Reconstructing Dream Content from Brain Activity: An Approach to Decoding Memory Consolidation Process during Sleep

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1. Introduction

It has long been thought that the brain utilized sleep to optimize the consolidation of newly acquired labile information in memory. In Norse mythology, Huginn (thought) and Muninn (memory) are a pair of ravens that fly off every morning all over the world in search of information. When they return to the god Odin at sundown, they would whisper into Odin what they have seen and heard.

Some recent studies [1-5] suggest that the brain adjusts its synaptic matrix during sleep and memory representations are changed quantitatively and qualitatively by sleep, whereas memory encoding and retrieval take place mostly during waking [6]. Rapid eye movement (REM) sleep and slow-wave sleep (SWS) seem to form the basis of synaptic consolidation in the cortex and system consolidation in the neocortical sites respectively [6].

Although the active system consolidation hypothesis [7] explains a re-activation dependent temporary enhancement and integration of newly entering memories into the network of preexisting long-term memories, the hypothesis alone does not explain “how post-learning sleep strengthens memory traces and stabilizes underlying synaptic connections in the long term” [6]. Despite a steady accumulation of positive and strong support for the existence of sleep-dependent memory consolidation over the past decade [8], the precise role of sleep in memory consolidation process[9] and what types of memory are consolidated during sleep [8] are still poorly understood.

Researchers used to rely on dream reports [8] given by the subjects themselves and other approaches to study dream content taking place during REM and SWS [6, 10]. Now, computational modeling of human brain can provide fundamental understanding about cortical representations [11, 12], and can support brain decoding mechanisms [13-15]. A latest study [16] showed that dynamic brain activity can be deciphered via current functional magnetic resonance imaging (fMRI) technology measuring blood oxygen level-dependent (BOLD) signals. The team used a motion-energy encoding model [17] in a Bayesian framework to predict BOLD signals, such that they, for the first time, reconstructed natural movies from human brain activity.

Figure 1: The top row shows segments of a Hollywood movie trailer that the subject viewd while in the magnet. The bottom row shows the reconstructions of these segments from brain activity measured using fMRI. In this static figure only the first frame of each segment is shown. (Attribution: Shinji Nishimoto & Jack L. Gallant, UC Berkeley, 2011 [16])

This modeling framework may form the basis for reconstruction of dream content of human or small animal brain during sleep. Another study demonstrated that BOLD signals evoked by visual imagery are more obvious in ventral-temporal visual areas than in early visual areas [18], which implies that a hybrid encoding model that combines the structural motion-energy model with a semantic model developed in previous studies [19] could provide better reconstructions of subjective experiences [16].

2. Objectives

- Proposing the best hybrid model which combines the structural motion-energy model with a semantic model to reconstruct dream content from human or small animal brain activity.
- Providing compelling evidence to support a relationship between sleep and memory consolidation.
- Determining what types of memory are consolidated during sleep.

- Demonstrating that the reconstruction of dream content can be applied to research purposes (such as Psychology) or entertainment.

3. Methodology

3.1 Functional Magnetic Resonance Imaging (fMRI)

Currently, fMRI, introduced by Ogawa et al. [20], is the best neuroimaging tool available for non-invasively measuring brain activity with high spatial resolution [16, 21, 22]. Besides conventional MRI and diffusion MRI, fMRI is getting more and more popular as a tool for understanding the mechanism of brain [23].

3.2 Electroencephalography (EEG)-fMRI Fusion

Due to the diverse nature of cerebral activity, it is reasonable that migrating from unimodal recordings (EEG or fMRI) to multimodal measurements will provide neuroscientists with more understanding of the nature of cerebral activity [24].

3.3 Motion Energy Analysis (MEA)

MEA is conducted on a series of movie frames [25]. Motion energy can be described as an input to first- and second-order motion systems by performing a three-dimensional Fourier analysis of the image cube [17, 26].

3.4 Bayesian Framework

Bayesian networks are graphical structures for representing the probabilistic relationships among a large number of variables and doing probabilistic inference [27].

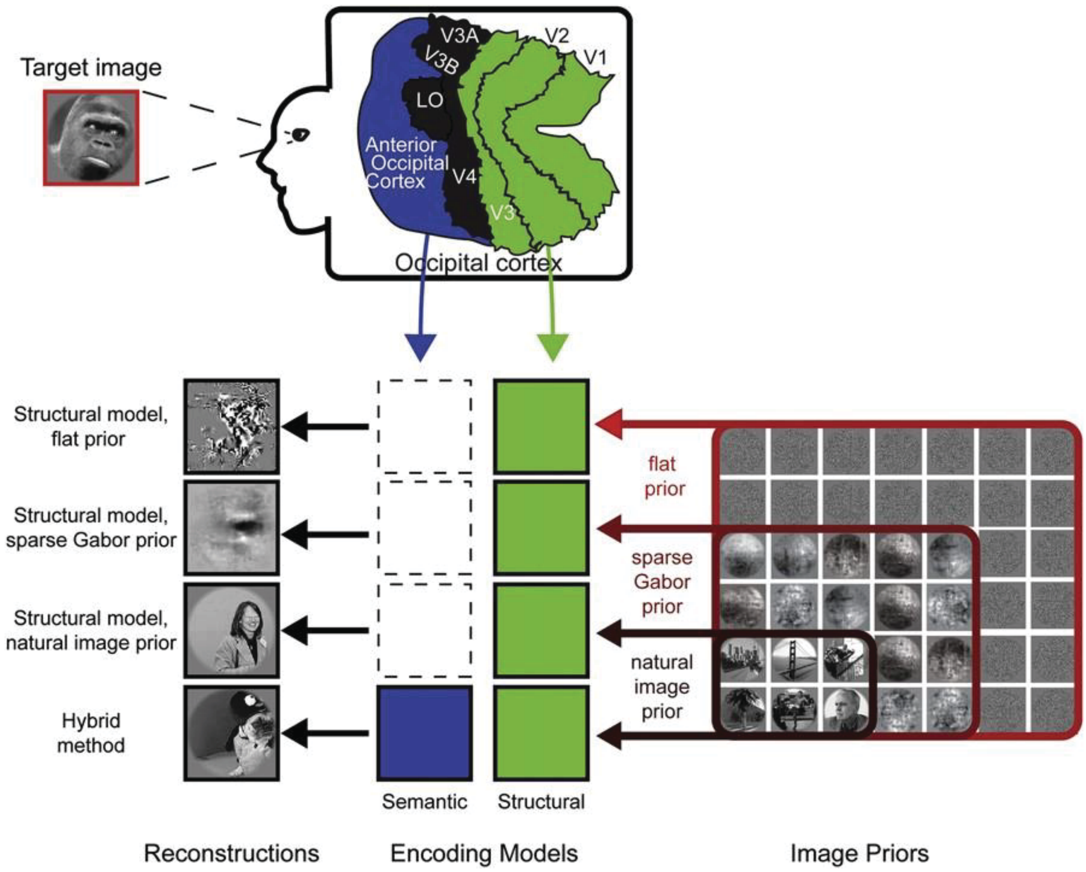

Figure2: The Bayesian Reconstruction Framework. (Attribution: Thomas Naselaris, Ryan J. Prenger, Kendrick N. Kay, Michael Oliver, and Jack L. Gallant, UC Berkeley, 2009 [28])

In [16, 28], researchers use a Bayesian framework (shown in Figure2) to combine voxel responses, structural and semantic encoding models, and image priors.

3.5 Parallel Computing

The availability of computational resources plays a key role in determining what kinds of computational investigations are possible [29]. When doing fMRI analysis, one of issues which has to be addressed is the large amount of spatio-temporal data that needs to be processed [23]. The growth of this bound used to be ruled by Moore's Law [30]. Currently, advances in highly-parallel graphics processing hardware, especially graphics processing units (GPU), have enabled over hundred-fold speed-ups when applied to the analysis of fMRI data [23]. GPU computing follows a parallel pattern called Single Instruction Multiple Thread (SIMT). With SIMT, a GPU executes the same instruction set on different data elements at the same time.

Although doing the fMRI analysis on the GPU opens up lots of possibilities [23], programming GPU is somewhat time-consuming and difficult. The Jacket MATLAB GPU Library developed by AccelerEyes is designed to write and run MATLAB code on the GPU in the native M-Language. Jacket accomplished this by automatically wrapping the M-Language into a GPU compatible form, which allows high level language as MATLAB to utilize GPU computational platform and therefore speeds up algorithms of the proposed research.

4. Summary

The motivation of this research is twofold: On one hand, reconstruction of dream content aims to help us understand the mechanisms that regulate memory consolidation process during sleep; On the other hand, this research can contribute to the emergence of new neural network architectures and training methods, which can then be used as a tool for testing and verifying new hypotheses and discoveries in neuroscience. Moreover, the reconstruction of dream content itself can have many other potential applications in academic fields and daily life.

This document has presented a research proposal to reconstruct dream content from brain activity. The main question is how we can use fMRI and proper computational model to encode and decode subtle and elusive subjective mental experiences from brain activity during sleep, and how we can use this information to understand the role of sleep. The use of fMRI is proposed, and an algorithm based on motion energy analysis and Bayesian framework will be followed. When possible, GPU parallel implementations and EEG-fMRI fusion will be considered.

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