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Directional loudness measurements for a multichannel system

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Loudness matching listening tests were conducted to quantify the difference in loudness sensitivity to a signal played from various horizontal directions. The multichannel system used for this test had 5 channels, set up according to the ITU Recommendation 775-1 “Multichannel stereophonic sound system with and without accompanying picture” and the test signals were octave bands of noise with centre frequencies from 125 Hz to 8000 Hz. The present paper reports on the results obtained from the subjective tests as well as binaural physical measurements made using the same loudspeaker setup.

1 Introduction

The effects of the relation between the receiver-source direction on loudness have been studied in the past [1,2]. The results from those experiments show a noticeable difference in loudness that is dependent on the source direction and the spectral characteristics of the signal. The reasons for these changes in loudness can be attributed to directional variation in the head related transfer functions (HRTF), and typical results for these and measurement methods are well documented in the literature [3,4]. The relation between the spectral changes caused by the HRTFs and the difference in loudness sensitivity has also been documented [5,6].

The present study was motivated by the awareness of these effects and the question of how they might apply in the context of home or professional surround sound systems. Most studies in the past have been conducted at angles different from those typically used in surround sound reproduction. The setup of this experiment was made as specified in the ITU Recommendation 775-1 “Multichannel stereophonic sound system with and without accompanying picture”, but in an anechoic room. In a previous experiment, the authors studied directional loudness sensitivity using a 5-channel system in a sound studio [7].

2 Method

2.1 Subjects

Twenty-one listeners participated in the experiment. The ages of the participants ranged from 21 to 46 with a mean of 28. The group was composed of eighteen male subjects and three female subjects.

2.2 Loudspeaker setup and listening room

The experiment was conducted in an anechoic chamber. The chamber was designed to be anechoic at and above the 1/3-octave band centred on 200Hz, and to provide a background noise environment that is below the hearing threshold. The results from impulse response measurements in the chamber show that the anechoic criterion is met for the source-receiver positions used.

The loudspeaker setup consisted of five Tannoy V8 passive loudspeakers. The loudspeakers were set at 1.2 m above the absorptive floor and 2 m away from the listening position. The ‘centre’ (or 0° azimuth) loudspeaker was positioned in front of the listening position; the left and right loudspeakers were positioned at a 30° azimuth angle with respect to the centre loudspeaker, and the left surround and right surround loudspeakers were positioned in a 110° azimuth angle with respect to the centre loudspeaker (Fig. 1). These angles are based on the Recommendation ITU-R BS.775-1.

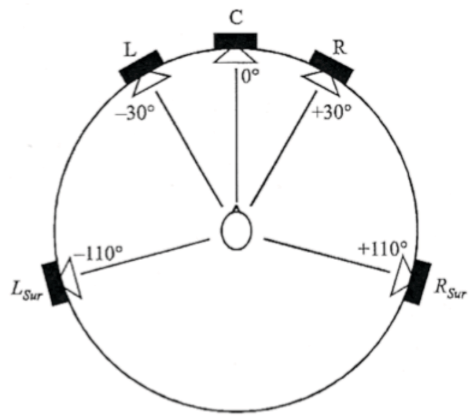

Figure 1. System setup.

The subject was seated in the centre of the loudspeaker circle (Fig. 1). A computer screen which was used for the experiment interface was positioned just below the centre loudspeaker. The subject was asked to face the centre loudspeaker at all times and this screen provided a visual reinforcement to make the subject look to the centre direction.

2.3 Signal playback and response data collection

A computer located outside the control room was used to provide playback and to record the response of the subjects. This computer was connected to a digital audio interface (MOTU 896HD), which provided individual playback for the five discrete channels. Individual signals for each loudspeaker were necessary to ensure proper calibration between channels.

The experiment was run using a program developed in Max/MSP. This program controlled the playback of the signals, provided a visual interface for the subject, controlled the level and recorded the octave band frequency and channel of the signals being tested and the level change made by the subject.

2.4 Stimuli

The stimuli used for the listening experiment was octave band pink noise, centered at 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz. During the experiment the appropriate stimulus was played continuously in a loop.

The differences in equalization from each loudspeaker were corrected by measuring the impulse response of each loudspeaker separately and then, from the impulse response, generating inverse filters. The inverse filter for each loudspeaker was convolved with each stimulus resulting in particular noise files for each loudspeaker. The files used a sampling rate of 44.1 kHz and 16-bit amplitude quantization.

The reference level of playback for each octave band was taken from NR60 curve values. With the loudspeakers in place and using a measurement microphone placed in the centre, each file was adjusted to conform to this level. No noticeable distortion was observed even at the highest playback level. The levels used are provided in the next table and figure. The system was calibrated using a Bruel & Kjaer type 2250 sound level meter with an error of ±0.3dB.

Frequency (Hz)	SPL (dB)
125	74
250	68
500	63
1000	60
2000	57
4000	55
8000	54

Table 1. Sound pressure level values used as reference, which are based on NR60 curve values.

2.5 Experiment design

In order to obtain results for multichannel equal loudness, the subjects were asked to match the loudness of two sounds; a reference sound was played first and marked as 'A' and the sound to be adjusted to match this was marked as 'B'. The sound matching procedure could yield sound pressure levels different to the reference's ('A') sound pressure level, and this level difference is the focus of the analysis. The pairs of sounds used were of the same octave band frequency content (in contrast with the previous experiment by the authors [7]). The reference in this experiment came from any of the five loudspeakers. This yielded a total of 140 different A-B pairs: five reference loudspeakers, four matching loudspeakers and seven frequency bands.

The stimuli were played back in a continuous loop so that the subject could switch between the reference and the stimulus sound to match as necessary (but the two sounds were not present at the same time). The subjects were given a keypad to make adjustments in level using up and down arrows. The steps of these adjustments were 1 dB, but the subjects were not told this or given any non-auditory feedback on the gain adjustments. When the subject made a decision a key would take him/her to the next A-B pair.

The order of the 140 stimuli pairs was randomized within and between subjects. The initial level of the sound to match was also randomized from -20 to +20 dB relative to the reference level. All the subjects completed the test in one session ranging from 45 minutes to 80 minutes. The subjects were advised to take a break at the middle of the session, indicated by a counter on the computer screen. This was done to prevent fatigue and unreliable results.

3 Results

3.1 Subject consistency

3.1.1 Left-right bias

The individual results were analyzed in order to exclude inconsistent subjects. The results were first checked for inconsistencies in left-right symmetry within the subject's own results. To perform this analysis, the subjectively adjusted level difference between the centre loudspeaker and the left loudspeaker, and also between the centre loudspeaker and the right loudspeaker, were averaged. These averages were then subtracted which would indicate a bias towards one of the ears. The same was done with the results for the surround channels and the two results averaged. The results for the direct comparison between stereo channels and surround channels were also analyzed. None of the subjects showed a strong bias towards a particular side, therefore no subject was excluded on this basis.

3.1.2 Combined results

Results were analyzed to identify outliers prior to the final analysis. Histograms of the results for each combination of centre to left, centre to right, centre to right surround and centre to left surround were plotted with normal distribution curves. The results tended to follow a normal distribution curve and the outliers were easily identified. The subjects that consistently lay outside the normal distribution curve were excluded. As a result one subject was excluded from the final analysis.

3.2 Results analysis

In this paper, results are collapsed into smaller categories to provide a succinct report of the results, done as follows:

-The results for each pair of loudspeakers were made consistent by reversing the symbol of one of the matches made. For example, the results between the pair C-reference/L-match were matched to the results L-reference/C-match by reversing the sign of the second pair.

-The results for the left and right loudspeakers were averaged as 'stereo' and the results for the left surround and right surround loudspeaker were averaged as 'surround'.

-The results for stereo and surround were averaged.

The results for the centre and averaged stereo channels are shown in Fig. 2 and Table 2.

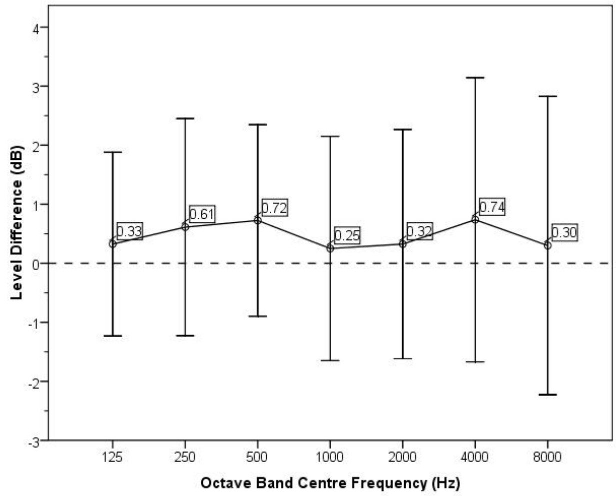

Figure 2. Mean level difference between the centre loudspeaker and stereo loudspeakers. A positive value indicates that subjects are more sensitive to sound arriving from the stereo loudspeakers than the centre loudspeaker. Error bars are ±1 standard deviation.

Frequency (Hz)	NR60 SPL (dB)	Adjusted SPL (dB)	Difference (dB)
125	74	73.68	0.33
250	68	67.39	0.61
500	63	62.28	0.72
1000	60	59.75	0.25
2000	57	56.68	0.32
4000	55	54.26	0.74
8000	54	53.70	0.30

Table 2. Sound pressure level difference between the stereo loudspeakers and the centre loudspeaker for equal loudness. The reference stimulus was presented at NR60. The difference values are plotted in Fig. 2.

The results for the centre and surround channels are presented in Fig. 3 and Table 3.

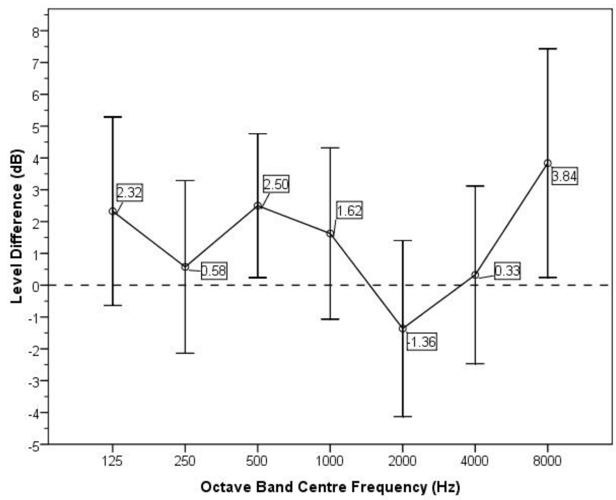

Figure 3. Mean level difference between the centre loudspeaker and surround loudspeakers. A positive value indicates that subjects are more sensitive to sound arriving from the surround loudspeakers than the centre loudspeaker. Note that this was not the case for the 2 kHz band. Error bars are ±1 standard deviation

Frequency (Hz)	NR60 SPL (dB)	Adjusted SPL (dB)	Difference (dB)
125	74	71.67	2.32
250	68	67.42	0.58
500	63	60.50	2.50
1000	60	58.38	1.62
2000	57	58.36	-1.36
4000	55	54.67	0.33
8000	54	50.16	3.84

Table 3. Sound pressure level difference between the surround loudspeakers and the centre loudspeaker for equal loudness. The reference stimulus was presented at NR60. The difference values are plotted in Fig. 3.

3.3 HATS and microphone measurements

Dummy head measurements were made in order to see if the results could be explained by direction-dependent head-related transfer functions (HRTFs). A Bruel & Kjaer 4128C HATS (head and torso simulator) in the listener position was used to record each of the stimuli used in this experiment, as well as impulse responses from each of the five loudspeakers to the HATS microphones. By doing this we could analyze the signals approximately as heard by the subjects. Although the HATS ear is a typical human ear shape, it is not completely interchangeable for an individual analysis.

Figures 4 and 5 illustrate data derived from the impulse responses recorded with the HATS for the centre, right and right surround positions. Rather than showing the HRTFs themselves, they show the level difference in HRTFs for the lateral loudspeakers compared to the HRTF of the centre channel.

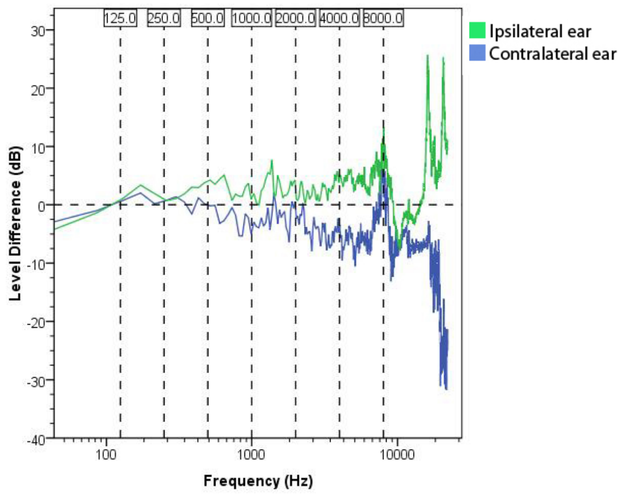

Figure 4. Level difference derived from the impulse responses recorded with the HATS from the centre loudspeaker and the right loudspeaker. A positive value indicates higher level received from the right loudspeaker.

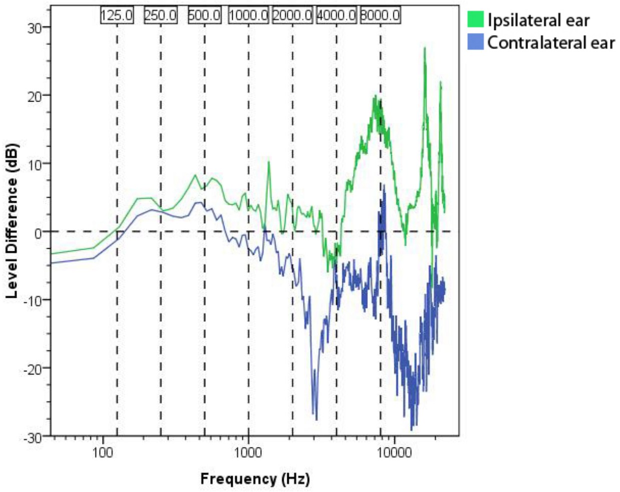

Figure 5. Level difference derived from the impulse responses recorded with the HATS from the centre loudspeaker and the right surround loudspeaker. A positive value indicates higher level received from the right surround loudspeaker.

4 Discussion

The subjectively determined gain differences for equal loudness between the centre and stereo loudspeakers are less than 1 dB for all frequencies, with the maximum difference for the 2000 Hz octave band at 0.74 dB. Nevertheless, all of these values are positive, which indicates greater loudness sensitivity for sound from the stereo loudspeakers than from the centre loudspeaker. We can assume that the sound of equal free field sound pressure level coming from a source located at 30º may sound slightly louder than a sound coming from 0º; but this difference is, according to previous studies, on the threshold of the just noticeable change in amplitude for 1000 Hz tones. [8]. This result is consistent with the previous similar study of loudness sensitivity conducted in a sound studio, for which differences between sensitivity to centre and stereo loudspeakers were not statistically significant [7] (although the method of the present study provides greater power for examining this question than that of the previous study).

Another feature that is apparent in these results is that the differences between the centre and stereo channels vary slightly across the frequency range. Such variation in the results could be caused by the change in direction-dependent HRTFs. Figure 4 lends some insight into this, but it is not clear how the signals at the two ears would combine in making a loudness judgment (various theories exist [e.g., 5, 9], and the authors are currently investigating this in more detail). Considering that the subjective sensitivity differences are considerably smaller than the HRTF differences of the ipsilateral ear, it appears that loudness judgements are made from a combination of ipsilateral and contralateral ears. Figure 6 explores this concept further – rather than showing the HRTF difference, it shows the difference in sound pressure level of the octave band stimuli between centre and stereo loudspeakers, measured using the HATS. The variation across the frequency range for the subjective responses is somewhat similar to the two-ear power sum difference between centre and stereo.

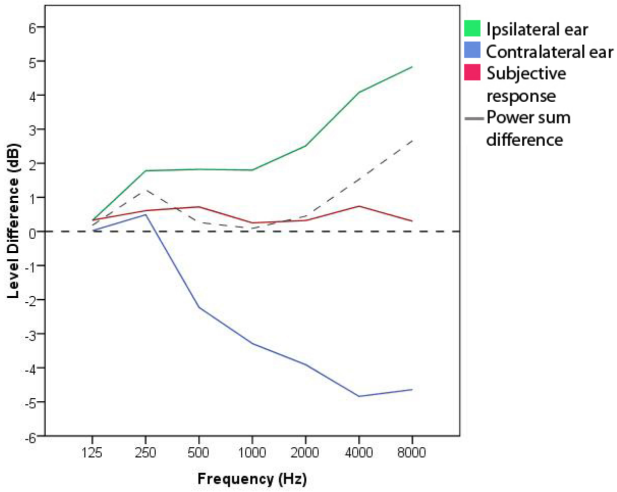

Figure 6. Difference in sound pressure level from the centre to right loudspeaker for the octave band stimuli measured using the HATS, also showing the subjective response from Figure 2.

The subjectively determined gain differences for equal loudness between the centre and surround channels are clearly more pronounced than the differences between the centre and stereo channels. An interesting feature is that the level differences are as high as 3.84 dB for the 8000 Hz octave band, showing a substantial increase in loudness sensitivity for the sound coming from 110º.

An even more interesting feature is the variation in difference across the frequency range – and for the 2000 Hz octave band the frontally incident sound has greater loudness sensitivity than the sound coming from the surround channels. The larger absolute values and greater range of the subjective results for the surround channels might be expected considering the greater level differences in the HRTFs when comparing centre to surround (Figure 5). Figure 7 makes this comparison for the sound pressure levels of the stimuli, recorded on the HATS.

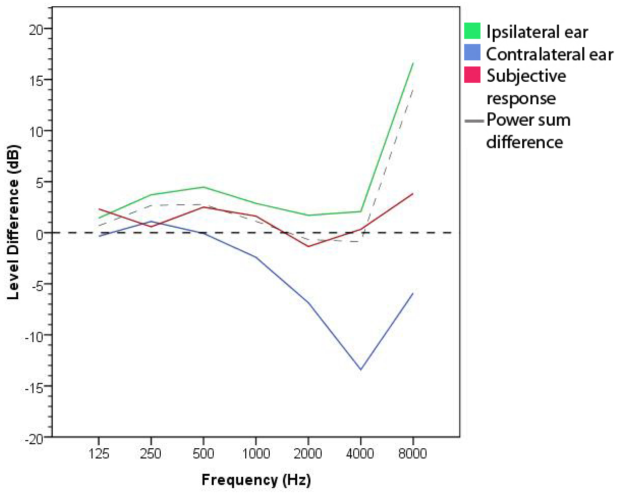

Figure 7. Difference in sound pressure level from the centre to right-surround loudspeaker for the octave band stimuli measured using the HATS, also showing the subjective response from Figure 2.

It might be supposed that the ipsilateral ear would have more influence for an azimuth angle of 110º than 30º, but the results in Figure 7 do not give this notion much support. Instead the subjective results roughly follow the two-ear power sum difference between centre and surround. The reduction in loudness sensitivity for the 2 kHz octave band coincides with a reduction in the HRTF level in this frequency range for the surround loudspeaker, which supports the hypothesis that the HRTF has a primary influence in directional loudness assessment. Even though the results are not directly comparable to previous studies [5] since the angles and stimuli used do not correspond, there are similar results where the stimuli and angles used are similar. In an anechoic directional loudness study [5] and another one done in a reverberant field [2] the subjective results also follow the binaural power sum.

Results for the surround loudspeakers are roughly congruent with the results of the previous experiment conducted in a sound studio [7], as shown in Figure 8. Values are more extreme in the present experiment, but a similar change in loudness sensitivity occurs in the sound studio experiment at 2 kHz. This reduction in the extent of the directional effects when the stimuli are presented in reverberant spaces is concordant with results from previous experiments [2, 5].

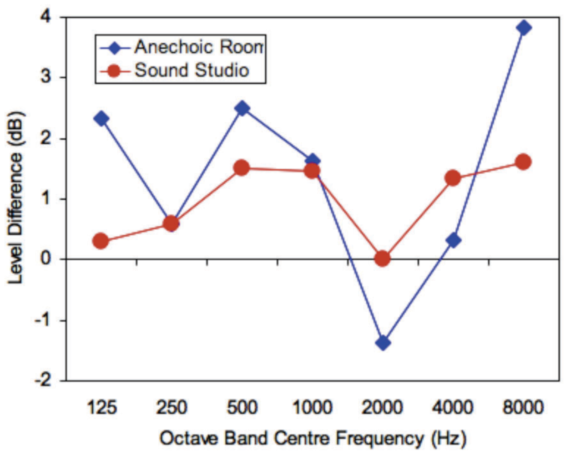

Figure 8. Mean level difference between the centre loudspeaker and surround loudspeakers for the present experiment (anechoic room) and a similar previous experiment conducted in a sound studio [7]. A positive value indicates that subjects are more sensitive to sound arriving from the surround loudspeakers than the centre loudspeaker.

5 Conclusion

This study provides information on directional loudness sensitivity for seven octave bands of pink noise, using loudspeaker azimuth angles that are common in surround sound audio systems. Results could be used in developing systems for loudness monitoring and perhaps tuning of surround sound systems. However, it appears that sensitivity variation is less extreme in non-anechoic room acoustical environments. This study provides a first-order explanation of the results based on the variation of HRTF with azimuth angle.

Acknowledgments

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