Volitional Phase Control of Neural Oscillations Using a Brain-Machine Interface

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Abstract— Strong oscillations present in local field potential (LFP) recordings at specific frequencies are thought to be correlated with behavior and involved in communication and coordination across brain areas. LFP-based brain-machine-interfaces (BMIs) lay the groundwork for using closed-loop BMIs to study oscillations across brain regions and to test hypotheses about the rigidity of relationships between oscillations. In this study, we demonstrate the first reported use of inter-regional phase differences to control a BMI. In a one-dimensional two target task where phase difference is mapped to cursor velocity, we show that a macaque monkey, implanted with microwire arrays bilaterally is able to control phase extracted from distal electrodes in left motor cortex (M1) and right dorsal pre-motor cortex (PMd) at frequencies of 20 Hz, 31 Hz, and 40 Hz well above chance, but not at 10 Hz and 50 Hz. Our results imply that within the beta band (15-40Hz) in motor cortex and pre-motor cortex, phase relationships can be volitionally controlled.

I. INTRODUCTION

The phase of neural oscillations is hypothesized to be involved in neural computation. On the microscopic level, oscillatory external electric fields applied to a cortical slice entrain neurons to fire at a preferred phase of the applied oscillation [1], [2]. In vivo, there is evidence of phase-locking of single-unit spikes to local field potential (LFP) oscillations in visual cortex, motor cortex, and hippocampus [3], [4].

Several theories suggest that phase locking of oscillations may play a functional role within the brain. The communication through coherence paradigm advocates that transient synchronization between distinct brain areas enables information to pass between those areas preferentially [5], [6]. Other work shows that the phase of lower frequency oscillations can be coupled to the power of higher frequency oscillations, implicating a phase-driven hierarchical relationship of oscillations [7]. Beta oscillations have been shown to propagate through primary motor cortex (M1) and dorsal pre-motor cortex (PMd) during motor preparation with a spatiotemporal structure resembling traveling waves [8]. However, what remains unclear is first, how rigid the structure of coupled oscillations and propagating waves are and second, what role if any these relationships play in neural computation.

To study phase locking of oscillations in vivo, we use an operant conditioning paradigm in the form of a closed-loop brain-machine-interface (BMI) task. In this setup, subjects receive feedback of their neural activity mapped into a task, and are rewarded for specific neural modulation patterns. Canonically, BMI has relied on modulation of the firing rate of single neurons [9]. However, volitional modulation of low-gamma LFP power has recently been demonstrated [10]. This result inspired us to use phase of LFPs as a BMI control signal to: 1) determine if it is possible to modulate the phase relationship of ongoing oscillations, and 2) to probe the degree of flexibility of these relationships across motor cortex. In our ‘Phase-BMI’ task, phase differences between two distal regions of motor cortex control the velocity of a cursor confined to moving on a one-dimensional line toward targets for a liquid reward. Here we show results from one monkey performing Phase-BMI.

II. METHODS

A. Task

The Phase-BMI task consists of a cursor that is moved on a one-dimensional horizontal line. The task requires that the cursor first reach a central cue and hold for 200ms. Then, either a left or a right target appears 6.5 cm away and the subject has 20 seconds to move the cursor to the new target. If the target is successfully reached, a liquid juice reward is delivered, and the center cue reappears indicating the start of the next trial. If the target is not reached in 20 seconds, the target disappears requiring the monkey to restart the trial. The order of targets occurs in pairs of one left and one right target, but either left or right target can appear first. Both the central cue and peripheral targets are 1.7 cm in radius. The subject performs as many trials as he can within a block of 10 minutes. In a single day of testing, 8-12 blocks are performed.
B. Electrophysiology

One adult male rhesus macaque (Macaca mulatta) was used in this study. One microwire array of 128 teflon-coated tungsten electrodes (35 μm diameter, 500 μm wire spacing, 8×16 array configuration; Innovative Neurophysiology, Durham, NC) was chronically implanted in each hemisphere, targeting the arm areas of M1 and PMd. All procedures were conducted in compliance with the National Institute of Health Guide for Care and Use of Laboratory Animals and were approved by the University of California, Berkeley Institutional Animal Care and Use Committee.

Electrodes selected for use in the task were chosen in left M1 and right PMd to maximize the physical distance between them. Previous work has shown strong phase-coupling between prefrontal and motor cortex [8]. Therefore, using a pair of electrodes that maximized physical distance would increase the chance that a subject could decouple the two signals and use their relative phase difference to control the BMI.

C. Phase Calculation

To calculate phase difference at a desired center frequency $f_c$, the LFP signal from each electrode was convolved with a complex-valued chirplet function:

$$g(t|t_0, s_0, v_0, c_0) = 2^4 \exp \left( -\frac{1}{4} s_0 \right) \exp (-s_0) + \ldots \pi (t - t_0) (c_0 (t - t_0 + 2v_0) \right)$$

where $t_0$ is the center time, $v_0$ is the center frequency, $s_0$ is the duration parameter, and $c_0$ is the chirp rate. In this study we use a fixed chirp rate of 0 Hz/s (no chirping) and a fixed fractional bandwidth (FWHM/center frequency) of 0.2. The convolution generates a complex-valued time series. The angle of this time series defines the phase of the LFP at each time point for the particular center frequency $f_c$.

D. Cursor Movement

Cursor position is restricted to a horizontal line. For two selected electrodes ($e_1$, $e_2$), phase calculations are made in real-time and smoothed over a 500 ms window. The phase difference between $e_1$ and $e_2$ ($\Delta \theta = \theta_1 - \theta_2$) is calculated and mapped to cursor velocity (cm/s) through the following function:

$$\vec{v}(\Delta \theta) = a \ast \text{speed}_{\text{max}} \ast \sin(\Delta \theta)$$

where $a = 6.5$ (scales velocity to cm/s). This sine function was chosen so that a perfectly synchronized electrode pair ($\Delta \theta = 0$) would map to a velocity of 0 cm/s. In addition, the function is continuous between $-\pi$ and $\pi$ allowing for smooth control of the cursor.

Some of the tested frequencies and electrode pairs tested exhibited a non-zero mean phase difference, which would give the cursor a directional bias in the task. For these cases, the mean phase difference ($\bar{\Delta} \theta$) is determined and velocity is subsequently calculated as:

$$\vec{v}(\Delta \theta) = a \ast \text{speed}_{\text{max}} \ast \sin(\Delta \theta - \bar{\Delta} \theta)$$

The speed$_{\text{max}}$ parameter defines the maximum permitted cursor speed, which is reached when $\Delta \theta = \bar{\Delta} \theta = -\pi/2$ or $\pi/2$. If speed$_{\text{max}}$=1, the maximum cursor speed is 6.5 cm/s, allowing the cursor to move from the center position to a target in 1 second. During initial learning of the task, speed$_{\text{max}}$ is set to 0.8 but then later is reduced to 0.5. This reduction increased the difficulty of the task by requiring $\Delta \theta$ to be modulated away from $\bar{\Delta} \theta$ for a longer period of time in order to reach the targets that were the same distance away from the center.

E. Chance calculation

Three methods of estimating chance level are used. In the first method, after completing several task blocks the screen is shut off with the task and reward still running. Neural activity is recorded, the cursor position is updated, and rewards are given if the cursor hits targets. This method targets the expected performance when the subject’s ongoing neural activity is not responding to feedback from the task.
The second method of calculating chance is done offline by preserving the original cursor trajectory, but evaluating task performance for a new set of random targets. This procedure tests the direction-specificity of cursor movement when it is under closed-loop volitional control.

The final control generates simulated cursor trajectories by sampling phase differences from an empirically defined distribution from a 10-minute block of neural activity. Random samples drawn from this distribution are used as neural activity and the correct number of targets is recorded.

III. RESULTS

A. Behavioral performance

We tested performance on Phase-BMI with five different center frequencies: 10 Hz, 20 Hz, 31 Hz, 40 Hz, and 50 Hz and speed$_{\text{max}} = 0.5$ (except 50 Hz where speed$_{\text{max}} = 0.8$) compared to task performance without visual feedback, or screen off, (blue).

Figure 2 Comparison of subject’s performance during task (black) using the phase differences at center frequencies of 10, 20, 31, 40, and 50 Hz and speed$_{\text{max}} = 0.5$ (except 50 Hz where speed$_{\text{max}} = 0.8$) compared to task performance without visual feedback, or screen off, (blue).

Figure 3 (A) Distribution of reward trials when a block’s cursor trajectory from runs through simulated tasks with randomized order of targets. Blue dashed lines mark mean and three s.d. away. The black bar marks actual performance. (B) Subject performance normalized by mean and s.d. of simulated distribution from day, plotted by frequency. Blue dashed line marks three s.d. above mean of simulated distribution.

Figure 4 Block-by-block performance over days with different frequency conditions tested (color). Number of reward trials acquired in each block is normalized by the mean of the distribution of simulated trials (second chance method). First block of day is an open circle.
from the mean are shown with the blue dashed lines, and the black bar marks the monkey’s performance on the actual task. In Figure 3b, for each frequency condition, a marker and three standard deviations away from the mean are shown with the blue dashed lines, and the black bar marks the monkey’s performance on the actual represents the average number of trials per block averaged over each day, normalized by the mean and standard deviation of the distribution of reward trials expected by chance. The average performance for each frequency is 2.13, 5.57, 9.77, 5.66, and 1.43 standard deviations above mean chance level for frequencies 10 Hz, 20 Hz, 31 Hz, 40 Hz, and 50 Hz respectively.

The final method of chance calculation yielded zero reward-trials for all conditions. Since this method did not account for the temporal structure of the phase differences, it produced unrealistic trajectories resulting in no targets.

To visualize what the subject does to succeed in the task, Figure 5a illustrates an example mean distribution of phase differences (\(\Delta \theta - \Delta \hat{\theta}\)) over one day of blocks 31 Hz at speed_{max} = 0.5 split into trials toward the left target (blue) and toward the right target (red). To quantify and compare the difference between the distributions, KL divergence was calculated (Figure 5b). For frequencies with performance well above chance, KL divergence is high compared to frequencies with performance below chance.

IV. DISCUSSION

This is the first demonstration using phase difference of neural oscillations as a control signal in BMI. Figure 3b shows that phase difference at frequencies of 20, 31, and 40 Hz are easiest to control above chance level, and phase differences at 10 and 50 Hz may not be possible to control or may be more difficult to control.

These results may be interpreted as showing only that longer exposure to the task results in improved performance. Figure 4 shows that this is not the case since there is a drop in performance from testing at 20 Hz to 10 Hz, indicating the difficulty of the 10 Hz condition compared to 20 Hz. In the 31 and 40 Hz condition, however, there appears to be a positive sloped learning curve, indicating that longer testing could have resulted in higher performance and perhaps that the subject uses similar strategies for 31 Hz and 40 Hz.

The frequencies 20, 31, and 40 Hz all fall within the beta band (15-40 Hz), which is the dominant rhythm in motor cortex during task-related events. The finding that the subject could only modulate the phase of oscillations in beta band implies that an ongoing oscillation may need to be prominent in order to volitionally modulate its phase. In particular, it was noted that this subject explored motor movements, albeit not in a consistent manner, while he was learning the task. These motions may have increased power of beta band oscillations, enabling him to control their phase.

These results demonstrate this subject’s ability to volitionally control phase differences in the beta band between electrodes in left M1 and right PMd. In future work, we plan to vary the spatial location of electrodes and increase the difficult of the task to better understand the limits of spatiotemporal control of cortical oscillations.

REFERENCES