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Perception of binaural tonal components in noise

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ABSTRACT

Audible tonal components in a stimulus often have a detrimental effect on the perceived quality of the sound, i.e., they are more annoying than sounds without these components. Since many technical sounds contain audible tonal components, it is important to characterise the perceived magnitude of the tonal portion of the sound. Tonal components are only audible if their levels are above their masked thresholds. Masked thresholds can be lowered by introducing interaural disparities. This could occur if the tonal sounds originate from a different location in space than the noise. Also an increase in number of tonal components can lower masked thresholds. The present study investigates how these parameters affect suprathreshold perception. This perceived magnitude of the tonal portion is quantified by measuring the partial loudness of the tonal portion of the sound. Apart from pure tones also complex tones with up to four components were considered. The tonal portion was either diotic or dichotic (phase difference of π). Both stimulus parameters (interaural phase and number of components) have a considerable impact on the perceived magnitude of the tonal portion. It remains to be investigated if this higher perceived magnitude also leads to a higher annoyance of the sounds.

Keywords: Tone perception, Loudness, binaural, complex tones, noise evaluation
I-INCE Classification of Subject Number: 61, 69

1. INTRODUCTION

In our urban environment, we are constantly surrounded by sounds from different sound sources. Some of these sources, such as machinery with rotating parts, can emit tonal components in noise, which have a negative impact on the perceived quality of the sound. Several standards on noise evaluation consider this higher annoyance of stimuli with tonal portions than those without tonal portions (ISO 1996-2 [1], DIN45681 [2], ANSI S1.13 [3], IEC61400-11 [4]). A common approach is to quantify the perception of the tonal component by calculating the difference between the level associated with the tonal portion and that of the noise background. It is also common that this level difference is related to the masked threshold of a pure tone in noise, since only audible components should adversely affect the perception of the stimulus.

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However, the threshold values used by the standards do not take into account that thresholds depend on interaural parameters and number of tonal components. Changing the interaural phase of a pure tone emdedded in diotic noise from 0 (diotic) to 180° (dichotic) can reduce thresholds by more than 10 dB (e.g., van de Par and Kohlrausch [5]). Increasing the number of components of a (complex) tone in noise can lower thresholds by about 1.5 dB per doubling according to Green [6].

This is also observed at suprathreshold levels. For example, Vormann [7] measured the perceived strength of the tonal portion in noise for complex tones and found that this perceived strength increases as the number of components increases. He argued that this may be due to spectral loudness summation. Different terms have been used for the perceived strength of the tonal portion, such as tonality, tonalness or magnitude of tonal content (see Hansen et al. [8], for a review). The problem is that listeners are unfamiliar with these terms or they associate them with other meanings than the perceived strength of the tonal portion in noise. Several studies have, however, shown that the partial loudness of the tonal portion of the stimulus is highly correlated with tonalness (Hansen and Weber [9], Verhey and Heise [10], Badel et al. [11]). Thus this study uses this sensation in the experiments to quantify the tonalness of the sound.

The study investigates the perceived strength of the tonal component for diotic and dichotic tonal portions which either consisted of one, two or four sinusoids. The perceived strength of the tonal component is quantified by a matching experiment with a diotic pure-tone at a given level embedded in noise. This reference was used since it is a sound that is well captured by the current standards.

2. METHODS

2.1 Listeners

Five normal-hearing listeners aged between 21 and 34 years (average 26 years) participated in the experiment. Four were males and one was a female participant. All were experts in the field, i.e., had prior knowledge about psychoacoustic experiments and the meaning of the sensation that was measured in the experiment. Their audiometric thresholds were 15 dB HL or better in the relevant frequency range up to 2 kHz.

2.2 Apparatus

Listeners were seated in a double walled sound-attenuating booth**.** Stimuli were generated digitally in Matlab, converted to analogue signals (RME Fireface UC), and presented to the listener via Sennheiser HDA200 headphones. The headphones were free-field equalised according to ISO389-8. For the response of the listeners a keyboard was provided. A screen in front of the listener indicated which interval was presented and for the threshold measurement, feedback whether the response was correct or not was provided on the screen.

2.3 Stimuli

The stimuli were 500 ms long, including 50-ms raised-cosine ramps at stimulus on- and offset. Each stimulus contained a noise. The noise was a bandlimited uniform exciting noise with a lower cut-off frequency of 87.5 Hz and an upper cut-off frequency of 5600 Hz. The overall level of the noise was 60 dB SPL. Some stimuli also contained a tonal portion, which was either a pure tone or a complex tone. Pure-tone frequencies were 175, 350, 700 and 1400 Hz. The complex tones consisted either of two frequencies, 350 and 700 Hz, or of the four pure-tone frequencies. Different levels of the tonal portions were used (see Procedure). The tonal portion was either presented with the same starting phase at the two ears (i.e., was diotic, S_0) or with an interaural phase difference of 180° (i.e., was dichotic, S_π). The noise was always presented diotically (N_0).

2.4 Procedure

The experiment consisted of three parts. In the first part of the experiment, thresholds of the four pure-tones were measured using a three-interval, three-alternative forced choice procedure. All intervals of a trial contained the noise and one randomly chosen interval also contained a pure tone. The listener's task was to indicate the interval with the pure tone. The initial level of the pure tone was 63 dB SPL, i.e., the signal was well audible at the beginning of the experimental run. The level of the pure tone was varied adaptively according to the listener's response. After two correct responses the level was decreased and after one false response it was increased. The initial step size was 6 dB; it was reduced to 3 dB after first upper reversal (i.e., a false response followed by two correct responses) and to 1 dB after the second upper reversal. The run continued with this minimum step size for six reversal. The mean of the levels at these six reversal was taken as an estimate of the level at threshold. The run was repeated three times. The mean of the threshold estimates of these three runs was taken as the final threshold estimate. Threshold runs for the four pure-tone frequencies with two interaural conditions were randomized.

In the second part of the experiment, thresholds were measured for the complex tones. The level of each component of the complex tones was adjusted to the individual pure-tone threshold with the corresponding interaural phase, i.e., for a diotic complex diotic pure-tone thresholds were used and for a dichotic complex the dichotic pure-tone thresholds were used. The initial level of the 700-Hz component of the complex tone was 63 dB. The procedure to estimate thresholds was the same as used for the estimation of the pure-tone thresholds.

In the third part of the experiment, the level at equal loudness of the tonal portion of the stimulus was measured with a two-interval, two-alternative forced choice procedure. One randomly chosen interval of a trial contained the reference sound, i.e., a diotic 700-Hz pure tone embedded in the noise. The level of the pure tone was either 5, 13 or 21 dB above the individual masked threshold of the listener for this frequency as measured in the first part of the experiment. The other interval contained the test sound, i.e., the noise and one of the tonal portions that were used in the first two parts of the experiment. The initial level above threshold of the 700-Hz component of the test sound was either equal to the level above threshold of the reference sound or was 10 dB higher than that of the reference sound. The level was varied adaptively according to the listener's response. The level was decreased if the listener indicated that the tonal portion of the test signal was louder than that of reference sound; it was increased if the tonal portion of the reference sound was louder than that of the test sound. The initial step size was 8 dB. It was reduced to 4 dB after the first upper reversal and to 2 dB after the second upper reversal. The run continued with this minimum step size for four reversals. The mean level at these last four reversal was taken as an estimate of the level at equal loudness. The mean of the estimates of these two runs was taken as the final estimate of the level at equal loudness. For each number of components of the test signal, the tracks for all combinations of levels of the tonal portion of the reference, the two interaural conditions and the two starting levels were interleaved.

3. RESULTS AND DISCUSSION

3.1 Thresholds

Table 1 shows thresholds for all stimuli that were used in the experiment.

Table 1: Levels in dB SPL of the tonal components at threshold for the diotic (second row) and dichotic (third row) conditions. For the complex tones (sixth and seventh columns), the level of the 700-Hz component at threshold is shown.

Binaural condition	Frequencies in Hz					
	175	350	700	1400	350,700	175,350, 700,1400
S_0N_0	40	41	42	42	41	39
$S_\pi N_0$	28	27	30	34	29	28

Masked thresholds for the diotic pure tones in the presence of a uniform exciting noise hardly change with frequency. For the complex tone with four components, the threshold is 3 dB lower than that of the 700-Hz pure tone. This agrees with previous studies (e.g., Buus et al. [12]). It is in agreement with the hypothesis that information is integrated across critical bands (Green [6]). According to this hypothesis thresholds decrease by about 1.5 dB per doubling of the number of components. Dichotic thresholds are about the same for the two lowest pure-tone frequencies and increase towards higher frequencies, resulting in a decrease in binaural masking level difference as the frequencies increase from 350 Hz to 1400 Hz. This finding agrees with previous results in the literature on the effect of target frequency on the binaural masking level difference for broadband noise maskers (van de Par and Kohlrausch [5], Nitschmann and Verhey [13]). Also for the dichotic condition, thresholds tend to decrease as the number of components increases. The decrease is almost as large as for the diotic condition.

The results show that both stimulus parameters (number of components and interaural phase) can reduce levels at threshold when expressed as the level of one component. This is not considered in current standards on the perception of tonal components in noise.

3.2 Partial loudness of the tonal portion

Figure 1 shows the differences between the level of the tonal portion of the reference sound and that of the test sound at equal loudness of the tonal portion. The level of the 700-Hz reference tone was either 5, 13 or 21 dB above masked threshold, as indicated on the abscissa. Each symbol indicates results of a specific combination of spectral characteristics and binaural condition of the tonal portion of the test signal (see legend in the top portion of the figure). Error bars indicate interindividual standard errors. Results are shown as a function of the level of the tonal portion of the reference sound. Data points for different conditions are slightly shifted against each other to improve the readability of the figure.

As expected, the level difference is close to 0 dB when the spectral characteristics and interaural phase (diotic) of the tonal portion are the same for reference and test signal (open circles). For the diotic condition, adding a second component (open squares) increases the level difference by 5 to 6 dB, irrespective of the level of the pure tone in the reference sound. An increase of 3 dB was expected on the basis of the total energy of the complex tone above threshold. That the increase is larger than 3 dB is due to spectral loudness summation of the tonal components, which is also observed under masking (Scharf [14]). The level difference is further increased if the tonal portion of the test sound consists of four diotically presented sinusoids (open diamonds), as expected. As for the two-tone complex, the level of the tonal portion of the reference sound hardly affects the level difference at equal loudness of the tonal portion of the sounds.

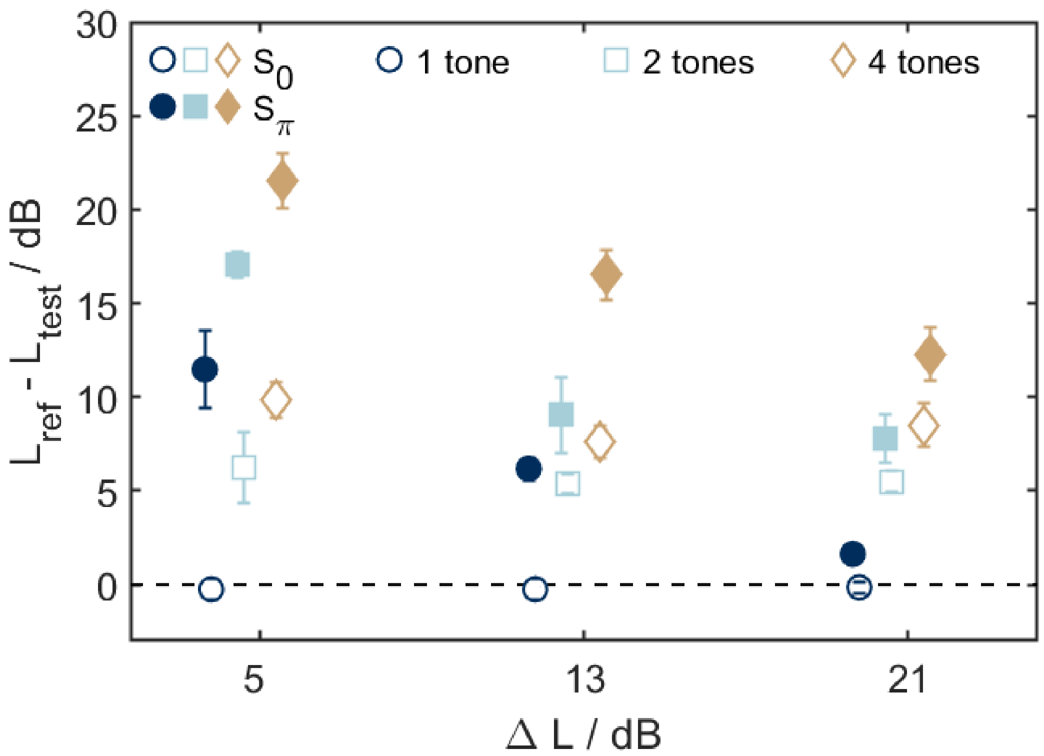

Figure 1: Level (L) difference between reference (ref) and test signal (test) at equal loudness of the tonal portion as a function of the level of the tonal portion of the reference. The level of the tonal portion of the reference was expressed as the level above masked threshold (ΔL). The reference signal was a diotic pure tone. The level of the test signal refers to the level of the component at the frequency of the reference. Different symbols indicate different spectral characteristics of the test signals: pure tone (circles), two-tone complex (squares) and four-tone complex (diamonds). Open and filled symbols indicate results for the diotic and dichotic signals, respectively.

For the dichotic test signals, the reference level has a large effect on the level difference at equal loudness of the tonal portion. For the dichotic pure tone in noise (filled circles) it is 11 dB for the reference level of 8 dB above the level at threshold. This is almost as large as the BMLD of 12 dB at threshold (see Table 1, fourth column). At a reference level of 13 dB above threshold, it is 6 dB and, at 21 dB, it is only 2 dB. Thus, the difference in audibility due to the interaural phase difference is most prominent at threshold and decreases with level above threshold. This agrees with several studies in the literature (Townsend and Goldstein [15], Soderquist and Schilling [16], Zwicker and Henning [17], Verhey and Heise [10]). In general, they reported a negligible effect of interaural disparities for levels of 20 dB above the diotic threshold. An exception is Zwicker and Henning [17], who reported a measurable effect of interaural disparities of up to 30 to 40 dB above the diotic threshold.

The results for dichotic complex tones indicate a combined effect of interaural disparity and number of components. At the lowest reference level of 5 dB above threshold, the level difference at equal loudness of the tonal portion of the dichotic complex tones is the sum of the level difference for the dichotic pure tone and that for the diotic complex tone with the same number of components. For the dichotic two-tone complex (filled squares), this is also true for the two higher reference levels. In contrast, the level difference is slightly higher than that sum for the four-tone complex, indicating a nonlinear combination of the effect of interaural disparity and number of components. This was already observed at even higher levels of the 700-Hz tone in the reference sound than used in the present study and for a different set of listeners (Verhey et al. [18]). It remains to be seen, if this effect is also observed in a larger group of listeners.

The present data for levels at equal loudness of the tonal portion indicate that different stimulus parameters affect the level at equal loudness for the tonal portion. The effect of interaural disparities decreases with level, whereas the effect of number of components hardly changes with level in the investigated level range. Thus, it is not sufficient to consider the altered masked thresholds to quantify the perceived strength of the tonal portion in noise.

4. SUMMARY AND CONCLUSIONS

The present study investigated the influence of the two stimulus parameters number of components and interaural disparities on the perceived strength of tonal portion in noise. The strength was quantified as the level at equal loudness of the tonal portion of the sound. The reference was a 700-Hz pure tone in noise. Both parameters affected the level at threshold. The effect of the interaural disparity on threshold was larger than that of the number of components. The effect of these stimulus parameters was also observed at suprathreshold levels although their level dependence differed. This indicates that the effect of these parameters on the perception of suprathreshold tonal components in noise cannot be quantified by their effect on the thresholds. Current standards on the noise evaluation of tonal components do not consider the influence of interaural parameters and number of components. Thus for sources emitting multiple components and a noise emitting source that is located at a different position in space, the perception of the tonal portion may be largely underestimated. According to the present study, it is underestimated by more than 20 dB for a dichotic four-tone complex in noise. It remains to be seen if a loudness model can be used to predict the present results on the loudness of the tonal portion. While the effect of number of components is already accounted for by such a model, the masking-release due to binaural cues may be simulated by reducing the masker level in those conditions, as suggested in Heise and Verhey [10].

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