 m distance and 0 azimuth, were 490, 418, 487, 578, and 557 ms at 0.5, 1, 2, 4, and 8 kHz, respectively (Ihlefeld & Shinn-Cunningham, 2011).

Figure 39. The figure illustrates the generation of artificial reverberation used in Chapter 5. The y-axis is the amplitude of the sound and the x-axis is the time (seconds). Box A is a Gaussian noise sample, box B is an exponentially decaying envelope and box C is the reverberant impulse response (box A and box B multiplied). Box D is the 100-ms dry target signal, box E is the computed reverberation (the target signal convolved with the impulse response), box F is the signal and reverberation combined at 0 DRR and box G is the signal and reverberation combined at +10 DRR.
5.3.2 Stimuli

The wideband/wideband, wideband/low-pass and wideband/high-pass, high-pass/ high-pass and low-pass/low-pass target masker combinations were presented at direct to reverberant ratios of +20, +10, +0, and -5 dB. Target levels varied with DRR from 80 to 55 dB SPL to match the levels used in Experiment II. Each block of trials in Experiment III used a single target/reverberation combination and SNR, and consisted of the 56 location/bias combinations described in Chapter 2 (General Methods) presented in a randomized order. Each block of trials in Experiment III used a single target/reverberation combination and DRR, and consisted of the 56 location/bias combinations described in Chapter 2 (General Methods) presented in a randomized order. Table 17 shows the target masker combinations in the reverberant condition that were chosen to match the noisy target masker combinations. Listeners completed two repetitions for each of the combinations presented in Table 17, except for listeners L112, L116 and L117. Listener L112 missed one wideband/ high-pass +10-dB DRR repetition, listener L116 missed one low-pass/low-pass 0-dB DRR repetition, and listener L117 missed one low-pass/low-pass 0-dB DRR repetition.

Table 17. The target-masker combinations used in Chapter 5 that were presented at the different DRRs

<table>
<thead>
<tr>
<th></th>
<th>WB/WB</th>
<th>WB/LP</th>
<th>WB/HP</th>
<th>LP/LP</th>
<th>HP/HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>+20 DRR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>+10 DRR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>0 DRR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
5.3.3 Subjects

Eight subjects participated in the reverberant condition, all of whom had previously completed the quiet condition. None of the subjects in the reverberant condition were in the noisy condition.

5.4 Results

Each individual’s raw data were processed to produce graphs for auditory cue weighting. First of all, example scatter plots illustrate how individual listener’s responses were recorded and how the ITD and ILD bias were computed from their raw data. Then examples of the individual ITD and ILD weighting for all the subjects in the reverberant condition are presented to demonstrate the listeners’ different weighting patterns. Lastly, mean cue weighting and localization performance and statistical analyses are presented for each target/ reverberation combination.

5.4.1 Wideband target/Wideband reverberation

The scatter plots below (Figure 43 & 44) show the raw data for subject L115 in the wideband target/wideband masker condition with an imposed ITD and ILD bias. The graphs in the middle column show trials with no imposed ITD or ILD bias presented at different DRRs (from top to bottom: dry, +20, +10, 0 and -5 dB DRR). The x-axis on the graphs is the target lateral angle and the y-axis is the response lateral angles of the listener.

The responses of the listener show that they have accurate responses in the no-bias condition. The scatter plots in the right column show trials that had an imposed +300-μs
ITD bias to the right at different DRRs. The plots show that when the bias is imposed, the listeners shifted their responses toward the right side (upwards on the y-axis). The scatter plots in the left column have an imposed -300-µs ITD bias to the left at different DRRs. The plots show that when that bias is imposed, the listeners shifted their responses to the left (downwards on the y-axis). The scatter plots of L115 are representative of the rest of the listeners in the reverberant condition.

The scatter plots on the right side have an imposed +10 dB bias to the right at different DRRs. The plots on the left side have an implemented ILD bias of -10dB. The results show when the ILD bias is implemented, the listeners do not shift their localization responses as much as they did in the imposed ITD bias condition. A possible explanation for this could be that in the wideband target and high-pass masker condition, listeners relied on their low-frequency ITD cues to localize the target. Therefore, the imposed ITD bias greatly impacted their localization responses, whereas the ILD bias did not since they were relying less on ILD cues to localize. The scatter plots of L115 are representative of the responses of the rest of the listeners in Experiment III.
Figure 40. The wideband target/ wideband reverberation ITD imposed response scatterplots for subject L115 at different DRRs (quiet, +20, +10, 0 and -5)
Figure 41. The wideband target/wideband reverberation ILD imposed response scatterplots for subject L115 at different DRRs (quiet, +20, +10, 0 and -5)
The bar plots below display the ITD and ILD auditory cue weighting for listeners L104, L105, L112, L114, L115, L116, L117 and L118 in the wideband target/ wideband condition. The x-axis are the different DRRs (quiet, +20, +10, 0 and -5) and the y-axis are the listeners ITD weighting for both Figures 45 and 46. In Figure 45 the weighting patterns of all the listeners are similar except for listeners L104 and L105. The graphs for the other listeners show they tend to heavily weigh their ITD cues until they reach lower a lower DRR (-5). In contrast, listener L104 did not have a high ITD weighting across DRRs and did not decrease their weighting at lower DRRs and listener L105 had a very high ITD weighting across the DRRs and also did not decrease their weighting at a lower DRRs. In Figure 45 the weighting pattern of all listeners are similar except L05 and L118. The graphs for the other listeners show they tend to increase their ILD weighting as the DRR decreases. However, both L105 and L118 decrease their ILD weighting as the DRR decreases.
Figure 42. Individual ITD auditory cue weighting functions in the wideband target/wideband reverberation condition. The individual weighting functions presented are for listeners L104, L105, L112, L114, L115, L116, L117 and L118. The x-axis represents the four different DRRs and the y-axis represents the ITD bias slope.

Figure 43. Individual ILD auditory cue weighting functions in the wideband target/wideband reverberation condition. The individual weighting functions presented are for listeners L104, L105, L112, L114, L115, L116, L117 and L118. The x-axis represents the four different DRRs and the y-axis represents the ILD bias slope.
Listeners were presented with a wideband target sound simultaneously with wideband reverberation for the direct to reverberant ratio of quiet, +20, +10, 0 and -5. An ITD bias was implemented by delaying the sound at one ear and not the other. The wideband target/ wideband reverberation ITD and ILD bias graphs (Figure 47 and 48) presents the mean values from the 15 listeners in the study and illustrates whether the listeners are paying attention to the implemented ITD cues, and thus whether the listeners are using their ITD cues to localize target sounds in this reverberant condition at varying DRR.

5.4.1.1 Mean ITD and ILD weights for Wideband target/Wideband Reverberation

The general trend in both graphs show the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues. It also depicts that as the DRR decreases the ITD weighting also decreases, however the ILD weighting does not change.
Figure 44. Mean ITD weight in the wideband target/wideband reverberation condition as a function of DRR. The x-axis represents the different DRRs and the y-axis represents the ITD bias slope.

Figure 45. Mean ILD weight in the wideband target/wideband reverberation condition as a function of DRR. The x-axis represents the different DRRs and the y-axis represents the ILD bias slope.
To test the statistical significant of these trends a one-way, repeated measures ANOVA was performed, which showed a significant main effect of DRR on ITD weight in the wideband target/ wideband reverberation condition (F (4, 28) = 2.876, p=0.041). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results showed a significant difference between: the +20-dB DRR condition and -5-dB DRR condition. There was also a significant linear trend (p=0.028) between decreasing DRR and decreasing ITD weight.

Table 18. The P-values of the significant differences in ITD weight between the different DRRs in the wideband target/ wideband reverberant condition.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20DRR</th>
<th>+10DRR</th>
<th>0DRR</th>
<th>-5DRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>+20DRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P=0.027</td>
</tr>
</tbody>
</table>

A one-way repeated measure ANOVA showed no main effect of DRR on ILD weighting (F (4, 28) = 0.237, p=0.951)
5.4.1.2 Mean sound localization performance results for wideband target/wideband masker combination

Sound localization measures were examined with the listener’s lateral gain, lateral scatter and front/back confusions. The slope and RMS deviation from the intercept of the listener’s raw data were used to compute the lateral gain and later scatter. The front/back confusion was computed by the percentage of the trials in which the listener reported the front/back hemisphere correctly. The front/back confusion did not include other errors when it was calculated.
Figure 46. The wideband target/ wideband reverberation sound localization performance measure graphs
To test the statistical significant of these trends a one-way, a repeated measures ANOVA was performed, which showed no significant main effect of DRR on lateral gain, lateral scatter and front/back confusion in the wideband target/ wideband reverberation condition.
Table 19. The P-values of the significant differences between the different DRRs in the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral Gain</th>
<th>Lateral Scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.3643</td>
<td>0.5072</td>
<td>0.0856</td>
</tr>
</tbody>
</table>

5.4.2 Wideband target/low-pass reverberation

In the wideband target/low-pass reverberation condition with an imposed ITD bias, the listeners were presented with a wideband target sound simultaneously with low-pass reverberation for the direct to reverberant ratios of quiet, +20, +10, 0 and -5.

5.4.2.1 Mean ITD and ILD weights for Wideband target/Low-pass reverberation

The general trend from both graphs show the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues. The graphs (Figure 50 & 51) further illustrated that as the DRR decreased, the listeners started to rely less on their ITD cues and more heavily on their ILD cues.
Figure 47. Mean ITD weight in the wideband target/wideband reverberation condition as a function of DRR.

Figure 48. Mean ILD weight in the wideband target/wideband reverberation condition as a function of DRR.
To test the statistical significance of these trends a one-way ANOVA was used to determine the differences between the direct to reverberant ratios were observed in the wideband target/ low-pass reverberation condition with an imposed ITD bias (F (4, 28)= 4.840, p=0.004). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, there was an observed significance difference between the +20 DRR condition and the -5 DRR condition.

Table 20. The P-values of the significant differences between the different DRRs in the wideband target/low-pass reverberation condition with an imposed ITD bias.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20DRR</th>
<th>+10DRR</th>
<th>0DRR</th>
<th>-5DRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>+20DRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P=0.006</td>
</tr>
</tbody>
</table>

The one-way ANOVA on the ILD weights showed a significant main effect of DRR on ITD weight (F (4, 28) = 7.975, p= 0.000). When post-hoc pairwise comparisons based on the 95% confidence intervals were applied, the results showed a significant difference between the quiet and -5-dB DRR conditions. There was also a significant linear trend (p=0.001) between the decreasing DRR and the increasing ILD weighting.

Table 21. The P-values of the significant difference between the different DRRs in the wideband target/low-pass reverberant condition with an imposed ILD bias.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20DRR</th>
<th>+10DRR</th>
<th>0DRR</th>
<th>-5DRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>p=0.010</td>
</tr>
</tbody>
</table>
5.4.2.2 Mean sound localization performance results for wideband target/low-pass masker combination

Sound localization measures were examined with the listener’s lateral gain, lateral scatter and front/back confusions. The slope and RMS deviation from the intercept of the listener’s raw data were used to compute the lateral gain and later scatter. The front/back confusion was computed by the percentage of the trials in which the listener reported the front/back hemisphere correctly, regardless of any other errors shown in Figure 52.
Figure 49. The wideband target/low-pass reverberation sound localization performance measure graphs.
Table 22. The P-values of the significant differences between the different DRRs on the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral Gain</th>
<th>Lateral Scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.9908</td>
<td>0.4329</td>
<td>0.2856</td>
</tr>
</tbody>
</table>

5.4.3 Wideband target/ High-pass reverberation

In the wideband target/ high-pass reverberation condition with an imposed ITD bias the listeners were presented with a wideband target sound simultaneously with high-pass reverberation for the direct to reverberant ratios of quiet, +20, +10, 0 and -5.

5.4.3.1 Mean ITD and ILD weights for Wideband target/ High-pass reverberation

The general trend in both graphs (Figure 53 & 54) showed that the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues.
Figure 50. Mean ITD weight in the wideband target/high-pass reverberation condition as a function of DRR
To test the statistical significance of these trends a one-way ANOVA was used to determine the differences between the direct to reverberant ratios in the wideband target/high-pass reverberation condition with an imposed ITD bias. The results from a one-way ANOVA further which showed no significant main effect of DRR on ITD weight (F (4, 28) = 0.593, p= 0.671).

In the wideband target/high-pass reverberation condition with an imposed ILD bias the listeners were presented with a wideband target sound simultaneously with wideband reverberation for the direct to reverberant ratios of quiet, +20, +10, 0 and -5. The one-way ANOVA analysis also showed a significant main effect of DRR on ILD weight (F (4, 28) = 0.300, p=0.875) in the wideband target and high-pass reverberation.
5.4.3.2 Mean sound localization performance results for wideband target/high-pass reverberation combination

Sound localization measures were examined with the listener’s lateral gain, lateral scatter and front/back confusions. The slope and RMS deviation from the intercept of the listener’s raw data were used to compute the lateral gain and later scatter. The front/back confusion was computed by the percentage of the trials in which the listener reported the front/back hemisphere correctly, regardless of their other sound localization errors.
Figure 52. The wideband target/high-pass reverberation sound localization performance measure graphs.
Table 23. The P-values of the significant differences between the different DRRs in the lateral gain, lateral scatter and front/back confusion localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral Gain</th>
<th>Lateral Scatter</th>
<th>Front/back confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.3053</td>
<td>0.7432</td>
<td>0.6183</td>
</tr>
</tbody>
</table>

There were no statistically significant differences between the DRRs in the lateral gain; lateral scatter and front/back confusion measurements in the wideband target/ high-pass reverberation condition.

5.4.4 Low-pass target/Low-pass reverberation

In the low-pass target and low-pass reverberation condition with an imposed ITD bias the listeners were presented with a low-pass target sound simultaneously with low-pass noise for the direct to reverberant ratios of quiet, +20, +10, 0 and -5.

5.4.4.1 Mean ITD and ILD weights for Low-pass target/Low-pass Reverberation

The general trends of both graphs (Figure 56 & 57) illustrates that the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues. However, the listeners do not change their auditory cue weighting as the DRR decreased and the target signal becomes more diluted.
Figure 53. Mean ITD weight in the low-pass target/low-pass reverberation condition as a function of DRR.

Figure 54. Mean ILD weight in the low-pass target/low-pass reverberation condition as a function of DRR.
To test the statistical significance of these trends, a one-way repeated measures ANOVA was conducted. The ANOVA analysis showed no significant main effect of DRR on ITD weight \( (F(4, 28) = 0.746, p=0.569) \) in the low-pass target and low-pass reverberation condition.

In the low-pass target/low-pass reverberation condition with an imposed ILD bias the listeners were presented with a low-pass target sound simultaneously with low-pass reverberation for the direct to reverberant ratios of quiet, +20, +10, 0 and -5. The one-way ANOVA analysis also showed no significant main effect of DRR on ITD weight \( (F(4, 28)= 0.569, p=0.687) \) in the low-pass target and low-pass reverberation.
5.4.4.2 Mean sound localization performance results for low-pass target/low-pass reverberation combination

Sound localization measures were examined with the listener’s lateral gain, lateral scatter and front/back confusions. The slope and RMS deviation from the intercept of the listener’s raw data were used to compute the lateral gain and later scatter. The front/back confusion was computed by the percentage of the trials in which the listener reported the front/back hemisphere correctly, regardless of any other errors Figure 58.
Figure 55. The low-pass target/low-pass reverberation sound localization performance measure graphs.

Table 24. The P-values of the significant differences between the different DRRs in the lateral gain, lateral scatter and front/back confusion localization measures.
<table>
<thead>
<tr>
<th></th>
<th>Lateral Gain</th>
<th>Lateral Scatter</th>
<th>Front/back Confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.4657</td>
<td>0.575</td>
<td>0.1498</td>
</tr>
</tbody>
</table>

There were no statistically significant differences between the DRRs in the lateral gain, lateral scatter and front/back confusion measurements in the low-pass target/ low-pass reverberation condition.

5.4.5 High-pass target/High-pass reverberation

In the high-pass target/ high-pass reverberation condition with an imposed ITD bias the listeners were presented with a high-pass target sound simultaneously with high-pass noise for the direct to reverberant ratios of quiet, +20, +10, 0 and -5.

5.4.5.1 Mean ITD and ILD Weights for High-pass target/ High-pass Reverberation

The general trends from both graphs (Figure 59 & 60) depict that the listeners gave a low weighting to their ITD cues and a high weighting to their ILD cues. The graphs further show that as the DRR decreased and the target signal became more diluted, listeners started to decrease their ITD weighting but did not increase their ILD weighting.
To test the statistical significance of these trends a one-way ANOVA showed a significant main effect of DRR on the ILD weight ($F(4, 28) = 4.181, p=0.009$) in the
high-pass target and high-pass reverberation condition. However, when post hoc comparisons were conducted with a Bonferroni correction, no pair-wise comparisons were significant (p>0.05) but there was a significant linear trend (p=0.041) between the decreasing DRR and the decreasing ITD weighting.

Table 25. The P-values of the significant differences between the different DRRs in the high-pass target/ high-pass reverberant condition with an imposed ITD bias.

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>+20DRR</th>
<th>+10DRR</th>
<th>0 DRR</th>
<th>-5 DRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>+20DRR</td>
<td></td>
<td>P=0.037</td>
<td></td>
<td></td>
<td>p=0.041</td>
</tr>
<tr>
<td>+10DRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>p=0.035</td>
</tr>
</tbody>
</table>

In the high-pass target/ high-pass reverberation condition with an imposed ILD bias the listeners were presented with a high-pass target sound simultaneously with high-pass reverberation for the direct to reverberant ratios of quiet, +20, +10, 0 and -5. The one-way ANOVA showed which showed no significant main effect of DRR on ILD weight (F (4, 28)= 1.851, p=0.147) in the low-pass target and low-pass reverberation.
5.4.5.2 Mean sound localization performance results for high-pass target/high-pass masker combination

Sound localization measures were examined with the listener’s lateral gain, lateral scatter and front/back confusions. The slope and RMS deviation from the intercept of the listener’s raw data were used to compute the lateral gain and later scatter. The front/back confusion was computed by the percentage of the trials in which the listener reported the front/back hemisphere correctly, regardless of any other sound localization errors.
Figure 58. The high-pass target/ high-pass reverberation sound localization performance measure graphs.
Table 26. The P-values of the significant differences between the different DRRs in the lateral gain, lateral scatter and front/back percent correct localization measures.

<table>
<thead>
<tr>
<th></th>
<th>Lateral Gain</th>
<th>Lateral Scatter</th>
<th>Front/back Confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>P value</td>
<td>0.0074</td>
<td>0.9477</td>
<td>0.0037</td>
</tr>
</tbody>
</table>

In the front/back confusion there is a significant effect between the DRRs, however, when a post hoc analysis done with a Bonferroni correction factor was applied, it resulted in no significant differences between the DRR conditions.

Table 27. The P-values of the significant differences between the different DRRs in the front/back percent correct localization measure.

<table>
<thead>
<tr>
<th></th>
<th>+20 DRR</th>
<th>+10 DRR</th>
<th>0 DRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>+20 DRR</td>
<td>p=0.016</td>
<td>p=0.026</td>
<td></td>
</tr>
<tr>
<td>Quiet</td>
<td>p=0.030</td>
<td>p=0.046</td>
<td></td>
</tr>
</tbody>
</table>

The table shows the p-values of the significant differences between the different DRRs in the front/back confusion localization measure.
5.5 Discussion

In Experiment III, we measured ITD and ILD weighting as a function of the target/masker combinations and DRR. The results show that when low-frequency ITD cues were available, the addition of interfering reverberation resulted in a slight decrease in ITD weighting. Also, as the DRR decreased there was an increase in ILD weighting even when the masking noise also affected the high frequency ILDs.

Over the range of DRRs tested, there was little effect of DRR on localization performance for most target/masker combinations. These results are discussed in more detail in Chapter 6.
6 General Discussion

The present study addressed the auditory cue weighting of the interaural time difference (ITD) and interaural level difference (ILD) during sound localization in quiet, noisy and reverberant environments. It also measured listeners’ localization performance in all three conditions.

Cue weighting was measured using stimuli generated with the listeners’ individualized head related transfer function (HRTF) measurements and imposing either an ITD or ILD bias during the sound localization process. The listeners’ cue weighting was measured by computing the amount of listener’s response bias in comparison to the imposed bias. It was hypothesized that the localization performance of listeners in quiet would be accurate, however in reverberant or noisy conditions that listeners would adapt their weighting of low- and high-frequency ITD and ILD cues to maximize their localization performance. Listeners were expected to start using their ILD cues instead of their dominant ITD cues, when the low frequencies were de-correlated and unreliable. In contrast, listeners were expected to start using their ITD cues instead of their ILD cues when the high-frequency ILDs were reduced by the presence of noise or reverberation. In quiet, the balance of low- and high-frequency energy in a wideband stimulus was expected to strongly influence the ITD and ILD weighting. It was hypothesized that as the low-frequency energy increased, the listeners’ ITD weighting would increase and as the low-frequency energy decreased, the listeners’ ITD weighting would decrease. In comparison, as the high-frequency energy increased, the listeners’ ILD weighting would increase, and as the high-frequency energy decreased then the listeners’ ILD weighting
would also decrease. The hypotheses are in accordance with the duplex theory of sound localization and previous studies of localization cue weighting.

The following sections discuss the results of the three conditions in more detail, how the results compare to previous findings, the limitations of the project, and the significance of the final results. To assist the discussion, Tables 28 and 29 present the significant ITD and ILD linear trends in the noisy and reverberant condition and Figure 62 presents the mean ITD and ILD weights across listeners for all conditions in all three experiments.
Table 28. Significant ITD/ILD linear trends for the noisy experiment. The top row illustrates the types of targets and the left row illustrates the types of maskers. The table shows whether the listeners linearly increased or decreased their auditory cue weighting as the SNR decreased.

<table>
<thead>
<tr>
<th></th>
<th>WB target</th>
<th>LP target</th>
<th>HP target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WB masker</strong></td>
<td>ITD ↓/ILD ↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LP masker</strong></td>
<td>ITD ↓/ILD ↑</td>
<td>ILD ↑</td>
<td></td>
</tr>
<tr>
<td><strong>HP masker</strong></td>
<td></td>
<td></td>
<td>ITD ↓</td>
</tr>
</tbody>
</table>

Table 29. Significant ITD/ILD linear trend for the reverberant experiment. The top row illustrates the types of targets and the left row illustrates the types of maskers. The table shows whether the listener’s linearly increased or decreased their auditory cue weighting as the SNR decreased.

<table>
<thead>
<tr>
<th></th>
<th>WB target</th>
<th>LP target</th>
<th>HP target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WB masker</strong></td>
<td>ITD ↓</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LP masker</strong></td>
<td>ILD ↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HP masker</strong></td>
<td></td>
<td></td>
<td>ITD ↓</td>
</tr>
</tbody>
</table>
Figure 59. The mean ITD versus ILD weights across the listeners for the quiet, noisy and reverberant conditions.
The y-axis represents the ILD weighting of the listeners and the x-axis represents the ITD weighting of the listeners. The top graph is for the quiet target spectra where each color represents one of the nine different spectral profiles. The bottom left graph is for the noisy condition and the bottom right graph is for the reverberant condition, where each colored dot represents a different target/masker combination. Each dot represents a different SNR/DRR and the filled in dot represents the lowest SNR/DRR.
6.1 Sound localization in quiet

The low-pass and high-pass results are in accordance with the duplex theory of sound localization. The low-pass condition yielded a high ITD weighting and low ILD weighting. In comparison, the high-pass condition resulted in a high ILD weighting and a low ITD weighting and the wideband condition resulted mainly in a high ITD weighting. In the wideband condition with the varying low and high frequency energy balance, the results illustrated that as the amount of high frequency increased in the wide band stimuli, the listeners increased their ILD weighting from that measured for the flat-spectrum, wideband target. However, as the amount of low frequency energy increased in the wide band stimuli, the listeners did not increase their ITD weighting from its already high value.

The ILD weight findings were consistent with the proposed hypothesis. As the high-frequency energy in the wideband target stimuli increased, the listeners’ ILD weighting also increased. However, the ITD weight findings were inconsistent with the hypothesis because as the low-frequency energy in the wideband target stimuli increased, the listeners’ ITD weighting did not change. Across the three experiments, there was no signal condition that significantly increased the weighting of ITD above its wideband, flat-spectrum quiet value.

The sound localization performance of the listeners across the nine different stimulus spectra was approximately equal, although lateral scatter slightly increased with decreasing low-frequency energy and front/back localization was poor for the low-pass target spectrum, which did not carry any high-frequency spectral cues. The results of this
study show that the bandwidth does not greatly affect the sound localization performance of the listeners if the target stimulus bandwidth is 2-octaves or wider. These findings are consistent with Yost’s finding (Yost, 2013) showing that listeners had the same localization performance across low-pass, high-pass and wideband 200-ms, 2-octave target stimuli.

6.2 Sound Localization in noise

The present study addressed the auditory cue weighting of the interaural time difference (ITD) and interaural level difference (ILD) during sound localization in the noisy condition with different combinations of target and masker spectra and SNRs (SNRs). It also measured the sound localization performance of the listeners in noise at the different SNRs.

This was measured by using the listeners’ individualized head related transfer function (HRTF) measurements and imposing either an ITD or ILD bias during the sound localization process. A masker was then added to the listeners’ HRTFs-filtered stimuli. The listeners’ cue weighting was measured by computing the amount of imposed bias in comparison to the listeners’ response. It was hypothesized that the listener’s localization performance would be accurate at a higher SNR and would start to decrease as the SNR decreased. It was also hypothesized that depending on where in frequency the masker was placed in reference to the target noise spectrum, the listener would adapt their weighting of low and high frequency ITD and ILD cues to maximize their localization performance. Listeners’ were expected to increase their low frequency ITD weighting when the masker was masking the high frequency portion of the target signal. In
comparison, listeners were expected to increase their high frequency ILD weighting when the masker was masking the low frequency portion of the target signal.

### 6.2.1 Interpretation of findings

The findings show a significant change in the weighting of both auditory cues for the wideband target/wideband masker condition and the wideband target/low-pass masker condition. In the wideband/wideband condition at a high SNR, listeners heavily rely on their ITD cues to localize the target sound, however as the SNR decreases the listeners start to decrease their ITD weighting and increase their ILD weighting. This demonstrates that although the ITDs are the dominant cue for sound localization in the quiet environment, listeners weigh cues differently in adverse listening conditions. 

In the wideband/low-pass condition the listeners heavily weighted their ITD cues at a high SNR, however as the SNR decreased to -5 dB SNR the listeners start to decrease their ITD weighting and increase their ILD weighting. This shows the listeners will use their ITD cues when low frequencies are available, however when the SNR decreases and the low frequencies become interaurally de-correlated, the listeners start to give a higher weighting to their ILD cues instead. This condition also shows that although ITDs are dominant in quiet conditions, they might not be dominant in noisy conditions. Therefore, in both the wideband/wideband and wideband/low-pass condition the listeners will give a high weighting to their ITD cues if reliable low frequency ITD cues are available to them. However, they will start to decrease their ITD weighting and increase their ILD weighting if the masker is de-correlating the low frequencies. This illustrates that listeners will always give a higher weighting to their ITD cues when they are available, however when they aren’t available the listeners are able to weigh their auditory cues
differently in order to maintain their sound localization performance. This could explain why the listeners’ sound localization performance decreased at 0 SNR.

The findings show a significant change in the weighting of one auditory cue in the low-pass target/low-pass masker condition and the high-pass target/ high-pass masker condition. In the low-pass/low-pass condition the listeners heavily weigh their ITD cues in the different SNR conditions, however they increase their ILD weighting as the SNR decreases. Although the listeners are weighting their auditory cues differently, there is no tradeoff between the ITD and ILD cues in the presence of a masker to maximize their auditory cue weighting. By maintaining a high ITD weighting and also increasing their ILD weighting, this may be the listeners’ strategy for maintaining their sound localization performance at lower SNRs in the absence of high-frequency ILDs.

In the high-pass/high-pass condition the listeners decreased their ITD weighting as the SNR increased, however in the ILD bias condition the listeners did not change their weighting as the SNR decreases. This could explain why their sound localization performance decreased at 0 SNR.

The findings show no significant changes in the weighting of either auditory cue for the wideband target/ high-pass masker condition. The listeners heavily weigh their ITD cues in all the SNR conditions and they do not change their auditory cue weighting as the SNR decreases to maximize their localization performance in the presence of the masker. The high-pass noise is only masking the high frequencies and therefore the low frequency ITDs were not affected. Thus, the listeners continue to use their ITD cues because the masker does not affect the low frequencies.
In conclusion, when listeners are localizing target sounds in their environment they are shown to have a tradeoff between their ITD and ILD auditory cues in the wideband target/ wideband masker and wideband target/ low-pass masker conditions. The listeners either increase or decrease the weighting of an auditory cue in the low-pass target/ low-pass masker and high-pass target/ high-pass masker conditions. Lastly, the listeners were not shown to have any auditory cue weighting changes in the wideband target/ high-pass masker condition. There are multiple similarities between the results of the different target masker combinations in the noisy condition. First of all, the listeners always gave a high weighting to the ITD cue when low frequencies were available in the target signal. Secondly, when both auditory cues are available and the low frequencies are masked, the listeners will increase their ILD weighting. This demonstrates that although ITDs are dominant in quiet conditions they may not be dominant in adverse listening conditions. The third similarity is that when the high frequencies are masked, listeners do not change their ILD weighting because they mainly used their ITD cues for sound localization, not their ILD cues. Thus when low-frequency ITDs are available, high frequencies do not significantly impact the listeners sound localization when they are either un-masked or masked. Lastly, due to the fact that listeners always give maximal weighting to their ITD cues, their ITD weighting will only decrease and never increase.
6.2.2 Effect of masking noise on ITD and ILD cues

To explore the effect of background noise on the available ITD and ILD cues, for one listener’s HRTFs we computed the interaural coherence (the maximum of the interaural cross-correlation, related to ITD reliability) and overall ILD as a function of azimuth for each target/masker combination and SNR. The coherence results (Figures 63 and 64) in the noisy condition illustrates that even in quiet conditions or at a higher SNR, the listener’s high frequency coherence was somewhat less compared to the low frequencies. For example, Figure 63 illustrates in all the combinations where both auditory cues are available such as the wideband target/ wideband masker, wideband target/ low-pass masker and wideband target/ high-pass masker the high frequencies are less coherent than the low frequencies. However, with the addition of noise the low and high frequencies’ coherence are equally affected. In addition, with the addition of the masking noise, the coherence decreased for whichever frequencies were masked. For example, Figure 64 shows that in the wideband target/wideband masker condition the coherence across all the frequencies decreased because the masker is affecting all the frequencies equally. In comparison in the wideband target/low-pass masker condition where the low frequencies are masked, only the coherence in the low frequencies decreased.

Comparing the coherence for the low frequencies between Figure 63 (+20 dB SNR) and Figure 64 (0-dB SNR) illustrates the coherence decreasing from ~1.0 to ~0.5 when they are masked, resulting in the ITDs becoming less reliable in noisy conditions. This relates to previous findings by Kolarik & Culling (2009), who showed in an ITD discrimination task that as coherence was halved from 1 to 0.5 by the addition of interaurally uncorrelated noise, ITD thresholds more than doubled. Their results show that the ITD
thresholds for 100-ms noise stimuli increased from 25 to 90 µs. Although this is a significant increase, compared to the ±700-µs range of normal ITDs, 90 µs is still reliable and useful for sound localization (Kolarik & Culling, 2009). This might explain why listeners continue to use their ITD cues in noisy conditions.

Figure 60. Interaural coherence versus azimuth graphs for different target masker combinations in the noisy condition at +20 SNR. The y-axis represents the coherence of the target signal and the x-axis represents the azimuth of the target sound.
Figure 61. Coherence graphs for different target masker combinations in the noisy condition at 0 SNR. The y-axis represents the coherence of the target signal and the x-axis represents the azimuth of the target sound.
To estimate the effect of masking noise on ILD cues, in Figures 65 and 66, we plot for one listener computed ILD-versus-azimuth functions for unbiased (solid lines) and +10-dB-biased (dashed lines) in quiet (blue) and masked (red) conditions. The ILD was based on the overall (target + masker) intensity in each ear over the duration of the target. The ILD in the noisy condition shows that with the addition of noise the ILD cues were made smaller. Figure 65 shows that at a higher SNR of +20 dB, the listeners’ ILD cues are similar to their ILD cues in quiet. Figure 66 shows that at a lower SNR of 0 dB, the listeners ILD cues become compressed to about one-half the quiet values compared to their ILD cues in quiet for all the target masker combinations. The effect of the imposed ILD bias is also reduced by the addition of the masking noise.

Although the listeners’ ILD cues are compressed by the addition of noise, it does not make the cues less reliable since they are still relatively large; Hartmann and Constan (2002) have shown that ILD discrimination thresholds for interaurally uncorrelated noise are only slightly higher than those for correlated noise. Listeners are still able to maintain the same localization performance when ILD cues are compressed. This could be due to one of two reasons: The first one is that the listeners are able to separate the masker noise from the target signal and thus are able to ignore the noise. However, this may be difficult because the masker and target signal are very acoustically similar to one another and thus hard to separate. The alternative reason may be that listeners interpret the overall ILDs in the masked conditions based on the compressed ILD-versus-azimuth functions.

Therefore a small change in the overall ILD might produce the same change in perceived azimuth as in the quiet condition. If this is true then the ILD weights would be expected
to increase twofold in the 0 dB SNR high-pass target/high-pass masker condition, where only the ILD cues are available to this listener. However Figure 40 shows that the ILD weights remained approximately constant with SNR, instead of increasing as expected. A possible explanation could be that the calculation of ILD weights in the Noise experiment compared the listener’s response bias to the ILD bias imposed on the target, and not to the smaller actual imposed bias that resulted in the masked conditions (Figure 66). Using smaller masked ILD bias values instead of larger target ILD bias values would result in larger computed ILD weights. This would ultimately explain how listeners continue to localize accurately even at low SNRs.

Figure 62. Graphs of ILD versus azimuth for different target masker combinations in the noisy condition at +20 SNR. The y-axis represents the ILD (dB) response and the x-axis represents the target azimuth of the sound.
Figure 63. Graphs of ILD versus azimuth for different target masker combinations in the noisy condition at 0 SNR. The y-axis represents the ILD (dB) response and the x-axis represents the target azimuth of the sound.
6.2.3 Effect of audibility on ILD weighting at low SNRs

In the wideband target / wideband masker and high-pass target / high-pass masker conditions, there was a large increase in ILD weighting in the 0-dB SNR condition. We wondered if this large weight might be caused by loss of audibility of the target signal in the attenuated ear when ILD bias was imposed. To impose an ILD bias of 10 dB, the sound was decreased by 5 dB on one side and increased by 5 dB on the opposite side, resulting in a 10 dB difference between the ears. If the target sound came from the right side and we imposed a bias toward the right ear, then the target sound should remain audible in the right ear, but that target’s lower level at the left ear (due to head shadowing) combined with the 5 dB attenuation due to the imposed bias, might make it inaudible in the left ear.

To explore this, the author performed an informal listening experiment. Using stimuli created with the HRTFs of listener L103, four blocks of trials were run in the 0-dB SNR condition for each of the wideband/wideband, low-pass/low-pass, and high-pass/high-pass target/masker combinations. Two blocks were run listening only to the right-ear signal (left headphone unplugged) and two listening only to the left-ear signal. The listener did not localize these monaural stimuli, but simply reported on each trial whether a target was audible. Figure 67 shows, as a function of azimuth and imposed bias, the number of trials rated monaurally inaudible for each target/masker combination (columns) and for the right (top row) and left (bottom row) listening ears. This figure illustrates that targets on the right or in the rear could be rendered inaudible in the left ear by a rightwards ILD bias and that targets on the left or in the rear could be made inaudible in the right ear by a leftwards ILD bias.
This suggests that the listeners might have overly biased their weighting response towards the side the of the bias, which could have resulted in the larger overall ILD weighting in the wideband target/ wideband masker, low-pass target/ low-pass masker and wideband target/low-pass masker noisy condition.

Figure 64. Monaural audibility plots for all target/masker combinations in the noisy condition at 0 SNR. The y-axis represents the number of target sounds that were reported as inaudible and the x-axis represents the azimuth of the target sound.
6.3 Sound localization in reverberation

The present study addressed the auditory cue weighting of the interaural time difference (ITD) and interaural level difference (ILD) during sound localization in the reverberant condition with different direct to reverberant ratios (DRRs). It also measured the sound localization performance of the listeners in noise at the different DRRs. The sound localization procedures as well as the auditory cue weighting hypotheses are the same as the noisy condition.

The findings show significant changes in the weighting of both auditory cues in the wideband target/low-pass reverberation condition. In this condition the listeners give a high weighting to their ITD cues and a low weighting to their ILD cues during sound localization. However, as the DRR decreases the listeners start to decrease their ITD weighting and increase their ILD weighting. This demonstrates that although ITD cues are dominant in quiet conditions, they may not be dominant in adverse listening conditions.

The findings show a significant change in the weighting of both auditory cues in the wideband target/wideband reverberation condition and the high-pass target/high-pass reverberation condition. In the wideband/wideband condition the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues. As the DRR decreased, the listeners’ ITD weighting also started to decrease. However, the listeners’ ILD weighting did not significantly increase.
In the high-pass/ high-pass condition the listeners gave a low weighting to their ITD cues and a high weighting to their ILD cues. As the DRR decreased, the listeners’ ITD weighting also started to decrease but their ILD weighting did not significantly increase. The results of this condition in reverberation are similar to the high-pass/ high-pass condition in noise, and could explain why the listeners’ sound localization performance decreased at 0 SNR.

The findings show no significant change in the weighting of auditory cues in the low-pass target/ low-pass reverberation and wideband target/ high-pass reverberation conditions. In the low-pass/ low-pass condition the listeners gave a high weighting to their ITD cues and a low weighting to their ILD cues. However, the listeners did not change their auditory cue weighting as the DRR decreased and the direct target sound became less dominant. This may be because the listeners do not have access to high frequency ILD cues during sound localization in the low-pass/low-pass condition and that the effect of the reverberation was not large enough to change their ILD weighting, in contrast to the low-pass/low-pass condition in which ILD weighting did increase at 0-dB SNR.

In the wideband/ high-pass condition the listeners gave a high weighting to their ITD cues and a low-weighting to their ILD cues. However, the listeners did not change their auditory cue weighting as the DRR decreased and the direct target sound became less dominant. This may be because the high-pass reverberation is only masking the high frequency ILDs and the listeners were only using their ITD cues to localize, thus the masker had no impact on their sound localization performance.

In conclusion, when localizing target sounds in their environment the listeners are shown to have a trade off in auditory cues in the wideband /low-pass reverberation condition.
They are shown to change the weighting of only one auditory cue in the wideband/wideband and high-pass/high-pass reverberation condition and lastly, their auditory cue weighting did not change for either cue in the low-pass/low-pass and wideband/high-pass conditions.

6.4 Common Results

There are many common trends among the three different conditions. In the quiet, noisy and reverberant conditions the ITD bias was given a high weighting when there were low frequencies available to the listeners. The ITD weighting in all three conditions was also shown to only decrease and never to increase compared to the quiet, wideband-spectrum weighting. This is because the ITDs are usually already given a high weighting and the listeners can not increase their ITD weighting more.

There are also some common trends amongst the noisy and reverberant conditions. The pattern of cue changes in the noisy and reverberant conditions is the same, excluding the wideband/wideband reverberant condition. The only difference is that the effects are smaller in the reverberant condition in comparison to the noisy condition, which may be due to the listeners paying attention to the cue onset before the build up of reverberation.

The first similarity is when both the auditory cues are available and the low frequencies are masked the listeners will resort to increasing their ILD weighting to maintain their sound localization performance. This shows that although ITDs are dominant in quiet conditions, they may not be dominant in adverse listening conditions. Secondly, in the conditions where both auditory cues are available and the high frequencies are masked, listeners do not change their ILD cue weighting because they mainly used their ITD for
sound localization. Thirdly, in both the noisy and reverberant high-pass/high-pass combinations as the SNR decreases, the listeners decreased their ITD weighting but did not increase their ILD weighting to compensate at 0 SNR. This could explain why the listeners’ sound localization performance also decreases at 0 SNR.

There are multiple similarities among the different target masker combinations that were also in accordance with the noisy condition results, but also some differences. First of all, the results in the reverberant condition had smaller effects compared to the noisy condition. This could possibly be due to the fact that the listeners were using the onset target cues before the buildup of the reverberation to localize their target sound and therefore the reverberation did not affect their overall performance. Secondly, the listeners always gave a high ITD weighting when low frequencies are available. Thirdly, the listeners ITD cue weighting will only decrease and not increase compared to the weighting in wideband quiet targets. Lastly, in the target masker conditions where the high frequencies are masked, the listeners do not change their ILD cue weighting.

6.5 Comparisons to other studies

In the quiet condition the results of this study were in accordance with the results from the Macpherson & Middlebrooks (2002) and Wightman & Kistler (1992) studies because it showed that for a wideband target where both auditory cues are available, the listeners still give a high weighting to their ITD cue as opposed to their ILD cue. The sound localization performance results show the listeners’ sound localization performance was essentially the same across all the different stimulus spectra. These findings relate back to the Yost et al. study because we also used a 2-octave bandwidth, which was sufficient for accurate lateral localization across all target spectra (Yost et al, 2013).
In the noisy condition the results of this study were not in accordance with previous work done in sound localization performance in noise. Previous results show that when the SNR decreased, the listeners’ sound localization performance would also decrease (Abouchacra et al, 1998; Good & Gilkey, 1996; Lorenzi et al, 1999). However, the listeners’ sound localization performance in this study did not show any change as the SNR decreased which could be due to four possible reasons.

The first possible explanation is that the listeners were able to effectively change their auditory cue weighting to maximize their localization performance, allowing their sound localization performance to remain the same across the different SNRs. The second possible explanation could be that the SNRs were not at low enough levels to negatively affect the listeners sound localization performance. The SNR could only go down to -5 dB SNR before the target became inaudible to the listeners. This may be because the target signal and noise were similar sounds and thus the target became inaudible more quickly than if the target and noise were dissimilar sounds as used by Abouchacra et al, (1998; speech target) and Lorenzi et al, (1999; click-train target).

The third explanation is in this study used a different masker compared to previous studies. The masker was a diffuse uncorrelated masker that had no apparent direction, which may have impacted the overall results (Good & Gilkey, 1996). Lastly, previous studies concentrated on the worst errors for sound localization in noise, which are front/back confusion errors, and the analysis for the current study did not specifically concentrate on that.

The listeners’ auditory cue weightings were in accordance with the previous work done in sound localization in noise. In past studies, the results showed that the listeners were
able to localize as if they had re-weighted their auditory cues in a noisy environment. In the study done by Lorenzi et al (1999), they demonstrated that in a wideband target condition where both auditory cues are available, since the ITDs are less resistant in a noisy environment the listeners would give their ILDs a higher weighting (Lorenzi et al, 1999). These results relate to the wideband target/ wideband masker and wideband target/ low-pass masker in noise condition when the listeners initially give their ITDs a high weighting and their ILDs a low weighting at high SNRs. However, when the SNR starts to decrease the listeners start to change their auditory cue weighting and give a higher weighting to their ILDs and a lower weighting to their ITDs. Therefore, the results from this study and Lorenzi et al’s study show that although ITD cues are dominant in quiet environments, listeners are able to base their decision on the cues providing the most accurate direction of sound source when multiple cues are available.

The results for this study were similar to that of previous sound localization in reverberation studies, which showed reverberation was least effective with high-pass stimuli and most effective with low-pass stimuli. Therefore, implying that the high frequency ILD cues are least likely to be made unreliable by reverberation and the low frequencies are most likely to be de-correlated by reverberation. Previous results show listeners will continue to weigh ITD cues more heavily, even in adverse listening conditions when it is not advantageous to do so (Bharadwaj, 2013; Ihlefeld & Shinn-Cunningham, 2011). These results correspond to those of this study because listeners continued to give a high ITD weighting in the wideband target/ wideband reverberation and low-pass target/ low-pass reverberation condition, even when it was more advantageous to decrease their ITD weighting and increase their ILD weighting.
One difference between the findings of this study and others’ is the small effect on localization performance of reverberation, even at low DRRs. Only in the high-pass/high-pass reverberation condition was there a significant reduction in lateral angle gain with decreasing DRR. This contrasts with the finding of Ihlefeld & Shinn-Cunningham (2011) that low-frequency bands of noise were most affected by room reverberation. The effect they observed was a bias towards the midline, which is equivalent to a reduction in our lateral angle gain measure. One possible explanation is that our artificial reverberation lacked the discrete early reflections present in real rooms, and that the previously observed large reverberation effects depend on the presence of those reflections.

6.6 Future Work

In future studies we would suggest that since the effects in the reverberation condition were small in comparison to the noisy condition, it could be because the reverberation wasn’t realistically masking the target signal. This could be fixed by using a more realistic reverberation by recording real impulse responses in rooms. Secondly, we could only use certain SNRs because the target signal and masker were too acoustically similar and the target masker combination became inaudible quickly. For future work, we would use different target and signal stimuli potentially allowing us to go down to lower SNRs. For example, the Abouchacra et al. study decreased their SNRs down to -18dB because their target sound was speech and their masker was white noise therefore allowing them to go down lower in their SNRs (Abouchacra et al, 1998). Lastly, due to the inaudibility in the ILD bias condition instead of having a larger ILD difference implemented between the two ears (5dB in one ear and 5 dB in the second ear), we would implement a smaller
ILD between the two ears (for example, -3dB in one ear and +3dB in the second ear) or simply increase the level in one ear to implement the bias. Previous studies have shown that a smaller ILD bias has been shown to work as well (Macpherson & Middlebrooks 2002).

6.7 Conclusion

In conclusion, the study examined the weighting of the ITD and ILD auditory cues in both quiet environments and more adverse environments such as noisy and reverberant conditions. The quiet results showed that as the high-frequency energy in the wideband target stimuli increased, the listeners’ ILD weighting also increased. However, the ITD bias condition findings were inconsistent with our hypothesis because as the low-frequency energy in the wideband target stimuli was increased, the listeners’ ITD weighting did not change.

The common trends of the quiet, noisy and reverberant conditions ultimately showed that listeners give a very high weighting to their ITD cues and the weighting of the ITD cues only decrease not increase. The trends also show that the listeners’ lateral sound localization performance remains constant even when the high/low energy balance in the wide band target is altered and even when the SNR and DRR is decreased to reduce the target audibility. Furthermore, there were also common trends amongst the noisy and reverberant conditions that illustrated when both auditory cues are available to the listeners and the low frequency is masked, the listeners increased their ILD weighting. This means that even though ITDs are dominant in quiet conditions, they might not always be dominant in adverse conditions. The second trend demonstrated that in the conditions where both auditory cues were available and only the high frequencies were
masked, the listeners did not change their ILD weighting because they mainly only used their ITD cues for sound localization. Lastly, for the high-pass target/ high-pass masker for both the noisy and reverberant conditions as the SNR or DRR decreases, the listeners decreased their ITD weighting but did not increase their ILD weighting to compensate, at 0 dB SNR/DRR. Their weighting strategy in this particular target masker combination may explain why their sound localization decreased only in this particular condition.

6.8 Significance

This is the first study to examine the effects auditory cue weighting on a wideband target signal with altering low and high frequencies. It is also the first study to quantitatively measure the listeners auditory cue weighting in noisy and reverberant conditions. The data from this study will not only advance our knowledge of basic perceptual processes, but the results will also have practical applications in the design of virtual auditory display technology and may suggest techniques to improve auditory performance in different acoustic environments for both normal and hearing-impaired individuals.
References


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