Tracking Multiple Phase Coupling Dynamics on a Single Trial Basis

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Abstract—Phase synchronization plays a major role in the large-scale integration of information in the brain. Therefore, the quantification of phase coupling dynamics is of particular importance in the neuroscientific research. Recently, we developed a new multiple phase coupling measure that can be utilized to quantify multiple phase associations in multi as well as in single trial analyses. In this paper, we demonstrate how this method can be utilized to reveal changes in phase coupling on a single trial basis. Furthermore, we introduce a new test criteria that is based on surrogate data and apply the whole methodology to EEG data derived from an insight experiment. The results indicate enhanced alpha phase coupling between right occipitoparietal and left prefrontal regions whose strength differs between conditions. This outcome fits the hypothesis that these regions interact to coordinate insight-specific inhibition processes.

Keywords—phase coupling dynamics, eeg, multiple circular-circular correlation, insight, single trial analyses

I. INTRODUCTION

The synchronization of oscillatory neural responses plays a crucial role for the evolution of neuroscientific research. Phase couplings are usually associated with the transfer of information and they are discussed as the potential mechanism for large-scale integration in the brain [1]. Accordingly, phase couplings between more than two signals are of particular interest. Recently, we developed a multiple circular-circular correlation coefficient that can be utilized to quantify such multiple phase relationships in a reliable manner. In comparison to other phase coupling measures, it captures trigonometric phase associations and it may be applied in single trial analyses [2]. Therefore, this measurement is especially useful whenever complex cognitive phenomena are investigated. One example for this category process is the insight phenomenon. Insight designates the sudden understanding of a problem situation and is commonly known as "aha" moment or "eureka" effect. Like other complex cognitive abilities, it is characterized by a high inter-trial variability such that an examination on a single trials basis is advantageous [3]. In the following, we demonstrate how our new method can be utilized to track such phase coupling dynamics and discuss some implications for future research.

II. MATERIALS AND METHODS

A. Methodology

Prior to the actual coupling analysis, some basic processing steps are necessary. First of all, the EEG signals have to be preprocessed adequately. Afterwards, relevant frequency bands need to be extracted. To estimate the corresponding instantaneous phase values, the Hilbert transform can be utilized. This transformation provides a time series of phase values $\phi_j(t)$ for the signal at each electrode. On the basis of these phase values, phase synchronization processes can now be quantified regardless of existing amplitude associations. Usually, researchers create hypotheses in advance about which regions are involved or drive these coupling processes. According to this prior knowledge, $k$ predictive electrodes can be specified that are correlated with a certain independent electrode or each other electrode successively. The multiple circular-circular correlation between an independent phase variable $\phi_0$ and $k$ predictive phase variables $\phi_1, \cdots, \phi_k$ is then given by [2]:

$$MC(\phi_0, \cdots, \phi_k) := \frac{1}{2} tr \left( S_{\hat{u}_0\hat{u}_0} S_{\hat{u}_0\hat{u}_1} S_{\hat{u}_1\hat{u}_1} \cdots S_{\hat{u}_k\hat{u}_k} \right)$$  \hspace{1cm} (1)$$

In this equation, $+$ denotes the Moore-Penrose pseudoinverse of a given matrix and $tr$ its trace, while the variance-covariance matrix $S_{\hat{u}_v\hat{u}_w}$ for $v, w = 0, k$ is defined as:

$$S_{\hat{u}_v\hat{u}_w} := \sum_t \left( \bar{u}_v(t) - \bar{u}_v(t) \right) \left( \bar{u}_w(t) - \bar{u}_w(t) \right)$$  \hspace{1cm} (2)$$

with $\bar{u}_0 := (\cos \phi_0, \sin \phi_0)$ the unit vector corresponding to the independent phase variable $\phi_0$, $\bar{u}_k := (\cos \phi_1, \sin \phi_1, \cdots, \cos \phi_k, \sin \phi_k)$ the 2k-dimensional vector built of the unit vectors of all predictive variables $\phi_1$ till $\phi_k$ and $t$ the time. To track phase coupling dynamics, this correlation is not calculated for the entire trial but for distinct time windows $t \in [t_n, t_n + 1]$. The length of these time intervals depends on two important criteria: the sampling frequency and the frequency range that shall be investigated. The time window should be long enough to capture an entire period of the signal of interest and it should contain enough sampling points to receive a reasonable correlation estimation. Due to the natural dependencies between the
different time points, the usual multiple circular-circular correlation test cannot provide reliable results [2]. Instead, a test criterion based on surrogate data is applied. To calculate this test criteria, the sample \( \phi(t) \) is shuffled pseudorandomly 200 times. Afterwards, the correlation of \( \phi_1, \cdots, \phi_k \) with each shuffled sample is calculated. The number of correlations greater than the correlation of the actual sample divided by 200 then gives an appropriate \( p \)-value estimation:

\[
\frac{1}{200} \sum_{i=1}^{200} \Theta(MC(\phi_0, \cdots, \phi_k) - MC(\sigma_i(\phi_0), \cdots, \phi_k))
\]

Here, \( \sigma_i \) denotes a pseudorandom permutation and \( \Theta \) the common step function that is zero for negative values and one otherwise. To summarize, the whole methodological chain consists of six different steps: an adequate preprocessing of the signals, the extraction of relevant frequency band(s), the estimation of the corresponding instantaneous signal phases, the determination of appropriate time windows in which the phase coupling should be quantified, the specification of reasonable predictive electrodes and, finally, the calculation of the multiple circular-circular correlations and the belonging \( p \)-values.

B. Experiment

To evoke insight experiences a german version of the compound remote association problems (CRA) introduced by Bowden and Jung-Beeman was utilized [4]. These problems consist of three distinct problem words (e.g. "french", "car" and "shoe") to which a fourth solution word shall be found that forms a compound word or a two-word phrase with each problem word (e.g. "horn"). CRA problems are particularly well suited to study insight experiences since they can be solved with and without "aha" moment [4]. The participants had 30 seconds to solve each problem and responded with a bimanual button press as soon as they found a possible solution word. To capture the induced oscillations following this solution moment, a 5-second break was incorporated in the experiment during which subjects focused on a fixation cross in the middle of the computer screen. After each trial, the test persons reported whether they solved the problem with or without insight on a three-step scale (I: with insight, U: unsure, NI: no insight). All resolved trials were included into analysis since, on the one hand, several problems had multiple solutions and, on the other hand, an insight experience could be independent of the correctness of a solution. All subjects participated voluntarily and signed an informed consent prior to the experiment. Data acquisition was in compliance with the Declaration of Helsinki and accomplished with the permission of the ethics review board. 63 Electrodes were placed according to the 10-20 system and recorded with linked mastoids as reference.

C. EEG Signal Analysis

As mentioned above, the EEG signals need to be preprocessed properly prior to any further examination. In the present case, this preprocessing includes an initial bandpass filtering to 1-45Hz, a raw data inspection to detect major motion artifacts and an independent component analysis to correct eye movements. Afterwards, the alpha frequency band is extracted as a Morlet Wavelet layer, as several neuroimaging studies point out the importance of alpha band activity for insightful problem solving [5, 6, 7]. Since this alpha enhancement is most pronounced over right occipito-parietal regions, electrodes PO8 and PO4 are chosen as predictive variables in the following coupling analyses [5]. In order to enable a comparison of alpha couplings prior and post solution, time segments are examined that start 4.5s before the solution button press and end 5s after it. However, the 500ms immediately prior to this moment are excluded from the analysis because they comprise motor components like the readiness potential that may confound the results. Accordingly, the first second after the solution is eliminated to rule out any effect arising from solution-related potentials. Hence, two 4-second time segments arise. These time segments are divided into four 1-second time intervals in which the multiple circular-circular correlation of PO8 and PO4 with each other electrode is calculated. With it, eight time windows result TW1: \([-4.5, -3.5]\)s, TW2: \([-3.5, -2.5]\)s, TW3: \([-2.5, -1.5]\)s, TW4: \([-1.5, -0.5]\)s, TW5: \([1, 2]\)s, TW6: \([2, 3]\)s, TW7: \([3, 4]\)s and TW8: \([4, 5]\)s. In the following, the results for three subjects are presented to demonstrate the applicability and some advantages of the introduced methodology exemplarily.

III. Results

As expected, phase couplings in the alpha band range can be detected for both insightful and non-insightful solution trials. In particular, mean up to high correlations between right occipito-parietal regions and left prefrontal areas are obtained. Exemplarily, figure 1 shows the mean multiple circular-circular correlations for each electrode with electrode PO8 and PO4 averaged over all insightful trials and subjects. In the figure, the left column demonstrates the results for the four time intervals prior to solution, while the right column illustrates the outcomes for the four time windows after it. As can be seen, the phase coupling strength grows over time and higher frontal correlations are obtained.
For $\alpha = 0.05/61$, these phase couplings become significant in all time intervals and trials. The same holds true for non-insightful solutions. However, as figure 2 demonstrates both conditions differ in terms of phase couplings strength. Thus, insightful trials show a stronger synchronization prior to the solution, while non-insightful trials exhibit more pronounced alpha phase couplings afterwards. Even though these mean results already capture some interesting phase coupling dynamics that distinguish the two conditions, a lot of information gets lost by taking the mean. As an example, figure 3 shows the synchronization pattern of one subject in the first three insightful trials. Obviously, there is a relevant strong bilateral synchronization during the second time interval in the first two trials that is a little delayed in the third. Hence, it is blotted out by the averaging process.

IV. DISCUSSION

As mentioned above, various neuroimaging studies indicate a crucial involvement of alpha band oscillations in insight experiences. This alpha enhancement is associated with the inhibition of an appropriate solution due to an initial misdirection of the problem solver [5]. Only after the end of this attenuation the solver becomes aware of the solution and it literally pops into his mind [6]. Since the right hemisphere is associated with a coarse semantic coding, as required in the present task, right occipito-parietal regions are likely to be involved in this inhibition process [5, 8]. Moreover, several authors point out the importance of the prefrontal cortex for insight problem solving [9, 10]. The prefrontal cortex is usually considered as an executive system that coordinates and integrates neural activity. Hence, it is active during most higher cognitive functions [10]. This fits the results of the
previously presented coupling analysis. This analysis reveals enhanced phase coupling between left frontal areas and right occipito-parietal areas during the solving of semantic riddles. Prior to solution, this synchronization is stronger in insight-ful trials than in non-insightful trials, which might reflect an insight-specific inhibition coordination between these two brain regions. After a solution is found, non-relevant information can be deactivated. This deactivation might cause the higher phase coupling post solution. Interestingly, the consideration of individual trials indicates that even more subprocesses may be involved in insightful problem solving. These subprocesses might vary slightly in time and space such that they are eliminated if the results are blindly averaged across trials. However, by enhancing the dynamic approach introduced with an appropriate cluster analysis, repetitive patterns prior or post solution could be detected. The development of such methodology is the subject of our ongoing research. Moreover, higher frequency bands like beta and gamma are investigated regarding potential phase couplings since they are also associated with the moment of aha and transformative reasoning [5, 7]. These examinations promise interesting findings. For example, a beta band coupling analysis with electrodes PO3 and PO7 as predictors indicates enhanced synchronization between left parietal and right frontal regions, which is in line with the results of Sheth et al. 2008.

V. CONCLUSION

In this paper, we demonstrated how our new phase coupling measure can be used to trace the dynamics of multivariate phase couplings on a single trial basis. By applying the method to distinct time windows instead of an entire trial, changes in phase synchronization strength could be detected that reveal an interesting distinction between insightful and non-insightful solutions. Since this distinction is based on temporal modifications, it could not have been discovered with non-dynamic methods or multi trial analyses. However, a thorough inspection of the phase coupling pattern in individual trials could provide even more information about the specific processes underlying insight experiences. Such a single trial examination is not possible with usual phase coupling measures since they are typically restricted to multi trial analysis or the analysis of bivariate phase relations [2]. Therefore, multiple circular-circular correlations along with the presented test criteria based on surrogate data and the introduced windowing approach seem to be an appropriate method of analysis. Used reasonably in future research, they might contribute to a better understanding of complex cognitive phenomena and especially the subprocesses underlying them.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES