Chapter 12
Topological Coding in the Hippocampus

Yuri Dabaghian
University of California at San Francisco, USA

Anthony G. Cohn
University of Leeds, UK

Loren Frank
University of California at San Francisco, USA

ABSTRACT

The brain constructs internal representations of the external world, and one essential element of efforts to understand neural processing focuses on understanding the nature of these internal representations. This chapter examines the currently available experimental evidence concerning the physiological and cognitive mechanisms of space representation in humans and in animals, and in particular, on the role of the hippocampus. The hippocampus is essential for the ability to navigate through space, and hippocampal neurons tend to fire in specific subregions of an animal's environment. At the same time, it is not clear how the hippocampal representation of space is best described in terms of well-established mathematical definitions of space, nor is it clear whether the hippocampal representation is sufficient to construct a mathematical space. This chapter shows that, using only the times of spikes from hippocampal place cells, it is possible to construct a topological space, and it is argued that the hippocampus is specialized for computing a topological representation of the environment. Based on this observation, the chapter discusses the possibility of a constructive neural representation of a topological space.

BACKGROUND

The task of space perception and spatial orientation is one of the most fundamental tasks faced by animals. An animal plans and executes essentially every aspect of its behavior in the context of the space that it experiences through neural activity in its brain. Currently, there exists a significant amount of
data concerning the mechanisms of spatial encoding based on cognitive experiments and electrophysiological recordings from human, primate and rodent (notably rat’s) brain. These experiments suggest that the complete representation of the spatial environment appears as a result of a complex association of several complementary types of spatial information computed in different parts of the brain, which are involved in a complex neurophysiological interaction (Andersen, Synder, Bradley, & Xing, 1997; Burgess, Jeffery, & O’Keefe, 1999). A fundamental conceptual challenge in understanding the neurophysiological principles of space perception is the task of interpreting the patterns of neuronal activity in the brain as equivalent to a particular aspect of the spatial realm. This was recognized as early as 1895-1902 in the works of H. Poincaré (Poincaré, 1895), and E. Mach (Mach, 2004), who pointed out that spatial cognition and the cognitive basis of geometry are provided by the brain’s ability to build its own internal “representative” (Poincaré, 1895; Poincaré, 1898), or “physiological” (Mach, 2004), space. The analysis of the physiological organization of the sensory inputs known at the turn of the last century allowed them to make a number of interesting observations about the nature of various sensory (i.e. visual, tactile etc.) spaces. The current level of knowledge about the neurophysiology of spatial information processing as well as the mathematical concepts that can be used for interpreting the results of experimental observations are far more advanced, which allows for a much more detailed study of the phenomenon of representative space. Here we ask the following question: in what sense is it possible to define and to construct a space, as a physical and as a mathematical object, given the semantics of the neuronal system, i.e. the parameters of the spiking activity of neurons? We focus on currently available experimental results concerning the neural activity in the hippocampus – a brain area essential for spatial cognition (O’Keefe & Nadel, 1978; Hassabis, Kumaran, Vann, Maguire, 2007; Morris, Moser, Reidel, Martin, Sandin, Day, O’Carroll, 2003). Numerous experiments have shown that if the hippocampus is partially or completely damaged or impaired, the animal loses its full ability to solve many spatial navigation tasks, especially tasks based on following sequences of cues and on retrieving sequential (episodic) memories (Sharp, 2002), (Eichenbaum & Cohen, 2001; Kesner, Gilbert & Barua, 2002). The exact nature of the spatial information represented in the hippocampus remains somewhat unclear.

We propose an approach to hippocampal data analysis that allows us to not only describe many important aspects of the representative space and to match them with the properties of the environment. In addition, we address the deeper question of how can the neuronal firing patterns have spatial properties, i.e. in what sense a space can be build constructively out of neuronal activity. The goal of this enterprise is to understand, in a formal mathematical sense, the elements of the mental representation of space.

NEURONAL SPATIAL MAPS

Electrophysiological experiments examine the statistical correlations between patterns of neural activity and various external sensory and behavioral parameters. This approach led to the discovery that pyramidal cells in the rat hippocampus become active only when the animal is located in a relatively small portion of the environment and remain basically silent elsewhere (O’Keefe & Dostrovsky, 1971). Hence these cells (called “place cells”, $PC$) highlight a certain system of regions (called “place fields”, $PF$), and define a system of spatial “tags” via their firing activity. This place specific activity led to the hypothesis that the $PC$s encode a qualitative representation of the environment which has been referred to as “cognitive map” by O’Keefe and Nadel (O’Keefe & Nadel, 1978) and that this representation serves as one of the key elements of a rat’s spatial awareness.
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