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Grid cell firing field detection using compressed sensing

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A R T I C L E I N F O

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The discovery of the striking tessellating firing fields of the grid cells has boosted research on brain circuits that dynamically represent self-location. The detection of such cells demands long-ran recordings, in order for the whole grid mosaic to be clearly revealed. The scope of this study is to present a methodology for unraveling the complete firing field of a grid cell even when it is poorly represented by the recorded spikes. The proposed approach is based on the fact that the recorded spikes of a grid cell during random navigation in the environment can be considered as a sampling process of the respective whole grid field (GF) seen as a binary image. In this work the Approximate Message Passing algorithm is used to reveal the whole GF image of a grid cell only by a few samples. The proposed approach was tested both in simulated and real data with promising results (mean squared error less than 0.15). The efficiency of the reconstruction process appeared to depend on the rat's route within the environment and on the respective probability of changing route direction in every step. The proposed approach pave the way for efficient methods to detect and identify grid cells. Nevertheless, experimentation with real rats' sample routes would further enhance the reconstruction efficiency. Overall, this paper tackles, for the first time, the problem of detecting grid cells' firing fields even if the corresponding recorded spikes do not represent their figure adequately and proposes respective signal processing methodology for its solution.

1. Introduction

The Medial Entorhinal Cortex (MEC) contains a two-dimensional (2D) map of spatial location expressed via the activity of functionally dedicated cell types: the grid cells [1], [2]. The grid firing fields (GF) of these cells are hexagonally arranged, independent of external sensory cues [3] and tile the entire surface of the environment exhibiting different spacing, orientation, and phase properties [4] (Fig. 1). In order to reveal the GF of a specific grid cell, e.g., a rat should navigate in the environment (e.g., a square room) while the activity of that grid cell is simultaneously recorded. The whole GF is revealed after long-ran recordings, while the rat's route has spanned the whole surface of the environment multiple times.

The main objective of this work is to present, for the first time, a method that will allow to reveal the whole GF shape, even if the recorded grid cell activity corresponds to only a portion of the surface of the environment or the GF is misrepresented by the recorded spikes. Towards this endeavor, the GF could be considered as a grayscale image where spiking and non-spiking activities are represented by zero pixel intensity and maximum intensity, respectively. Due to the fact that the intermediate intensities are not applicable, i.e., the existence or absence of a spike are represented by values 0 or 255 respectively, the GF image can be considered to be a binary image. GF images, as all natural images, are sparse signals in many dictionaries, such as wavelet or discrete cosine transform dictionaries (DCT) [5]. Thus, a subsampled version of the GF binary image (i.e., the image resulting after a short sample route of a rat within an environment) can be used to reconstruct the whole GF image by exploiting the Compressed Sensing (CS) Theory [6], [7] if certain requirements are fulfilled.

CS theory provides with the appropriate tools that aim to reconstruct images and signals, in general, using significantly fewer measurements than traditional approaches require. Reconstruction of images exploiting the benefits of CS theory have been extensively studied for various applications and a vast literature concerns reconstruction of biomedical images [8–15]. More importantly, CS theory has also been used for the reconstruction of natural binary images, as the ones used in this work, with DCT dictionaries [16]. One of the most popular scheme in terms of reconstruction under the CS framework, consists of linear programming (LP) methods [17]. Nevertheless, despite the reliable sparsity-undersampling tradeoff offered by LP methods they fall short in terms of computational efficiency. Iterative thresholding algorithms have been proposed in order to overcome the computation burden of LP approaches [18]. However, despite being fast, the iterative approaches fall short in terms of the sparsity-undersampling tradeoff. Recently, the Approximate Message Passing (AMP) algo-

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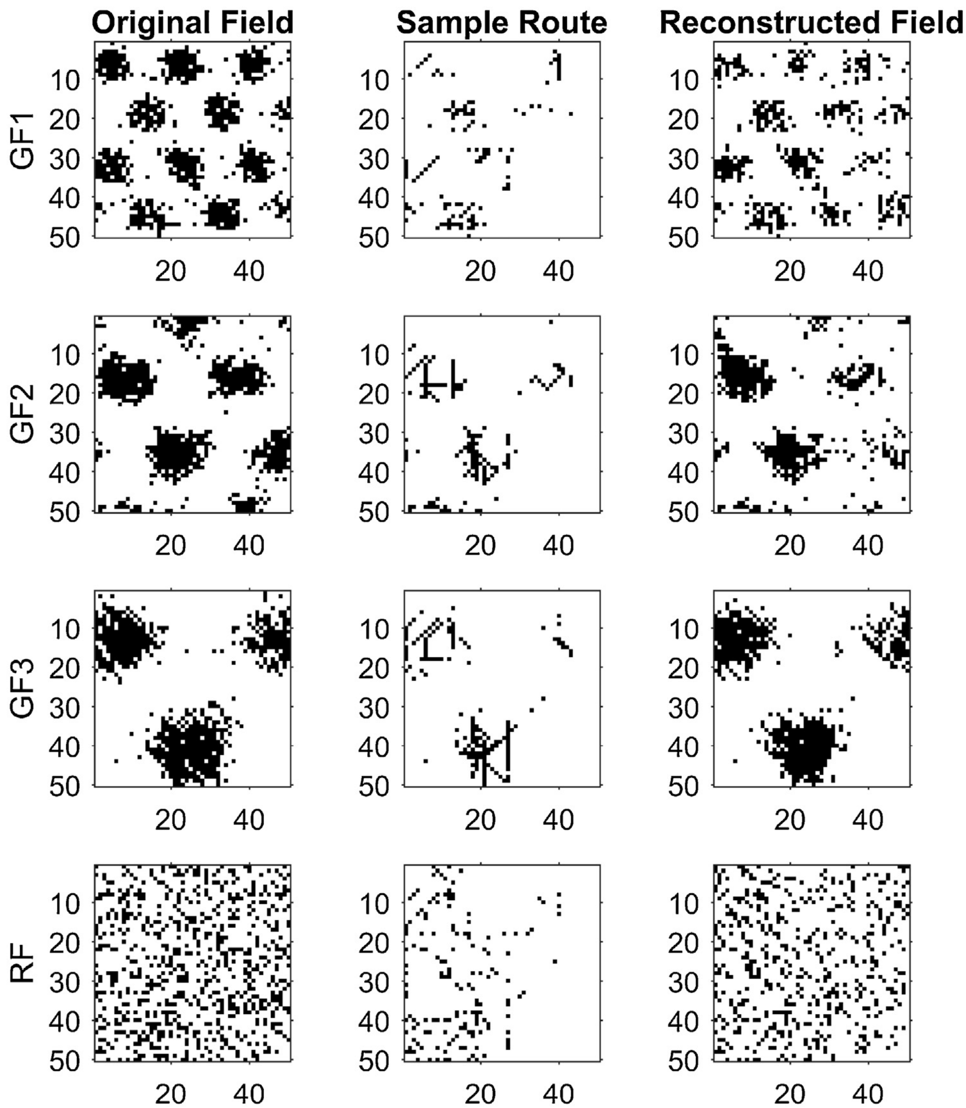

Fig. 1. Reconstruction of simulated grid cell firing fields (GFs) using Compressed Sensing. First column, GFs of three simulated grid cell activities with different phase, orientation and spacing along with a random firing field (RF). Middle column, simulated 750-step sample route (same for all GFs and RF) and corresponding spikes along the route for the GFs and RF. Third column, reconstructed GFs and RF using Approximate Message Passing [17] algorithm.

rithm was proposed [17] and regards to an iterative algorithm approach that not only achieves reconstruction performance identical to the LP methodologies but it also runs dramatically faster both from LP methods and other iterative algorithms. Moreover, AMP algorithm's performance has been evaluated on a wide range of image reconstruction showing its extensive applicability and reliability in image reconstruction problems [19–21].

Thus, in this work, we exploit the principles of the CS to propose a methodological approach to unravel the whole GF binary image from subsampled versions of it, using the AMP algorithm that guarantees reliable reconstruction along with fast implementation. To our knowledge, this is the first time the field of a grid cell is treated as a binary image and is reconstructed from subsampled versions that correspond to sample roots of, e.g., a rat.

The following section presents the methods that were developed in this work along with corresponding datasets used. Subsequently, Section 3 presents the results of the application of the proposed approaches on simulated and real data whereas Section 4 elaborates on limitations and future considerations. Finally, Section 5, sums up the presented work and concludes the paper.

2. Materials and methods

The methodological rationale behind the proposed approach originates from the fact that the final shape of the GF can be considered as a binary image (1s and 0s wherever there is a spike or not, respectively) depicting the hexagonal structure (Fig. 1, first column). Thus, each spike of the recorded grid cell corresponds to a random sample of the GF image (absence of spike is also a sample). Gathering such samples during the navigation of the rat in an environment (each step can be considered as a sampling act) will lead to a subsampled instance of the whole GF-image (Fig. 1, second column). Under this perspective, it is possible to use signal processing methodologies to unravel (reconstruct) the grid cell's firing field by using only the sample route recordings without knowing a priori the actual, whole GF shape (Fig. 1, third column). In essence, the grid cell's activity during sample route is considered as the sampling process of an image depicting the hexagonal GF structure. Indeed, in the proposed methodology the CS theory [22], [23] was utilized to unravel the whole hexagonal structure of a grid cell field from its sub sampled version.