Letter

A Plastic Neural Network Model for Sound Therapy of Tinnitus

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Tinnitus is the perception of phantom sounds in the ears or in the head. Accordingly sound therapy for tinnitus has been proposed. To account for mechanisms of tinnitus generation and the clinical effect of sound therapy from the viewpoint of neural engineering, this paper describes a neural network model with a plastic coupling on the human auditory system. Through numerical simulations we observed an oscillatory state and a non-oscillatory state in the model; it was also noticed that the value of the plastic coupling changes by external stimulus, and subsequently the oscillation is inhibited. By associating the oscillatory state with the state of tinnitus generation, this could explain the fact that the habituated human auditory system temporarily stops perceiving tinnitus after sound therapy.

Keywords: Tinnitus, habituation, neural network model, plasticity, inhibition of oscillation, residual inhibition

1. Introduction

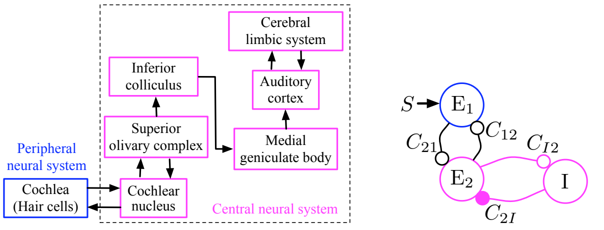
Tinnitus is the perception of phantom sounds in the ears or in the head. There are sound therapy techniques where those who suffer from tinnitus hear these therapeutic sounds for several hours a day (1). The sound therapies have the clinical effect that the sufferers temporarily stop perceiving tinnitus after the treatment.

The purpose of our study is to explain mechanisms of tinnitus generation and the clinical effect of the sound therapies from the viewpoint of neural engineering. Approximate models to account for a neural excitation phenomenon have been proposed (2) (3). In particular, Nagashino and Kinouchi (3) have reported that we can control an oscillation observed in the approximate model with a plastic coupling using external stimuli.

In this paper we describe a plastic neural network model which is associated with the human auditory system. We also discuss generation of an oscillation and its inhibition by external stimuli in the model, and subsequently we show that their phenomena could explain generation and inhibition of tinnitus.

2. Plastic neural network model

We illustrate a summary structure of the human auditory system in Fig. 1(a). The arrows denote channels of neural signals. Acoustic vibrations received by the ear is transformed into neural signals at the cochlea. The neural signals reach the cerebral limbic system through some neural tissues, and subsequently the brain perceives the neural signals as sound. When cochlear dysfunction occurs, abnormal neural signals from the cochlea causes abnormality in the central neural system. Consequently, tinnitus can be triggered. Note that the cochlear nucleus has an efferent neural bundle to control the sensitivity of the hair cells (4).



(a)Channels of neural signals (b)Neural network model

Fig. 1. The human auditory system and its conceptual neural network model

The current paper describes a conceptual neural network model to account for tinnitus generation and its inhibition from the viewpoint of neural engineering. Figure 1(b) shows the proposed neural network model of the human auditory system. The hair cells are represented by an aggregate of excitatory neurons "E$_1$". This is an incoming signal, S, which is associated with a sound signal. The central auditory pathway is simply represented as a neural oscillator. It consists of an aggregate of excitatory neurons and an aggregate of inhibitory neurons: "E$_2$" and "I". The neural coupling from the j-th aggregate to the i-th aggregate is expressed by the positive constant C_{ij}, $(i, j \in \{1, 2, I\})$. However, from the fact the efferent auditory pathway controls the sensitivity of outer hair cells (4), we assume that the coupling from E$_2$ to E$_1$ is plastic, i.e., C_{12} is one of variables. Then the dynamics of the model is described by

$$dx_1/dt = (-x_1 + C_{12}z_2 + S)/\tau_1 \cdots\cdots\cdots\cdots (1)$$
$$dx_2/dt = (-x_2 + C_{21}z_1 - C_{2I}z_I)/\tau_2 \cdots\cdots\cdots (2)$$
$$dx_I/dt = (-x_I + C_{I2}z_2)/\tau_I \cdots\cdots\cdots\cdots\cdots\cdots (3)$$
$$dC_{12}/dt = (-C_{12} + C_0 + bz_1z_2)/\tau_c, \cdots\cdots\cdots (4)$$

where z_j is the output of the j-th aggregate, which is given by

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$$z_j = (2/\pi)\tan^{-1}(x_j). \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

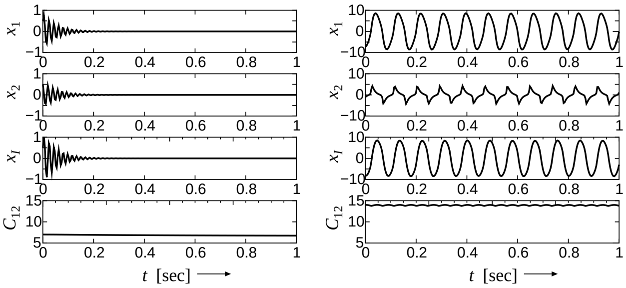
The x_j and τ_j are the membrane potential and the time constant of the j-th aggregate, respectively. The C_0, b, and τ_c are also positive constants which denote the equilibrium of C_{12} under $z_1 z_2 = 0$, the efficiency of strengthening the synaptic coupling based on Hebb's hypothesis (5), and the time constant of C_{12}, respectively.

3. Results of numerical simulation

We fixed the parameters in Eqs.(1)–(4) such that τ_1=0.01, τ_2=0.01, τ_I=0.02, τ_c=0.5, C_{21}=10, C_{2I}=10, C_{I2}=20, C_0=6.7, and b=20. We can easily find an equilibrium point in the dynamical system: (x_1, x_2, x_I, C_{12})=(0, 0, 0, 6.7). Figure 2(a) shows the behavior of a solution which starts at the initial point (x_1, x_2, x_I, C_{12})=(0.5, 0.5, 0.5, 7.0). This point is at the vicinity of the equilibrium point. The behavior eventually converges to the equilibrium point, i.e., the stable state according to the Lyapunov stability theory. On the other hand, we illustrate the behavior of another solution in Fig. 2(b); its initial point is (x_1, x_2, x_I, C_{12})=(-7.3, -1.0, -8.0, 14.0), which is far away from the equilibrium point. As a result, the behavior converges to the oscillatory state, and its fundamental frequency is about 11Hz. Through other simulations we observed that the behavior converges to the oscillatory state whenever the initial values are arranged at any point at the vicinity. Therefore, the oscillatory state is stable, and the model has the bistable state under the same parameters.

Let us demonstrate tinnitus generation and its inhibition based on the bistable state. We hypothesize that the oscillation and the equilibrium (non-oscillation) correspond to generation and inhibition of tinnitus, respectively. The result of a numerical simulation is shown in Fig. 3. The initial state is the equilibrium, i.e., tinnitus does not appear. The E_1 was provided with an external stimulation of $S = 1.5\sin 40\pi t$ for a small duration of $2 \leq t \leq 2.5$. At this point the value of $z_1 z_2$ increases substantially, and the value of C_{12} also increases from 6.7 to around 14. Concurrently the states of x_js change into the oscillatory states. Then the oscillatory states are sustained since they are stable. This phenomenon could be associated with the perception of tinnitus by abnormal sound generation from ears.

Let us add the sound, which is expressed by $S = 2.0\sin 10\pi t$, for treatment of tinnitus for a duration of $7 \leq t \leq 10$. As a result the waveform of $z_1 z_2$ decreases to a reduced vibration as it is represented in Fig. 3. This also results in the reduction of C_{12} value. Consequently, the oscillatory states of x_js are inhibited. By hypothesizing that the decrement of C_{12} corresponds to the habituation of the human auditory system for tinnitus, the phenomenon could explain the fact that the habituated human auditory system temporarily inhibits perception of tinnitus (i.e., residual inhibition) after sound therapy.



(a) Non-oscillatory state (b) Oscillatory state

Fig. 2. Non-oscillatory state and oscillatory state observed under the same parameters

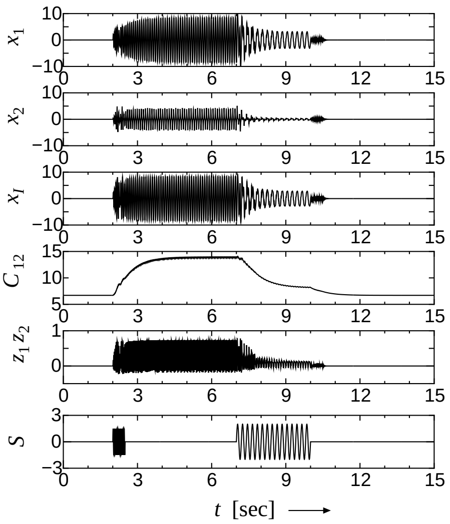


Fig. 3. Generation of oscillation and its inhibition by two kinds of external stimuli

4. Conclusions

We described a conceptual neural network model with a plastic coupling for the human auditory system. The model has an oscillatory state and an equilibrium state under the same parameters. The value of the plastic coupling alters as a result of an external stimulus. In other words generation and inhibition of the oscillation depends on the value of this plastic coupling. By hypothesizing that the oscillation and the equilibrium correspond to generation and inhibition of tinnitus, respectively, these phenomena could explain the fact that the habituated human auditory system temporarily halts perception of tinnitus following sound therapy.

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