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Cartesian Abstraction Can Yield 'Cognitive Maps'

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Abstract

It has been long debated how the so called cognitive map, the set of place cells, develops in rat hippocampus. The function of this organ is of high relevance, since the hippocampus is the key component of the medial temporal lobe memory system, responsible for forming episodic memory, declarative memory, the memory for facts and rules that serve cognition in humans. Here, a general mechanism is put forth: We introduce the novel concept of Cartesian factors. We show a non-linear projection of observations to a discretized representation of a Cartesian factor in the presence of a representation of a complementing one. The computational model is demonstrated for place cells that we produce from the egocentric observations and the head direction signals. Head direction signals make the observed factor and sparse allothetic signals make the complementing Cartesian one. We present numerical results, connect the model to the neural substrate, and elaborate on the differences between this model and other ones, including Slow Feature Analysis [17].

Keywords: cognitive map, Cartesian factorization, autoencoder, comparator hypothesis

1 Introduction

What is mammalian intelligence about? What are the key components necessary for the scientific and technological progress of mankind in the last 20,000 years or so? Are those very special to the human race, or for primates, or for mammals? Recent review suggests that the basic mechanisms, or algorithms are similar in rats and humans [8]. In their paper, Buzsáki and Moser propose that planning has evolved from navigation in the physical world *and* that navigation in real and mental space are fundamentally the same. They also underline the hypothesis that the entorhinal cortex and the hippocampus, the hippocampal entorhinal complex (EHC) support navigation and memory formation.

The importance of this complex was discovered many years ago [44]. Now, it is widely accepted that the EHC is responsible for episodic memory, see, e.g., [46] and [35] for an earlier review and for a recent one, respectively. The intriguing puzzle is that people are able to describe autobiographic events, can discover rules, in spite of the many dimensional inputs, such as the retina (millions of photoreceptors), the ear (cca. 15,000 inner plus outer hair cells), the large number of chemoreceptors as well as proprioceptive, mechanoreceptive, thermoceptive and nociceptive sensory receptors. This looks like an impossible mission, since the number of the sensors influence the size of the state space observed in the exponent and make it enormous. This number is gigantic even if the basis of exponent is only two. How is it possible to remember for anything in such a huge space?

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An illuminating observation to us is the fact that the brain develops low dimensional topographic maps manifested by retinotopy in the visual system, tonotopy in the auditory system, somatotopy in the somatosensory system, among many others. Such maps are related to some metric of the sensed space, being visual, auditory, or body related. The dimensionality of the maps are low unlike the number of the sensors that give rise to the map. One may say that (i) the representation, i.e., the topographic map, discretizes a low dimensional variable, (ii) both the space and the actual state are described by such variables, and (iii) the variables are like Cartesian coordinates at different cognitive levels, examples including the 'where' and 'what' system, or, the form and the color of an object, or, the face and facial expressions, or, the position and the direction of an animal in the world among others. In turn, we distinguish two factor types

Type 1 factors: These factors make no (or minor) assumptions on each other. Non-negative matrix factorization (NMF), for example, originates from chemistry: it is used in mass spectrometry and radiology among other fields, where absorbing or radiating components sum up. In a given environment and for a given detector system, the presence of different Radon isotopes depends on the environment and the detector, but they do not influence each others spectrum except that to a good approximation they sum up.

Type 2 factors: These factors assume each other and they are supposed to characterize objects and episodes. For example, texture, shape, weight, material components are all relevant when considering the value of a sword like a Damascus Khanjar. Nonetheless, the set of such factors is insufficient for providing a full description of the state of a sword; the state of the atoms or molecules. On the other hand, these Cartesian factors can give a fairly good and highly compressed description, suitable for communicating the usage and the value of the sword.

Sensory information brings about two interdependent task types: Information fusion and the related pattern completion make the first type. For example, when searching for food, the animal may use either visual information, or smell, or both. Thus, information fusion is about the Cartesian product of sensory modalities and pattern completion occurs in this product space. This task can be accomplished efficiently with sparse compressed sensing methods [13] that may have neuronal implications [42]. The other task is the formation of new, low dimensional maps, at least in a discretized form that are *not* having dedicated sensors. This is a kind of abstraction, when irrelevant details, judged from the point of view of the tasks, are cleaned off.

The concept of numbers is such an abstraction; it eliminates material properties. Two plus two equals four, no matter if we are concerned with apples or peaches. Such abstractions enable concise formulations for many similar tasks. The world of numbers is one dimensional and material properties are orthogonal to it, so it is like a coordinate system: quantity is one coordinate and the material substance is another. We are concerned with such generalized Cartesian factors.

Geometry uses concepts like points and straight lines, disregards physical interactions, which can be described by a different set of Cartesian factors. Geometry can serve many tasks including the computation of homing distance [9] and the prediction of the paths of planets. Cartesian coordinates or concepts are typically low dimensional. In the brain, the computations of Cartesian factors, like the estimation of homing distance, should be based on high dimensional sensors, including visual and vestibular information and the representation of novel Cartesian factors that are derived from those.

Laboratory coordinate system also called allothetic representation is the landmark of geometry representation. Such representation appears already in rats and supports path planning and navigation, possibly because it detaches the egocentric direction from the other parameters of the environment. The allothetic description is robust against certain changes in the environment, e.g., (i) the abstraction can be used both in light and in dark and (ii) it can be used efficiently in obstacle avoidance, since it is not

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