Perception of across-frequency interaural level differences

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(Dated: Accepted for publication in JASA on 19 Aug 2007)

Abstract

The interaural level difference (ILD) is an important cue for the localization of sound sources. Just noticeable differences (JND) in ILD were measured in 12 normal hearing subjects for uncorrelated noise bands with a bandwidth of $1/3$ octave and a different center frequency in both ears. In one ear the center frequency was either 250 Hz, 500 Hz, 1000 Hz or 4000 Hz. In the other ear, a frequency shift of 0, $1/6$, $1/3$ or 1 octave was introduced. JNDs in ILD for unshifted, uncorrelated noise bands of $1/3$ octave width were 2.6, 2.6, 2.5 and 1.4 dB for 250, 500, 1000 and 4000 Hz respectively. Averaged over all shifts, JNDs decreased significantly with increasing frequency. For the shifted conditions, JNDs increased significantly with increasing shift. Performance on average worsened by 0.5, 0.9 and 1.5 dB for shifts of $1/6$, $1/3$ and 1 octave. Though performance decreases, the just noticeable ILDs for the shifted conditions were still in a range usable for lateralization. This has implications for signal processing algorithms for bilateral bimodal hearing instruments and the fitting of bilateral cochlear implants.

PACS numbers: 4366Pn, 4366Qp, 4366Ts, 4364Me

I. INTRODUCTION

An important cue for localization of sound sources is the difference in sound pressure level between both ears, the so-called interaural level difference (ILD). The ILD is considered especially useful for localization at higher frequencies (> 1000 Hz). As the wavelength of low-frequency sounds is long compared with the size of the head, low-frequency sounds “bend” around the head, resulting in a small ILD. While ILDs are very small below about 500 Hz, they may be as large as 20 dB at high frequencies (Moore, 2003).

Nevertheless, the human auditory system is able to perceive ILDs in the low frequencies with Just Noticeable Differences (JNDs) as small as ± 1 dB, measured with pure tones (Yost and Dye, 1988; Mills, 1960). Low frequency ILD cues are used for localizing nearby sources (Brungart *et al.*, 1999; Brungart, 1999), in the so-called “proximal region”, the region within 1 m of the centre of the head.

Mills (1960) presented 5 subjects with a reference stimulus with no ILD, followed by a stimulus with an ILD. The stimuli were pure tones. Using the method of constant stimuli, the JND in ILD was determined from half the interquartile separation of the psychometric curves for each subject. JNDs were around 1 dB for 1000 Hz, somewhat smaller for lower frequencies and around 0.5 dB for frequencies higher than 1000 Hz.

Yost and Dye (1988) measured JNDs in ILD for pure tones and different reference signals at 75 % correct, using a linear fit of the psychometric curve. For the reference at $ILD = 0$ dB they found JNDs of approximately 0.75, 0.85, 1.20, 0.70 and 0.73 dB for 200 Hz, 500 Hz, 1000 Hz, 2000 Hz and 5000 Hz. In the 2AFC procedure, subjects heard one stimulus on the right side and one on the left side and had to respond which one was on the right.

Hartmann and Constan (2002) tested the hypothesis of the level meter model: can the ILD be seen as an integrated measure of stimulus energy, independent of stimulus details? Differences between correlated and uncorrelated stimuli were assessed using white noise and

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low pass filtered noise (< 1000 Hz). A 2AFC, 1up/3down adaptive procedure, targeting the 79 % correct point was used and subjects had to determine the direction of change (right-to-left or left-to-right). They conclude that the level meter model is sound within half a dB, i.e., the thresholds for each of the four tested correlation conditions were within 0.5 dB of each other. JNDs for uncorrelated white noise are in the order of 0.6 dB. For the low pass noise condition they are in the order of 0.9 dB.

Users of a combination of a cochlear implant (CI) in the one ear and a hearing aid in the other (a so-called bilateral bimodal system), are in the situation where normal (high-frequency) ILD cues are absent, because their residual hearing in the acoustically aided ear in many cases does not extend beyond 500 Hz. Because of the different nature of stimulation in both ears and current signal processing schemes for cochlear implants, they also do not have access to precise interaural time difference (ITD) cues for localization (Ching *et al.*, 2005; Seeber *et al.*, 2004).

As in most practical situations sound sources are not in the proximal region, bimodal hearing aid users are extremely bad at localizing sound sources (Seeber *et al.*, 2004; Ching *et al.*, 2001, 2004; Tyler *et al.*, 2002). This could be improved by artificially introducing or amplifying ILDs in the low frequencies, even if the latter are not present in the incoming auditory signal.

For many bimodal hearing instrument users, it is probably not possible to stimulate the same frequency regions in both cochleas, because on the one hand the tip of the electrode array of the cochlear implant does not reach the apex of the cochlea, so the lowest frequencies cannot be stimulated. On the other hand the usable residual hearing of the other ear does not in many cases extend beyond 500 Hz. This is illustrated by the pitch-matching data of Boex *et al.* (2006). They measured the acoustic pitch corresponding to the place pitch elicited by stimulation of certain electrodes of the cochlear implant in 6 users of bimodal systems. For the most apical electrode of each subject, they found pitches of 460, 100, 290, 260, 570 and 300 Hz. Though these pitches are lower than could be expected based on Greenwood's function (Greenwood, 1990), they are in most cases still high enough to make

it difficult to stimulate the same acoustical frequencies in the other ear.

For users of bimodal systems, due to current clinical fitting procedures, the cochlear implant in the one ear and the hearing aid in the other will most certainly not stimulate the same frequency ranges. The same is true for users of bilateral CIs: currently both CIs are fitted more or less independently and the electrode positions along the left and right basilar membrane are not tuned to the same frequencies.

The object of the work described in this article was to assess whether it is possible for normal hearing subjects to perceive ILDs for different degrees of frequency mismatch between the signals in both ears. Therefore, JNDs in ILD were determined for different frequency shifts in one of the two ears. This was done for different base frequencies, using uncorrelated noise band stimuli to simulate the difference in stimulation between the acoustic and electric part of a bimodal system and to eliminate potentially confusing ITD cues. Note that uncorrelated stimuli result in a diffuse sound image that is not externalized, i.e., it is perceived inside the head. This makes the task harder (Hartmann and Constan, 2002), but also more realistic when considering binaural bimodal hearing systems, where subjects are presented with largely uncorrelated signals.

Similar work for ITDs was done by Nuetzel and Hafter (1981) and Saberi (1998). They tested subject sensitivity to interaural delay in the envelope of respectively high-frequency amplitude modulated sinusoids and frequency modulated sinusoids and found that as the carrier frequency difference increases, time differences are still detected, but performance drops rapidly. Given that critical bands in binaural experiments have a bandwidth similar to estimates in monaural experiments (Holube *et al.*, 1998; Breebaart *et al.*, 2001), we expect performance detecting ILDs to deteriorate when large frequency shifts are introduced.

II. METHODS

A. Procedure

1. *General procedure*

The JND in ILD was determined for each condition using several runs of an adaptive 1up/2down procedure, targetting the 71 % correct point. The procedure determined the ILD of the stimulus that was presented. The start value was 10 dB and the initial stepsize was 2 dB. After 2 reversals, the stepsize was decreased to 0.4 dB and after 10 reversals to 0.2 dB. The procedure continued until 12 reversals were obtained. No feedback was given. The mean of the last 6 reversals was taken as the JND for a certain run. If the procedure saturated, i.e., the parameter was 10 dB or 0 dB, the run was discarded and repeated.

In each trial, first a standard was presented, which contained no ILD, followed by a short pause of 0.1 s, followed by the stimulus that contained a certain ILD. The ILD pointed with equal probability to left or right and the magnitude was selected according to the parameter adapted by the adaptive procedure. The subjects had to respond whether they heard the stimulus on the left or right side of the standard. One specific case is illustrated in figure 1.

Two experiments were done. In the first experiment, to avoid subjects using monaural cues, the overall stimulus level was roved uniformly over ± 5 dB. It can be shown that in this case, a JND of 4.2 dB could theoretically be attained by only attending to one ear. Because some of the found JNDs were larger than 4.2 dB, a second experiment was done with a level rove of ± 10 dB.

Subjects were instructed to respond whether they heard the stimulus on the left or right side of the standard. If they were not able to lateralize, they were encouraged to compare the left and right loudness levels. They were also asked to close their eyes during the runs to avoid visual disturbances (there are indications that visual cues can influence responses on localization tests (Lewald and Getzmann, 2006)). They responded using the left and right arrow keys of a computer keyboard. The experiments were unattended by the experimenter,

FIG. 1. Example of a standard-stimulus sequence with a positive rove. For this trial, the correct answer would be “The stimulus sounded on the left hand side of the standard”.

except for the introduction to the task and regular checks. One run took, depending on the subject, between 78 s and 388 s, with a median of 160 s. This resulted in an average total time of 3.5 h or more of testing per subject in experiment 1, excluding any breaks or short pauses between different runs. The subjects participating in experiment 2, were tested for an additional 1.5 h.

2. Conditions

JNDs in ILD were determined for 4 base frequencies: 250 Hz, 500 Hz, 1000 Hz and 4000 Hz. The most relevant base frequencies for the application on bimodal hearing are 250 Hz and 500 Hz, because the residual hearing of most subjects that use a bimodal hearing system is restricted to the low frequencies. The 1000 Hz and 4000 Hz base frequencies were added as higher frequency reference conditions.

For one adaptive run, the center frequency of the one ear was always one of the base frequencies and the center frequency of the other ear was the base frequency shifted with 0 oct, 1/6 oct, 1/3 oct or 1 oct. As noise bands of 1/3 oct wide were used, this results in

respectively full overlap, partial overlap, marginally no overlap and no overlap at all of the shifted noise band with the base noise band. The shifts were performed in upward direction.

Per subject, two of the base frequencies and all of the shifts were presented for each selected base frequency. A condition consists of a certain base frequency combined with a certain shift. In experiment 1 each condition was presented 8 or 10 times and in experiment 2 it was presented 4 times. To minimize the chance of training effects influencing only a single condition, conditions were always interleaved.

B. Experimental setup

1. *Stimuli and test setup*

The stimuli were noise bands of 1/3oct wide, filtered with a 50th order Butterworth filter to ensure a minimal amount of overlap beyond the cutoff frequencies of the noise bands presented to both ears. To avoid confusing interaural time difference cues, noise bands were at all time instants uncorrelated between both ears and new noise bands were generated for each standard and each stimulus. Linear in and out ramping was performed over 0.2 s to avoid clicks and confusing onset cues. The total stimulus duration was 1 s.

For every run, the ear to be presented with the frequency-shifted stimulus was selected at random. On the whole, each ear was presented an equal number of times with the unshifted stimulus.

To obtain an approximately centered reference signal, the left and right channels were equalized in RMS level with respect to the dBA scale. In this way, the left and right channels sounded approximately equally loud, so the reference signal was centered in the head. Note that as a consequence of the dBA weighting, especially at the lower frequencies, the levels of the channels differ between ears if measured in dBSPL in conditions with frequency-shifted noise bands.

The ILD was introduced as follows: if S_L and S_R are the levels of the left and right channels of the standard measured in dBSPL, I the ILD to be introduced, r the rove level,

randomly selected from the interval $[-5, 5]$ or $[-10, 10]$, and L_L and L_R the levels of the left and right channels of the stimulus, the stimulus was generated according to the following equations (all in dBSPL):

$$L_L = S_L + I/2 + r \quad (1)$$

$$L_R = S_R - I/2 + r \quad (2)$$

If the same center frequency was presented at both ears, when measuring absolute levels in dBSPL, S_L was the same as S_R and the ILD was I . If different center frequencies were presented, S_L and S_R differed because of the dBA weighting, and the resulting ILD was $I + S_L - S_R$.

All stimuli were presented in a soundbooth using the Apex (Laneau *et al.*, 2005) program running on a personal computer, driving a LynxOne sound card that was connected via a mixer to a set of Sennheiser HD250 Linear II headphones.

Calibration of the left and right channels was done by setting the mixer such that a 1/3 oct noise band with a center frequency of 1000 Hz had an overall RMS level of 65 dBSPL. The level of the other stimuli in dBA was equal to the level of the 1000 Hz stimulus in dBA.

2. Subjects

Twelve subjects participated in experiment 1 and came to the lab for 3 or 4 sessions of 1 up to 2 hours. Six of those subjects participated in experiment 2 and came to the lab for an additional 1 or 2 sessions.

All subjects were volunteers and were paid for their cooperation. Their hearing was normal, except for one subject who had a threshold of 40 dBHL at 4000 Hz. He was only presented the conditions with base frequencies 250 Hz and 500 Hz and only participated in experiment 1. Two subjects were male, ten female and all between 18 and 28 years of age.

III. RESULTS

A. Experiment 1

JNDs in ILD were repeatedly measured for all base frequencies and all frequency shifts. To assess possible training effects, the sequence of results of runs for each frequency/shift condition of each subject is shown in figure 2. Each sequence was normalized by dividing by the mean of the last 6 runs in that sequence. The full line connects the averages at each time instant. No clear average long term training effect is evident from this figure. Also, no clear training effect can be seen for any of the subjects separately. As there seems to be a small effect in the first few runs, the first 2 measurements of each condition were discarded from further analysis.

A summary of the results of experiment 1 is presented in figure 3. Results are shown per base frequency and frequency shift, but averaged over all runs and over all subjects. The error bars are at least partly due to inter-subject variance, as opposed to intra-subject variance, as was seen from an ANOVA. The JND in ILD increases per increasing shift (i.e., it is harder to discriminate loudness differences when the frequencies in both ears are less similar) and the JND decreases per increasing base frequency (i.e., it is easier to discriminate ILDs when the center frequencies in both ears are higher). All frequency conditions differ significantly from each other ($F(3, 391) = 25.8, p < 0.00001$) as well as all shift conditions ($F(3, 391) = 39.9, p < 0.00001$) except for the shifts of 1/3 oct and 1/6 oct.

As the JNDs for the one octave shift conditions are in the neighbourhood of the 4.2 dB value that could theoretically be monaurally attained when using a rove of ± 5 dB, this experiment was repeated in experiment 2 with a rove of ± 10 dB.

B. Experiment 2

The small training effect in the first few runs of experiment 1 is not observed in the results from experiment 2. This is probably due to the fact that all 6 subjects who participated

FIG. 2. All normalized sequences of runs of experiment 1. All values of each sequence were divided by the mean of the last 6 runs of that sequence. Each dot represents the result of an adaptive run. The full line connects the averages at each time instant.

in experiment 2 also participated in experiment 1 during about 3 hours. Therefore no measurements were discarded from experiment 2 based on training effects.

An ANOVA with factors subject, frequency and shift indicates a significant effect for shift ($F(3, 161) = 24.5, p < 0.0001$). Post hoc analysis with Bonferroni correction shows that all shift conditions differ significantly from each other, except for the shifts of $1/3$ oct with 0 oct and $1/6$ oct with 0 oct.

Figure 4 shows the differences in threshold values between experiment 1 and 2. On

FIG. 3. JNDs in ILD (in dB) as a function of base frequency and frequency shift for experiment 1 (± 5 dB rove). The total length of the error bar is twice the standard deviation. The data were checked for normality using the Kolmogorov-Smirnov test.

average the JND increased by 0.06 dB towards experiment 2. This difference is however not significant in an ANOVA with extra factor experiment. In what follows, we will therefore focus on the results of experiment 1 because it was performed with more subjects and most results are below the 4.2 dB threshold anyway.

FIG. 4. Differences between experiment 1 and 2. The bars show the difference in JND. The error bars represent the combined error of both experiments. Positive values indicate that the JND in experiment 1 (± 5 dB rove) was larger than the JND in experiment 2 (± 10 dB rove).

IV. DISCUSSION

Figure 3 shows that the JND in ILD increases per increasing shift and the JND decreases per increasing base frequency. The unshifted conditions yield JNDs of 2.6, 2.6, 2.5 and 1.4 dB for 250, 500, 1000 and 4000 Hz. Hartmann and Constan (2002) report a JND of 0.6 dB for white noise stimuli and 0.9 dB for low pass noise (< 1000 Hz). Their procedure

is similar to ours, but to compare the results, their values have to be multiplied by a factor 2 to compensate for the difference in definition of ILD. Translating their results yields ILDs of respectively 1.2 and 1.8 dB. Further differences are due to the fact that, in our experiments, noise bands of a much smaller bandwidth are used. Hartmann and Constan (2002) observe that, for both bandwidths used, JNDs decrease (i.e., performance increases) when the bandwidth increases. Buus (1990) reports that the JNDs for monaural level discrimination decrease when the bandwidth increases. He however used different stimuli: both ears were stimulated sequentially, while in this study both ears were stimulated simultaneously.

When considering the results in terms of frequency overlap between the ears, it can be seen that as soon as the overlap decreases by $1/6$ oct, performance decreases significantly. Further decreasing the overlap by $1/3$ oct does not yield a significant change versus the $1/6$ oct shift. This can be explained by the fact that while physically the spectra of the unshifted and $1/3$ oct shifted noise band are nearly perfectly separated, there is some spread in the excitation patterns in the cochlea, resulting in a certain amount of overlap. The 1 oct shifted noise band yields significantly worse performance than all other shift conditions, caused by even less overlap in the excitation patterns in the cochlea.

Though significantly larger for the shifted conditions, JNDs are still in a range usable for lateralization of sound sources. The results for the shifted conditions partly confirm the simple level meter model proposed in Hartmann and Constan (2002). The results roughly confirm that the auditory system integrates energy over different frequencies, even over critical band boundaries. Performance however worsens on average by 0.5, 0.9 and 1.5 dB for shifts of respectively $1/6$, $1/3$ and 1 oct, relative to the unshifted condition. This refines the level meter model.

According to Hartmann and Rakerd (1989) the interpretation of our results could be complicated by the fact that the subjects could have ignored the standard that was presented before each stimulus and compared the stimuli to each other, resulting in a larger ILD cue than when comparing the stimulus to the standard. However, this seems unlikely because

1) in contrast to Hartmann and Rakerd (1989), we used level roving, making stimuli with the same ILD sound differently, 2) the subjects were repeatedly encouraged to always listen carefully to the standard, 3) an adaptive procedure was used, resulting in a reduction of the effect described by Hartmann and Rakerd (1989) and 4) the results of our unshifted baseline condition correlate well with the results found in the literature. Moreover, even if the absolute values of our results would not be accurate, this does not influence the main conclusions which are based on comparisons between conditions, unless the subjects would have changed detection strategies between conditions, which seems unlikely.

Though we did not directly measure whether subjects were able to lateralize the stimuli or rather compared level differences between both ears, we did ask them how they did it for each condition. All 12 subjects reported being able to lateralize in all conditions except for the 1 oct shift. In the 1 oct shift condition, they reported to “sometimes” attend to level differences instead of lateralizing. This attending to level differences can indicate a non-fused image which might be part of the cause of the increased JNDs in the 1 oct shift condition versus the other shift conditions.

V. CONCLUSIONS

From our JND in ILD experiments with 12 normal hearing subjects, we can conclude that

- ILDs can be detected for uncorrelated narrowband ($1/3$ oct) noise, with JNDs in the range 1.4 - 5.2 dB
- When a frequency shift is introduced in one of both ears, ILDs can still be detected, albeit with a slightly higher JND.

The fact that ILDs can be detected across frequencies has important implications for localization using bilateral cochlear implants and contralateral bimodal systems.

For bilateral CIs, it means that bilateral matching of electrodes is less important for ILD perception than could be assumed (though performance is still best for the unshifted condition).

For bilateral bimodal systems, it implies that lateralization using ILDs might be improved by introducing or amplifying ILD cues between the acoustical part (the hearing aid) and the low-frequency electrodes of the electrical part. A signal processing system that has access to full band signals of both ears could determine the direction of a prominent sound source and use that direction to calculate a corresponding ILD to introduce in the low frequencies. The patient would then have to be trained to localize sound sources using these artificial ILD cues.

Acknowledgments

This research was carried out in the frame of the IWT (Institute for the Promotion of Innovation by Science and Technology in Flanders) project 050445 and was partly sponsored by Cochlear Ltd. We thank our test subjects for their patient and enthusiastic participation to the experiments. We also thank the editor and three reviewers for their helpful criticism on earlier versions of the manuscript.

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