Zwicker Tone Illusion and Noise Reduction in the Auditory System

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Abstract

The Zwicker tone is an auditory aftereffect. For instance, after switching off a broad-band noise *with a spectral gap*, one perceives it as a lingering pure tone, the pitch being in the gap[1,2]. It is a unique illusion in that it cannot be explained by properties of the auditory periphery alone and has no direct analog in the visual system either. Here we present psychoacoustic experiments that reveal the crucial role of noise[3,4]. Habituation is ruled out as a driving mechanism. Furthermore, we propose a neuronal model that predicts both the pitch and whether a sound can generate a Zwicker tone at all. We show that dominantly unilateral inhibition in conjunction with a neuronal noise-reduction mechanism explains the effect.

1 Introduction

- The typical sound generating the Zwicker tone is a broad-band noise with a spectral gap presented during several seconds.
- When the noise is switched off, a faint, almost pure, tone is audible for one up to six seconds. It is decaying and has a sharp pitch in the spectral gap[1,5]. That is to say, exactly there where no stimulus was available.
- Both the Zwicker tone's localization in the brain and its explanation are longstanding open problems.
- Quite a few noise configurations generate a Zwicker tone[2,5–7]. Figure 1 gives an overview.

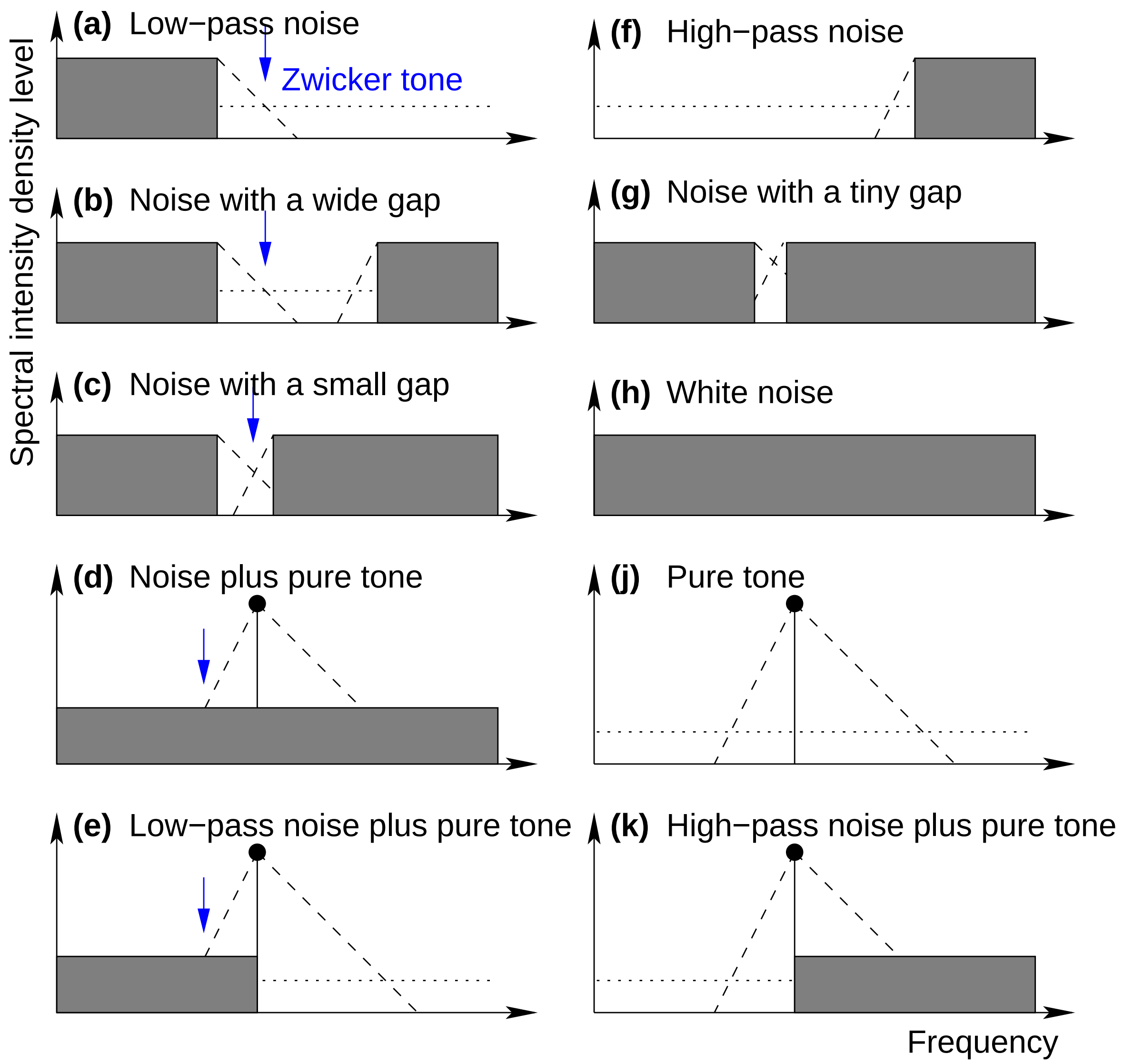


Figure 1: **Zwicker tones generated by various noise configurations.** The horizontal axis denotes increasing frequency, the vertical one indicates the corresponding sound amplitude (arbitrary units). Shaded areas denote noise and vertical lines ending in a filled circle indicate pure tones. Zwicker tone generating sounds (left column) are low-pass noise (a), noise with a gap (b) & (c), or noise plus a pure tone (d) & (e). The pitch of the Zwicker tone is indicated by a downward arrow. According to the psychoacoustic description of Krump[7,8], the pitch of the Zwicker tone in (a)–(c) is located at the lower frequency crossing of the so-called auditory excitation[2] (dashed lines) and the threshold in silence (dotted lines). No Zwicker tone has been observed in (f)–(k). Cases (e) and (k) represent new experimental results motivated by the *hole burning* concept of the noise-reduction model presented here.

2 Psychoacoustic Experiments

To test our models we have performed psychoacoustic experiments where we combined band-pass noise with a pure tone.

2.1 Experimental Setup

- Sounds were presented monaurally in a soundproof booth by an electrodynamic headphone (Beyer DT48) with free-field equalizer[2].
- In a pre-experiment with clearly audible Zwicker tones the subjects could choose with which ear they felt most comfortable in perceiving the Zwicker tone, but subjects then had to stick to the same ear during the main experiment.
- Subjects had a switch with which they could choose between three positions: Zwicker tone generating sound, silence and pure tone. Subjects were told to switch between sound and silence to perceive the Zwicker tone and then switch to the pure tone and adjust it in pitch and loudness to the Zwicker tone. They were allowed to repeat the procedure as long as they liked until they reported a match between the Zwicker tone and the pure tone.

2.2 Experimental Results

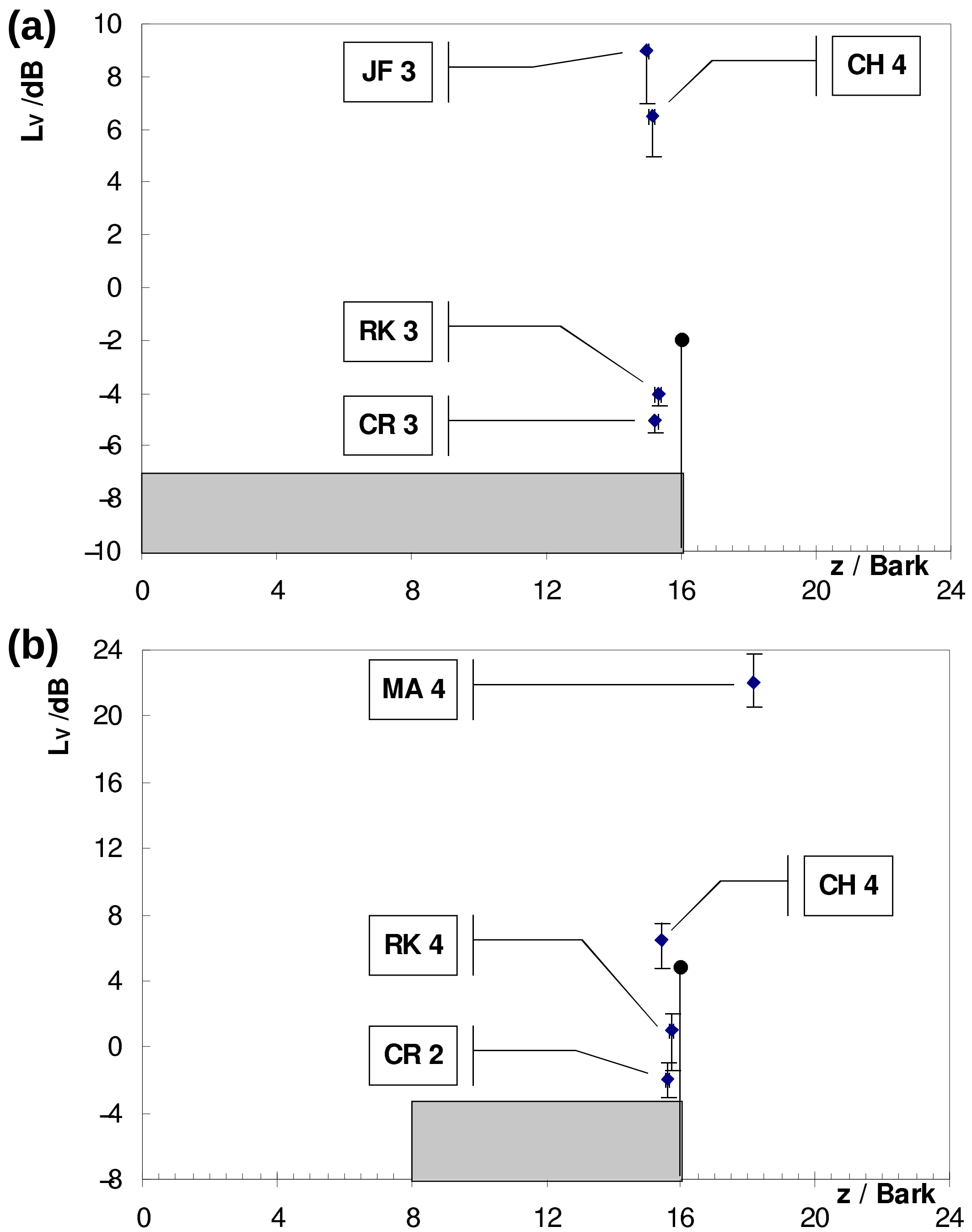


Figure 2: **Psychoacoustic Experiments.**
The labeled dots specify the pitch in Bark and level in dB of comparison tones matched to Zwicker tones by the indicated subjects. The number of times out of four a subject could perceive a Zwicker tone are given in the boxes. The labeled dots indicate the median of the pitch and loudness of the pure tones matched by each individual subject. The bars specify the upper and lower quartile of the data. The spectral level density of the Zwicker tone generating sounds is indicated schematically. The Zwicker tone is perceived below the pure tone by almost every subject.

3 Model 1 — Habituation (No Good!)

3.1 Model assumptions

To explain the Zwicker tone by means of a neuronal model of the first auditory processing stages, we start with a few basic assumptions.

- Neurons are tonotopically ordered along a frequency axis corresponding to the cochlea.
- Neurons habituate to a steadily stimulating sound so that their spontaneous rate after switching off the sound is lower than in their resting state.
- There is lateral inhibition.
- Spontaneous activity in the auditory system is high, in the range of 100 Hz. A sound is only 'perceived' if neurons fire at a rate above their spontaneous one.

3.2 Consequences

- Habituation with symmetric lateral inhibition can only explain cases (a), (g) and (h) of Fig. 1. See also Fig. 3, left column.
- To account for cases (b) and (f) of Fig. 1, we are bound to assume that lateral inhibition between neurons is asymmetric, effective from low to high frequencies but not conversely.
- Let us now consider a pure tone at a low-pass noise edge as in Fig. 1(e). Habituation and asymmetric inhibition predict a Zwicker tone *above* the pure tone whereas in experiment we have found that this configuration generates one *below* the pure tone.

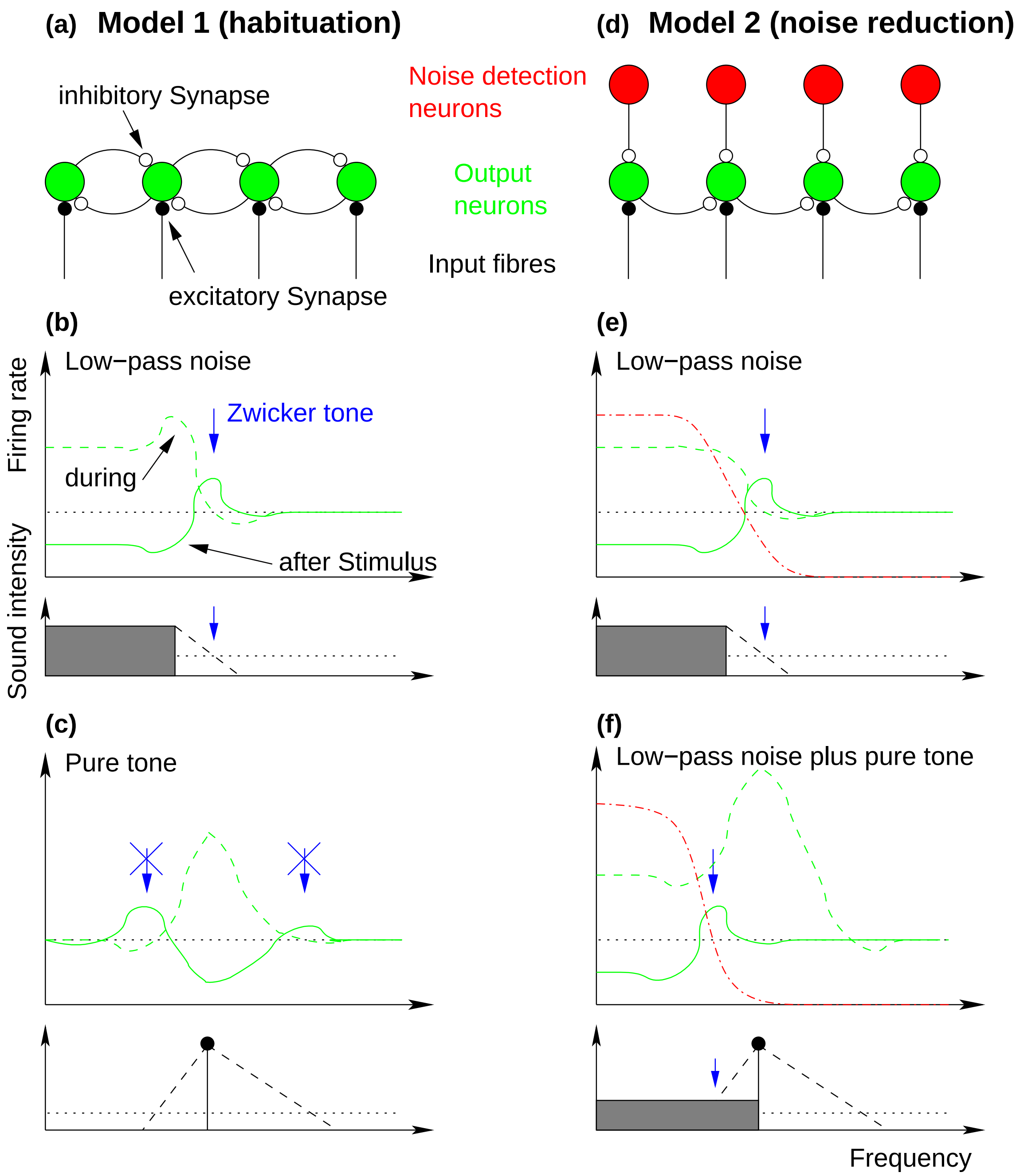


Figure 3: **Comparison of the two models.**
(a) Neuronal implementation of symmetric lateral inhibition.
(b),(c) Response (upper panels) of the habituation model (a) to sounds (lower panels). Firing rates of the output neurons before (horizontal dotted line, spontaneous rate), during (dashed line) and immediately after (solid line) the sound presentation are shown schematically. Downward arrows indicate Zwicker tones predicted by the model. In the case of the pure tone in (c) the habituation model predicts even two Zwicker tones (crossed arrows) whereas in experiment there is none.
(d) Neuronal implementation of the noise reduction model.
(e),(f) Response of model (d) to two sounds. Dash-dotted lines indicate firing rates of noise-detection neurons.

4 Model 2 — Noise Reduction

Noise plays a key role: without noise no Zwicker tone. The deficiencies of model 1 are overcome by a model that incorporates noise detection.

4.1 Model assumptions

- We neglect habituation.
- Asymmetric inhibition is still present.
- We assume a tonotopic array of *noise-detection neurons*. These only become active with noisy input around their best frequencies and inhibit 'output neurons', as shown in Fig. 3(d). They are slow in responding so as to catch the noise characteristics, i.e. their inhibition lasts on the order of a few seconds after the noise has been switched off. Noise-detection neurons suppress activity generated by noise whereas they highlight non-noisy features.

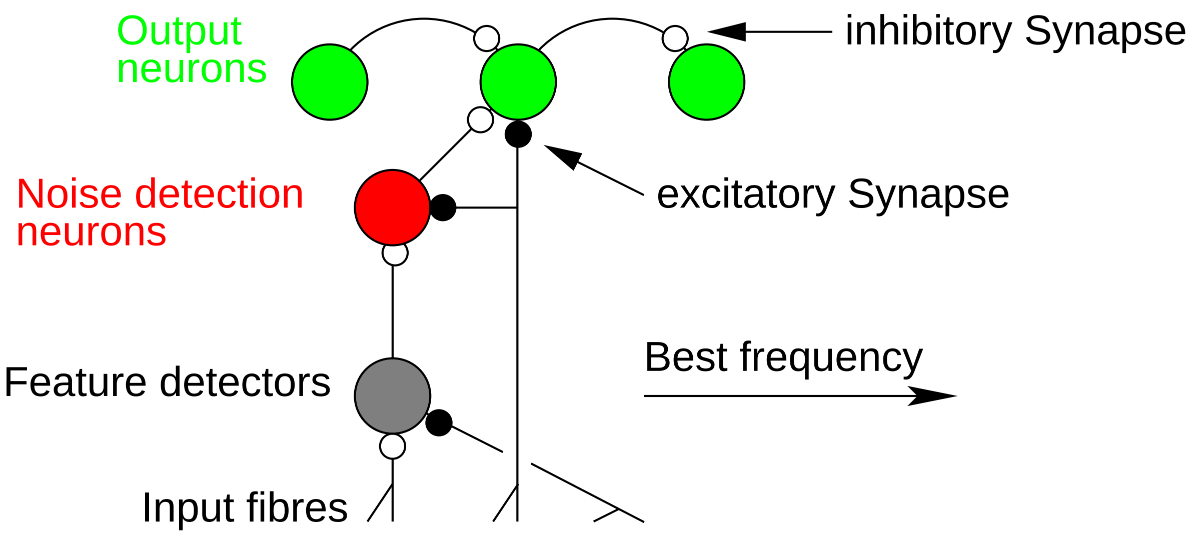


Figure 4: **Implementation of noise-detection neurons.**
The feature detectors are active if there is a rising edge, i.e., steeply rising spectral intensity as frequency increases. Feature detectors inhibit corresponding noise-detection neurons.

4.2 Consequences

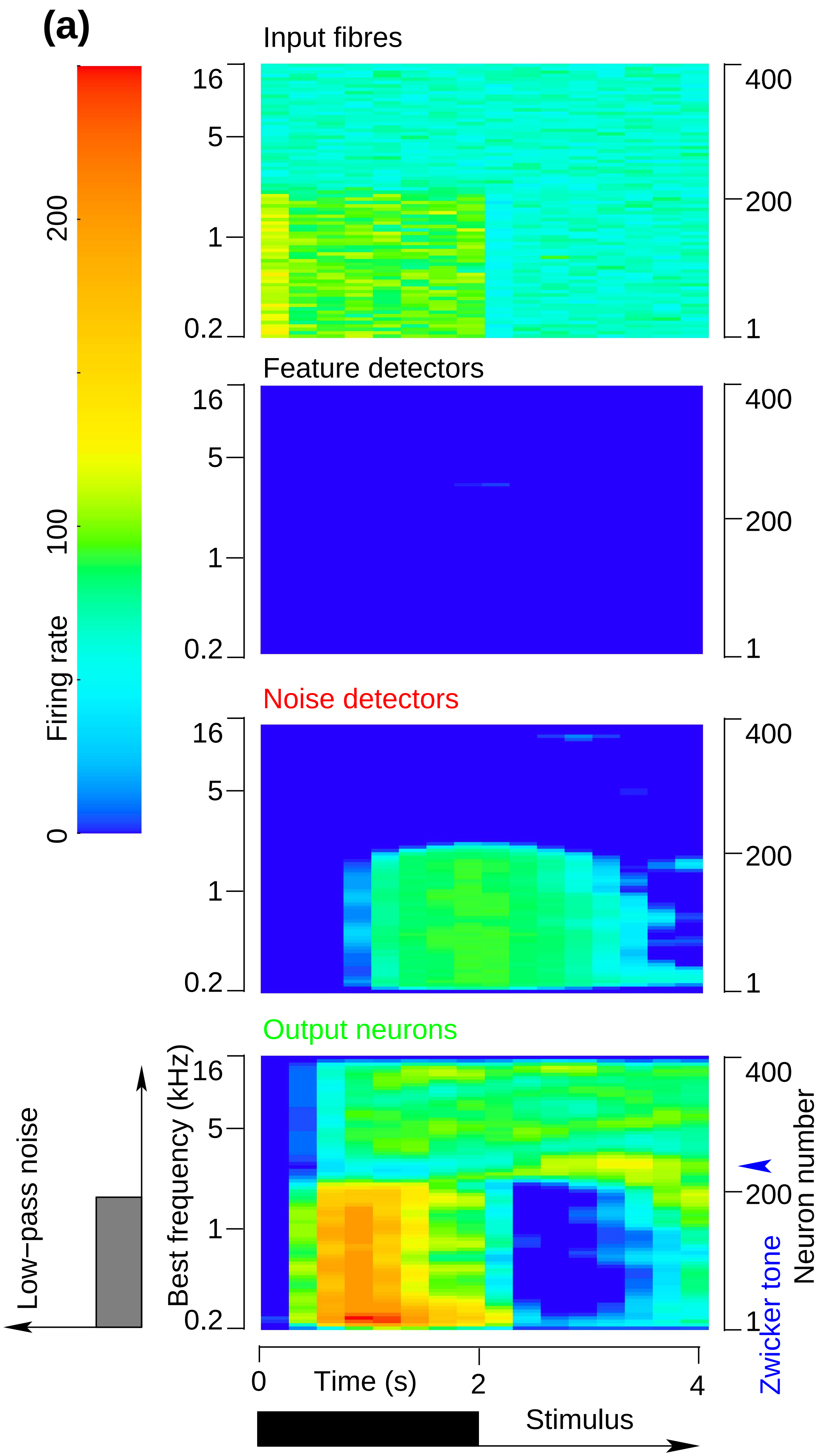
- In order to reveal the consequences of model 2 we have simulated 400 auditory nerve fibers and 400 neurons of each type.
- To get a realistic input we have modeled the basilar membrane as a set of fourth-order linear gamma-tone filters. The amplitude of the basilar membrane calculated by these filters is coupled to the stereocilia of a Meddis inner-hair-cell model[9,10].
- All neurons have been modeled by the 'spike response model'[11].

Figure 5: **Numerical simulation of Zwicker tones.**

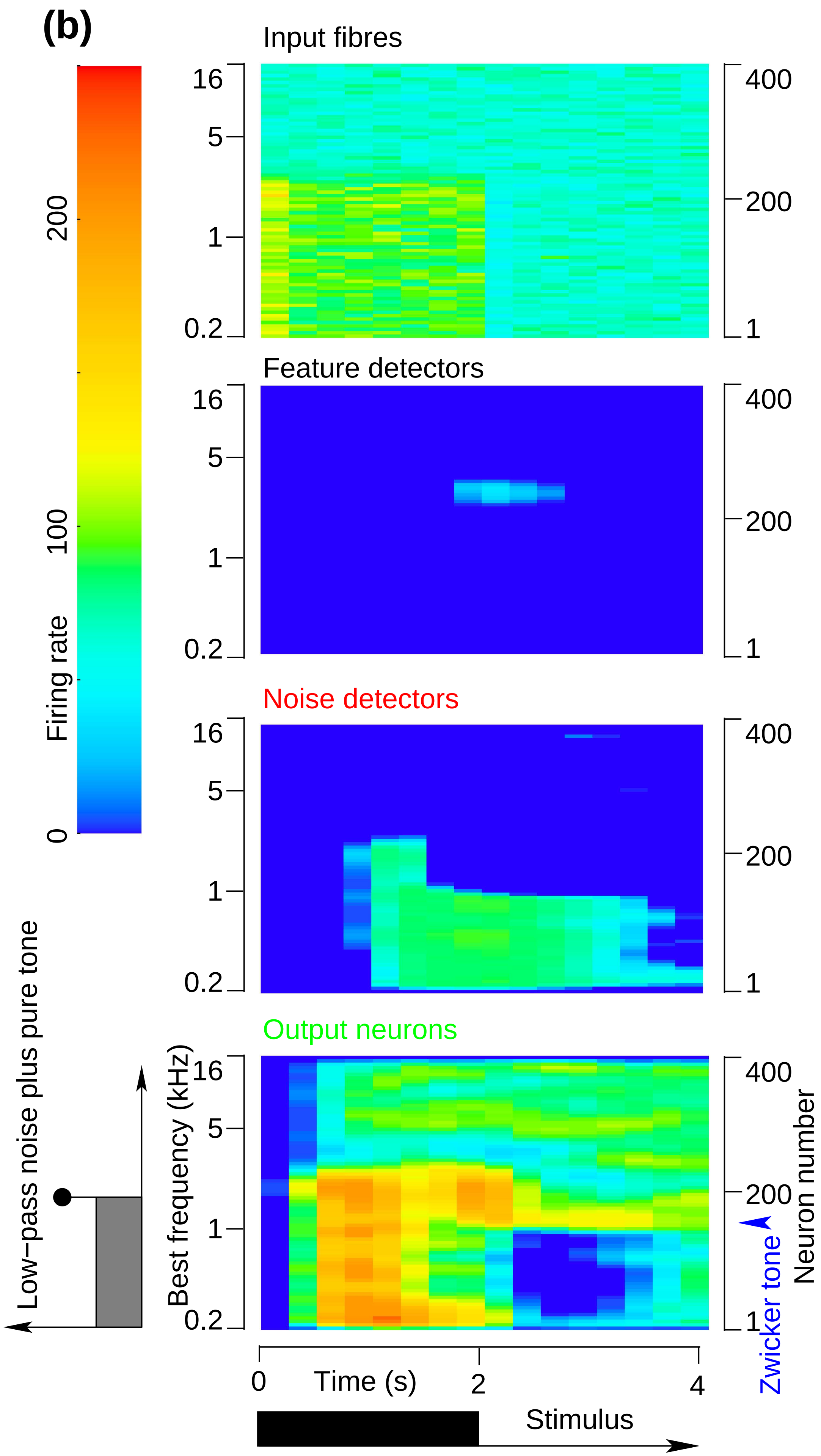
Firing rates (color coded) of 400 output neurons as a function of time and the neurons' best frequency in a tonotopic array.

(a) The stimulating sound is low-pass noise with a cutoff frequency of 1700 Hz as in Fig. 3(e). Only input neurons with low best frequencies are therefore activated. Feature detectors do not react in this case because the stimulus contains only noise and no tonal feature, but noise detector neurons do. They continue firing after the sound has been switched off because of their long time constants and thus still inhibit their corresponding output neurons. Because of lack of inhibition from low to high frequencies in the output layer at the position indicated by an arrow, output neurons fire at a higher rate than in their resting state. So a Zwicker tone is audible at the corresponding frequency, indicated by an arrow head.

(b) The stimulus is low-pass noise plus a pure tone at the edge as in Fig. 3(f). Feature detectors respond to the pure tone, 'burning' a 'hole' in the noise-detector layer since noise-detector neurons are inhibited by feature detectors; cf. Fig. 4. The Zwicker tone is perceived *below* the pure tone and is indicated by an arrow head.



(a)
Firing rate
0
100
200
Input fibres
Feature detectors
Noise detectors
Output neurons
16
5
1
0.2
400
200
1
Best frequency (kHz)
Neuron number
Zwicker tone
Low–pass noise
0
Time (s)
2
4
Stimulus



(b)
Input fibres
Feature detectors
Noise detectors
Output neurons
Firing rate
0
100
200
16
5
1
0.2
400
200
1
Best frequency (kHz)
Neuron number
Zwicker tone
Low−pass noise plus pure tone
0
2
4
Time (s)
Stimulus

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