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Research on the bandwidth effect on binaural loudness summation on the Cam scale

Shao, Zhiyue [1]
Shanghai Academy of Environmental Sciences
Shanghai Engineering Research Center of urban environmental noise control
508 Qinzhou Road, Shanghai, China

Zhang, Weichen [2]
Shanghai Academy of Environmental Sciences
Shanghai Engineering Research Center of urban environmental noise control
508 Qinzhou Road, Shanghai, China

Zhu, Wenying [3*]
Shanghai Academy of Environmental Sciences
Shanghai Engineering Research Center of urban environmental noise control
508 Qinzhou Road, Shanghai, China

ABSTRACT

Researches have showed that stimulus bandwidth has an effect on binaural loudness summation. Yet there was no systematic research on that. This paper presents a research on binaural loudness summation adopting different stimulus bandwidths on the Cam scale. The loudnesses of dichotic stimuli with interaural level differences (ILDs) of 2-12 dB were matched by those of diotic stimuli at the same bandwidth (reference stimuli). The center frequency of stimuli was 1 kHz and the bandwidths of stimuli were 1-ERB, 3-, and 5-ERBs. Results showed that the wider the stimulus bandwidth, the more slowly the overall loudness increased with ILD. A function describing the characteristic of overall loudness changing with ILD and bandwidth was derived.

Keywords: Binaural loudness summation, Cam scale, Bandwidth
I-INCE Classification of Subject Number: 79

1. INTRODUCTION

Loudness is an important parameter in psychoacoustics, and it is the basis of research on sound quality and noise evaluation. Due to the great value of loudness, there are many researches on it. Stevens[1] proposed a calculation method of loudness, which was adopted as method A of ISO 532: 1975[2]. Based on the characteristic of loudness summation among critical bands, Zwicker[3] also proposed a calculation method of loudness, which was the method B of ISO 532 (1975)[2]. Yet, the two methods could not calculate the

[*] Corresponding author: zhuwy@saes.sh.cn

overall loudness of dichotic sounds. However, dichotic listening conditions are very common in daily life, because sounds at the two ears could hardly be the same.

Moore et al.[4] proposed a calculation method of loudness, which can calculate the loudness at each ear and yield the overall loudness by summing them. Later Moore and Glasberg[5] modified their method by adjust the binaural-to-monaural loudness ratio from 2 to 1.5. In the revised version of ISO 532: 2017[6, 7], Zwicker method[6] was adopted as Part 1, and Moore-Glasberg method[7] was Part 2. Yet Shao et al.[8] found the ratio might not be constant, and it varied across the stimulus bandwidth. The results from Keen[9] also supported the finding. Nevertheless, systematic researches on the effect of stimulus bandwidth on binaural loudness summation were not found. A lot of work is needed to investigate the perception characteristics of binaural loudness summation. As the forms of dichotic sounds are complicated, the condition, in which only the loudness differ at both ears, is relatively simple and usually adopted to explore binaural loudness summation. Shao et al.[8] studied the effect of stimulus bandwidth with the octave scale used. Yet, in the loudness model[7], as the whole audible frequency range was divided by equivalent rectangular bandwidth (ERB), the Cam scale was used. Thus, this paper intended to investigate the bandwidth effect on binaural loudness summation on the Cam scale.

2. LOUDNESS MATCHING EXPERIMENTS

2.1 Apparatus

Experiments were performed in a semi-anechoic chamber with a background noise level of about 25 dB (A). A laptop, a HPS IV equalizer (HEAD Acoustics, Herzogenrath, Germany), and Sennheiser HD 650 headphones constituted a Hi-Fi playback system controlled by the software Artemis (HEAD Acoustics, Herzogenrath, Germany). Before the experiment, the system was calibrated. The results of calibration showed that the deviation between the two channels was lower than 0.3 dB and the deviation of frequency response was lower than 0.5 dB between 0.63 and 1.6 kHz.

2.2 Stimuli

The center frequency of stimuli was 1 kHz. According to the definition of ERB (Equation 1), the upper and lower cutoff frequency could be determined for stimuli with bandwidths of 1-ERB, 3-, and 5-ERBs, which were listed in Table 1. Stimuli were produced by filtering white noise with 6th order Butterworth filters in Artemis.

$$ERB_N = 24.673 * (0.004368 * fc + 1 \text{ Hz}) \quad (1)$$

Table 1: The lower and upper cutoff frequency for 1-ERB, 3-, and 5-ERBs at 1 kHz

	1-ERB		3-ERBs		5-ERBs	
Center frequency (Hz)	Lower frequency (Hz)	Upper frequency (Hz)	Lower frequency (Hz)	Upper frequency (Hz)	Lower frequency (Hz)	Upper frequency (Hz)
1000	934	1066	816	1215	709	1379

For each bandwidth case, a diotic stimulus with a calculated loudness level of 70 phons was generated, which was achieved by codes for Moore-Glasberg method[7] in MATLAB. By increasing levels by 1–6 dB (in 1-dB steps) in the left channel and correspondingly decreasing levels by 1–6 dB in the right channel, the dichotic stimuli were generated with ILDs of 2–12 dB (in 2-dB steps). Then it yielded six test stimuli with different ILDs at the same bandwidth.

The diotic stimuli were used as the reference stimuli to be matched in loudness to the test stimuli with ILDs. The bandwidths of the reference stimuli were the same as those of the corresponding test stimuli, literature showed that it would be easier for subjects to judge. A sequence of diotic stimuli of the same bandwidth as the reference stimuli (and amplified by -2–6 dB in 0.5-dB steps) were generated.

The duration of reference and test stimuli was 5 s, with a 1-s silent interval between them.

2.3 Procedure

Literature showed that 5 to 7 subjects could complete an adaptive loudness matching experiment, so five subjects were recruited, aged 29~39 yr. All of them reported normal hearing. Before the experiments, the subjects were introduced the overall loudness of dichotic stimuli and instructed not to be affected by the position of sound image. All subjects were trained to be familiar with the task.

The level of the first reference stimulus was chosen randomly. If the reference stimulus was judged softer, its level was increased, vice versa. The step size was 2 dB until one reversal had occurred and 1 dB until another reversal had occurred and 0.5 dB thereafter. As the loudness reference stimuli varied very little late in the matching process, subjects were asked to approach the point of equal loudness at least three times, by repeatedly playing back the reference stimuli around the equal loudness point, until they confirmed it. The resulting level was recorded as the diotic loudness match. The six test stimuli at the same bandwidth were presented to subject in a random order, and the procedure above was repeated until the loudness of each test stimulus had been matched. Stimuli were presented to subjects first for the narrower bandwidth, then for the broader bandwidth.

3. RESULTS

3.1 Correlation coefficients

For each bandwidth, correlated coefficient of the results from each subject and the average was calculated and listed in Table 2-4 respectively for the bandwidth of 1-ERB, 3-, and 5-ERBs.

Table 2: Correlated coefficients for bandwidth of 1-ERB at 1 kHz

	ILD/dB						Correlated coefficient
Subjects	2	4	6	8	10	12	
TP1	0.5	2.0	1.5	2.0	3.5	3.5	0.95
TP2	0.0	0.5	1.0	1.5	2.0	2.5	0.98
TP3	0.0	0.0	0.0	1.0	1.5	2.0	0.97
TP4	0.0	0.0	0.5	0.5	2.0	2.5	0.97
TP5	-0.5	-0.5	-0.5	0.0	0.0	0.5	0.93
Average	0.0	0.4	0.5	1.0	1.8	2.2	0.96

Table 3: Correlated coefficients for bandwidth of 3-ERBs at 1 kHz

	ILD/dB						Correlated coefficient
Subjects	2	4	6	8	10	12	
TP1	0.5	1.0	1.0	1.5	2.0	2.0	0.98
TP2	0.5	0.5	1.0	1.0	1.5	2.0	0.94
TP3	0.0	0.5	1.0	1.0	1.5	2.0	0.98
TP4	-1.0	0.0	0.0	1.0	1.5	2.0	0.99
TP5	-0.5	0.0	0.0	0.5	0.5	0.5	0.93
Average	-0.1	0.4	0.6	1.0	1.4	1.7	0.97

Table 4: Correlated coefficients for bandwidth of 5-ERBs at 1 kHz

Subjects	ILD/dB 2	4	6	8	10	12	Correlated coefficient
TP1	0.0	0.5	0.5	1.0	2.0	2.0	0.93
TP2	0.0	0.5	1.0	1.0	1.0	1.5	0.94
TP3	0.0	0.0	0.5	1.0	1.0	1.0	0.94
TP4	0.0	-0.5	0.5	0.5	1.0	1.5	0.93
TP5	-0.5	0.0	0.5	0.5	0.5	1.0	0.94
Average	-0.1	0.1	0.6	0.8	1.1	1.4	0.94

It can be seen that all values are higher than 0.9.

3.2 Effect of stimulus bandwidth and ILD

To analyze the effect of stimulus bandwidth on binaural loudness summation, results of five subjects were averaged. The results of diotic loudness match at three bandwidths are presented in a Figure 1.

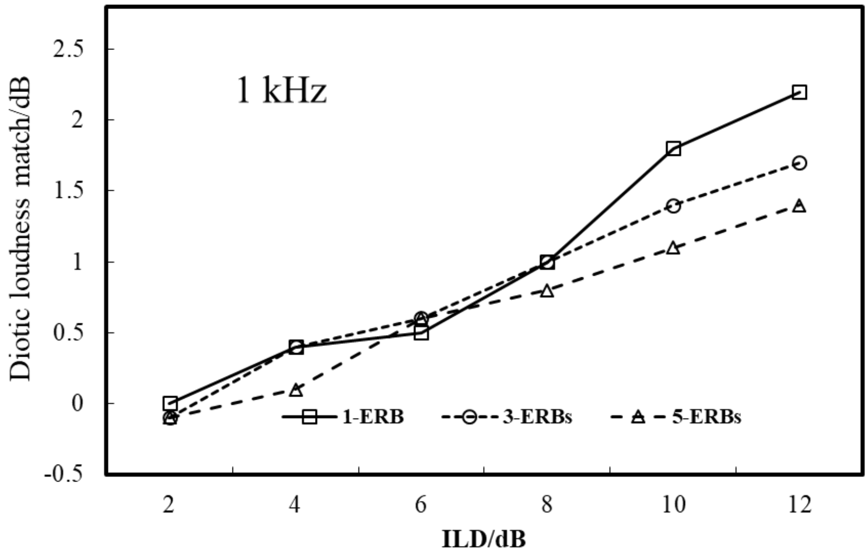

Figure 1: The results of diotic loudness match at three bandwidths

Figure 1 showed that for each bandwidth case, diotic loudness match increased nonlinearly with ILD, yet the increasing trends differed. The broader the stimulus bandwidth, the lower the increasing rate of diotic loudness match. The results were subjected to a within-subjects analysis of variance (ANOVA) with factors bandwidth, and ILD. The effect of bandwidth was not significant [$F(2,8) = 1.32$; p=0.320], and the effect of ILD was significant [$F(5,20) = 38.55$; $p<0.001$]. Although the result of ANOVA showed that the effect of stimulus bandwidth was not significant, from Figure 1 it could be seen clearly that the increasing trends of three curves were obviously different.

4. DISCUSSION

The correlated coefficients are all higher than 0.9, while for bandwidths of 1-ERB and 3-ERBs the standard deviations of the results at ILD 12 dB are 1.0 and 0.6, which were a bit high. This was because that the results of TP5 were obviously lower than those of other subjects. Thus, if results of the other four subjects were subjected to a within-subjects analysis of variance (ANOVA) with factors bandwidth, and ILD. The effect of bandwidth was almost significant [$F(2,6) = 4.31$; p=0. 069].

With results of TP1-4 adopted, a characteristic function were derived by curve fitting performed in MATLAB. The resulting characteristic function is

$$Dlm = 2.25 * (e^{ILD/12} -1) * (W + 1)^{-(1/2)} \text{ (dB)} \quad (2)$$

where Dlm is the diotic loudness match, ILD is the interaural level difference, and W is the factor representing the effect of bandwidth. If the bandwidth of stimuli is 3-ERBs, W is 3.

Figure 2 showed the comparison between experimental results and characteristic function predictions. The predictions of function basically agree well with the experimental results.

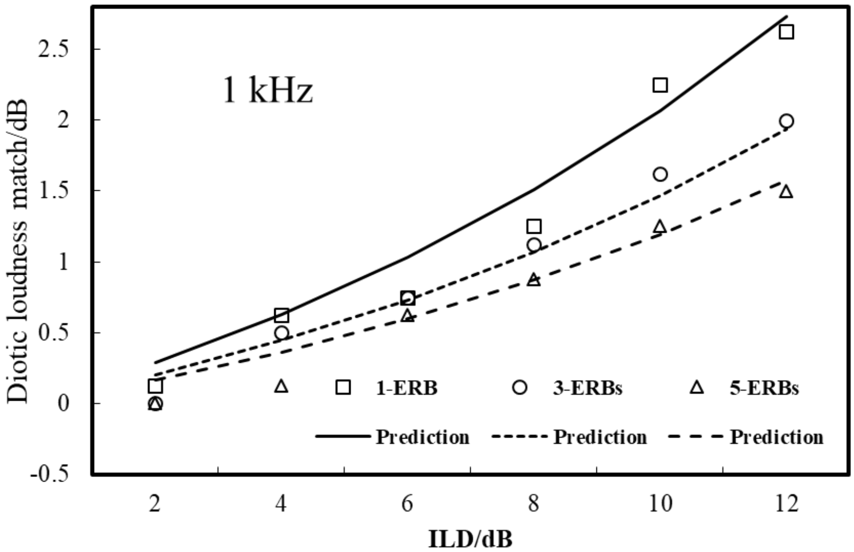

Figure 2: Comparison between experimental results (symbols) and characteristic function predictions (lines)

5. CONCLUSIONS

Loudness matching of diotic stimuli and stimuli with ILDs was performed using different stimulus bandwidths on the Cam scale. ANOVA showed that the effect of bandwidth on binaural loudness summation was not significant, yet the trends of overall loudness changing with ILD were different across stimulus bandwidth. The results were similar with previous research[8]. A characteristic function representing diotic loudness match changing with ILD has been derived, which could basically predict the subjective results.

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