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Effect of the interaural time difference on the loudness of pure tones as a function of the frequency

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1 Summary

Significant loudness variations with source azimuth (i.e. directional loudness) are generally accounted for by at-ear pressure modifications. An effect of the interaural time difference (ITD) was also reported in previous studies by the authors: the loudness of pure tones (200 and 400 Hz) significantly increased when the stimuli were presented with an ITD of 772 μ s, corresponding to an azimuth of 90°. The present study aims at observing this effect for higher frequencies, including frequencies at which ITD is no longer useful as a localization cue. The effect of ITD on the loudness of pure tones was thus studied at 500, 707, 1000, 1404 and 2000 Hz. Results show that the effect of ITD on loudness is not significant above 500 Hz, even for frequencies where ITD is still a localization cue. The effect observed at 500 Hz is still in agreement with the results reported by previous studies as the loudness of a pure tone significantly increases when its ITD is 772 μ s.

1 Introduction

Directional loudness (i.e. loudness variations with the direction of the sound source) has been highlighted by presenting bands of noise through loudspeakers located in various directions around a listener in an anechoic room [1, 2]. As an example, a third-octave noise band centered at 5000 Hz presented by a loudspeaker at an azimuth of 90° was perceived as being about 5 dB louder than when presented by a loudspeaker at an azimuth of 0°, in free field. The effect is indeed particularly salient in high frequencies when the sources are located in the horizontal plane. Physical modifications of the at-ear pressures caused by the acoustic shadow of the head largely account for this effect in this case. The directional loudness sensitivity (DLS) was even reported to be significantly different from zero at 400 Hz [2]. Below 500 Hz, shadowing effects are usually considered rather small [3] as variations of ILD with the azimuth do not exceed 5 dB at 500 Hz and decrease for lower frequencies. Whether or not these variations can be considered as small, it was suspected that at-ear pressure modifications could not

be the only cause of directional loudness.

Recent studies have highlighted a significant effect of interaural time differences (ITD) on the loudness of low-frequency pure tones (200 and 400 Hz) at 40 phon (but not at 70 phon) [4]. Loudness was significantly increased by 1.25 dB when the ITD was increased from 0 to 772 μ s. This effect was similarly observed when presenting the pure tones with an interaural level difference (ILD \leq 5 dB) [5]. This was observed when ITD and ILD were congruent, but also when opposite (i.e. leading to opposite sides). As such opposite interaural differences should compensate for the lateralization induced by each other, it suggests that the loudness increase with ITD is not related to the perceived source lateralization but that ITD itself affects the loudness process.

Above 500 Hz, it is still assumed that the variation of DLS with source position is mainly caused by at-ear pressure modifications. However, at 5000 Hz, model predictions reported that pressure modifications did not totally account for the loudness variations observed when varying the azimuth [6]. This model was designed to predict binaural summation for sounds differing in level at the two ears by taking into account contralateral inhibitions, assuming that a strong input to one ear can inhibit a weaker input to the other one. A tendency for the predicted DLS to be slightly below the measured values was found and reached 1.7 dB for the largest deviation. Such a deviation could be caused by a contribution of ITD to directional loudness for frequencies above 500 Hz as the binaural summation might also be affected by time differences at the two ears. Therefore, the aim of the present study is to observe further the effect of ITD on loudness that was observed at 40 phon for 200 and 400 Hz, when considering frequency from 500 Hz to 2000 Hz by half-octave steps.

2 Experimental setup

2.1 Stimuli

Interaural time differences were applied to pure tones whose frequencies were 500, 707, 1000, 1404 and 2000 Hz. As ITD may slightly vary with frequency,

85 it was computed according to two different models; 137
 86 Kuhn’s model [7]: 138

$$ITD = \frac{3a}{c_0} \sin \theta_{inc} \quad (1) \quad 139$$

87 and Woodworth’s model [8]: 140

$$ITD = \frac{a}{c_0} (\theta_{inc} + \sin \theta_{inc}) \quad (2)$$

88 where $a = 8.75$ cm is the standard head radius,
 89 $c_0 = 340$ m · s⁻¹ is the speed of sound in the air and
 90 θ_{inc} is the incidence angle for a sound source in the
 91 horizontal plane (i.e. azimuth). Eq. (1) provides a
 92 better estimate of the ITD than Eq. (2) below 800 Hz,
 93 whereas the opposite trend is observed above 1500 Hz
 94 [9].

95 For $\theta_{inc} = 90^\circ$, ITD = 772 μ s according to Kuhn’s
 96 model and ITD = 662 μ s according to Woodworth’s
 97 model. Smaller (607 μ s), intermediate (717 μ s) and
 98 larger (827 μ s) ITD values were also selected accord-
 99 ing to a 55 μ s step. Five non-zero ITD values were
 100 then under study, as well as a zero ITD for compar-
 101 ison. The six possible ITD values were introduced
 102 between the left and right channels of initially diotic
 103 pure tones by delaying one ear with respect to the
 104 other one. Stimuli were presented to the subject via
 105 headphones (Sennheiser HD 650, circumaural, open)
 106 and the possible head movements were not compen-
 107 sated. For low-frequency pure tones, ITD is an un-
 108 ambiguous information as long as the period of the
 109 sound is less than twice the maximum possible ITD,
 110 which corresponds to a frequency of about 725 Hz.
 111 The ambiguity can be resolved up to about 1500 Hz
 112 if head or source movements are possible [3]. So in the
 113 present study, ITD cannot provide localization infor-
 114 mation for $f = 2000$ Hz and may be ambiguous for
 115 $f = 1000$ Hz and $f = 1404$ Hz.

116 These stimuli were to be matched in loudness to
 117 diotic references at a loudness level of 40 phon. The
 118 reference level was set by placing the test headphones
 119 on a dummy head (Neumann KU 100) whose micro-
 120 phones are located at the entrance of the blocked ear
 121 canal. Firstly, the sound pressure level was adjusted
 122 to 94 dB SPL at 1000 Hz on each ear. Secondly, start-
 123 ing from this point, the sound pressure level was sub-
 124 sequently adjusted so as to produce 40 phon at the
 125 entrance of the ear canal for each of the five frequen-
 126 cies under test. The relationship between dB SPL
 127 and phon is defined by ISO 226 standard at the posi-
 128 tion where the center of the listener’s head would be,
 129 but in the absence of the listener [10]. Corresponding
 130 sound pressure levels at the entrance of the blocked
 131 ear canal were derived using KU 100 HRTF measure-
 132 ments that account for the pressure transformation
 133 from free field to the entrance of the ear canal [11].
 134 Sound pressure levels related to 40 phon at the cen-
 135 ter of the head in its absence and at the entrance of
 136 the blocked ear canal are indicated in Table 1. The

duration of each stimulus was 1.6 s. Its onset and off-
 set were smoothed by 100-ms-long raised-cosine func-
 tions. Similar stimuli proved to be well lateralized on
 the basis of interaural time differences [12].

Table 1: Sound pressure levels at the center of the head in its absence according to ISO 226 and at the entrance of the blocked ear canal of the KU 100 dummy head, as a function of the frequency for 40 phon.

f (Hz)	L (dB SPL)	
	ISO 226	KU 100
500	43.0	41.5
707	40.6	39.9
1000	40.0	40.8
1414	42.6	42.7
2000	39.2	38.9

2.2 Procedure 141

Loudness matches were obtained by using a two-
 interval two-alternative forced choice (2I2AFC) 142
 paradigm following a 1-up-1-down rule converging on 143
 the point of subjective equality (PSE). This proce- 144
 dure is similar to that used in the previous studies 145
 that revealed a significant effect of ITD on loudness 146
 [4, 5]. In each trial, a test sound (stimulus includ- 147
 ing interaural differences) and a reference sound (di- 148
 otic stimulus at 40 phon) lasting 1.6 s each were con- 149
 secutively presented in random order with a 500-ms 150
 pause in between. The subject’s task was to indicate 151
 whether the first or the second sound was perceived 152
 as louder, regardless of any other perceived difference. 153
 The instructions were given both orally and in writ- 154
 ten form. The subject responded by clicking a button 155
 on a MATLAB graphical user interface. 156
 157

The starting level of each test sound was randomly
 set 10 dB above or below the level of the reference
 sound (defined at the entrance of the blocked ear canal
 in Table 1) to provide a clearly noticeable loudness dif-
 ference at the beginning of the matching process. The
 sound pressure level of the test sound was stepwise
 varied from trial to trial depending on the subject’s
 response. It was lowered when the subject judged it
 to be louder, whereas it was increased when the sub-
 ject judged the reference to be louder. The step size
 was initially set to 4 dB and was decreased to 1 dB
 after two reversals (a reversal denotes a change in di-
 rection in the matching process). For each test sound,
 the adaptative sequence was ended at the eighth rever-
 sal. 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. 174

The 30 adaptive sequences related to the experi-
 mental conditions (5 frequencies, 6 ITDs) were ran-
 domly reordered. From the subject’s point of view,
 each test appeared thus as a succession of unrelated 175
 176
 177
 178

179 paired comparisons of loudness. The subject sat in
 180 an audiometric booth and was asked to place the test
 181 headphones comfortably over his ears and to not mod-
 182 ify this position once the test had started. The test
 183 lasted approximately 1 h and was preceded by a 3-min
 184 pretest to familiarize the listener with the task and
 185 the answering interface. Twenty sound engineering
 186 students (Bachelor’s and Master’s degree) from the
 187 University of Brest took part in this experiment and
 188 were remunerated for their participation. The sub-
 189 jects (six women and fourteen men, with ages ranging
 190 from 20 to 22 years) had normal hearing thresholds
 191 (≤ 10 dB HL) based on an audiogram taken in the
 192 month preceding this test. None of them had partic-
 193 ular experience in laboratory listening tests.

194 2.3 Results and discussion

195 For each frequency, a repeated-measures analysis of
 196 variance was carried out to assess the effect of ITD
 197 on loudness matches (results are collected in Table 2).
 198 The PSE is presented as the difference between the
 199 matched level and the reference level (see Table 1 for
 200 corresponding SPL values). The PSE is then expected
 201 to be 0 dB when $ITD = 0 \mu s$ as the test and reference
 202 sounds are identical in this case.

Table 2: Results of repeated-measures analysis of vari-
 ance, as a function of the frequency.

f (Hz)	$F(5, 95)$	p -value
500	3.041	0.014
707	1.592	0.170
1000	0.656	0.657
1414	1.613	0.164
2000	0.435	0.823

203 At 500 Hz, ITD had a significant effect on loud-
 204 ness ($F(5, 95) = 3.041$; $p = 0.014$). As can be noted
 205 from Fig. 1, the PSE appears negative when the ITD
 206 is different from zero. It can be inferred that related
 207 stimuli would have been perceived as louder than their
 208 respective reference if presented at the same physical
 209 level. The PSE obtained for $772 \mu s$ is significantly dif-
 210 ferent from the one obtained for a zero ITD ($p < 0.001$
 211 according to a two-tailed Fisher’s LSD test). It de-
 212 creases here by around 1 dB which is in agreement
 213 with the decrease of 1.25 dB that was observed at
 214 200 and 400 Hz for the same ITD in previous stud-
 215 ies [4, 5]. The effect is small but still superior to
 216 the minimum perceptible change in sound pressure
 217 level which is around 0.5 dB for a 500-Hz pure tone
 218 at 40 phon [13]. Previous results [4] indicated that
 219 the PSE tended to decrease with increasing ITD and
 220 that it became significantly lower than the reference
 221 (zero ITD) for $669 \mu s$ and $772 \mu s$, corresponding re-
 222 spectively to $\theta_{inc} = 60^\circ$ and $\theta_{inc} = 90^\circ$ according
 223 to Eq. (1). This is partially confirmed here as the
 224 PSEs obtained for $607 \mu s$ and $717 \mu s$ are significantly

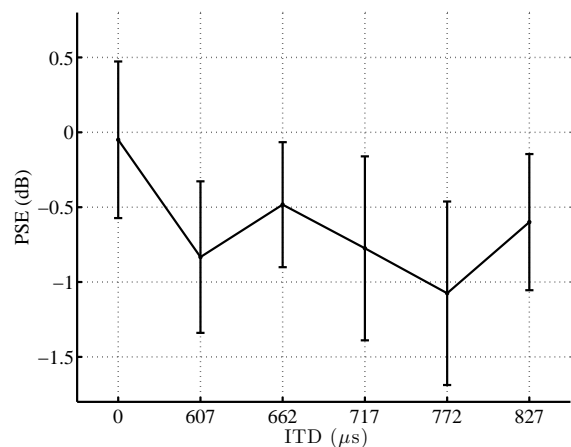


Figure 1: Mean PSE as a function of ITD at 500 Hz,
 with 95% confidence intervals.

225 different from the one obtained for a zero ITD (with
 226 $p = 0.007$ and $p = 0.012$ respectively), but this does
 227 not hold for $662 \mu s$ ($p = 0.132$). No significant dif-
 228 ference was either found between zero and $827 \mu s$
 229 ($p = 0.057$). The latter ITD value is notably higher
 230 than the maximum possible value at this frequency
 231 according to Eq. (1). It has been shown that when
 232 the ITD is higher than a quarter period [14], or close
 233 to a half period [15], a diffuse image or even two dis-
 234 tinct images may be perceived. At 500 Hz, $827 \mu s$ is
 235 higher than $T/4$ and close to $T/2$. As this could lead
 236 to the perception of diffuse or multiple images de-
 237 layed in time, other complex mechanisms related to
 238 auditory organization processes (auditory scene anal-
 239 ysis) might take place prior to loudness computation
 240 [16].

241 As indicated in Table 2, ITD had no significant
 242 effect on loudness at any of the four other frequen-
 243 cies under study. This was observed for frequen-
 244 cies where ITD could respectively provide unambigu-
 245 ous ($f = 707$ Hz), ambiguous ($f = 1000$ Hz and
 246 $f = 1404$ Hz) or unusable localization information
 247 ($f = 2000$ Hz). As can be noted from Fig. 2, where
 248 PSEs are depicted in the same range as in Fig. 1, the
 249 differences at these frequencies are much lower than
 250 those reported at 500 Hz. The maximum difference
 251 that can be observed between a PSE obtained for a
 252 non-zero ITD and a PSE obtained for a zero ITD falls
 253 between 0.4 and 0.6 dB. It was previously hypothe-
 254 sized that ITD could help separate the signal from in-
 255 ternal noise at low loudness levels [4, 5]. These results
 256 seem to indicate that it would only hold up to 500 Hz
 257 as the differences observed beyond this frequency are
 258 not significant and not likely to improve the separa-
 259 bility. Therefore, the contribution of ITD to direc-
 260 tional loudness appears significant only up to 500 Hz
 261 and significant loudness variations that would be ob-
 262 served at higher frequencies would rather be caused
 263 by at-ear pressure modifications, which significantly
 264 increase above 500 Hz [3]. The fact that directional

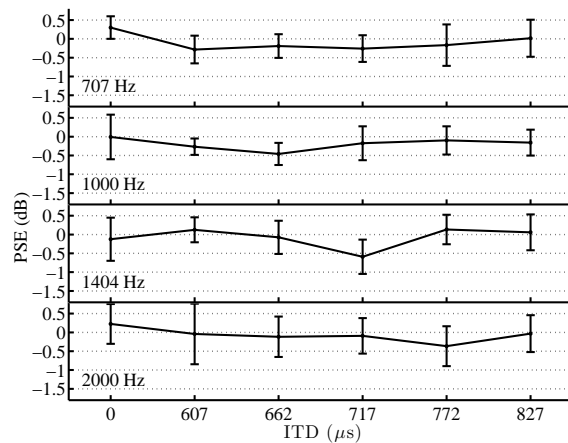


Figure 2: Mean PSE as a function of ITD at 707 Hz, 1000 Hz, 1404 Hz and 2000 Hz, with 95% confidence intervals.

loudness sensitivity at higher frequencies is underestimated by model predictions [6] may not be explained by an effect of time differences on binaural loudness summation (as hypothesized in section 1) but more probably by a different binaural interaction (i.e. contralateral inhibition) for stimuli exhibiting different levels at the two ears. As a result, it should be emphasized that ITD has no significant effect on loudness for frequencies above 500 Hz even if it may provide useful information about the source localization (e.g. at 707 Hz). This finding goes in line with the results establishing that the effect of ITD remained the same when the lateralization was compensated by an opposite ILD [5] and support the assumption that the effect of ITD on loudness is not related to the localization process.

3 Conclusion

The results of the present study confirm the effect of ITD on pure-tone loudness previously observed at 200 and 400 Hz, at a low loudness level. This effect proved to be significant at 500 Hz but not at higher frequencies. At 40 phon, ITD may thus contribute to the phenomenon of directional loudness only up to this frequency and loudness variations with the source azimuth that might be observed above would then be due to modifications of at-ear pressures. Moreover, the fact that ITD has no effect on loudness at 707 Hz, where it is still an unambiguous localization cue, confirms that the effect on loudness is caused by the ITD itself rather than by the related localization. These statements both indicate that directional loudness is not likely to be caused by the direction itself but rather by the modifications (pressure and time) that affect a stimulus coming from a given direction.

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