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Effects of Interaural Differences on the Loudness of Low-Frequency Pure Tones

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Summary
The loudness related to a sound may vary according to the localization of its source. This phenomenon is described as directional loudness and has been mainly observed for high-frequency sounds and for sources located in the horizontal plane. Because of the acoustic shadow of the head, the left and right ear pressures are modified depending on the source azimuth and the global loudness resulting from a summation process may vary accordingly. But directional loudness has also been reported to occur at 400 Hz, where shadowing effects are usually rather small. It might therefore be suspected that directional loudness effects could be influenced by other parameters involved in the localization process. In a previous study, a small but significant increase of loudness with increasing interaural time difference (ITD) was shown for low-frequency pure tones (200 and 400 Hz) at a low loudness level (40 phon). The present study aimed at getting insight into the potential cause and extent of this effect by assessing the loudness of similar pure tones lateralized with headphones by applying an interaural level difference (ILD) in addition to an ITD and by measuring the effect of ITD at the hearing threshold. It showed significant effects of both ILD and ITD on loudness, and no interaction between these factors. As the effects added even when the factors were contradictory, it supports the hypothesis that the effect is caused by the ITD itself and is not related to the localization process. However, the ITD effect was not significant at the hearing threshold.

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1. Introduction

Significant variations of loudness were observed when presenting bands of noise through loudspeakers that were located at various directions around a listener in an anechoic room [1, 2]. As an example, a third-octave noise band centered at 5 kHz emitted by a lateral source (±90°) was perceived as louder than the same sound emitted by a frontal source (0°). This effect, known as directional loudness, is largely accounted for by physical modifications affecting the sound pressure along its way to the listener's ears. The stimulation at each of the two ears is affected to a different extent depending on the source azimuth. Thus the overall loudness resulting from a binaural loudness summation process is affected by the source location [3]. This effect has been mainly reported for high-frequency sounds, for which at-ear pressures are modified because of the perturbation of the sound field by the head. The resulting interaural level difference (ILD) is used for high-frequency localization, above about 1500 Hz, but is often considered as negligible below 500 Hz [4]. However, it has been shown that directional loudness sensitivity (DLS) could be observed at 400 Hz [2], where there is little acoustic shadow of the head [4]. Moreover, a tendency for the measured DLS values to be slightly higher than model predictions based on the related pressure measurements was reported at 5000 Hz [5]. Therefore, regardless of whether or not the left and right ear pressures are equal, it may be suspected that directional loudness effects are not caused only by pressure modifications.

In a previous study, an effect of interaural time difference (ITD) on loudness has been shown for low-frequency pure tones at 200 and 400 Hz [6]. A small but significant increase of loudness with increasing ITD could be observed at a low loudness level (40 phon) but not a moderate one (70 phon). However, it was not clear why this effect only occurred at low loudness level and whether loudness was affected by ITD itself or by higher-level processes. As an example, it has been shown that perceived source distance had an effect on loudness [7]. Further experiments were therefore needed to get insight into the potential cause and extent of this effect.

As non-negligible ILDs were reported at 200 and 400 Hz [2], a first experiment was designed to investigate the effects of both ITD and ILD on the loudness of low-frequency pure tones at 40 phon. Stimuli were presented via headphones and lateralized by introducing ITD and ILD. These differences could be congruent and lead to

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the same side, but could also be opposite and compensate for the lateralization induced by each other [8]. The effects of ITD and ILD on loudness were observed by asking listeners to match dichotic stimuli (obtained by introducing interaural differences) with a diotic one (no interaural difference).

As the ITD effect proved to be significant at low loudness level only [6], a second experiment was designed to investigate the effect of ITD at the hearing threshold. The minimum audible field is measured in free, quasi-free or diffuse sound field using a loudspeaker that is generally placed in front of the listener [9]. Some data for monaural hearing thresholds related to other incidences (45° and 90°) can be found in the current standards for audiometric tests [9, 10]. As an example, the data indicate a slight decrease of the monaural hearing threshold when increasing the loudspeaker incidence from 0° to 90° at 125 Hz which suggests that directional effects could possibly occur at this level. However, these reference thresholds were derived from data based on measurements collected in various studies [11, 12]. In some of these studies, the loudspeaker was placed at 1 m from the reference point. The variations of the hearing threshold with the source azimuth could then simply be caused by the experimental conditions, i.e., at-ear pressure modifications with the azimuth because of the small distance between the loudspeaker and the listener's ear. In addition to these threshold data for non-frontal incidence, it has also been shown that interaurally out-of-phase 250-Hz tones were detected at a 0.9 dB lower level than when presented in phase [13]. Therefore, it was decided to investigate the effect of ITD at threshold level by measuring hearing thresholds of dichotic stimuli.

2. Experiment I: loudness of pure tones including ITD and ILD

The effects of both ITD and ILD on loudness were investigated by matching in loudness dichotic pure tones with a diotic reference of the same frequency.

2.1. Stimuli

The two frequencies (200 Hz and 400 Hz) at which the effect of ITD on loudness has been observed at low loudness level (40 phon) [6] were under study.

Three ITD values (−772 μs, 0 μs, +772 μs) were selected as ±772 μs were the ITD values for which the effect on loudness was the highest [6]. These values were obtained from Kuhn's low-frequency model [14], which is valid below 500 Hz,

$$\mathrm{ITD} = \frac{3a}{c_0} \sin\theta_{inc} \tag{1}$$

where $a = 8.75$ cm is the average head radius, $c_0 = 340\ \mathrm{m \cdot s^{-1}}$ is the speed of sound in the air and θ_{inc} is the incidence angle for a virtual sound source in the horizontal plane (respectively −90°, 0° and +90°). To elicit the impression of a lateralized sound, an ITD was introduced on the basis of Equation (1). ITDs of ±772 μs are higher than the interaural time/phase difference thresholds at those frequencies and should enable the lateralization of pure tones [15]. A negative sign means that the ITD leads to the left side.

In addition, although ILD is generally considered as small below 500 Hz [4], it can be seen on HRTF measurements [2] that it is not negligible for an azimuth of ±90° and can reach up to 2.5 dB at 200 Hz and 5 dB at 400 Hz. Those ILDs consist in a SPL increase on the leading side (respectively +2.5 dB and +5 dB), whereas it remains constant on the opposite side. Therefore, an ILD was also introduced between the left and right channels by increasing the level on the leading side only. Five ILD values were selected (+5 dB left, +2.5 dB left, 0 dB, +2.5 dB right, +5 dB right). ITD and ILD could be congruent or opposite (e.g. ITD = +772 μs and ILD = +5 dB left) and should compensate, at least partially, for the lateralization induced by each other in this case [8].

These stimuli were to be matched in loudness to diotic references whose level was fixed at 40 phon by placing the test headphones (Sennheiser HD650, circumaural, open) on a dummy head (Neumann KU100) whose microphones are located at the entrance of the blocked ear canal. Firstly, the sound pressure level was adjusted to 94 dB SPL at 1000 Hz on each ear. Starting from this point, the two frequencies under test were subsequently adjusted by following the 40-phon curve defined by ISO 226 [16]. The sound pressure levels corresponding to 40 phon are respectively 53.4 dB SPL at 200 Hz and 45.0 dB SPL at 400 Hz. The duration of each stimulus was 1.6 s. Its onset and offset were smoothed by 100-ms-long raised-cosine functions. The dummy head also enabled to verify the interaural synchronicity of the diotic pure tones.

2.2. Procedure

The point of subjective equality (PSE) was measured for each of the 30 experimental conditions (2 frequencies, 3 ITDs and 5 ILDs) by using a loudness matching task. A two-interval two-alternative forced choice (2I2AFC) paradigm was used with a 1-up-1-down rule [17]. In each trial, a test sound (stimulus including interaural differences) and a reference sound (diotic stimulus at 40 phon) lasting 1.6 s each were consecutively presented in random order with a 500-ms pause in between. The task was to indicate whether the first or the second sound was perceived as louder, regardless of any other difference. The instructions were given both orally and in written form. The subject responded by clicking a button on a MATLAB graphical user interface. The sound pressure level of the test sound was varied from trial to trial depending on the response of the subject. It was lowered by a given amount when the subject judged it to be louder, whereas it was increased by the same amount when the sub ject judged the reference to be louder. The same level change was applied to both ear signals, i.e., the interaural level difference of the test signal was preserved during the adaptive run. The step

size was initially set to 4 dB and was decreased to 1 dB after two reversals (a reversal denotes a change in direction in the matching sequence). The starting level of each stimulus was randomly set 10 dB above or below the diotic reference to provide clearly noticeable loudness differences with at the beginning of the matching process. As a reminder, the level was only increased on the leading side to achieve a non-zero ILD and this offset is thus defined with respect to the opposite side. For a given test sound, the adaptative sequence was ended at the eighth reversal [2]. The arithmetic mean of the levels at the last six reversals was used to derive the PSE of the test sound with respect to its reference. The 30 adaptative sequences related to the experimental conditions were randomly reordered and interleaved on a trial-by-trial basis, providing some random sampling of ITDs, ILDs, frequencies and starting levels. From the subject's point of view, each session appeared as a succession of unrelated paired comparisons of loudness.

The subject sat in an audiometric booth and was asked to place the test headphones comfortably over his ears and to not modify this position once the test had started as realistic changes in the position of such headphones can be audible [18]. The test lasted approximately 1 h and was preceded by a 3-min pretest to familiarize the listener with the task and the answering interface. Twenty sound engineering students (Bachelor's and Master's degree) from the University of Brest took part in this experiment and were remunerated for their participation. The subjects (seven women and thirteen men, with ages ranging from 20 to 22 years) had normal hearing thresholds ($\leq$ 10 dB HL) based on an audiogram taken in the month preceding this test. None of them had particular experience in laboratory listening tests.

2.3. Results

The PSE is presented as the difference between the matched level on the ear that is not affected by ILD and the reference level. As an example, for a test sound with ILD = 0 dB, a negative PSE would indicate that a lower level was required to achieve equal loudness with respect to the reference. Results were analyzed using repeated-measures analysis of variance with frequency (2 levels), ITD (3 levels) and ILD (5 levels) as within-subjects factors.

The effects of ILD ($F(4, 76) = 174.99$; $p < 0.001$) and ITD ($F(2, 38) = 37.51$; $p < 0.001$) were both significant. As there was no significant interaction ($F(8, 152) = 0.84$; $p = 0.573$) between these two factors, it can be concluded that their effects were additive. The analysis did not highlight any further significant effect or interaction.

For ILD = 0 dB (Figure 1), the PSE is significantly lower when ITD is ± 772 μs than when it is 0 μs ($p < 0.001$ in both cases according to Fisher's LSD test). Note that the difference is small (around 1 dB) but still higher than the just noticeable difference in sound pressure level for such stimuli [19]. This effect is very similar to the one already observed [6]. As the PSE is significantly lower when ITD = ± 772 μs than when ITD = 0 μs, it can be inferred that, at the same level, the dichotic signals are louder than the diotic signal.

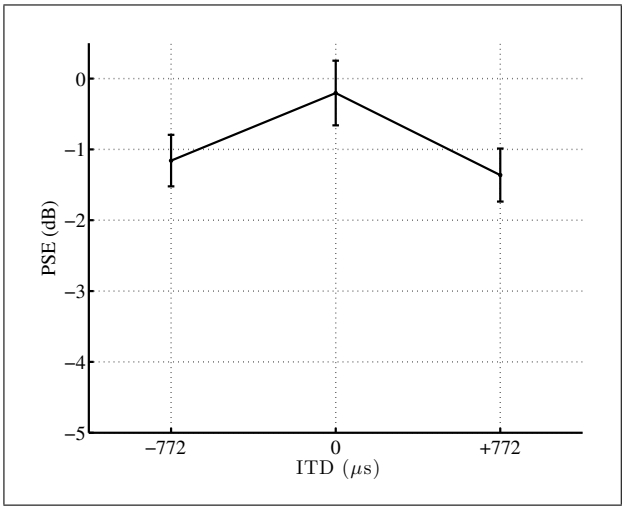

Figure 1. Mean PSE as a function of ITD when ILD is 0 dB, with 95% confidence intervals.

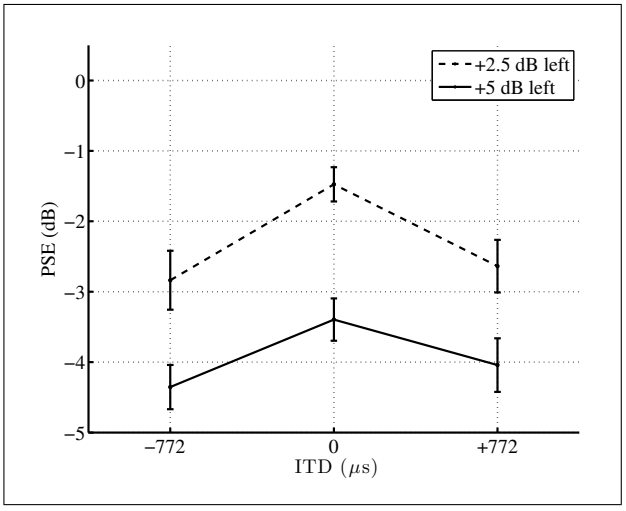

Figure 2. Mean PSE as a function of ITD when ILD leads on the left, with 95% confidence intervals.

The ILD was created by adding 2.5 dB or 5 dB on the leading side. As expected, the PSE significantly decreases with increasing ILD, namely by around 1.5 dB if ILD = +2.5 dB and by around 3 dB if ILD = +5 dB, whatever the leading side. Figures 2 and 3 depict the PSEs in the same range for each ILD value to highlight this effect. These figures also show that the ITD effect depicted in Figure 1 (ILD = 0 dB) applies for the 4 other ILD values. This effect is the same (i.e. a significant decrease of the PSE for ITD = ± 772 μs) when ILD and ITD lead to the same side as when they are contrary (i.e. non-significant interaction). As an example, the dashed line on Figure 2 shows that the PSE is the same for ITD = -772 μs and ITD = $+772$ μs although the latter leads to the opposite side of the ILD (+2.5 dB left). This is also found for all other non-zero ILDs (Figures 2 and 3).

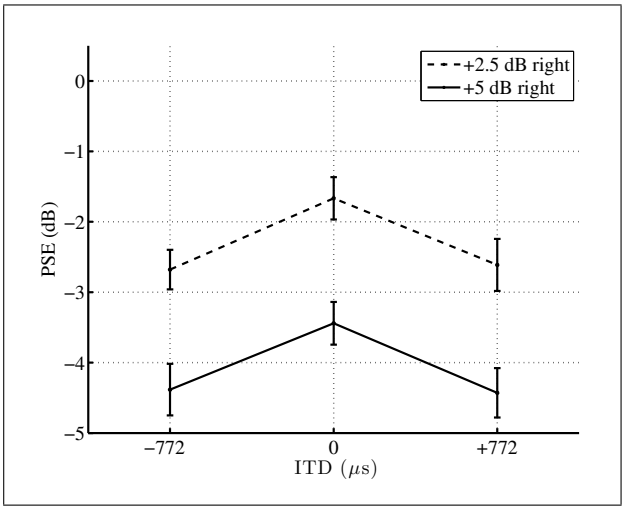

Figure 3. Mean PSE as a function of ITD when ILD leads on the right, with 95% confidence intervals.

3. Experiment II: hearing threshold of pure tones including ITD

The effect of ITD on loudness at absolute threshold level was investigated by measuring the hearing threshold of lateralized pure tones.

3.1. Stimuli

Five frequencies were under study in this second experiment:

- 200 and 400 Hz, where ITD had a significant effect on loudness at 40 phon according to a previous study [6] and which was confirmed in Experiment I,
- 125, 250 and 500 Hz which are the closest audiometric octave frequencies.

The frequencies ranged from 125 Hz, where pure tones may already be lateralized on the basis of ITD [15], to 500 Hz, where the acoustic shadow of the head is still small [4]. Thus for all signals used in this experiment, the same pressure at the two ears should appear natural to the listener.

Four ITD values (0 μs, +386 μs, +669 μs and +772 μs) were selected in order to lateralize the stimuli on the right. Only one side was chosen since the effect of ITD on loudness was symmetric in a previous study [6] and in Experiment I of the present study. These values were related to virtual incidence angles (0°, +30°, +60° and +90°) according to Kuhn's low-frequency model [14]. ITD values of +386 μs, +669 μs and +772 μs are higher than the interaural time/phase difference thresholds at these frequencies [20] and should enable the lateralization of pure tones. The headphones (Sennheiser HD650, circumaural, open) were calibrated the same way as in Experiment I. Firstly, the sound pressure level was adjusted to 94 dB SPL at 1000 Hz on each ear. Starting from this point, the five frequencies under test were subsequently adjusted by following the hearing threshold curve defined by ISO 226 [16].

Table I. Sound pressure level at the hearing threshold according to the frequency.

f (Hz)	L (dB SPL)
125	22.0
200	14.5
250	11.0
400	6.0
500	4.0

Table I indicates these standard threshold values. The duration of each stimulus was 1.6 s.

3.2. Procedure

Hearing thresholds were measured for the 20 experimental conditions (5 frequencies, 4 ITDs) by using a custom procedure [21] based on ANSI S3.21 [22]. Each threshold measurement was carried out by presenting the stimulus (pure tone) at a level set 50 dB above the standardized hearing threshold (Table I). A one-interval two-alternative forced choice (1I2AFC) paradigm was used with a 1-up-2-down rule. After each stimulus presentation, the listener was asked whether he had perceived the sound or not. Similarly to Experiment I, instructions were given both orally and in written form and the subject responded by clicking a button on a MATLAB graphical user interface. The level of the stimulus was lowered in the case of a positive answer, whereas it was increased in the case of a negative answer. The current procedure consisted of three bracketing series, each providing progressively smaller step sizes to finally result in threshold responses with 1-dB r esolution. The initial bracketing series provided step sizes of up 5 dB, down 10 dB to quickly bracket the threshold level to within 10 dB. Intermediate bracketing series provided step sizes of up 2 dB, down 5 dB and was entered after two reversals (a reversal denotes a change in direction in the measurement process). The final bracketing series, in which the hearing threshold was measured, was reached after two more reversals (four reversals in all) and provided step sizes of up 1 dB, and down 2 dB. The level at which a positive answer occurred was defined as the threshold if at least one of the two preceding positive answers within the final series occurred at the same level. Threshold value could not be reached this way before the eighth reversal.

The listener sat in an audiometric booth and was asked to place the HD650 headphones comfortably over his ears and to not modify this position once the test had started. It has also been shown that realistic changes in such headphones position could lead to significant differences in hearing threshold measurements [21]. In order to take into account test-retest variability [22], all subjects carried out the experiment twice, on two different days. The test lasted approximately 45 min and was preceded by a 3-min pretest to familiarize the listener with the task and the answering interface. Fifteen sound engineering students (Bachelor's and Master's degree) from the University of Brest took

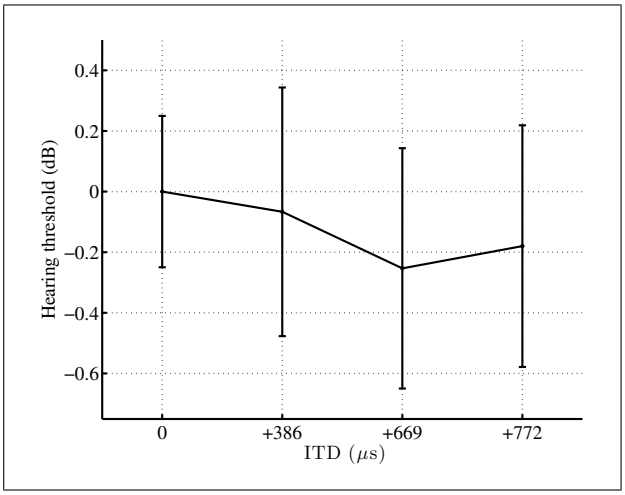

Figure 4. Mean hearing threshold as a function of ITD, with 95% confidence intervals.

part in this experiment and were remunerated for their participation. The subjects (five women and ten men, with ages ranging from 20 to 22 years) had normal hearing thresholds ($\leq$ 10 dB HL) based on an audiogram taken in the month preceding this test. None of them had particular experience in laboratory listening tests.

3.3. Results

For each listener at each frequency, the two measurements with zero ITD were averaged to define a sensation level reference (0 dB SL). All threshold measurements related to a given listener at a given frequency (4 ITDS and 2 repetitions) were subsequently shifted according to its respective reference, in order to take into account individual threshold differences. The thresholds were analyzed using repeated-measures analysis of variance with test repetition (2 levels), frequency (5 levels) and ITD (4 levels) as within-subjects factors.

This analysis did not highlight any significant effect or interaction among the factors under test. In particular, no simple effect ($F(3, 42) = 0.66$; $p = 0.581$) or interaction involving ITD proved to be significant. As can be noted from Figure 4, the hearing threshold was statistically equivalent for all ITD values under test.

4. Discussion

The results of Experiment I indicate significant effects of both ITD and ILD on loudness for low-frequency pure tones, but no interaction between these two factors. The loudness of the tones were the same whether their ILD led to the same side as their ITD or to the opposite one, which would compensate for the lateralization induced by each other in the latter case [8]. This does not support one of the two hypotheses developed to explain the ITD effect observed in a previous paper [6]. This hypothesis stated that the effect of ITD on loudness would be due to "high-level" processes as the lateralization of the source would have been taken into account in the loudness process. Such effects were reported about the influence of perceived source distance on loudness [7]. On the other hand, these results confirm the effect of ITD on loudness [6] and are consistent with the alternative hypothesis that ITD could help separate the signal from internal noise exhibiting a small positive correlation [13, 23]. This hypothesis relies on the assumption that the signal is perceived as a separate entity from the background noise and that its loudness might be enhanced if ITD provides a better separability [24]. This could explain why loudness is affected by interaural phase/time difference at a low loudness level (40 phon) independently of the ILD effect.

Following this hypothesis further, one would have expected the ITD effect to be observed at even lower levels. The hearing threshold can be considered as the starting point of measurable loudness, at which the loudness is very small [25] and considered to be a fixed value [26]. However, the results of Experiment II did not highlight any significant effect of the ITD values under test (+386 μs, +669 μs and +772 μs) at the absolute threshold. It might be primarily inferred that ITD has no effect on loudness at very small levels, but the lack of significance could be also due to the fact that the ITD effect is hardly measurable in this case. As an example, a difference of 1 dB in the PSEs was observed at 40 phon as it is superior to the differential threshold which increases with decreasing loudness level [19]. However, it has been reported for 250-Hz tones that reversing the interaural phase lowers the hearing threshold by 0.9 dB [13]. For the ITDs and frequencies under test, the corresponding interaural phase differences are always less than π which could imply an even lower effect. In addition, the sensitivity to the frequencies under test may vary from one listener to another because of the fine structure of the hearing threshold [27]. A given frequency could possibly lie within a range of minimum or maximum sensitivity, so that the ITD effect would not be the same and that the variability of the threshold measurements would be increased.

In summary, the results of this study and of a previous one [6] indicate both a significant effect of the ITD at a low loudness level (40 phon). At this level, ITD could have enabled a better separability from the internal noise and enhanced the loudness of the tone. Similarly, loudness increases with increasing interaural phase differences were reported up to 40 dB above the masked threshold [28]. However, several other studies did not show a significant effect over such a wide range [29, 30]. At higher loudness levels, the internal noise should be all the more negligible and such an effect was not observed at 70 phon [6]. The ITD effect was also not significant at the hearing threshold as it might be hardly observable at very small loudness levels.

5. Conclusion

The results of the present study show a significant effect of ITD on the loudness of low-frequency pure tones pre-

sented at a low loudness level (40 phon) independently of the ILD. As this effect applied even when ILD led to the opposite side of the ITD, it can be inferred that the effect of ITD on loudness is not related to the lateralization. This supports the assumption that directional loudness is rather due to the localization cues (namely ITD and ILD) than to the localization process itself. However, no significant effect of ITD was found for pure tones at the hearing threshold. A possible ITD effect on loudness at very low levels might therefore be hardly observable.

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