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Decoding of object categories from brain signals using cross frequency coupling methods

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ABSTRACT

The procedure by which information about conceptual category of visual objects is encoded in brain signals, is the topic of many studies in the field of visual system. A phenomenon that is recently mentioned as one of information encoding strategies in the brain is cross frequency coupling (CFC), means the interactions between different frequency bands in physiological signals such as EEG. This interaction can occur between various components of such signals including amplitude or power, phase and frequency. Different types of CFC have been reported in various cognitive tasks and within or between different brain regions. However the role of CFC in encoding of information about the category of visual objects is greatly unknown and here we attempted to investigate it. So in this paper, we used machine learning algorithms to find out whether CFC contains such information. To this end, we recorded EEG from 10 participants while they were observing stimuli from 12 different visual object categories. Then amplitude–amplitude coupling (AAC), phase–amplitude coupling (PAC) and phase–phase coupling (PPC) within each electrode were calculated for the recorded signals in order to use them as input to SVM classifier. The results show that phase-phase coupling can provide more information about the category of objects compared to other types of CFC, by classification performance of 92.33% against 70.28% and 60.52% for phase–amplitude and amplitude–amplitude coupling, respectively. In addition, this feature was more informative when occurred between alpha and gamma frequency bands. The performance of classification by means of CFC features was then compared with the result of classification by wavelet transform on the same data. We observed that PAC can improve the performance of categorical-based classification relative to wavelet coefficients (with the performance of 70.73%). So we can conclude that cross frequency coupling encompass useful information about semantic category of stimuli which is not available in time-frequency components of the signal obtained by wavelet transform.

1. Introduction

Human visual system is capable of perceiving the nature of different objects in a fraction of a second and categorizing them in various conceptual groups. Object recognition is the problem of discovering how brain can do it in spite of different ways of mapping the pictures of these objects on the retina. To understand it, we should first recognize the relevant regions in the brain and their communications then we must present algorithms and hypotheses which can explain the process of recognition of objects through the activity of these regions. To do it, at the first stage, it is essential to record the activities of various regions of the brain with an acceptable spatial and temporal resolution in response to stimuli consist of objects from various categories. Neural activity in different regions of the brain and different layers of the cortex results in generating oscillating electrical field potential which can be recorded from the surface of the scalp. The oscillating activity that is recorded in this way is named electroencephalography (EEG) and consists of several frequency bands. Five well known frequency bands in EEG signal include delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (above 30 Hz). When neural activity oscillates in a certain frequency band, it needs a period

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of time to complete its oscillation cycle. So the time window that is provided by oscillatory activity for neural signal to effect on the brain condition is specific to the quantity of working frequency. Accordingly, activity in different frequency bands leads to activity in different temporal and also spatial scale so that low frequency oscillation is a signature of the influence of neuronal activity in a more extensive space and a longer time window than high frequency oscillation [36,47].

Electrical activity of neuronal populations in each frequency band depends highly on the ongoing cognitive state of the brain. For example neural activity in alpha band, is often associated with the situation in which no considerable information is processed in the brain so that when the eyes are closed, this wave can be more observed [1]. In contrast, beta band oscillation is more associated with local processing and active inhabitation [2] and theta band activity is more reported in tasks related to memory, anxiety and punishment [3]. Delta oscillations are usually recorded in deep stage 3 of NREM sleep which is named slow-wave sleep too. Finally, the activity of neuronal populations which oscillates in Gamma frequency band usually participates in encoding of cognitive states such as attention [4,55] or object recognition [32–34].

Different frequency bands can occur simultaneously in the brain and recorded in EEG signal. In addition, according to the results of electrophysiological studies, these frequency bands have some mutual interactions with each other. These interactions that have the capacity of providing more complex control networks, than activity in distinct frequency band, are named cross-frequency-coupling (CFC) [5]. CFC can play an important role in providing a connection between distinct neuronal populations, computational neuronal processes and coordinating them. In fact CFC which often occurs within or between regions of brain is related to the type and stage of information analysis in brain processes. According to the main aspects of electrophysiological signals (such as EEG) including amplitude or power, phase and frequency, we can describe several types of coupling between different frequency bands. For example amplitude–amplitude coupling (AAC) is a kind of interaction in which the amplitude of the signal in a certain frequency band modulates the amplitude of the signal in another band [6]. Similarly, the other types of CFC including phase–amplitude coupling (PAC) [7], phase–phase coupling (PPC) and amplitude–frequency [8], phase–frequency and frequency–frequency coupling can be introduced [9].

There are some measures to quantify the amount of each type of CFC. For example to measure PAC we can use phase locking value (PLV) which is introduced to estimate the time variation of phase coupling of signals in two frequency bands [10]. The other criterion to measure PPC is n:m phase synchrony which can estimate the quantity of phase coupling between two signals oscillating in two distinct frequency bands by measuring synchrony between their phases [11–13].

Although some types of CFC is less studied and reported in brain processes, but some types, such PAC has attracted more researchers' attention in recent years. For example in [14–16] it has been shown that amplitude of oscillations in gamma band increased in a specific phase of signal in theta band. This interaction which is reported in Prefrontal Cortex (PFC) and entorhinal regions indicates the occurrence of PAC. This kind of CFC (coupling between theta phase and gamma amplitude) has been reported in a wide range of brain areas in different cognitive tasks such as word recognition [17]. Interaction between frequency bands is reported in various species include human, non-human primates [18,19] and also rodent [20].

Our main purpose in this paper is to investigate the role of CFC in object recognition means to know if brain uses this encoding strategy to distinguish the nature of visual stimuli it observes or not. Although the circuits and brain mechanisms of brain object recognition is not completely discovered, there are some works that have achieved acceptable results on this problem [21,22] among them there are some studies which have used EEG as their recording method [23–26], so we are sure that EEG signal contains such information. The result of such studies can be used to improve the performance of neural prosthesis or brain machine interface systems acting for translating the cognitive condition of the brain.

In this study, we designed a decoder which was able to classify the EEG signals according to the related category to evaluate how information about the semantic category of object is encoded in EEG. To do so, we tried to extract three types of cross-frequency coupling, including phase–phase, phase–amplitude and amplitude–amplitude CFC within each recorded electrode between different frequency bands. Then we used SVM classifier to separate the signals belonging to each category. We found that phase–phase coupling lead to the best classification accuracy. The frequency bands which their mutual interactions in the form of phase–phase coupling had the most information about the semantic categories were alpha–gamma and the most effective electrodes in classification process were the electrodes located in frontal and parietal lobes. In addition we found that PAC enhanced the classification performance compared with wavelet features.

2. Methods

2.1. Subjects

In this study we used the offline data recorded from 10 adult volunteers. Subjects consisted of 8 males and 2 females (18–28 years, 9 right and 1 left handed). They reported neither psychological and neurological disorder nor abnormally in vision. After pre-processing, the data from the 4th and 5th subjects were discovered to have a lot of uncorrected artifacts and were remove from the analysis.

2.2. EEG recording

EEG was recorded using a 19 channel recording cap which was designed for EEG recording based on standard techniques. 19 recording electrodes which were selected from 10–20 system of electrode positioning with linked ears montage were FP1, FP2, F3, F4, C3, C4, P3, P4, F7, F8, T3, T4, T5, T6, FZ, CZ, PZ, O1, and O2

2.3. Stimulus presentation

Images from 12 semantic categories including animals, flowers, fruit, transportation devices, body organs, clothing, food, stationery, buildings, electronic devices, dolls, and jewelry were taken from internet All these images were colored and the same size (600×800 pixels) and were displayed on the center of the LCD monitor which was located at a distance of 75 cm from the subject's eye. In order to minimize eye boredom and eye-blinking artifact on EEG, we designed the experiment in two sessions. In the first session, six categories were presented and the next six categories were displayed in the second session. Five exemplars were shown in each category. 360 images were totally presented to each subject during the whole period of the experiment. Subjects had a 3 min rest period between sessions. Categories were assigned to each session according to a fixed order for all subjects but they were selected randomly once at the beginning of the experiment. In each trial (related to a specific category) 30 images were presented, 15 images from a given category (target) and the other 15 images randomly selected from the other categories (non-target). Non-target images were presented among the target images. Each trial was presented only once for each subject and the subjects were not informed about the order of the trials.