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Dynamic population coding for detecting the distance and size of an object in electrolocation

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Abstract

Sensory systems utilize dynamical response properties of neurons to extract features of spatiotemporally varying stimuli. We propose a dynamic population coding of sensory stimuli in which the stimulus features are encoded into a spatiotemporal firing pattern of neuron population. Using electrolocation of weakly electric fish as a model system, we study how the spatiotemporal features of electric field modulated depending on the distance and size of an object are encoded into the spatial distribution and time interval between burst spikes of neuron population. We showed that the information about distance and size of object are represented as a function of the spatial area of and time interval between the synchronous firing of neuron population in a higher nucleus.

Keywords: Electrolocation; Dynamic population coding; Burst spike; Synchronous firing; Neural model

1. Introduction

In the early processing stages of many sensory systems, a stimulus is processed based on a specific map representing stimulus features. In the visual system, the features of visual stimuli are classified into elemental features such as boundary lines,

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their tilted angles, and colors and are represented in the neuronal maps specific to each feature: in the somatosensory system, the tactile information is processed based on the somatotopical map representing the location of a touch on the skin. The activity pattern of neurons on the map is well described by a Gaussian distribution whose maximum firing is given by the neuron tuned to the feature. This coding scheme has been well known as population coding. However, the populations of neurons in the early stages may also carry information about features of stimulus which are not explicitly represented on any map. The features are encoded into spatiotemporal firing patterns of relevant neuron population. The features of the patterns are not classified by the position of maximum firing neuron, but by the dynamical properties of response activity of neuron population such as spatial area of synchronized firing zone and interval between successive synchronized firings. We refer to this type of population coding as ‘‘dynamic population coding’’. However, it is not yet clear how the neuron population represents the stimulus features based on the dynamic population coding. To study the neural mechanism generating dynamic population coding, we adopted electrosensory system of a weakly electric fish. The electrosensory system gives us an ideal system to address this issue, because the electrosensory system has a relatively simple structure and the role of its circuitry in processing behavioral signals across multiple parallel sensory pathways has been well studied [7].

Electrosensory system allows fish to locate and identify an object in the absence of visual cue and signals from other sensory systems [1]. Weakly electric fish generates the electric discharge in its tail, and the current flow resulting from this electric organ discharge (EOD) causes a voltage to develop across the fish’s skin. The amplitude and phase of alternating voltage are modulated by an object, and they are measured by electroreceptors distributed over the fish body surface. An object, whose impedance is different from that of the surrounding water, will alter the spatiotemporal pattern of transepidermal voltage, and its alternation is encoded into neuronal impulse trains by the electroreceptors. The information about the modulations of amplitude and phase encoded by the electroreceptors is conveyed to electrosensory lateral-line lobe (ELL) and then transmitted to torus semicircularis (TS) as shown in Fig. 1.

When an object moves nearby a fish body, the receptors receive the electric signals with spatiotemporal structure. The fish can perceive a unique image of the object on the basis of the somatotopical mapping of receptor signals on ELL, which represents the location of the object on the fish body surface. However, the information about the distance and size of an object are not explicitly represented on the somatotopical maps, that is, there is no neuron tuned to each distance and size of an object. It has been demonstrated from the ethological experiments for pulse-type fish [13] that the fish can measure the distance of object using the ratio of maximum slope to maximum amplitude of the distribution of current across the skin over the body surface, suggesting that the information of object distance is encoded into the spatial firing pattern of receptor population. Experimental results [6,11] have also shown that the ELL neurons exhibit burst spikes under the application of electrosensory stimuli, suggesting that the features of the stimuli are represented by the