Directional dependence of binaural loudness

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Introduction

Even though there is a vast body of literature on spatial hearing, little is known on how the location of a sound source affects its loudness. The pertinent research on head-related transfer functions (HRTFs) primarily deals with issues of localization and spatial discriminability. The literature on binaural loudness summation, on the other hand, focuses on a highly artificial paradigm according to which unnatural combinations of sound pressure levels (such as monotic-diotic comparisons) are presented to listeners via headphones.

In order to reconcile these two approaches, we recently started a series of experiments determining the effect of sound incidence angle on loudness [1, 2, 3, 4]. The basic experiment to be reported on here was conducted in an anechoic chamber, in which loudspeakers were mounted to present sounds from a number of directions both in the horizontal, and median planes (the latter not reported here). The subject's task was to produce a loudness match to a frontal reference location, and matches were obtained via a two-interval adaptive forced-choice procedure. Narrow-band noises were used, in order to investigate the frequency-specific effects of direction on loudness. Furthermore, individual HRTFs were measured for each incidence angle, in order to relate the changes in actual at-ear exposure to the observed changes in loudness as a function of sound incidence. Combining the listening-test data with the physical measurements, an attempt was made to model the binaural summation underlying the directional loudness matches.

Method

Subjects

Eight listeners participated in the experiment. The listeners were checked for normal hearing using pure-tone audiometry, and their individual HRTFs were measured.

Apparatus

The setup consisted of six similar loudspeakers in an anechoic chamber, placed in the left hemisphere of the horizontal plane at azimuths of 0°, 30°, 60°, 90°, 135° and 180°. The loudspeakers were positioned on an arch with a radius of 2.1 m, and were equalized for a flat frequency response, as measured in the center position of the setup in the absence of a listener.

The listeners were seated in a chair and faced the reference loudspeaker ahead, i.e., at an azimuth of 0°. Responses were collected with a two-button hand-held unit. The rest of the setup consisted of a computer, a high-quality sound card, power amplifiers, and a programmable attenuator for individual level control of each loudspeaker.

Stimuli

Third-octave-band noises, centered at 0.4, 1.0, and 5.0 kHz, were used as stimuli. The length of each sound was 1.0 s, and the sounds were played back at an overall level of 65 dB sound pressure level (SPL), measured at the center of the setup with the listener absent.

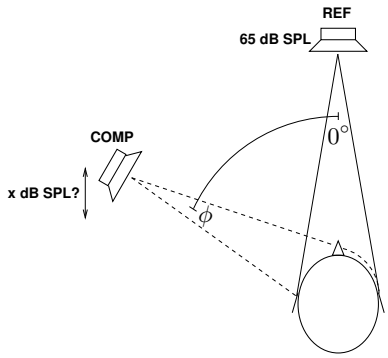

Figure 1: A schematic of the experimental setup for obtaining directional loudness matches.

Procedure

In the experiment proper, loudness matches were obtained between the frontal reference (REF) and each of the five comparison directions (COMP), separately for each stimulus center frequency, see Fig. 1. An adaptive, two-interval, forced-choice procedure using a one-up, one-down rule was utilized to obtain the matches, for details see [1]. Sixteen replications of each experimental condition (center frequency and incidence angle) were collected per subject, the adaptive tracks measuring a set of conditions being randomly interleaved.

Results and Discussion

Directional loudness sensitivities

The raw data from the experiment are the free-field sound pressure levels a given narrow-band noise from a particular incidence angle would have to be set to in order to be perceived equally loud as the frontal reference. In Fig. 2, the means of these levels across all 8 listeners are plotted, normalized to the frontal reference, and inverted in order to display *directional loudness sensitivities* (DLS) as a function of the direction of incidence. This way,

a positive value denotes a loudness enhancement and a negative value a loudness decrement for a given incidence angle.

If the matches coincided with the 0-dB line in Fig. 2, that would imply loudness to be constant across incidence angles. Clearly, that is not the case: While at 5 kHz, the directional loudness matches vary by some 7 dB over incidence angles, at 1 and 0.4 kHz, the effect size is smaller, but still on the order of 3 dB (see the bold, solid lines in Fig. 2), with maximal loudness observed at 60 or 90° of azimuth.

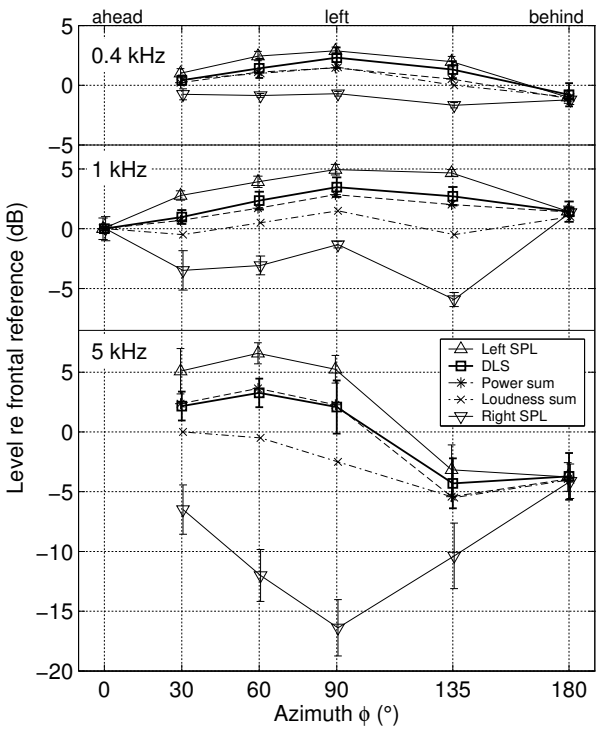

Figure 2: Mean directional loudness sensitivities (DLS) and the corresponding directional changes in the mean left- and right-ear SPLs ±95-% confidence intervals of the means, plotted along with predictions based on a binaural power and loudness summation, all normalized to the frontal reference.

When the behavioural data are compared to average at-ear exposure levels derived from the HRTFs (thin, solid lines in Fig. 2), it becomes evident that the matches fall between the left-ear and right-ear curves with a tendency to follow the (left) ear receiving the greater stimulation.

Modeling binaural loudness

In order to model how the at-ear levels are integrated to produce a single binaural loudness reading, a proposal made in the pioneering investigation by Robinson & Whittle [5] was modified to allow for a maximum binaural gain of 3 dB. The resulting *power summation* of the at-ear levels predicts the directional loudness sensitivities fairly well (asterisks connected by dashed lines in Fig. 2). Processing the stimuli by a loudness model [6], and subsequently adding right-ear and left-ear loudness did not fare as well (see the crosses connected by dashed-dotted lines in Fig. 2), and tended to overestimate the influence exerted by the ear receiving the lower sound pressure level.

Further work

Meanwhile, this research has been extended to include stimulation via binaural synthesis based on *generic*, i.e. dummy-head based HRTFs [3]. Furthermore, a larger, naive sample of listeners was recruited, and found to produce directional sensitivities that were statistically indistinguishable from those of the more trained listeners.

Further work investigated whether the presentation of wideband noise, or the inclusion of reverberation would make a difference [4]. It was found that these stimulation conditions attenuated the directional effects in systematic ways. Nevertheless, the mean data were well described by the power summation model in all of these situations, therefore a loudness-computation proposal for dummy-head measurements is given in [3].

Conclusion

Loudness - as measured in a real sound field - varies systematically with incidence angle. It can be reasonably predicted by a power summation of the at-ear levels derived from HRTF measurements.

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