Across-channel interaural-level-difference processing demonstrates frequency dependence^{a)}

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(Received 24 April 2017; revised 28 December 2017; accepted 4 January 2018; published online 5 February 2018)

Accurate localization of complex sounds involves combining interaural information across frequencies to produce a single location percept. Interaural level differences (ILDs) are highly frequency dependent and it is unclear how the auditory system combines differing ILDs across frequency. Therefore, ILD just noticeable differences (JNDs) and intracranial lateralization were measured in young normal-hearing listeners using single- and multi-band stimuli. The bands were 300-ms, 10-Hz narrowband noises; the multi-band condition had three bands; they started and ended synchronously; they were located around three different frequency regions (750, 2000, or 4000 Hz); they had five different frequency separations that ranged from unresolved to resolved; the bands were dichotic with the same non-zero ILD (targets) or were diotic with zero ILD (interferers). Results showed single-band ILD JNDs were marginally frequency dependent. If unresolved diotic interferers were added, ILD JNDs increased greatly because of interaural decorrelation. If well-resolved diotic interferers were added, ILD JNDs were frequency dependent and the worst performance occurred when targets were near 1000 or 4000 Hz. This frequency dependence might be partially explained by ILD vs azimuth non-monotonicities for free-field sound sources in this frequency region. These results suggest that binaural processing models need revision for the processing of complex sounds.

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Pages: 645–658

I. INTRODUCTION

Realistic sound sources, like speech, have complex spectra meaning that there is spectral energy distributed across a wide range of frequencies. To accurately localize a complex sound, the auditory system must combine interaural-time-difference (ITD) and interaural-level-difference (ILD) information across multiple frequencies. Sound localization appears to be dominated by low-frequency (<1500 Hz) ITDs (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). There are, however, situations when ITDs may not be available for accurate sound source localization, such as in reverberation (Devore and Delgutte, 2010; Rakerd and Hartmann, 2010) or when using cochlear implants (Seeber and Fastl, 2008; Aronoff *et al.*, 2010). Unlike normal-hearing listeners who show a low-frequency ITD dominance in sound localization, bilateral cochlear-implant listeners demonstrate an ILD dominance (Seeber and Fastl, 2008; Aronoff *et al.*, 2010). This occurs partially because cochlear implants do not encode temporal fine structure and are not bilaterally synchronized. Yet the contributions to sound localization with ILDs in the absence of appropriately encoded ITDs—as occurs with cochlear implants—is poorly understood because of the paucity of studies concerning across-channel ILD processing. Therefore, the purpose of this study was to investigate how normal-hearing listeners process and combine ILD information across different frequency regions.

ILDs are frequency dependent for a fixed and relatively large (about 1 m or greater) source distance; they are relatively small below 1000 Hz and generally become larger with increasing frequency because of diffraction and attenuation of the sounds as the wavelength becomes comparable to or smaller than the size of the head (Feddersen *et al.*, 1957; Macaulay *et al.*, 2010). Not only are ILDs highly frequency dependent, but they contain non-monotonicities between about 1000 and 4000–8000 Hz, a result of the constructive interference of sound traveling around the front and back of the head (i.e., an acoustical bright spot) (Macaulay *et al.*, 2010). This results in a decrease of the physical ILD for azimuthal angles greater than about 45° at these frequencies. If listeners relied on larger ILDs to indicate a larger azimuthal sound source angle, then the frequencies that have non-monotonic ILD vs azimuth functions would be potentially uninformative or even misinformative. Indeed, human perception falls victim to this misinformation in some cases, for example, when trying to localize 1500-Hz tones in the free field (Macaulay *et al.*, 2010). There is, however, apparently a mechanism in the auditory system to deal with this potentially misinformative ILD-based location information, using ITD information. The binaural system demonstrates a low-frequency dominance of ITDs in sound localization, meaning that ITDs below 1500 Hz are weighted heavily in the presence of conflicting ILD information (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). In addition, consistent ITDs across frequencies (Stern *et al.*, 1988) and slowly varying envelope modulations from complex sounds (Bernstein and Trahiotis, 1994; Majdak and Laback, 2009) extend the usability of ITDs to frequencies

^{a)}Portions of this study were presented at the 169th Acoustical Society of America Meeting, Pittsburgh, PA, USA.

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higher than 1500 Hz. Although it is unclear how fine-structure ITDs, envelope ITDs, and ILDs combine and are weighted across frequency to form a single location percept, a sensible and simple model would be that (1) low-frequency ITDs dominate most of the percept, (2) high-frequency ILDs (>4000–8000 Hz) that have reasonably monotonic ILD vs azimuth functions contribute relatively less weight, (3) envelope ITDs and across-channel ITDs would contribute at higher frequencies, and (4) mid-frequency ILDs are weighted minimally, disregarded entirely, or used to disambiguate ITDs (Dietz *et al.*, 2011). Such a model is theoretical and would need empirical evaluation. This study is a starting point for evaluating individual portions of such a model.

Several studies have investigated the frequency dependence of ILD processing of single tones presented over headphones (Mills, 1960; Grantham, 1984; Yost and Dye, 1988). Using a task where listeners discriminate small differences in intracranial lateral sound position, ILD just noticeable differences (JNDs) seem to be mostly frequency independent. One notable exception is that there are slightly elevated JNDs around 1000 Hz (Grantham, 1984; Yost and Dye, 1988). Comparisons of ILD frequency dependence across these studies are difficult because there were various level roving ranges (necessary to rule out the possibility that listeners were using monaural level cues), small numbers of listeners ($N = 3\text{--}5$), and different frequencies tested (see Table I). A small but measurable frequency dependence in ILD processing has also been shown using a task that measures extent of perceived intracranial laterality (Bernstein and Trahiotis, 2011; Stakhovskaya and Goupell, 2017). In summary, there may be ILD frequency dependence, but effects in past studies are small (thus warranting larger sample sizes) and comparisons across studies are limited by differences in methodologies.

One way to elucidate the frequency dependence of ILD processing is to use complex stimuli where some frequency bands are targets (i.e., a non-zero ILD was applied to create dichotic bands) and some bands are interferers (i.e., zero ILD was applied to create diotic bands). The interferers are aimed at elevating JNDs for the targets, or causing “binaural interference” (McFadden and Pasanen, 1976). Binaural

interference occurs for both ILD discrimination (Heller and Richards, 2010) and lateralization (Best *et al.*, 2011).

The approach used in this study was to present dichotic target bands and diotic interferers to investigate across-channel ILD processing, similar to what occurs in a binaural interference study. We measured ILD JNDs (experiments 1–3) and ILD lateralization (experiment 4) using narrowband noises as dichotic targets in the presence of diotic interferers over several center frequencies (CFs) and separations between bands. Four competing predictions were made about the outcome of the experiments in terms of the perceptual weighting for multi-band ILD processing and ILD JNDs. The first prediction was that the perceptual weighting for the multi-band ILD processing would be uniform across frequency. Therefore, multi-band ILD JNDs for dichotic target bands in the presence of diotic interferers would be frequency independent (Kelvasa and Dietz, 2015; Stakhovskaya and Goupell, 2017), similar to the mostly frequency independent ILD JNDs for single tones (e.g., Yost and Dye, 1988). The second prediction was that perceptual weighting for the multi-band ILD processing would favor ILDs at relatively higher frequencies because the head naturally produces larger ILDs at higher frequencies; therefore, multi-band ILD JNDs would be lower for higher-frequency targets compared to lower-frequency targets. The third prediction was that perceptual weighting for the multi-band ILD processing would favor ILDs at lower frequencies because large ILDs at lower frequencies are a relatively rare occurrence. In other words, it is not that the binaural system disregards ILDs at lower frequencies, it is that the head does not often produce large ILDs at lower frequencies. Alternatively, the auditory system may seek to achieve equal sensitivity to azimuthal differences (i.e., equal minimum audible angles) at all frequencies; to achieve this goal, lower-frequency ILDs would need to become weighted more heavily than higher-frequency ILDs. Therefore, multi-band ILD JNDs would be lower for lower-frequency targets compared to higher-frequency targets. The fourth prediction was that perceptual weighting for the multi-band ILD processing would have lower weighting for ILDs targets in the region between 1000 and 4000 Hz, which has strong non-monotonicities in the ILD vs azimuth function. Therefore,

TABLE I. Summary of previous studies that have investigated single-channel ILD JNDs and the four experiments in this study. The number of listeners, the roving range, stimulus type, and CFs are reported.

Study	Roving			CF (kHz)
	Listeners	Range (dB)	Stimuli	
Mills (1960)	5	0	Tones	0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6, 8, 10
Grantham (1984)	4	~5–20 ^a	Tones	0.5, 0.8, 0.9, 1, 1.1, 1.2, 1.5, 2, 4
Yost and Dye (1988)	3	8	Tones	0.25, 0.5, 1, 2, 5
Heller and Richards (2010)	4	10	Narrowband noises	0.5, 4
Experiment 1	11	20	Narrowband noises	0.3, 0.5, 0.65, 0.7, 0.73, 0.75, 0.77, 0.8, 0.85, 1, 1.2
Experiment 2	10	20	Narrowband noises	0.5, 1.25, 1.76, 1.88, 1.94, 2, 2.06, 2.12, 2.24, 2.75, 3.5
Experiment 3	10	20	Narrowband noises	1, 2.5, 3.544, 3.772, 3.886, 4, 4.114, 4.228, 4.456, 5.5, 7
Experiment 4	8	0	Narrowband noises	0.5, 0.75, 1

^aNote that Grantham (1984) performed an experiment where the level roving range changed depending on the target ILD (i.e., the range was smaller when the target ILD was smaller).

multi-band ILD JNDs would be highest where the ILDs do not naturally provide an informative ILD-based localization cue.

II. EXPERIMENT 1: DISCRIMINATION AROUND 750 HZ

Experiment 1 follows the approach of Dye (1990) and Dye and Stellmack (1990) to investigate across-frequency binaural processing at relatively low frequencies, below 1500 Hz.

A. Listeners

There were 11 young adult listeners (20–40 years, average = 22.7 years, nine females), but not all listeners completed all of the conditions. All listeners had normal audiometric thresholds of < 20 dB hearing level (HL) at octave frequencies between 250 and 8000 Hz. No listener had an asymmetry in thresholds > 10 dB at any tested frequency. One of the listeners was the second author. Listeners provide informed consent to the study and the procedures were approved by the University of Maryland-College Park Institutional Review Board.

B. Stimuli

The stimuli were similar to those used by Dye (1990) and Dye and Stellmack (1990). The stimuli consisted of 10-Hz narrowband noises of varying CF. Narrowband noises were used to diminish auditory grouping based on harmonicity and envelope fluctuations. The narrowband noises were digitally generated in the frequency domain by using a complex random number generator, which provided stimuli with random amplitudes and phases at each frequency. The frequency domain signal was then transformed into the time domain by inverse fast Fourier transform. Therefore, the stimuli were generated to have infinitely sharp spectral edges. Some conditions had stimuli with one noise band; other conditions had stimuli with three noise bands. Each noise band began as diotic and interaurally correlated.

Each noise band had a 300-ms duration and was temporally shaped by a Tukey window with a 10-ms rise-fall time. For multi-band stimuli, all three bands started and ended simultaneously. Each noise band was generated independently. Therefore, the envelope modulations were statistically independent across the three bands.

For the multi-band stimuli, the middle band was placed at CF = 750 Hz. The other two bands were placed symmetrically around the middle band. Five band separations were tested ($\Delta = 20, 50, 100, 250$, and 450 Hz) and the CF of each band is reported in Table I. The equivalent rectangular bandwidth of the auditory filter at 750 Hz is 106 Hz (Moore and Glasberg, 1983) and therefore there was a range of unresolved and resolved band separations that were tested. Each of the CFs used for the multi-band conditions were also tested using a single band as a control measurement.

Each noise band was presented at 65 dB-A with ± 10 dB of overall diotic level roving (i.e., the roving range was 20 dB), which was applied consistently across the bands. For the multi-band conditions, ILDs were applied to either one,

two, or three of the bands; therefore, a subset of the initially diotic bands became dichotic. ILDs were applied to the bands by increasing the level in one ear by ILD/2 and decreasing the level in the other ear by ILD/2. Positive ILDs were defined as having a higher level in the right ear. The largest ILD that was used was 20 dB.

For the multi-band conditions, bands were individually labeled as low, middle, and high. If a non-zero ILD was applied to the band and thus became dichotic, it was labeled with a capital letter (L, M, or H). If zero ILD was applied to the band and thus remained diotic, it was labeled with a lower-case letter (l, m, or h). A pictorial representation of an example stimulus is shown in Fig. 1. This example was a multi-band condition with $\Delta = 250$ Hz, where there were two dichotic bands at the low and middle CFs and one diotic band at the high CF (thus labeled “LMh”). There was a +10-dB ILD for the 500-Hz CF noise band, a +10-dB ILD for the 750-Hz CF noise band, and a 0-dB ILD for the 1000-Hz CF noise band.

C. Procedure

ILD JNDs were measured using a two-down-one-up adaptive staircase procedure, targeting 70.7% correct on the psychometric function (Levitt, 1971). Three simultaneous adaptive tracks were used for each condition, where each individual trial was randomly selected between the three staircases. Each trial consisted of two intervals where one interval had a right-ear-favoring ILD and the other had a left-ear-favoring ILD. The ILDs were applied to a diotic reference signal by amplifying the signal in one ear by ILD/2 and attenuating the signal in the other ear by ILD/2. The task of the listener was to identify whether the intracranial position of the second interval was to the left or right of the first interval. Diotic level roving was applied to each interval to limit the use of monaural level or profile analysis cues to perform the task.

Each staircase consisted of 12 reversals and the last eight reversals were used to calculate the average ILD JND.

FIG. 1. Pictorial representation of an example three-band “LMh” stimulus (see text). The frequency separation between bands is $\Delta = 250$ Hz. The “L” band has a 500-Hz CF, the “M” band has a 750-Hz CF, and the “h” band has a 1000-Hz CF. The 106-Hz critical bandwidth (CBW) at 750-Hz is shown by the gray box. ILDs of +10 dB were applied to the “L” and “M” bands; there was 0-dB ILD on the “h” band.

Each staircase started with a 20-dB ILD. The initial change in ILD in the adaptive procedure was 4 dB. After the second reversal, the change in ILD was 2 dB. After the fourth reversal, the change in ILD was 1 dB. After the sixth reversal, the change in ILD was 0.5 dB.¹ The JND was reported as twice the ILD of a single interval. In other words, if the ILD JND was 6 dB, this means that the listeners could discriminate a 3-dB left-favoring ILD from a 3-dB right-favoring ILD with 70.7% accuracy. The maximum ILD that was allowed in the adaptive procedure was 20-dB ILD; incorrect answers at this ILD occurred seldom in the testing.

Custom software written in MATLAB (Mathworks, Natick, MA) was used for stimulus presentation. Stimuli were delivered with a digital-to-analog converter, headphone buffer, and programmable attenuator (TDT System 3 RP2.1, HB7, and PA5; Tucker-Davis Technologies, Alachua, FL) over insert earphones (ER2; Etymotic, Elk Grove Village, IL). Testing occurred in a double-walled sound attenuated booth (IAC, New York). Listeners controlled the experiment via a computer interface and initiated each trial by pressing a button.

Before testing there were up to three training blocks provided to the listener, where there was correct answer feedback after each trial. The number of training blocks depended on the listener's familiarity with the testing procedure, but all listeners demonstrated saturation in performance before the testing was initiated. Listeners were trained on the $\Delta = 250$ -Hz LMH condition. Training lasted 0.5–1 h. Then testing was performed without feedback. There were 11 single-band and 35 multi-band conditions. The order of conditions was randomized across listeners. The experiment lasted 4–5 h, and was administered in 2–3 separate sessions that were at most 2 h in length.

D. Results

Figure 2(A) shows the ILD JNDs for the single-band conditions as a function of frequency for nine of 11 listeners who completed this portion of the experiment.² A one-way repeated-measures analysis of variance (RM ANOVA) [with

Greenhouse-Geisser correction (GGC) because of a lack of sphericity] showed that there was no significant effect of frequency [$F(3.8,30.2) = 1.20$, $p = 0.33$, $\eta_p^2 = 0.13$; GGC], although there were points suggesting trends towards lower (e.g., 650 Hz) or higher (e.g., 1000 Hz) ILD JNDs. Figure 2(B) shows the results for the consistent multi-band LMH conditions (i.e., these stimuli have three bands that are dichotic and have the same ILD consistently applied across CF) for all 11 listeners. A one-way RM ANOVA showed that there was no significant effect of Δ [$F(2.2,21.5) = 1.71$, $p = 0.20$, $\eta_p^2 = 0.15$; GGC]. In addition, there was no difference between the JNDs for the single-band conditions [all measurements in Fig. 2(A)] and consistent multi-band LMH conditions [all measurements in Fig. 2(B)] [two-tailed two-sample unpaired t-test assuming unequal variances; $t(152) = 0.99$, $p = 0.32$]. The average JND for the single bands was 1.9 dB and for the multi-band LMH conditions was 2.1 dB.

Figure 3 shows the data for the inconsistent multi-band conditions (i.e., only a subset of the bands was dichotic) for all 11 listeners. In Fig. 3(A), all three inconsistent multi-band conditions had one dichotic target band. A two-way RM ANOVA with factors condition (LMH, Lmh, IMh, and ImH) and Δ (20, 50, 100, 250, and 450 Hz) showed a significant main effect of condition [$F(3,30) = 54.5$, $p < 0.0001$, $\eta_p^2 = 0.85$], a significant main effect of Δ [$F(4,40) = 11.6$, $p < 0.0001$, $\eta_p^2 = 0.54$], and a significant condition $\times$ Δ interaction [$F(12,120) = 4.39$, $p < 0.0001$, $\eta_p^2 = 0.31$]. *Post hoc* tests (two-sample paired t-tests with Bonferroni correction so $p = 0.05/6 = 0.0083$ would be significant) were performed. All four conditions were significantly different ($p < 0.0001$ for all six comparisons). The Lmh JNDs were about twice as large as the LMH JNDs; both had JNDs that were independent of Δ . The significant interaction occurred because the JNDs for the IMh and ImH conditions were dependent on Δ . At $\Delta = 250$ and 450 Hz, the Lmh and IMh JNDs were similar. At smaller Δ s, the IMh conditions had higher JNDs compared to the Lmh condition. There was a similar pattern observed between the IMh and ImH conditions, but the ImH conditions had the highest JNDs, particularly for $\Delta \leq 100$ Hz.

FIG. 2. Single-band (A) and consistent multi-band (B) ILD JNDs for experiment 1. In panel (A), the single-channel conditions are plotted as a function of frequency. Symbols represent the average JND and error bars show ± 1 standard error. The solid line shows the average JND over all frequencies and the shaded area shows ± 1 standard error. In panel (B), the consistent multi-band conditions (LMH) are plotted as a function of the frequency separation between bands (Δ). The CFs of the three bands are located at the top of the panel. Symbols represent the average JND and error bars show ± 1 standard error. The solid line shows the average JND over all Δ s and the shaded area shows ± 1 standard error.

FIG. 3. (Color online) Consistent and inconsistent multi-band conditions as a function of frequency separation between bands (Δ) for experiment 1. The CFs of the three bands are located at the top of the panel. Panel (A) shows data for one dichotic target band and two diotic interferer bands. Panel (B) shows data for two dichotic target bands and one diotic interferer band. Symbols represent the average JND and error bars show ± 1 standard error. The open squares showing the consistent multi-band LMH conditions in panel (A) are replotted from Fig. 2(B). In panel (B), the open squares represent the average and standard error for nine listeners, and thus the values differ slightly between panels (A) and (B).

Figure 3(B) shows the ILD JNDs when there were two dichotic target bands for nine of 11 listeners. A two-way RM ANOVA with factors condition (LMH, LMh, IMH, and LmH) and Δ (20, 50, 100, 250, and 450 Hz) showed a significant main effect of condition [$F(3,24) = 11.8$, $p < 0.0001$, $\eta_p^2 = 0.60$] and that JNDs significantly decreased for increasing Δ [$F(1.8,14.7) = 4.32$, $p = 0.036$, $\eta_p^2 = 0.35$; GGC]; the condition $\times \Delta$ interaction was not significant [$F(2.46,19.7) = 1.59$, $p = 0.23$, $\eta_p^2 = 0.17$; GGC]. *Post hoc* tests showed that LmH JNDs were higher than LMH JNDs ($p < 0.0001$) and LMh JNDs ($p < 0.0001$). When comparing inconsistent multi-band conditions where there was one dichotic target band [Fig. 3(A)] with conditions where there were two dichotic target bands [Fig. 3(B)], JNDs were lower for the two target band conditions and much more comparable to the LMH condition JNDs.

E. Discussion

This experiment investigated single- and multi-band ILD processing below 1500 Hz. The magnitude of the ILD JNDs were highly consistent with those reported for ten normal-hearing listeners in Spencer *et al.* (2016) using 500- or 4000-Hz 1/3-octave narrowband noises and ± 5 dB of diotic level roving. They found ILD JNDs at 500 Hz between 0.9–5.0 dB, with an average of 1.9 dB. The current study used a range of CFs from 300 to 1200 Hz, 10-Hz narrowband noises, and ± 10 dB of diotic level roving. We found ILD JNDs at 500 Hz between 0.9–3.6 dB, with an average of 1.9 dB.

Single-band ILD JNDs were independent of frequency [Fig. 2(A)], which was mostly consistent with other reports (Mills, 1960; Grantham, 1984; Yost and Dye, 1988). Consistent multi-band ILD JNDs were independent of separation Δ [Fig. 2(B)]. Single-band and consistent multi-band conditions had the same JNDs [compare Figs. 2(A) and 2(B)], meaning that there was no summation (i.e., improved JNDs) from adding more frequency content to the stimuli. The lack of summation might have occurred because of a floor effect.

The inconsistent multi-band conditions, where there was one dichotic target band and two diotic interferer bands [Fig. 3(A)], showed binaural interference (i.e., worse JNDs) compared to the consistent multi-band conditions. For example, the LmH conditions had ILD JNDs that were roughly double that of the LMH conditions. For inconsistent multi-band conditions with one dichotic target band, JNDs were mostly independent for $\Delta \leq 100$ Hz. Such a result should occur because the information passing through a single auditory filter is now interaurally decorrelated (an analysis of the amount of interaural decorrelation can be found in Sec. V, Fig. 9). Nonetheless, this is an interesting result when compared to the equivalent rectangular bandwidth of the auditory filter at 750 Hz, which is 106 Hz. With such a bandwidth, JNDs should have been mostly independent of Δ for $\Delta \leq 50$ Hz. ILD JNDs that are independent of Δ are predicted to occur for only unresolved bands. This possibly suggests a larger effective binaural critical bandwidth than monaural critical bandwidth (Zurek and Durlach, 1987; however, see contrary evidence in Kohlrausch, 1988) and/or that even minimal energy, greatly attenuated because it is well outside the critical bandwidth, can increase JNDs. The JNDs were generally smallest for the LmH conditions, followed by the IMh conditions, followed by the LmH conditions; however, there were many notable interactions in the data. For $\Delta \geq 250$ Hz, placement of the target band at the low, middle, or high CF did not affect JNDs, except when the target band was at 1000 Hz (ImH, $\Delta = 250$ Hz).

In summary, ILD JNDs for single bands were frequency independent [Fig. 2(A)] and for consistent multi-band conditions were independent of frequency separation Δ [Fig. 2(B)]. There were complex frequency-dependent patterns for the inconsistent multi-band conditions, particularly when there was one dichotic target band. JNDs were affected by the CF of the dichotic target and/or the separation Δ [Fig. 3(A)]. Those patterns of binaural interference mostly disappeared when there were two dichotic target bands and one diotic interferer band [Fig. 3(B)].

FIG. 4. Single-band (A) and consistent multi-band (B) JNDs for experiment 2. Conventions are the same as in Fig. 2, with one important exception. The shaded area in both panels (A) and (B) represent the average multi-band data from panel (B).

III. EXPERIMENT 2: DISCRIMINATION AROUND 2000 HZ

Experiment 2 followed the same approach as experiment 1, but moved the frequency region of interest to 2000 Hz, the region where strong non-monotonicities in the ILD vs azimuth function are observed for free-field sources (Macaulay *et al.*, 2010).

A. Methods

Ten adult listeners (18–40 years, average = 22.5 years, eight females; one was the second author) participated in this experiment. Two listeners from experiment 1 participated in experiment 2; eight listeners were new. The stimuli were the same as in experiment 1 except that (1) the middle-band CF was 2000 Hz, (2) $\Delta = 60, 120, 240, 750$, or 1500 Hz, and (3) the conditions with two dichotic target bands were omitted. The CFs used in the experiment are shown in Table I. The equivalent rectangular bandwidth of the auditory filter at 2000 Hz is 240 Hz, and therefore there was again range of unresolved and resolved bands that were tested. The procedure was the same as in experiment 1.

B. Results

Figure 4(A) shows the ILD JNDs for the single-band conditions as a function of frequency for nine listeners. A one-way RM ANOVA showed that there was no significant effect of frequency [$F(2.9,23.3) = 1.68$, $p = 0.20$, $\eta_p^2 = 0.17$; GGC], but the lowest JNDs tended to be near 2000 Hz. Figure 4(B) shows the results for the consistent multi-band LMH conditions for eight listeners. A one-way RM ANOVA showed that there was no significant effect of Δ [$F(1.6,11.7) = 0.67$, $p = 0.50$, $\eta_p^2 = 0.09$], which is consistent with experiment 1 [Fig. 2(B)]. Note that the consistent multi-band LMH conditions had the same JND as the single-band conditions near 2000 Hz [compare open circles to shaded area in Fig. 4(A)] and that the LMH conditions always included a 2000-Hz band. The single-band condition JNDs (all measurements in Fig. 4A) were significantly

higher than the multi-band LMH condition JNDs [two-tailed two-sample unpaired t-test assuming unequal variances; $t(122.7) = 4.90$, $p < 0.0001$]. The average ILD JND of the multi-band LMH conditions across Δ s was 1.0 dB, half of the 2.1-dB average JND for the multi-band LMH conditions in experiment 1.

The inconsistent multi-band conditions where there was one dichotic target band and two diotic interferer bands (Fig. 5, eight listeners) showed binaural interference compared to the consistent multi-band conditions, similar to what occurred in experiment 1 [Fig. 3(A)]. A two-way RM ANOVA with factors condition (LMH, Lmh, IMh, and ImH) and Δ (60, 120, 240, 750, and 1500 Hz) showed a significant main effect of condition [$F(1.2,8.6) = 17.1$, $p = 0.002$, $\eta_p^2 = 0.71$; GGC], no significant effect of Δ [$F(2.2,15.7) = 0.90$, $p = 0.44$, $\eta_p^2 = 0.11$], and a significant condition $\times \Delta$ interaction [$F(3.6,25.0) = 2.85$, $p = 0.0496$, $\eta_p^2 = 0.29$; GGC].

FIG. 5. (Color online) Consistent and inconsistent multi-band conditions as a function of frequency separation between bands (Δ) for experiment 2. Conventions are the same as in Fig. 3.

C. Discussion

Experiment 2 moved the frequency region of the middle band to 2000 Hz, which is a frequency region known for relatively poor performance in minimum audible angle (Mills, 1958) and sound localization tasks (Stevens and Newman, 1936). One reason this may occur is that ITDs are not useable for sine tones above 1500 Hz (Brughera *et al.*, 2013) and ILDs are non-monotonic functions of azimuth because of constructive interference (i.e., an acoustical bright spot occurs; Macaulay *et al.*, 2010). Therefore, under the fourth prediction in the Introduction, the patterns of binaural interference in experiment 2 were expected to change compared to experiment 1.

Figure 4(A) showed that there was no significant frequency dependence in single-band ILD JNDs, similar to what occurred in experiment 1 [Fig. 2(A)]. Figure 4(B) showed no effect of frequency separation Δ for the multi-band LMH conditions, similar to what occurred in experiment 1 [Fig. 2(B)]. Unlike experiment 1, the multi-band LMH conditions had significantly lower JNDs compared to the single-band conditions. The multi-band LMH conditions in this experiment always contained a band at 2000 Hz, near the region of the best single-band JNDs. Therefore, it may be that the JND for the consistent multi-band LMH conditions was mediated by the single-band with the best JND.

Figure 5 shows binaural interference for the inconsistent multi-band conditions, similar to what occurred in experiment 1 [Fig. 3(A)]; however, the pattern of binaural interference was very different across experiments 1 and 2. Even though the LMH conditions had the best ILD JNDs, similar to experiment 1, the patterns of the JNDs for the LMh and lmH conditions in this experiment (Fig. 5) were quite different to those seen in experiment 1 [Fig. 3(A)]. For example, it is not simply that the lmH conditions always had the highest JNDs because listeners attended to the lower-frequency bands or that the upward spread of excitation might have affected the higher-frequency bands. Rather, the complex patterning of ILD JNDs in Fig. 5

suggests that some frequencies carry a greater intrinsic importance than others.

IV. EXPERIMENT 3: DISCRIMINATION AROUND 4000 HZ

Experiment 3 followed the same approach as experiments 1 and 2, but moved the frequency region of interest to 4000 Hz, the frequency region where ILDs become relatively large compared to low frequencies and are thought to be the primary localization cue.

A. Methods

Ten adult listeners (19–40 years, average = 22.7 years, 10 females; one was the second author) participated in this experiment. One listener from experiments 1 and 2 participated in experiment 3; five listeners from experiment 2 participated in experiment 3; four listeners were new. The stimuli were the same as in experiment 2 except that the middle-band CF was 4000 Hz and $\Delta = 114, 228, 456, 1500$, or 3000 Hz. The CFs used in the experiment are shown in Table 1. The equivalent rectangular bandwidth of the auditory filter at 4000 Hz is 456 Hz and therefore there was again a range of unresolved and resolved bands that were tested. The procedure was the same as the other experiments.

B. Results

Figure 6(A) shows the ILD JNDs for the single-band conditions as a function of frequency for ten listeners. A one-way RM ANOVA showed that there was a significant effect of frequency [$F(2.5, 22.1) = 3.64$, $p = 0.035$, $\eta_p^2 = 0.29$; GGC], where the highest JND was at 1000 Hz and the lowest JNDs were above 4000 Hz. Figure 6(B) shows the results for the multi-band LMH conditions. A one-way RM ANOVA showed that there was no significant effect of Δ [$F(2.2, 19.6) = 0.30$, $p = 0.76$, $\eta_p^2 = 0.03$; GCC], which is consistent with experiments 1 and 2 [Figs. 2(B) and 4(B), respectively]. The single-band condition JNDs [all measurements in Fig. 6(A)]

FIG. 6. Single-band (A) and consistent multi-band (B) JNDs for experiment 3. Conventions are the same as in Fig. 4.

were significantly higher than the multi-band LMH condition JNDs [all measurements in Fig. 6(B)] [two-tailed two-sample unpaired t-test assuming unequal variances; $t(148.8) = 5.15$, $p < 0.0001$]. The average ILD JND of the multi-band LMH conditions across Δ s was 1.0 dB, the same as the 1.0-dB average JND measured in experiment 2.

The inconsistent multi-band conditions where there was one dichotic target band and two diotic interferer bands (Fig. 7, nine listeners) showed binaural interference compared to the consistent multi-band conditions; however, the pattern is different than both experiment 1 [Fig. 3(A)] and experiment 2 (Fig. 5). Most notable is that Lmh JNDs were larger than lmH JNDs for $\Delta \geq 456$ Hz.

C. Discussion

Experiment 3 moved the frequency region of the middle band to 4000 Hz, which is where ILDs produced by the human head for relatively distant free-field sources can be 10–16 dB (Feddersen *et al.*, 1957; Macaulay *et al.*, 2010). If certain frequencies have intrinsically higher weights, it seems logical that frequencies ≥ 4000 –8000 Hz would carry higher ILD weights (the second prediction from the introduction). In comparison to the other experiments, this experiment tested the largest range of frequencies.

Figure 6(A) showed the strongest single-band frequency dependence of the three experiments, where the single-band JNDs generally decreased with increasing frequency. Figure 6(B) shows, like the previous experiments, that there was no effect of frequency separation Δ for the consistent multi-band conditions.

Figure 7 shows binaural interference like the other experiments; however, the ordering of conditions is again different than the other two experiments. Since the CF of the bands and frequency separation Δ changes for each experiment, the data across the three experiments were

FIG. 7. (Color online) Consistent and inconsistent multi-band conditions as a function of frequency separation between bands (Δ) for experiment 3. Conventions are the same as in Figs. 3 and 5.

plotted together as a function of frequency and described in Sec. V.

V. COMPARISON ACROSS FREQUENCY REGIONS

Figure 8 shows all the single-band ILD JNDs in the study. Note that different listeners participated in each experiment, so some of the discrepancy between ILD JNDs at a single frequency (e.g., 500 or 1200 Hz) is likely a result of listeners having different overall ILD sensitivity. The data show a frequency dependence, where there is a general improvement in JNDs with increasing frequency and notable regions of worse performance near 1000 and 4000 Hz. Previous reports have also shown higher JNDs near 1000 Hz (Grantham, 1984; Yost and Dye, 1988). Previously, the most ILD JND measurements as a function of frequency were made by Mills (1960); if one compares the data from this study and that one, there is a relatively good correspondence of JNDs as a function of frequency, including possible increased ILD JNDs at 1000 and 4000 Hz. The limiting factor is the relatively sparse sampling of the function and limited number of listeners in Mills (1960) (see Table I for a summary of conditions in several studies).

Figures 3, 5, and 7 showed the largest ILD JNDs for the smaller Δ s. This is likely a result of the interaural decorrelation that occurs when the bands are unresolved and processed within a single auditory filter. Figure 9 shows calculations of the amount of interaural decorrelation as a function of Δ . First, we generated 25 stimulus tokens for target ILDs from 0 to 20 dB in 1-dB steps. We focused our analysis on the IMh condition from experiment 1 where the middle band had a CF = 750 Hz. Since the ILD was applied to the target band at 750 Hz, we used a fourth-order gamma-tone filter (Patterson *et al.*, 1992) with CF = 750 Hz and BW = 106 Hz before calculating the resultant ILD and interaural cross-correlation. The normalized interaural cross-correlation was defined as

FIG. 8. (Color online) Single-band JNDs from all three experiments. Symbols represent the average JND and error bars show ± 1 standard error.

$$\rho = \frac{\int x_L(t)x_R(t)dt}{E_LE_R}, \quad (1)$$

where x_L is the signal in the left ear, x_R is the signal in the right ear, E_L is the root-mean-square energy of the signal in the left ear, and E_R is the root-mean-square energy of the signal in the right ear.

Figure 9(A) shows the resultant ILD as a function of target ILD and the band spacing Δ . The resultant ILD increased as the target ILD increased. As Δ increased, the resultant ILD was less affected by the diotic bands below and above the CF of the center band. Resultant ILDs were smaller than the target ILDs for the middle band alone for $\Delta \leq 100$ Hz, but were the same for $\Delta = 250$ and 450 Hz. Likewise, Fig. 9(B) shows the resultant interaural cross-correlation ρ . The resultant ρ decreased for increasing Δ , but only when $\Delta \leq 100$ Hz. Also, note that there is a reversal in the ρ vs target ILD function, where the cross-correlation for $\Delta = 20$ Hz is slightly above $\Delta = 50$ Hz. This occurred because as the lower and higher diotic bands move completely in the filter, there is more diotic signal energy than dichotic, and thus a slight increase in the cross-correlation for $\Delta = 20$ Hz. For the largest band spacings of $\Delta = 250$ and 450 Hz, there was negligible energy from the diotic interferer bands to affect the

resultant ILD and interaural cross-correlation of the target band centered at 750 Hz. In other words, the bands are confirmed to be well-resolved and within-channel arguments about increases in ILD JNDs for these conditions do not apply; any change in ILD JNDs for the two largest Δ s occurred because of a frequency dependency in across-channel ILD processing. Likewise, calculations for the 2000- and 4000-Hz CF conditions showed that the two largest Δ s were confirmed to be well resolved. Resultant ILDs using a gammatone filter were within 0.001 dB of the target ILD = 20 dB; resultant interaural cross-correlations were within 0.001 of $\rho = 1$, well below the limit of a detectable change in ρ (Gabriel and Colburn, 1981; Goupell and Hartmann, 2006).

Figure 10 shows the ILD JNDs for the multi-band conditions with one dichotic target band. Only the two largest Δ s are plotted in each experiment; the well-resolved bands had no quantifiable within-channel interaural decorrelation [Fig. 9(B)]. Figure 10(A) replots the data from experiment 1. Most of these multi-band conditions demonstrated about 3 dB of binaural interference (i.e., difference between multi-band and single-band JNDs) except when the target was placed at 1000 Hz and there was about 5 dB of binaural interference.

Figure 10(B) shows the ILD JNDs from experiment 2. These data show that separation Δ and/or CF of the target band affect the amount of binaural interference. There was almost no binaural interference when the target band was at 500 or 1250 Hz. There was 3–4 dB of binaural interference when the target was at 2000 Hz, and little difference for the two Δ s. The amount of interference was also roughly the same between 2000 and 2750 Hz. When the target band was at 3500 Hz, the largest amount of binaural interference was demonstrated in this experiment, about 4 dB.

Figure 10(C) shows the ILD JNDs from experiment 3. These data show that *both* Δ and CF of the target band affect the amount of binaural interference. This is because the JNDs are highest at 4000 Hz for each individual curve, but there was much more binaural interference for the 3000-Hz Δ . For this experiment, the lower target CFs showed binaural interference and the higher target CFs showed little, the opposite pattern that was observed in experiment 2 [Fig. 10(B)].

Comparing across all three panels of Fig. 10 reveals that, in general, ILD JNDs and the amount of binaural interference is largest when the target band CF is near 1000 or 4000 Hz, which is best observed by focusing on the data points near the shaded regions. Such a result is not adequately explained by any of the predictions, the closest is arguably the fourth prediction, which suggested that frequencies between 1000 and 4000 Hz, the frequencies that have strongly non-monotonic ILD vs azimuth functions, would demonstrate the lowest weighting and largest JNDs. The relatively better ILD JNDs for targets between 2000 and 3000 Hz compared to 1000 and 4000 Hz [Figs. 10(B) and 10(C)], however, argue against explaining the complex pattern of data with a single factor as suggested by the fourth prediction.

FIG. 9. (Color online) Analysis of resultant ILD [panel (A)] and interaural correlation ρ [panel (B)] as a function of the target ILD when a fourth-order gammatone filter with a 106-Hz BW and 750-Hz CF is applied. The stimulus was the IMh condition where the middle band was at CF = 750 Hz.

FIG. 10. (Color online) Comparison of single- and multi-band JNDs across experiment 1 [panel (A)], experiment 2 [panel (B)], and experiment 3 [panel (C)]. Only the two largest separations Δ are plotted for each experiment. Symbols represent the average JND and error bars show ± 1 standard error. The JND is plotted at the frequency of the dichotic target band. For example, for $\Delta = 250$ Hz in panel (A), there are bands at 500, 750, and 1000 Hz. For the lmH condition that has a dichotic target at 1000 Hz, the JND is plotted at 1000 Hz. The average of the single-channel JNDs is shown by the horizontal solid line. Shading was added around 1000 and 4000 Hz to provide a visual aid.

VI. EXPERIMENT 4: LATERALIZATION AROUND 750 HZ

The previous three experiments used a discrimination task to determine the effects of Δ , CF, and number of dichotic targets by measuring ILD JNDs. Such an approach measures the smallest differences in ILDs that can be perceived. Another approach is to present a large range of ILDs and ask the listeners to report the intracranial position of the sound image (i.e., use a lateralization task). Here we performed a lateralization experiment using some of the stimuli from experiment 1.

A. Methods

Eight adult listeners (21–39 years, average = 24.9 years, seven females; one was the second author) participated in this experiment. One other listener from experiment 1 participated in experiment 4. The stimuli were the same as in experiment 1. This experiment contained a subset of the conditions tested in experiment 1, where bands were near CF = 750 Hz. Namely, single-band conditions, the consistent multi-band condition (LMH), and the inconsistent multi-band conditions with a single target (Lmh, IMh, and ImH) were tested. Only $\Delta = 250$ Hz was tested because that condition showed the largest frequency effects in experiment 1. ILDs of 0, ± 3 , ± 6 , ± 9 , ± 12 , and ± 18 dB were tested. The conditions and ILDs were tested in a method of constant stimuli. There were 20 trials per condition. The interface provided a bar across the face to indicate intracranial position; the position of the response on the bar was converted using a scale that places -10 at the left ear, 0 at the center, and $+10$ at the right ear (Stakhovskaya and Goupell, 2017). The single-band and consistent multi-band conditions were previously reported in Stakhovskaya and Goupell (2017).

B. Results

Figure 11 shows the data for the inconsistent multi-band conditions. To analyze these data, a two-way RM ANOVA was performed with factors ILD and condition. Listeners perceived larger lateralization for larger ILDs [$F(1.7, 12.0) = 185.8$, $p < 0.0001$, $\eta_p^2 = 0.96$; GGC]. The main effect of condition was not significant [$F(3, 21) = 0.62$, $p = 0.61$, $\eta_p^2 = 0.08$], but there was a significant ILD $\times$ condition interaction [$F(4.5, 31.5) = 25.8$, $p < 0.0001$, $\eta_p^2 = 0.79$; GGC]. This interaction occurred because there was a progressively shallower slope as the conditions changed between LMH, Lmh (target band at 500 Hz), IMh (target band at 750 Hz), and ImH (target band at 1000 Hz).

FIG. 11. (Color online) Lateralization data from experiment 4. Symbols represent the average lateralization and error bars show ± 1 standard error. Curves were fit using a cumulative Gaussian function (Stakhovskaya and Goupell, 2017).

C. Discussion

Many studies have not observed frequency dependence for ILD lateralization using narrowband stimuli (e.g., Yost, 1981); two others have shown small effects (Bernstein and Trahiotis, 2011; Stakhovskaya and Goupell, 2017). Using this binaural interference paradigm, the data from the current study showed more pronounced frequency effects. The lateralization data from this experiment (Fig. 11) mirrored important aspects of the discrimination data from experiment 1 (Fig. 3). As the target band for the inconsistent multi-band condition was increased from 500 (Lmh) to 750 (IMh) to 1000 Hz (ImH), perceived lateralization was reduced. Likewise, ILD JNDs became larger for these conditions in experiment 1.

These data can be compared to the data reported previously in Stakhovskaya and Goupell (2017, Fig. 2). The single-band and consistent multi-band conditions (LMH) have very similar lateralization curves, and there may have been a small $\text{ILD} \times \text{condition}$ interaction. Namely, the 500-Hz single-band and LMH conditions may have slightly sharper slopes than the 750- and 1000-Hz conditions, but that interaction in Stakhovskaya and Goupell (2017, Fig. 2) is small compared to the interaction seen in data for the inconsistent multi-band conditions of Fig. 11 in the current study.

Broadly, it appears that the discrimination and lateralization experiments are consistent with each other. There may be small frequency effects in single-band and consistent multi-band using discrimination (Fig. 8) and lateralization (Stakhovskaya and Goupell, 2017, Fig. 2), the largest ILD JNDs and shallowest lateralization functions occurring at 1000 Hz. Using inconsistent multi-band conditions magnifies those frequency effects, where 1000-Hz targets show the largest ILD JNDs (Fig. 10) and shallowest slopes (Fig. 11).

VII. GENERAL DISCUSSION

The most simple form of Duplex Theory states that ITDs are utilized for sound localization at frequencies <1500 Hz and ILDs are utilized at frequencies >1500 – 4000 Hz (Strutt, 1907; Stevens and Newman, 1936). For a sound emitted from a source in the free field that is sufficiently far from the listener, ILDs are relatively small at frequencies <1500 Hz. Studies have shown that ILDs can be perceived at frequencies <1500 Hz if the sounds are presented over headphones (Mills, 1960; Grantham, 1984; Yost and Dye, 1988). To summarize the two most recent of those studies, it was thought that ILD JNDs were mostly independent of frequency, except for higher JNDs around 1000 Hz (Grantham, 1984; Yost and Dye, 1988).

One main finding from this study is that single-band ILD JNDs demonstrated significant frequency dependence [Figs. 2(A), 4(A), 6(A), and 8]. The frequency dependence was not large; the range of single-channel JNDs was 0.9–2.6 dB (Fig. 8). Our study showed that this frequency dependence was significant only in experiment 3 [Fig. 6(A)]. The significant effect of frequency may have occurred in this study because of increased statistical power (our study had about ten listeners per discrimination experiment) and the

use of a consistently large level roving range (20 dB) that limited the use of monaural level cues to perform the task (see Table I). The frequency dependence of the JNDs seems not to follow the human audibility curve (Killion, 1978). Since ILD JNDs seem mostly unaffected by overall level (Dietz *et al.*, 2013), there is not a compelling reason to predict that audibility and ILD sensitivity would follow similar trends. It is unclear why the ILD sensitivity frequency dependence occurs, and thus provides a direction for future studies that should more carefully and systematically characterize the frequency dependence of single-channel ILD sensitivity.

Another main finding from this study was the difference in the frequency dependence when comparing the consistent and inconsistent multi-band stimuli. The multi-band stimuli contained three noise bands. Target bands had consistent ILDs applied for each band; interfering bands remained diotic. They had varied spacing between bands Δ , frequency location of the target band(s), and the number of target bands. The stimuli were similar to those used by Dye (1990) in an ITD discrimination task; however, we tested ILD not ITD discrimination, our stimuli were narrowband noises not tones, our procedure included level roving, we performed a laterality discrimination task not a simple discrimination task (where many potential detection cues exist, including changes in interaural correlation), and we tested around three different frequency regions. The consistent multi-band conditions had the same or lower ILD JNDs compared to the single-band conditions. The consistent multi-band conditions did not show frequency dependence [Figs. 2(B), 4(B), and 6(B)], likely because of the small differences between JNDs across frequency.

In contrast to the consistent multi-band conditions, the inconsistent multi-band conditions showed a relatively large frequency dependence. The largest ILD JNDs were seen when the three bands were relatively close to each other, when values of Δ were within two critical bandwidths (Figs. 3, 5, and 7). This increase might be explained by the decrease in interaural correlation within a single auditory filter (Fig. 9). As the ILDs of the bands became increasingly different but remained within a single critical band, the interaural correlation decreased. Decreased interaural correlation causes increased ITD JNDs (Rakerd and Hartmann, 2010) and ILD JNDs (Brown and Tollin, 2016). If listeners in this study used changes in intracranial position to perform the task, interaural decorrelation will perceptually blur the sound images (Blauert and Lindemann, 1986; Whitmer *et al.*, 2012), making it more difficult to discriminate a small difference in intracranial position. Note that when broadband stimuli are used, ILD JNDs are not affected by the interaural correlation of the signals (Egnor, 2001; Hartmann and Constan, 2002).

The most interesting conditions are the ones with large frequency separations Δ , where one must consider mostly across-channel binaural processing. For the larger values of Δ , the stimuli are like those used in “binaural interference” studies, where remote diotic interferers can be used to investigate across-channel binaural processing (McFadden and Pasanen, 1976; Heller and Richards, 2010). Diotic interferers

increased ILD JNDs in a frequency-dependent manner (Figs. 3, 5, 7; best seen in Fig. 10). Because interaural decorrelation would not occur for the well-resolved bands (see Fig. 9), it appears that the diotic interferer bands pull the perceived intracranial position of the target band toward the midline (Fig. 11), thus elevating JNDs. This pattern of results clearly does not reflect the first prediction where binaural interference would be frequency independent. It also does not reflect the second prediction where higher frequencies always have less binaural interference than lower. Nor does it fully support the third prediction that suggests less binaural interference at lower frequencies. Experiments 1 and 2 had higher JNDs and more binaural interference for the ImH conditions with large Δ s (Fig. 10). In contrast, experiment 3 had lower JNDs and almost no binaural interference for the ImH conditions with large Δ s. Perhaps the data are most consistent with the fourth prediction; the largest ILD JNDs and the most binaural interference occurred for target frequencies around 1000–4000 Hz, where increasing azimuth does not produce monotonically increasing ILDs for sources in the free field (Macaulay *et al.*, 2010). The fourth prediction, however, cannot account for the small amount of binaural interference that occurred when the target band was placed at 1250 Hz [Fig. 10(B)]. What is clear from these data is that the location of the target and interfering bands both matter when measuring ILD sensitivity and binaural interference, and the frequency dependence is non-monotonic.

The results of experiment 4, where a lateralization task was performed, showed that listeners were likely attending to the change in intracranial position to perform the tasks in this study. The data in experiment 1 [Fig. 3(A)] and experiment 4 (Fig. 11) show patterns that are consistent with this interpretation. Another piece of evidence that some of the listeners were mostly using changes in intracranial position to perform the discrimination task comes from how large the JNDs were for some of the conditions, >10 dB in the worst cases [e.g., Fig. 3(A)]. For these conditions, changing one's strategy to use monaural cues would have produced lower JNDs. Such a strategy would have yielded ILD JNDs of $23.5\% \times 20\text{-dB roving range} = 4.7\text{ dB}$ (Green, 1988; Appendix A).

Heller and Richards (2010) investigated binaural interference for ITD and ILD discrimination. There was one dichotic target and one diotic interferer, and the stimuli were narrowband noises at 500- and 4000-Hz CFs. ILD JNDs for a 500-Hz target significantly increased from 1.1 to 1.5 dB for a 4000-Hz interferer. ILD JNDs for a 4000-Hz target significantly increased from 0.7 to 0.9 dB for a 500-Hz interferer. The binaural interference for ILDs seems relatively small when compared to what occurs for ITDs, where a 500-Hz interferer greatly increased ITD JNDs for a 4000-Hz target, but a 4000-Hz interferer showed a much smaller change in ITD JNDs for a 500-Hz target (e.g., Heller and Richards, 2010). Because we had three bands, not two, direct comparisons between our study and Heller and Richards (2010) are complicated. Nonetheless, we found much larger ILD JNDs and binaural interference than their study. This may have occurred because of a much larger level roving range in our study (20 dB) compared to theirs (10 dB).

There are relatively few psychophysical ILD processing models compared to ITD processing models. One simple model, the level-meter model by Hartmann and Constan (2002), suggests that the energy in each ear is compared and therefore lacks a true binaural comparison. Our data are incompatible with such a model as it predicts no frequency dependency. Breebaart *et al.* (2001) developed a form of the equalization-cancellation model that predicted single-channel ILD JNDs. They found ILD JNDs that were frequency independent; the model was unable to predict the higher ILD JNDs at 1000 Hz (Grantham, 1984; Yost and Dye, 1988). Two across-channel ILD processing models have been proposed where there is a simple summation of ILD information across frequency (Kelvasa and Dietz, 2015; Stakhovskaya and Goupell, 2017). This type of model would be able to handle the frequency dependency of ILD as well as non-monotonicities in ILD vs azimuth functions between 1000 and 4000 Hz, as long as the input stimuli were complex. An across-frequency summation ILD model could explain the lateralization data from bilateral cochlear-implant users presented controlled single- and multi-electrode ILDs using direct stimulation. Stakhovskaya and Goupell (2017) found that assuming equal weighting across frequency explained most of the variance in the data (87%), and that additional variance (90%) could be explained assuming unequal weighting across frequency (i.e., allowing for frequency dependence). Furthermore, the model from Kelvasa and Dietz (2015) could cope with some of the non-monotonicities in the physical ILDs to reproduce sound localization errors in bilateral cochlear-implant users. To model the data from the present study, a model would necessitate a frequency dependence in sensitivity and across-frequency weighting. This weighting may be related to the sensitivity of listeners at individual frequencies. For example, the largest single-channel ILD JNDs were observed at 1000 Hz (Fig. 8) and some of the largest inconsistent multi-channel ILD JNDs were observed in conditions that placed the target band at 1000 Hz (Fig. 10). It is unclear if such a strong correspondence between single- and multi-band ILD JNDs was also seen at 4000 Hz, which was a frequency that also showed large JNDs for the inconsistent multi-band conditions. Bernstein and Trahiotis (2011) showed that the extent of ILD lateralization of 4000-Hz modulated tones was greater than that for 500-Hz modulated tones; note that their result is in the opposite direction from what would be predicted from the inconsistent multi-band conditions in our study. Therefore, it may not be that the single-channel ILD sensitivity is indicative of the weight that would be applied in an across-frequency weighting of ILD processing. Future studies should consider a more complete mapping of ILD sensitivity investigating the number of bands, frequency, and separation effects.

It is unclear from this study if the frequency dependence of ILD processing has consequences for sound localization of sources in the free field. Stevens and Newman (1936) showed worse sound localization performance occurs for tones between 1000 and 4000 Hz, which was best explained by the non-monotonic nature of the ILD as a function of azimuth by Macaulay *et al.* (2010). Future work exploring free

field sound localization in reverberation using complex signals may move our understanding of the consequences of the ILD frequency dependence observed in the present earphone study. Furthermore, this work has assumed that the ILDs produced by the head are for relatively distant sources in the free field (>1 m). The magnitude and frequency dependence of ILDs change greatly for nearer sources (Brungart and Rabinowitz, 1999).

In summary, it appears that both single- and multi-channel ILD sensitivity are frequency dependent. The frequency dependency becomes particularly clear when there are diotic interferers present. What is unclear is why this frequency dependency exists. Binaural processing models that can predict ILD discrimination sensitivity, perceived intracranial lateralization, and sound localization are typically narrow in scope; they will need revision and extension to incorporate the frequency dependence of multi-channel ILD processing (e.g., Breebaart *et al.*, 2001; Hartmann and Constan, 2002; Kelvasa and Dietz, 2015; Stakhovskaya and Goupell, 2017). Given that ILD sensitivity is necessary for localization in reverberant environments (Rakerd and Hartmann, 2010) and ILDs are the primary localization cue for cochlear-implant users (Seeber and Fastl, 2008; Aronoff *et al.*, 2010), advancing models of ILD processing for complex stimuli is an important future direction for binaural hearing research.

ACKNOWLEDGMENTS

We would like to thank Raymond (Toby) Dye, Catherine Carr, Mathias Dietz, Steve Colburn, and Gerald Kidd for useful discussions about this study and these data. We would also like to thank Mikalya Abrams, Sarah Shin, Elizabeth McAllen, Kelly Miller, and David Yun for help with data analysis and collection. Research reported in this publication was supported by the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health under Award Number R01 DC014948 (M.J.G.). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. This study was also funded partially by a seed grant from the College of Behavioral and Social Sciences at the University of Maryland–College Park (M.J.G.).

¹The data from these experiments showed that the error bars increased with the mean performance, which indicates that the staircase step size should have been on a log(ILD) scale, similar to what was done in Dietz *et al.* (2013) and Spencer *et al.* (2016).

²See supplementary material at <https://doi.org/10.1121/1.5021552> for the raw data files for all four experiments.

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