Zwicker-tones for pure tone plus bandlimited noise

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1. Introduction

After switching off a broadband noise with a spectral gap, a pure tone can be heard which was named after its discoverer a Zwicker-tone (Zwicker 1964, Lummis and Guttman 1972). The Zwicker-tone phenomenon was extensively studied (e.g. Fastl 1986, 1989), and it was found (Krump 1993) that a broadband noise plus a pure tone can also elicit a Zwicker-tone. Models of the Zwicker-tone were elaborated, which are based on masking patterns (Fastl and Krump 1995) as well as neural processing (Franosch et al. 2000), and neuronal correlates of the Zwicker-tone were reported (Hoke et al. 1996, Tomlinson et al. 1998).

In the present paper, results of experiments with combinations of pure tone plus lowpass noise, pure tone plus bandpass noise, as well as pure tone plus lowpass and highpass noise as Zwicker-tone exciters are presented and compared to predictions by current models.

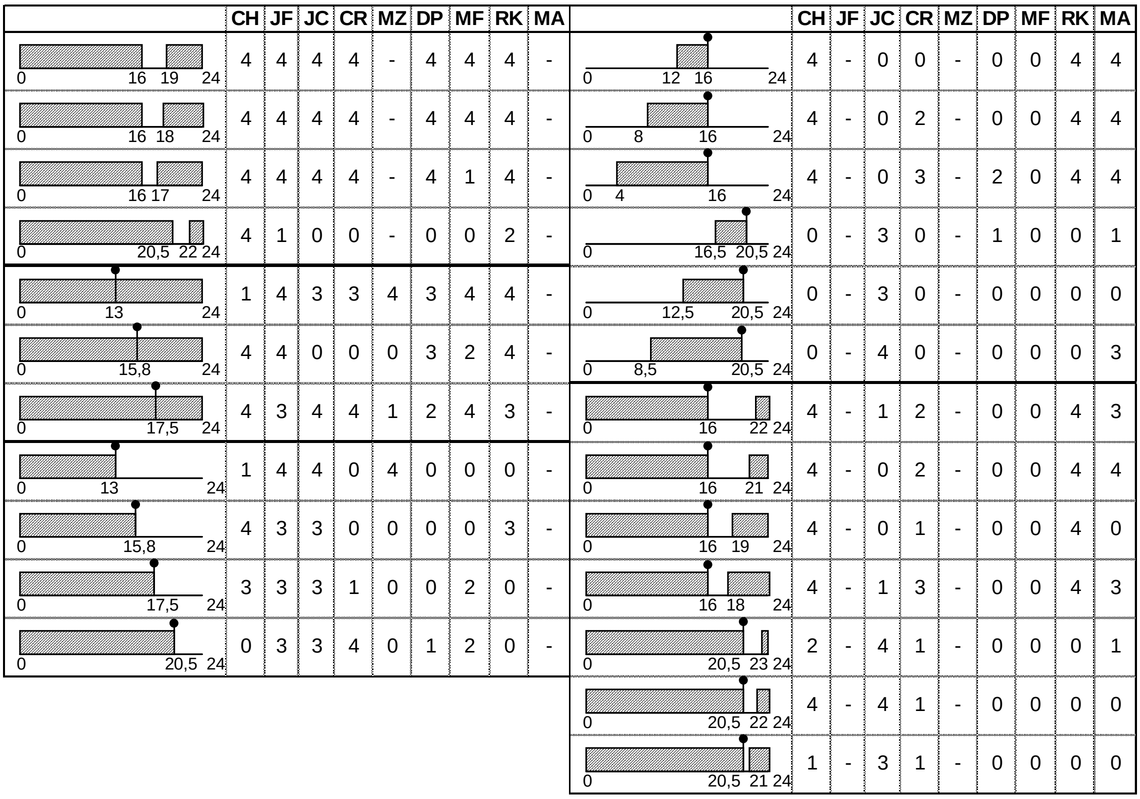
2. Experiments

Nine subjects with normal hearing ability and an age between 25 and 33 (median 29 years) took part in the experiments. At least seven out of the nine subjects participated in a session. Sounds were presented monaurally in a soundproof booth by an electrodynamic headphone (Beyer DT48) with freefield equalizer (Zwicker and Fastl 1999, page 7).

Pure tones with 60 dB SPL were combined with noises of -3 dB spectrum level. Sounds were digitally synthesized with 1 Hz line spacing and random phase. For further detail about the sounds and the procedure see Fastl and Krump (1995).

3. Results and discussion

In figure 1, the Zwicker-tone-exciter sounds are schematically displayed. For each of the nine subjects (CH though MA) it is indicated how often they could perceive a Zwicker-tone when the sounds were presented four times in random order. This means that the number 4 indicates that the subject could perceive a Zwicker-tone for all presentations, the number 0 that no Zwicker-tone was perceived, and a dash that the subject did not participate in the specific session of the experiment.



	CH	JF	JC	CR	MZ	DP	MF	RK	MA
0 16 19 24	4	4	4	4	-	4	4	4	-
0 16 18 24	4	4	4	4	-	4	4	4	-
0 16 17 24	4	4	4	4	-	4	1	4	-
0 20,5 22 24	4	1	0	0	-	0	0	2	-
0 13 24	1	4	3	3	4	3	4	4	-
0 15,8 24	4	4	0	0	0	3	2	4	-
0 17,5 24	4	3	4	4	1	2	4	3	-
0 13 24	1	4	4	0	4	0	0	0	-
0 15,8 24	4	3	3	0	0	0	0	3	-
0 17,5 24	3	3	3	1	0	0	2	0	-
0 20,5 24	0	3	3	4	0	1	2	0	-

	CH	JF	JC	CR	MZ	DP	MF	RK	MA
0 12 16 24	4	-	0	0	-	0	0	4	4
0 8 16 24	4	-	0	2	-	0	0	4	4
0 4 16 24	4	-	0	3	-	2	0	4	4
0 16,5 20,5 24	0	-	3	0	-	1	0	0	1
0 12,5 20,5 24	0	-	3	0	-	0	0	0	0
0 8,5 20,5 24	0	-	4	0	-	0	0	0	3
0 16 22 24	4	-	1	2	-	0	0	4	3
0 16 21 24	4	-	0	2	-	0	0	4	4
0 16 19 24	4	-	0	1	-	0	0	4	0
0 16 18 24	4	-	1	3	-	0	0	4	3
0 20,5 23 24	2	-	4	1	-	0	0	0	1
0 20,5 22 24	4	-	4	1	-	0	0	0	0
0 20,5 21 24	1	-	3	1	-	0	0	0	0

Figure 1: Overview of the audibility of Zwicker-tones for pure tone plus band limited noise

In line with data from the literature (e.g. Fastl and Krump 1995), for spectral gaps with a lower edge at 16 Bark, all subjects can perceive a Zwicker-tone, and for pure tone plus broadband noise, most subjects can hear a Zwicker-tone.

For pure tone plus lowpass noise, the results depend more on the individual subject: while subject DP can hear only one out of 16 possible Zwicker-tones, subject JF hears 13 out of 16 possible Zwicker-tones.

For pure tone plus bandpass noise, five out of seven subjects can hear a Zwicker-tone for a bandpass between 4 and 16 Bark, whereas only one out of seven subjects can perceive a Zwicker-tone for bandpass noise between 12.5 and 20.5 Bark. Subject RK hears Zwicker-tones for each presentation with a pure tone at 16 Bark, but no Zwicker-tone for sounds with the pure tone at 20.5 Bark.

For pure tone plus lowpass and highpass noise, a maximum of five out of seven subjects or at least three out of seven subjects can perceive a Zwicker-tone. Two of the subjects (DP, MF) never can hear a Zwicker-tone for this stimulus configuration. While subject RK hears Zwicker-tones for combinations with pure tone at 16 Bark and no Zwicker-tones for combinations with the pure tone at 20.5 Bark, for subject JC the situation is quite opposite.

Figure 2 shows the critical band rate as well as the level of the comparison tones matched to the Zwicker-tones. The spectral distribution of the Zwicker-tone-exciter is schematically indicated. In line with data from the literature the pitch of the Zwicker-tone (median) occurs about 1 Bark above the lower edge of the gap or below the pitch of the pure tone added to the broadband noise (c.f. Fastl and Krump 1995).

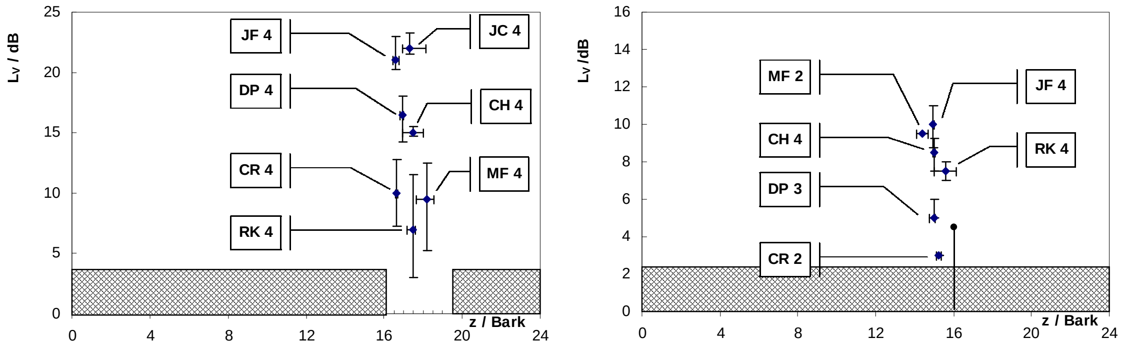


Figure 2: Pitch z in Bark and level L_V in dB of comparison tones matched to Zwicker-tones for broadband noise with a spectral gap (left) or pure tone plus broadband noise (right).

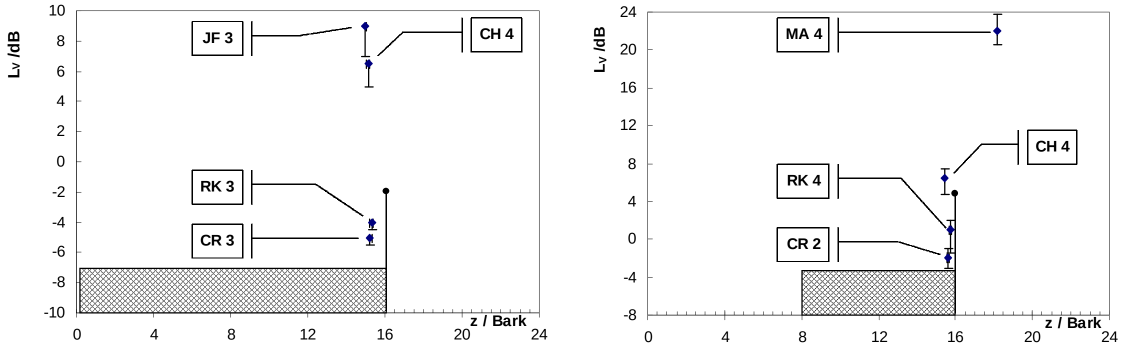


Figure 3: Same as figure 2 but for pure tone plus lowpass noise (left) or bandpass noise (right).

Figure 3 (left) shows the results for the combination of pure tone plus lowpass noise. Four out of seven subjects can perceive a Zwicker-tone with pitch and loudness rather similar to that for the combination of pure tone plus broadband noise. For the combination of pure tone plus bandpass noise (right), for subjects CH, RK, and CR data are very similar to the previous ones, i.e. pitches lower than the pitch of the pure tone. In contrast, for subject MA pitches higher than the pitch of the pure tone show up at significantly higher levels of the comparison tone. This behavior suggests that subject MA shows an otoacoustic emission around 18 Bark (cf. Krump 1993).

The results for the combination of pure tone plus lowpass and highpass noise are rather similar to those shown in figure 3 (right), and therefore are not displayed in a seperate figure. Again, for subject CH, RK, and CR, the pitch of the Zwicker-tone is below the pitch of the pure tone, whereas for subject MA again the comparison tone has a significantly higher level and lies around 18 Bark, corresponding to an OAE.

Figure 4 shows schematic masking patterns for the combinations of pure tone plus noises, adapted from Zwicker and Fastl (1999). The excitation level L_E is given as a function of the Bark scale z. The dash-dotted line indicates the absolute threshold, the masking pattern of a pure tone at 16 Bark with 60 dB SPL is illustrated by the solid line. Different types of hatching indicate the different Zwicker-tone-exciter sounds, i.e. pure tone plus broadband noise, lowpass noise, bandpass noise as well as lowpass and highpass noise. According to the model proposed by Krump (Krump 1993, Fastl and Krump 1995), the pitch of the Zwicker-tone is determined by the first crossing of the masking pattern of the noise and the pure tone, which is highlighted in figure 4 by a circle. For all the situations illustrated in figure 4, i.e. pure tone at 16 Bark plus broadband noise, lowpass noise up to 16 Bark, bandpass noise from 8 to 16 Bark as well as lowpass noise up to 16 Bark and highpass noise from 21 Bark, a pitch of the Zwicker-tone around 15 Bark is predicted. This prediction is at least qualitatively in line with the pitches of the Zwicker-tones indicated by the subjects.

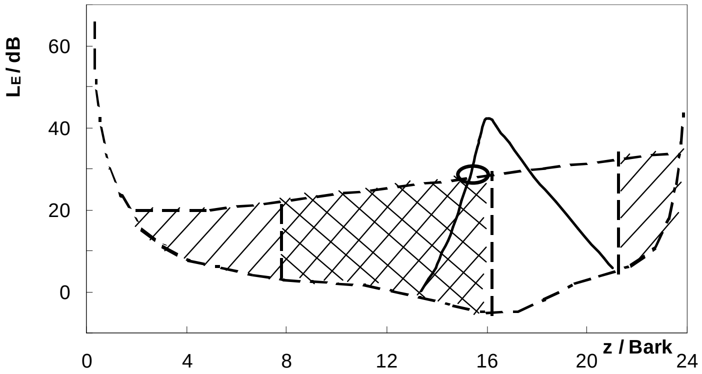


Figure 4: Schematic representation of excitation patterns for pure tone (solid) plus bandlimited noise. Pitch of the Zwicker-tone illustrated by circle.

To explain the Zwicker-tone by means of a neuronal model of the first auditory processing stages, we start with a habituation argument and show why it cannot hold. It is based on three, at the moment generally accepted, assumptions. First, neurons habituate to a steadily stimulating sound so that their spontaneous rate after switching off the sound is lower than in their resting state. Second, neurons are tonotopically ordered. Third, there is lateral inhibition between them. Figure 5 shows the corresponding neuronal interactions (A) and, schematically, the neurons' firing rates before, during, and after the Zwicker-tone exciters (B,C).

Habituation would explain why lowpass noise generates a Zwicker-tone. Lowpass noise excites neurons with low best frequencies. Because the cochlea is not a perfect frequency filter (Yost 1994), neurons slightly above the cutoff frequency are also excited. Since there is lateral inhibition, neurons directly to the right of the cutoff frequency (the edge) have the highest firing rate corresponding to the maximum of the dashed line in figure 5B. Neurons with best frequencies far above the edge are firing at their spontaneous rate. After the lowpass noise is switched off, neurons with best frequencies below the edge are habituated and fire at a low spontaneous rate. Hence these neurons can hardly inhibit the neurons above the edge that have always been in their resting state. So these neurons now fire at a higher rate than the spontaneous ones and generate a Zwicker-tone. Obviously only firing rates significantly above the spontaneous rate can cause an audible effect. The pitch of the Zwicker-tone is assumed to be perceived at the best frequency of the neuron with the highest firing rate.

The Zwicker-tone is inherently asymmetric: in the presence of broadband noise with a spectral gap, it exists above the band edge on the left but not below the band edge on the right (cf. figure 2). We are therefore bound to assume that lateral inhibition is stronger from low to high frequencies than conversely and call this "asymmetric". As a consequence, highpass noise cannot generate a Zwicker-tone because there is hardly inhibition from high to low frequencies.

Habituation, however, asymmetric or not, cannot explain all the cases where noise plus a pure tone elicit a Zwicker-tone. Let us consider e.g. a pure tone at a lowpass noise edge (figure 5C). Habituation and asymmetric inhibition predict a Zwicker-tone above the pure tone, whereas in reality this configuration generates one <u>below</u> the pure tone (figures 2 and 3). Why is that?

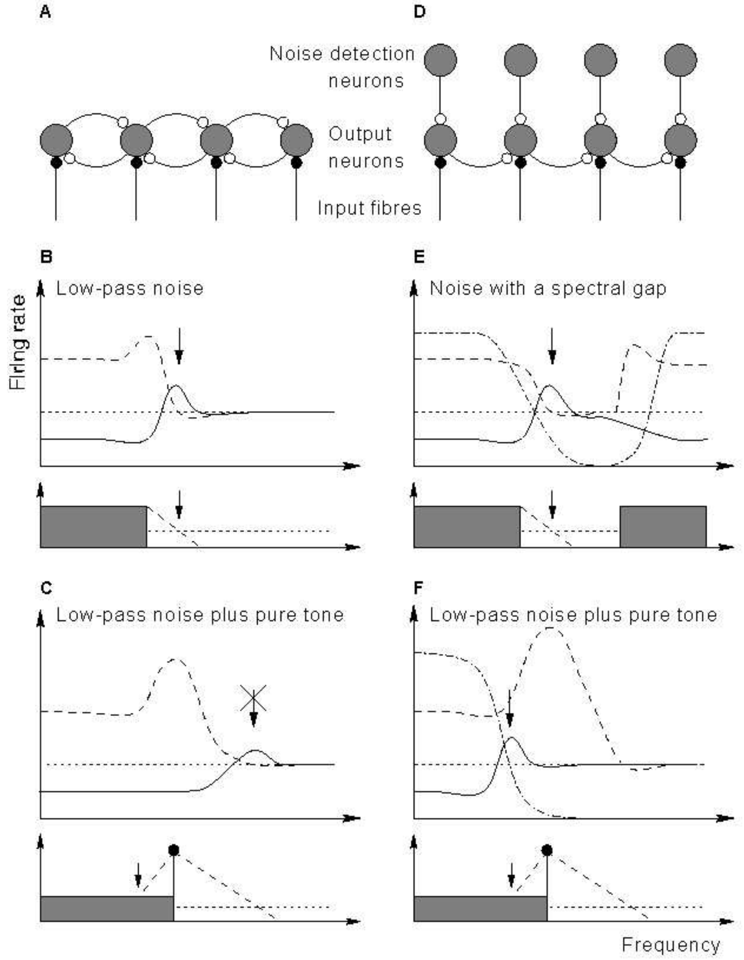


Figure 5: Habituation (left column) and noise detection (right column).

A: Neuronal implementation of simple (symmetric) lateral inhibition. Black circles denote neurons, small filled circles indicate excitatory synapses and small open circles inhibitory synapses.

B,C: Response (upper panel) of the habituation model (A) to two sounds shown in the lower panels (cf. figures 2 and 3, dashed lines indicate excitation patterns as in figure 4). Firing rates of the neurons before (horizontal dotted line, spontaneous rate), during (dashed line) and immediately after (solid line) the sound presentation are shown schematically. Downward arrows indicate Zwicker-tones predicted by the model. In the case of the lowpass noise plus a pure tone (C), the habituation model predicts a Zwicker- tone <u>above</u> the pure tone (crossed arrow) whereas in reality there is one <u>below</u> (figures 2 and 3).

D: Neuronal implementation of the full model with asymmetric inhibition and noise detection.

E,F: Response (upper panels) of the model in D to two sounds (lower panels, see also figures 2 and 3). Dash-dotted lines indicate firing rates of noise-detection neurons.

Until now we did not exploit the fact that noise plays a key role: no Zwicker-tone without noise. We define noise to be a sound of sufficiantly constant amplitude over a broad frequency range (exceeding 1 Bark) and with a duration much longer than 100 ms. The deficiencies of the above habituation argument are overcome by a model that also incorporates noise detection. To simplify the ensuing discussion, we neglect habituation, though one could easily add it. Asymmetric inhibition is still present. In addition, we assume a tonotopic array of noise-detection neurons: only with noisy input do they become active and inhibit "output neurons" projecting to higher-order centers; cf. figure 5D. They are slow in responding so as to catch the noise characteristics. Therefore, their inhibition lasts longer than any other integration time in the auditory system and, thus, is of the order of a few seconds after the noise is switched off. Noise-detection neurons adjust the threshold of output neurons. So they can suppress activity generated by noise whereas they highlight non-noisy features.

To illustrate why a noise reduction mechanism is important to generating a Zwicker-tone, we now return to the new psychophysical experiments that cannot be explained by habituation, i. e. a pure tone at a noise edge (figure 2 and 3). Habituation and asymmetric inhibition predict a Zwicker- tone above the pure tone whereas in reality we observe one below the pure tone. In this case the noise-detection neurons react against the noise except where they are inhibited by the pure tone; cf. figure 5F. This causes a "hole burning" around the pure tone (the important feature). After the sound is switched off, output neurons in the tonotopic neighborhood of the pure tone are not inhibited by the noise detection neurons whereas the others still are. Because of asymmetric inhibition, a Zwicker-tone arises below the pure tone. In case of a pure tone embedded in white noise (figure 2), hole burning is even the more true, and a Zwicker-tone is perceived.

For lowpass noise and noise with a spectral gap (figure 2 and 5E), we have nearly the same situation as with pure habituation. Neurons in the output layer that get noisy input are inhibited by their noise-detection counterparts. After the noise is switched off, the latter are still active so that the firing rate of the output neurons at lower frequencies is reduced. This generates a Zwicker-tone just above the edge of the lowpass noise because the neurons there now get less inhibition than in their resting state. Using the properties of the model, one now easily sees why, when, and where in figures 2 and 3 a Zwicker-tone is generated.

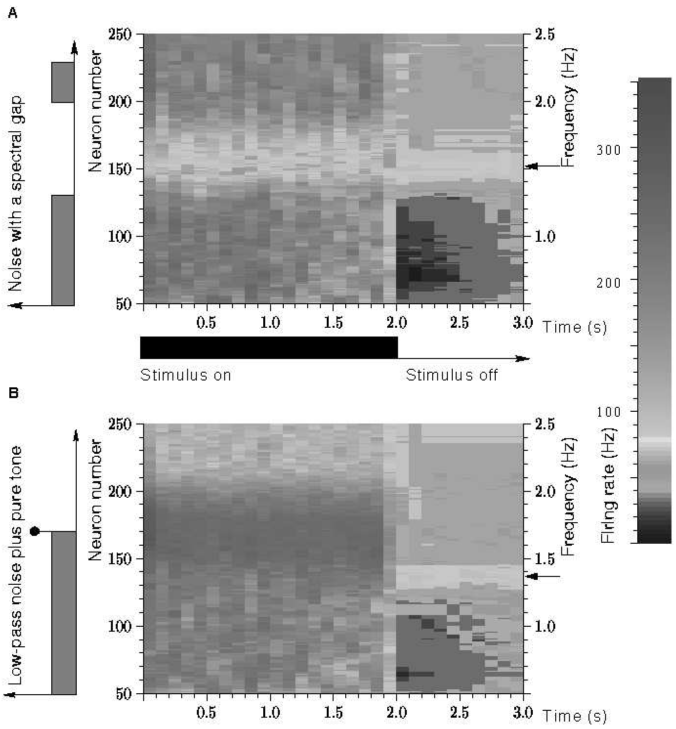


Figure 6:
A: Firing rates of output neurons from figure 5D as a function of time. The firing rate is averaged over 100 ms and color-coded. The stimulus is white noise with a spectral gap from 1300 to 2000 Hz so that we have the same situation as in figure 2 (left). Clearly, a Zwicker-tone is audible at the frequency denoted by the arrow. By comparing the excitation of the output layer with that caused by a low-level pure tone, the level can be estimated to be 10-20 dB.
B: Stimulus is lowpass noise with a cutoff frequency of 1700 Hz plus an additional pure tone at 1700 Hz so that we have the same situation as in figure 3. The Zwicker-tone has a level of about 10 dB.

Finally, computational evidence is provided by figure 6. It exhibits the result of a careful simulation and explains the characteristics of the Zwicker-tone; in particular, position, low amplitude, and pure tone.

In summary it can be stated that the combinations of pure tone plus lowpass noise, bandpass noise as well as lowpass and highpass noise can also elicit Zwicker-tones. However, usually only some subjects can hear the Zwicker-tone with a preference in pitch height: while some subjects can hear Zwicker-tones for pure tones at 16 Bark plus noises, others more often hear Zwicker-tones for pure tones at 20.5 Bark plus noise. The reasons for the fact that some persons do not hear Zwicker-tones for combinations of pure tones plus bandlimited noise, and that persons who can hear Zwicker-tones have some preferences with respect to height are not clear so far. However, for those persons who can hear Zwicker-tones for combinations of pure tone plus bandlimited noise, the pitch of the Zwicker-tone can be predicted by a simple model based on masking patterns as well as by a more elaborate neural model.

4. Acknowledgements

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