High pitch perception through coherent stimulation of neurons in different refractory phases

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Abstract

A system of n neurons, stimulated by a single electrode, is capable of carrying at most a frequency n/r, where r is the absolute refractory period.

PACS numbers: 87.19.Dd,43.64.+r,87.19.La,43.71.+m

Keywords: information processing in hearing, physiological acoustics, speech perception, neuroscience

Speech perception, in particular perception of higher frequencies than the inverse of the absolute refractory period of the auditory neurons, has been a long-standing problem. We present a novel approach by considering the correlated effect of such signals on groups of neurons, rather than considering the spike activity resulting from a single auditory neuron.

Suppose several neurons whose refractory phases are all different, are confronted with a mono-frequency signal, whose pitch would require an effective absolute refractory period of r/n, where r is the absolute refractory period of a stand-alone neuron, and n is the number of such neurons. It is not totally unreasonable to ask whether, possibly by the coherent stimulation of neurons, a collective pattern of neural activity forms which would properly contain the frequency information otherwise unattainable by single auditory neurons.

We indeed find that such an effect exist. It is based on the assumption that these neurons either have a different offset of the refractory period, or have different absolute refractory periods (within a certain frequency range) altogether. In such a case, different neurons are stimulated by successive peaks. The sum over the neural activity of this group of neurons then properly represents information about the high-pitch signal, although its frequency is too high to be resolved by a single stand-alone neuron alone.

We demonstrate this effect by an elementary model of $n = 3$ neurons, all having the same absolute refractory period r, which are equidistributed over n periods of length r/n, starting from time $t = 0$. That is, these three neurons can effectively be successively stimulated at times $0, \frac{r}{3}, \frac{2r}{3}$, and then over again with a total offset of the absolute refractory period r of each single one of these five neurons; i.e., at times $r, r+\frac{r}{3}, r+\frac{2r}{3}$, and so on.

For such a configuration, each one of the neurons can take up a signal for the successive wave trains at a frequency $\frac{3}{r}$. Fig. 2 depicts the temporal evolution of this system of neurons, stimulated by successive wave peaks.

The price to be paid for this "optimal" resolution of a mono-frequency signal is the narrow (indeed, of width zero) bandwidth which is resolved by the five neurons. This can be circumvented by considering a *stochastic* distribution of the offset phases. Stochastic offsets will be discussed below in greater detail.

Another issue is the attenuation of the signal by an effective factor of n with respect to the single, stand-alone neuron activation in the case of signals with frequencies so low that they can be resolved within the absolute refractory period. This attenuation should be compensated by either the plasticity of the auditory perception system, or by the integration of more neurons which

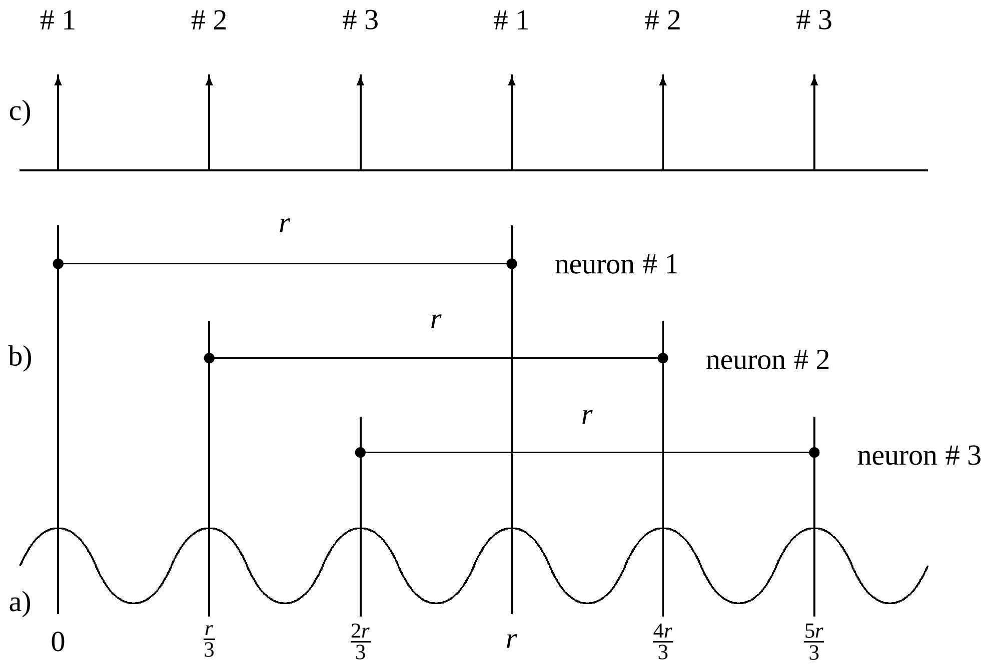

FIG. 1: Temporal evolution of a system of three neurons with equidistributed onsets of identical absolute refractory periods r, stimulated by successive wave peaks and thus being capable of resolving signals of frequency $3/r$. a) Original signal; b) neuron activation cycle; c) sum of spike trains from neuron activity.

effectively contribute to the overall signal.

In what follows we present detailed numerical studies of multi-neuron systems with a stochastic distribution of absolute refractory periods within an interval $\left[r-\frac{\Delta}{2}, r+\frac{\Delta}{2}\right]$ and initial offsets of the order of r. The driving signal is modelled by a regular spiking activity of Frequency $\omega = k/r$. In the $k > 1$ regime, coherent stimulation can be expected to contribute to high pitch perception. As for the regular case described above, the mechanism can be expected to work for $k \leq n$.

Fig. 2 depicts a numerical simulation of the intensity of the spiking activity as a result of 11 nerves driven by a signal corresponding to 17 times the inverse mean absolute refractory period. Fig. 3 depicts a numerical simulation rendering the relative error ratio ε of missed signal spikes to the absolute number of signal spikes as a function of frequency ω for a number of asynchronous neurons ranging from a single neuron ($n = 1$) to 30 neurons. The numerical studies indicate a reliable performance of coherent stimulation for frequencies corresponding to lower than to equal to the number of participating neurons.

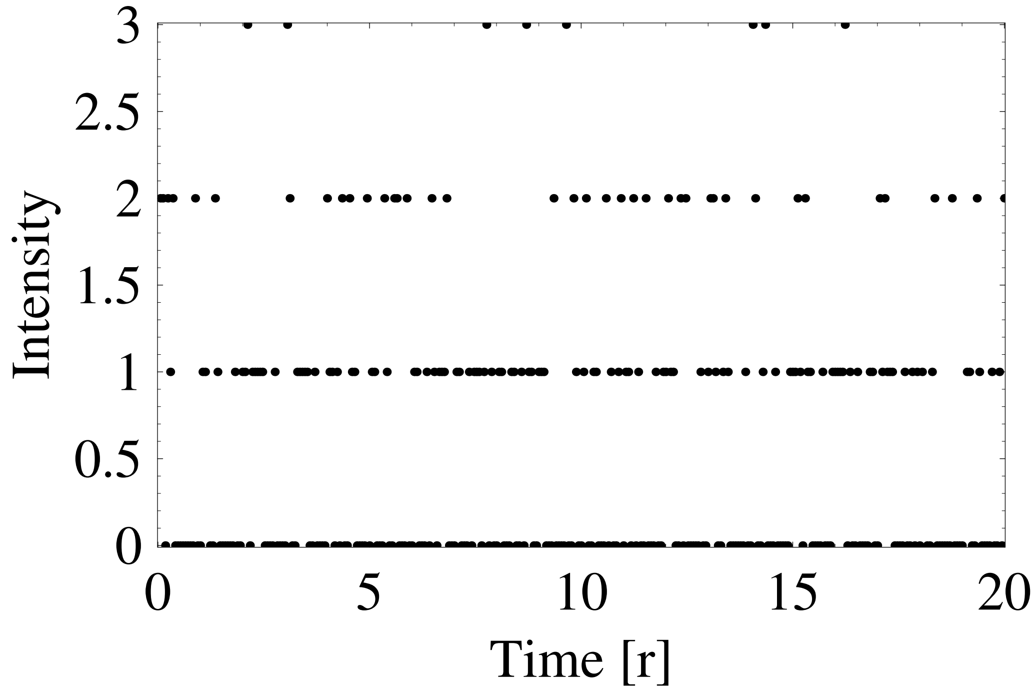

FIG. 2: Numerical simulation of the intensity of the spiking activity as a result of 11 nerves driven by a signal corresponding to 17 times the inverse mean absolute refractory period.

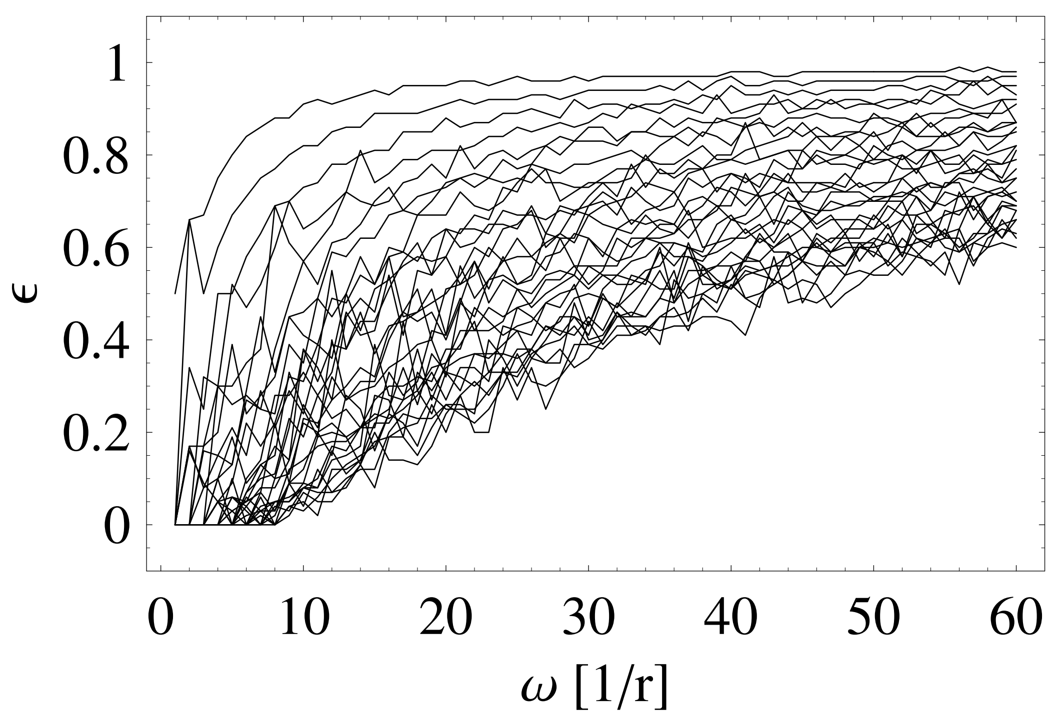

FIG. 3: Numerical simulation of the relative error ratio ε as a function of frequency ω for a number of asynchronous neurons ranging from a single neuron ($n = 1$) to 30 neurons.

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