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Study of perceptual balance for designing comb filters for binaural dichotic presentation

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ABSTRACT

Earlier studies on binaural dichotic presentation by spectral splitting of speech signal using a pair of complementary comb filters, for improving speech perception by persons with moderate bilateral sensorineural hearing loss, have shown mixed results: from no advantage to improvements in recognition scores corresponding to an SNR advantage of 2 - 9 dB. The filters used in these studies had different bandwidths and realizations. For an optimal performance of the scheme, the perceived loudness of different spectral components in the speech signal should be balanced, especially for components in transition bands which get presented to both the ears. For selecting magnitude responses of such filters, we have investigated the relationship between the signal amplitudes for binaural presentation of a tone to evoke the same loudness as that of monaural presentation. Listening tests were conducted, on eight normal-hearing subjects, for comparing the perceived loudness of monaural presentations to that of the binaural presentation with different combination of amplitudes for the tones presented to the left and right ears, at 250 Hz, 500 Hz, 1 kHz, and 2 kHz. The sum of the amplitudes of the left and right tones in binaural presentation being equal to that of the monaural tone resulted in monaural-binaural loudness match, indicating that the magnitude response of the comb filters used for dichotic presentation should be complementary on a linear scale. An analysis of the magnitude responses of the comb filters used in earlier studies showed large deviations from the perceptual balance requirement, and those with smaller deviations were more effective in improving speech perception. A pair of comb filters, based on auditory critical bandwidths and magnitude responses closely satisfying the requirement for perceptual balance, was designed as 512-coefficient linear phase FIR filters for sampling frequency of 10 kHz. Listening tests on six normal-hearing subjects showed improvements in the consonant recognition scores corresponding to an SNR advantage of approximately 12 dB. Tests using 11 subjects with moderate bilateral sensorineural hearing loss showed an improvement in the recognition score in the range 14 - 31 %. Thus the investigations showed that binaural dichotic presentation using comb filters designed for perceptual balance resulted in better speech perception.

INTRODUCTION

Several investigations have been reported on binaural dichotic presentation, by splitting the speech signal using a pair of comb filters with complementary magnitude responses, for improving speech perception by persons with moderate bilateral sensorineural hearing loss [1 – 6]. In this scheme, alternate bands are presented to left and right ears. These studies have shown mixed results: from no advantage to improvements in recognition scores corresponding to an SNR advantage of 2 - 9 dB. All the filters used in these studies have linear phase responses. The variations in the results reported may be because of differences in the magnitude responses. The comb filters for spectral splitting should have a small ripple in the pass bands and a large attenuation in the stop band. As filters have finite transition bands between pass and stop bands, the spectral components of the speech signal in the transition bands are presented to both the ears. For an optimal performance of the scheme, the perceived loudness of different spectral components in the speech signal should be balanced, especially for components in the transition bands. Therefore the two filters should have magnitude responses such that perceived loudness for spectral components in the transition bands is same as that in the pass bands.

The objective of the investigation presented in this paper is to study the perceptual balance in binaural hearing, i.e., finding a relationship between the signal amplitudes in the left and the right ear in binaural presentation which will evoke the same loudness as a monaural presentation. Responses of the comb filters used by different researchers are examined for the rquirement of perceptual balance. A pair of comb filters, based on auditory critical bandwidths and magnitude responses closely satisfying the requirement for perceptual balnce, was designed. It was evaluated for improving the speech perception by persons with normal-hearing in the presence of broad-band masking noise and by persons with moderate bilateral sensorineural hearing loss.

LOUDNESS OF BINAURAL PRESENTATION

Several studies comparing the loudness of binaural and monaural sounds have been reported [7 – 14]. A study by Scharf [7] reported the binaural level difference for equal loudness (BLDEL) to be about 5 dB at low presentation levels, 7 dB at moderate presentation levels, and about 6 dB at high presentation levels. In another study by Scharf [8], involving dichotic presentation of two tones, the subjects perceived two distinct auditory images. There was no change in the perceived loudness for the tones, when the frequency separation between the tones presented to the two ears was varied over a wide frequency range. In the investigation by Hall and Harvey [9] involving presentation of 2 kHz pure tone at 70 and 80 dB SPL, the BLDEL was found to be 3 – 4 dB for hearing-impaired subjects and 8 – 9 dB for normal-hearing subjects. For 2 kHz tone, at 90 dB, both the groups had BLDEL of about 9 dB. For tone of 500 Hz, presented at the three levels, the BLDEL was about 9 dB for both the groups. In a study by Hawkins et al. [10] using 4 kHz pure tone with a presentation level ranging within listener's most comfortable level to the discomfort level, the BLDEL for impaired listeners was in the range of 5 – 12 dB and it was not significantly different from that for listeners with normal hearing.

Zwicker and Henning [11] conducted listening tests to match the loudness of monaurally and binaurally presented tone bursts. The presentation consisted of four binaural bursts of 60 ms each alternating with four similar bursts presented monaurally. The subjects were asked to adjust the level of one type of bursts to match the perceived loudness of the other type. The test tones were of frequency 250 Hz, 710 Hz, and 2 kHz. The binaural presentation had same intensity in both the ears. An increment of 10 dB was needed for the monaural sound to match the perceived loudness of the binaural sound. This difference was almost the same across the three test frequencies and presentation levels. Similar experiment was conducted by adding the stimuli to low pass filtered noise with cutoff frequency of 840 Hz, 1.5 kHz, and 4 kHz for the test tone of 250 Hz, 710 Hz, and 2 kHz respectively. The stimuli were added with (i) in-phase noise and (ii) out-of- phase noise and then presented binaurally with varying inter-aural phase difference. For both the noise conditions, the inter-aural phase difference had a significant effect on perceived loudness for 250 Hz, a moderate effect for 710 Hz, and minimal effect for 2 kHz tone bursts.

Cheeran [12] conducted listening tests to find the difference in levels of monaural and binaural presentations, such that they evoke the same perceived loudness. The stimuli used were four pure tones (0.25, 1, 2, and 4 kHz) of 1 s duration each, sustained vowel /a/, and broad-band noise. Five normal-hearing subjects participated in the listening tests. The stimulus was presented monaurally and binaurally, one after the other, with an inter-stimulus interval of 1 s. The monaural intensity was fixed at 85 dB and binaural intensity was varied in the range 70 – 84 dB. The task of the subject was to mark each binaural sound as "high", "same", or "low" depending on the perceived loudness with respect to the monaural sound. This procedure was repeated for different binaural levels. The results showed that the perceived loudness matched when binaural level was 4 – 12 dB lower than the monaural level. Whilby et al. [13] investigated BLDEL for normal and hearing-impaired listeners using 1 kHz pure tone of 5 ms and 200 ms duration. They used loudness matching procedure: (1) monaural level was fixed and binaural level was varied and (2) binaural level was fixed and monaural level was varied for equal loudness. The fixed level ranged from 10 to 90 dB SL. Their study showed that BLDEL for normal-hearing subjects ranged from 2 to 15 dB, and for hearing-impaired listeners it was 1.5 to 12 dB.

Marks [14] investigated binaural summation of loudness using pure tone stimuli of frequency 0.1, 0.4, and 1 kHz. A set of nine SPLs were used for left and right ears resulting in a total of 81 combinations of binaural stimuli. Fourteen normal-hearing subjects participated in the test for estimation of perceived loudness. The study showed a linear additivity of the numerical responses for loudness, for all the test tone frequencies. In the same study [14], an experiment was conducted to obtain a set of equal loudness curves at four presentation levels, using 1 kHz test tone for finding various combinations of sound pressure levels to the left and right ears that produced a given level of loudness. The standard tone was presented binaurally, with equal intensity in both the ears, at the four presentation levels of 20, 30, 40, or 50 dB SPL. The variable tone was also binaural, set to give a fixed intensity ratio at the two ears. However, in every match, subjects controlled the absolute levels of the left or the right ear components. During matching process, the stimulus sequence was continuous: the standard tone of 1 s duration, 1 s of silence, variable tone of 1s duration, 1 s of silence and so on. The subject matched the loudness of the variable tone, by controlling either the left or right ear components, to that of the standard tone. Three normal-hearing subjects participated in the listening test. A plot of equal loudness curves were obtained for four presentation levels of the standard tone. The shape of the curves for different presentation level was the same with a small inter-subject variation. It was obsereved that a monaural sound needed to be 5 – 7 dB above the binaural sound for it to evoke same loudness as that of binaural.

The main objective of most of these studies was to find BLDEL, for different stimuli and presentation levels, for normal-hearing and hearing-impaired listeners. However, for the design of comb filters with perceptually balanced response in the transition band, we need to know the relation between the gains of the two filters (for left and right ears) such that there are no irregular variations in the perceived loudness of spectral components in the transition bands. The aim of our investigation is to study the relation between the two amplitude scaling factors for binaural presentation which will result in a match of the loudness of the binaural presentation to that of the monaural presentation.

METHODOLOGY

The listening tests were conducted for obtaining the relation between the two amplitude scaling factors, for the left and the right ears, so that the binaural presentation evokes the same loudness as the monaural presentation. As shown in Fig. 1, the input signal was scaled by scaling factor α for the left ear and by β for the right ear for presentation through a pair of headphones.

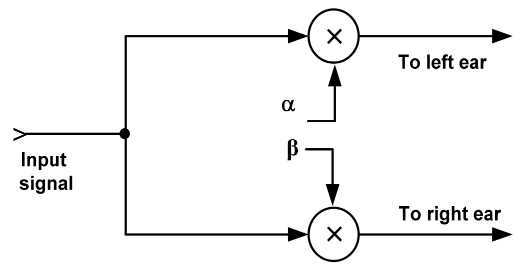

Figure 1. Scheme for perceptual balance test

Signal amplitudes were scaled to compensate for any unbalance in the response of the two headphones at the test tone frequencies. The values of α and β were in the range from 0 to 1, with an increment of 0.1. The overall investigation involved two experiments. In the first experiment (Exp. I), perceptual balance was investigated for pure tones of frequencies 250 Hz, 500 Hz, 1 kHz and 2 kHz, presented at the most comfortable level (MCL) for the individual listener. The second experiment (Exp. II) was conducted to examine the effect of presentation level on perceptual balance. The test involved tone of 500 Hz presented at three presentation levels: MCL – 6 dB, MCL, and MCL + 6 dB.

The listening tests were conducted using three-interval, three-alternative forced choice (3I, 3AFC) paradigm [21]. Each presentation had three observation intervals: reference (monaural), test (binaural), and reference (monaural), separated by 0.5 s silences. Depending on whether the perceived loudness of the binaural sound was lower than, equal to, or higher than that of the monaural sound, the subject marked the response as L, E, or H on the response sheet. The subject could listen to the sounds more than once before finalizing the response. Combinations of α and β in binaural presentation were selected randomly.

In Exp. I, there were a total of 484 presentations for each subject: 4 test frequencies × 11 values of α × 11 values of β. A total of eight normal-hearing subjects participated in the listening tests. In Exp. II, there were a total of 363 presentations for each subject: 3 presentation levels × 11 values of α × 11 values of β. These tests were conducted on six normal-hearing subjects. In both the experiments, a mean of values of β which correspond to a monaural-binaural loudness balance was calculated, for each value of α.

RESULTS AND DISCUSSION

The results of Exp. I are summarized in Table 1. For each α, it gives the β values, averaged across the eight subjects for perceptual balance, for the four frequencies.The standard deviations, given in parentheses, are found to be small, indicating only a small inter-subject variation in the β values. Figure 2 shows a plot of values of β vs. α, obtained for perceptual balance. For all the four frequencies, the plots indicate an approximately linear relationship.

The results of Exp. II are summarized in Table 2. It gives the β values for perceptual balance, for three presentation levels: MCL – 6 dB, MCL, and MCL + 6 dB for 500 Hz tones. The standard deviations given in parentheses are similer to those in Exp. I. Figure 3 gives a plot of values of α vs. β, obtained for perceptual balance. For all the three presentation levels, the plots indicate an approximately linear relationship.

A plot of scaling factors on dB scale, for all the tone frequencies and the three presentation levels, is shown in Fig. 4. The shape of the curves for loudness balance is similar to those reported in the study by Marks [14].

Earlier studies have shown that loudness generally grows as a power function of sound pressure [15 – 18]. Assuming that the loudness of binaural sound is a power law summation of the two individual sounds [4, 19, 20], the scaling factors α and β should have following relationship for perceptual balance,

$$(\alpha)^{p} + (\beta)^{p} = 1 \qquad (1)$$

where, p is the power relating amplitude to the loudness.

Table 1. Exp. I: Mean values of β, obtained for perceptual balance, for four test tone frequencies, (s. d. in parentheses, n = 8). Level = MCL.

α	Frequency (kHz)			
	0.25	0.5	1.0	2.0
0.0	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
0.1	0.91 (0.04)	0.89 (0.06)	0.89 (0.08)	0.91 (0.05)
0.2	0.86 (0.05)	0.83 (0.08)	0.82 (0.08)	0.78 (0.07)
0.3	0.76 (0.07)	0.71 (0.07)	0.76 (0.07)	0.70 (0.11)
0.4	0.63 (0.08)	0.57 (0.09)	0.64 (0.09)	0.61 (0.12)
0.5	0.46 (0.09)	0.45 (0.06)	0.55 (0.10)	0.50 (0.12)
0.6	0.37 (0.07)	0.40 (0.09)	0.45 (0.11)	0.41 (0.15)
0.7	0.29 (0.10)	0.27 (0.06)	0.36 (0.14)	0.28 (0.11)
0.8	0.20 (0.06)	0.20 (0.06)	0.21 (0.09)	0.19 (0.09)
0.9	0.13 (0.04)	0.09 (0.03)	0.11 (0.06)	0.12 (0.08)
1.0	0.10 (0.03)	0.08 (0.03)	0.06 (0.05)	0.07 (0.06)

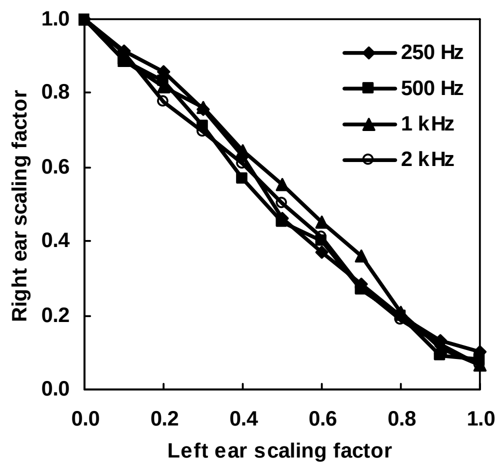

Figure 2. Exp. I: Relation between the two scaling factors α and β for perceptual balance, for four test tone frequencies. Level: MCL.

Table 2. Exp. II: Mean values of β, obtained for perceptual balance, for three presentation levels, test tone frequency: 500 Hz, (s.d. in parentheses, n = 6).

α	Presentation level		
	MCL – 6 dB	MCL	MCL + 6 dB
0.0	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
0.1	0.88 (0.08)	0.91 (0.06)	0.91 (0.07)
0.2	0.78 (0.06)	0.83 (0.10)	0.85 (0.08)
0.3	0.65 (0.06)	0.72 (0.08)	0.70 (0.10)
0.4	0.59 (0.11)	0.58 (0.10)	0.59 (0.07)
0.5	0.48 (0.13)	0.46 (0.06)	0.48 (0.05)
0.6	0.30 (0.13)	0.41 (0.10)	0.36 (0.11)
0.7	0.19 (0.10)	0.26 (0.07)	0.23 (0.06)
0.8	0.06 (0.06)	0.20 (0.07)	0.04 (0.04)
0.9	0.02 (0.03)	0.10 (0.03)	0.02 (0.03)
1.0	0.00 (0.00)	0.09 (0.02)	0.02 (0.03)

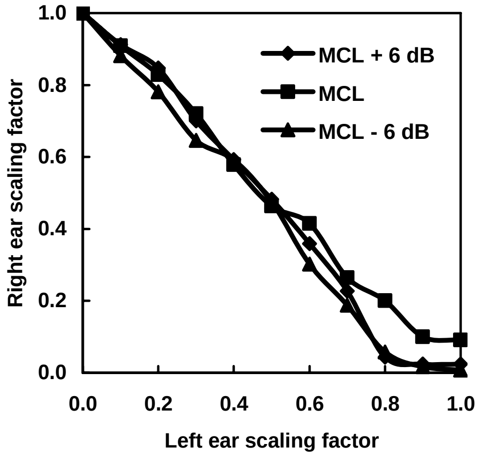

Figure 3. Exp. II Relation between the two scaling factors α and β on for perceptual balance, for three presentation levels taking MCL as the reference, tone frequency = 500 Hz.

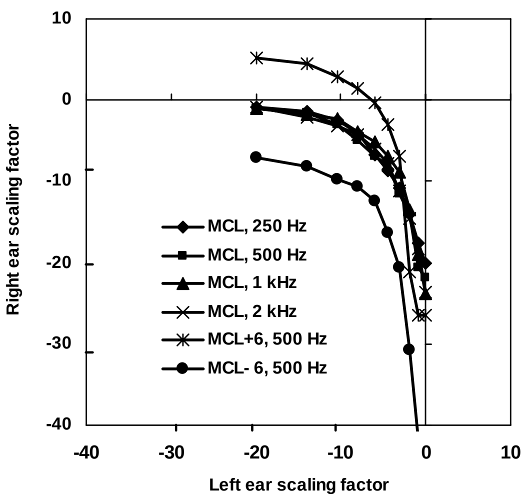

Figure 4. Relation between the two scaling factors (α and β) on dB scale, for perceptual balance, for three presentation levels and four frequencies.

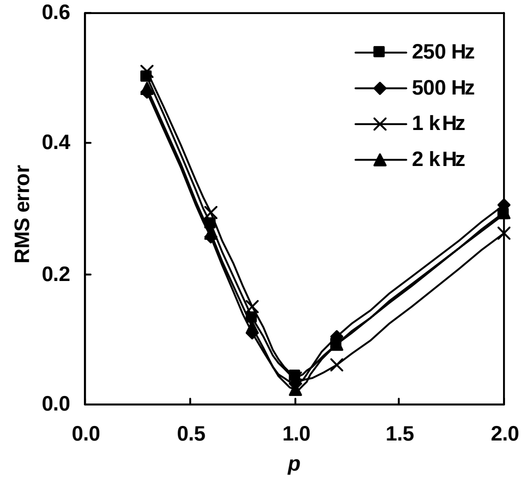

Figure 5. RMS error in approximation of β as computed from Eqn. 1 shown as a function of *p*.

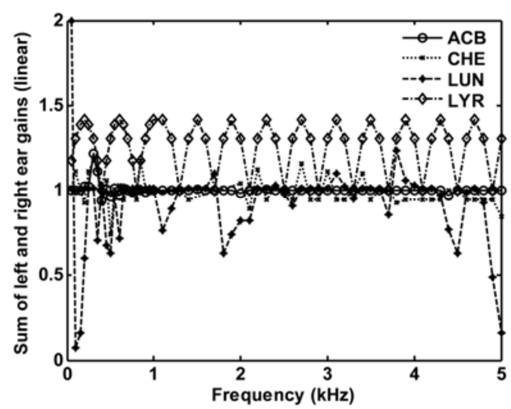

Figure 6. Sum of the left and right ear gains ($G_l(f) + G_r(f)$) for different comb filters used for spectral splitting. ACB: filters based on auditory critical bandwidth and designed with perceptually balanced responses, CHE: filters used by Cheeran and Pandey [4], LUN: Lunner et al. [2] LYR: Lyregaard [1].

To find an approximate fit to the observed values of β, its values were computed for different values of *p* (0.3, 0.6, 0.8, 1.0, 1.2, and 2), from Eqn. 1. Figure 5 shows the RMS error, in the approximation of β using the power law addition model, as a function of *p*. For all the four frequencies, minimum error was observed for $p \approx 1$, indicating that perceptual balance is achieved by $\alpha + \beta \approx 1$.

Various ranges for the BLDEL have been reported in the earlier investigations: 5 – 7 dB [8], 8 – 9 dB [9], 5 – 12 dB [10], 4 – 12 dB [12], and 2 – 15 dB [13]. In the current investigation, perceptual balance is obtained for the binaural sound when the two amplitude scaling factors are nearly linearly related which means a BLDEL of about 6 dB. Thus, the BLDEL obtained in the current investigation nearly falls in the middle of the various ranges of BLDEL reported in the previous investigations.

A pair of comb filters based on the auditory critical bandwidth (ACB) and magnitude responses closely satisfying the requirement of perceptual balance were designed as 512-coefficient linear phase FIR filters, at sampling frequency of 10 kHz, with pass band ripple less than 1 dB and minimum stop band attenuation of 30 dB. The magnitude responses of the comb filters used in earlier studies [1, 2, 4] and ACB filters based on perceptual balance were examined for the condition of magnitude responses being complementary on a linear scale. Figure 6 shows a plot of sum of the filter gains, as a function of frequency, for pairs of comb filters as reported earlier by Lyregaard [1], Lunner et al. [2], Cheeran and Pandey [4], along with the ACB filters used in the present investigation. It is observed that the filters used in the current study have much smaller deviations from the condition for perceptual balance as compaired to other filters. Hence these are not likely to introduce any perceptual imbalance due to dichotic presentation.

The effectiveness of spectral splitting scheme based on auditory critical bandwidth (ACB) filters was assessed by conducting listening tests, for recognition of consonants, using modified rhyme test (MRT), on six subjects with nornal-hearing in the presence of broad-band masking noise. At 75

% recognition score, improvement in the recognition scores corresponding to an SNR advantage of 12 dB was observed. Listening tests conducted on 11 subjects with moderate bilateral sensorineural hearing loss showed improvement in the recognition scores in the range 14 – 31 %. Processing reduced the response time for both the group of subjects (0.04 - 0.33 s for normal-hearing subjects and 0.04 - 0.57 s for hearing-impaired subjects), indicating a reduced load on perception process.

CONCLUSIONS

The comb filters used in spectral splitting, for binaural dichotic presentation to improve speech perception by persons with moderate bilateral sensorineural loss, should have perceptually balanced magnitude responses. The objective of the present study was to investigate the relationship between the two signal amplitudes in binaural presentation which will evoke the same loudness as the monaural presentation. Listening tests conducted with 250 Hz, 500 Hz, 1 kHz, and 2 kHz pure tones, showed that the sum of the two amplitude scaling factors, should be approximately constant, indicating that the magnitude responses of the comb filters should be complementary on a linear scale. An examination of magnitude responses of the comb filters used in the earlier studies showed a large deviation from the requirement for perceptual balance. A set of comb filters with linear phase responses and magnitude responses nearly complementary on a linear scale was designed, and its effectiveness in improving the speech perception, was assessed by conducting modified rhyme test (MRT) on normal-hearing subjects in the presence of broad-band masking noise and on subjects with moderate bilateral sensorineural hearing loss. These tests showed a significant improvement in speech perception for both the groups of subjects.

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