NEURONAL MECHANISMS OF DETERMINATION THE DIRECTION UPON THE SOUND SOURCE

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Abstract

A model of the neuronal structures of the auditory system is worked out to determine the direction upon the 6ource of the sound signal with steep-sided front. The direction upon the sound source is determined on the basis of a generalized parameter which is the result of two measurements: (I) moments of arrival of the signals at each ear; (2) amplitudes of these signals. The result i6 the precision determination of the direction upon the sound source.

The model represents a five-level neuronal structures, each level consisting of the elements of the same kind. The intormations about the direction upon the source of sound is encoded in the location of the excited region at the output level of the model.

Introduction

The system determining the direction upon the source of sound is able to detect exactly only with the use of the parameters Δt_{rl}, A_r, A_l, *) where R (the distance from the source) is unknown. Where ft is given, the determination problem may be solved with the uze either of Δt_{rl} (based on the equation (I)) or A_r and A_l (based on the equation (2)) [I]. Under real conditions, however, the parameter R is unknown, so it is necessary to use the information about the difference of the moments of arrival of the signals and about their amplitudes (see (3)).

Where the direction is determined on the base of the parameter Δt_{rl} only and the information about the amplitudes is notused, it means the case the sound source is located at infinity. *) But because of the finite value of R in this method of evaluating φ the greater error is committed the smaller is the value of R. **)

Living organisms determine φ by us:Lng the parameters, Δt_{rl}, A_l, A_r. This conclusion is based on the following: I) If two signals differing in amplitude arrive simultaneouslly (via headphones) at the right and left ear, the subjective sensation is that the sourse is shifted to the side of the largest signal. 2) Electrophysiological characteristics of neurons of the medial superior olivary nuclei (taking part in sound localization) are similarly dependent on the difference of arrival moments and the difference of signal amplitudes ([2] , page 77)

The main stages in the transformstion in the model.

On the strength of what has been said, it may be concluded that neural structures evaluating φ calculate either the exact value of φ (according to equation (3) or a similar, more correct formula, taking account of the diffraction of sound waves on the head and the helixes), or its approximation. For a typical case where $R \gg d$, φ in a first approximation (calculated by (3)) is the following;

$$\sin^2\varphi_l \approx \left(\frac{v\,\Delta t_{rl}}{d}\right)^2 + \frac{1}{4}\left(\frac{A_l - A_r}{A_l}\right)^2 \quad (4)$$

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*) The determination of the direction upon sound source with the help of two point-receivers, situated at distance d from each other comes to solving a set of 2 equations relative to φ :

$$\Delta t_{rl} = \frac{R}{v}\left(\sqrt{1+\frac{d}{R}\sin\varphi+\frac{d^2}{4R^2}} - \sqrt{1-\frac{d}{R}\sin\varphi+\frac{d^2}{4R^2}}\right) \quad (I)$$

$$\frac{A_r}{A_l} = \frac{\sqrt{1-\frac{d}{R}\sin\varphi+\frac{d^2}{4R^2}}}{\sqrt{1+\frac{d}{R}\sin\varphi+\frac{d^2}{4R^2}}} \quad (2)$$

where Δt is the difference between the moments of signal arrival at the right and left receiver; V is the velocity of sound wave in the enviroment; A_r and A_l are the amplitudes of the signals at the right and left receivers. Solving the equations (I) and (2), we have φ :

$$\sin^2\varphi = \frac{\frac{1}{2}\left(\frac{v\,\Delta t_{rl}}{d}\right)^2 \cdot \frac{(A_l+A_r)^2}{(A_l^2+A_r^2)}}{1 - \frac{(A_l-A_r)^2}{2(A_l^2+A_r^2)} \Big/ \left(\frac{v\,\Delta t_{rl}}{d}\right)^2} \quad (3)$$

*) In this case the wave becomes plane ($A_r = A_l$), so $\sin\varphi = \frac{v\,\Delta t_{rl}}{d}$ (from (3)).

**) E.g. if $R \approx d$, and $\varphi = 30^\circ$ the undgrstating of estimation of φ by 4.4° is allowed.

The analysis of biological data warrents the assumption that this kind of estimation ie calculated in neural structures of living organisms with passive sound source localization. The evaluation is then produced in two stages, so that there are two structure- functional blocks in the model described below.

At the first stage in the block of monaural transformaclon (from both the right and left side) the amplitude of sound impulse (or the impulse front, to be more precise) is transformed into an equivalent time delay. This time delay is summed up with the actual moment of arrival from this very side. Finally, some resultant moment (phase) of appearance of the standard signal is formed (from each side of model). This resultant moment is determined by two parameters: I) the real moment of impulse arrivai at the given ear; and 2) the amplitude of signal coming from this side.

At the second stage, in the block of binaural processing the actual determination of direction on the sound source is produced by calculating of the resultant interaural delay, i.e. the difference between the moments when signals appear from each side of the first block. What is important here is that the difference between the resultant moments of appearance of the signals (determined in the first block) is calculated. So the result is the function both of the difference of phases and the difference of amplitudes.

The model structure.

The first level L_1 of the model is formed by the receptive elements (mainly the internal hair cells of the cohlea, which perceive the vibrations of the basilar membrane. The basilar membrane is represented roughly as a regulated set of frequency sensible elements, the inertia of the latter increases monotonously along the axis X (longitudinally along the membrane).

The consideration of the basilar membrane model [3] shows that the sound pulses differing in their stepness and duration produce the maximum in the different parts of the latter. The greater the steepness of the pulse and/or its duration the closer to the apical end of the membrane is the region of the maximum vibrations. On the strength of this property we assume that the membrane distributes the received sound signal over a great number of channels (the receptor being the beginning of each channel). As a result, the transmission of the information about the sound pulses differing in steepness and duration is produced through the different channels. The coordinate x of the working channel thus gives the concrete input signal.

Each receptor - the element of the level L_1, of the model transforms the deviation of the membrane Into the membrane potential. The receptor is connected with a column of neurons, their thresholds increasing monotonously along Y. These columns of neurons in the model fill up a two-dimensional layer (the level L_n) with coordinate axes I (along the m&mbrane) and Y (the direction of the varying of the threcholds of the elements). (The level L_2 corresponds to the spiral ganglion of the auditory system). Each element of the level Lp responds to the input signal with only one pulse, i.e. it works discretely. In response to the pulse sound signal an excited region appears at the level Lp. This excited region dilates along the Y-axis (a column with coordinate x), the velocity of the dilation depending on the type of signal - the steepness and the amj>litude of the pulse front.

The neurons of the level $L_,$ are the speed detectors, or, more exactly, the detectors of a velocity variation law. Each detector with the coordinates $x_f y_,$) is triggered if in the inferior at the level Lp) column (with the same coordinate x) the propogation velocity hae a peak about the point where $j_j \sim y_,$| increases if y_0 $y_,$ and decreases if y_2 $y_,$. The larger^the coordinate $j^\wedge$ of the point (at the level Lp), where the propogation velocity curve reaches its peak, the greater is the corresponding coordinate T_2 of the triggered detector at the level $L_,$. The result is that the triggering of the detector in channel x at the level L_3 with the largest coordinate j_3 determines the amplitude of the sound pulse at the moment when its steepness ie maximal.

The level L_3 models the operation of the anterior division of the ventral cochlear nucleus. The presence of the detectors of steepness of sound pulse fronts in these nuclei has been established in electrophysiological experiments

The fourth level of the model L_n (that corresponding to the superior medial olivary nuclei) consists of the neurons which are coincidence elements. The pulses from the right and left side arrive at the inputs of these neurons through the delay lines - the neuronal dendrites. Here the neurons are also organized in "columns", each having the coordinate x and oriented in Y -direction.

At the level L^ the encoding of the sound amplitude in an additional delay takes place with the help of the following connection between $L_,$ and $L_,$: the greater the coordinate y/of the neuron - detector at the level L_7, the closer to coincidence element-^ at L.) will this detector signal be at the delay line (dendrite). Thus, on the right and left inputs of the element the "resultant" moments of signal arrival

(t_{rr} and t_{rl}) are formed. The coincidence element responds with a probability equal to 1, if the difference of the moments ($\Delta t_r = t_{rr} - t_{rl}$) of signals arrival from right and left is less than zero. The probability of response of the element decreases monotonously as Δt_r increases. Owing to the difference in the duration of the delay lines on the right and left in elements with different coordinates y_4, the shift of the above- mentioned characteristics occurs by a magnitude proportional to y_4. Finally, the distribution of probabilities of the responses of the neurons - coincidence elements - along axis Y is equal to 1 if the difference of the resultant moments is less than or equal to y_4 ($\Delta t_r \leq y_4$) and decreases monotonously if $\Delta t_r > y_4$. The coordinate y_4 of the point where the probability begins to decrease is equal to the difference of the resultant moments At - This y* thus determines the direction upon the sound source ($y^* \sim Y$)

The designation of the level L_5 (the analog of the inferior colliculus) is to effect the precision determination of coordinate y_4^*. Y_4 is brought out by statistical processing of the responses of a large number of elements at the level L_4. This operation is carried out by neuronal structures with lateral couplings.

As the final result at the level L_5 a local region of excited elements appears with coordinates x_5^* and y_5^*. The coordinate x_5^* describes the shape of the signal, and the coordinate y_5^* - the direction upon the source. At this point the determination of the direction is completed.

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