User Research

Causal Influence of Gamma Oscillations on the Sensorimotor-Rhythm

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High-frequency oscillations of the electromagnetic field of the brain, commonly referred to as γ-oscillations, are believed by some authors to play a central role for information processing in the brain (reviewed in [1]). However, while γ-oscillations have been shown to be correlated with a variety of brain signals and cognitive tasks, to date no empirical evidence for a causal role of γ-oscillations has been presented.

In a forthcoming article [2], we investigate the relationship of EEG recordings in the γ-range (55-85 Hz) and the sensorimotor-rhythm (SMR), and provide evidence that processes generating distributed γ-range oscillations also exert a causal influence on the SMR. Besides shedding new light on the role of γ-oscillations for brain processes in general, this causal relationship is of particular interest to research on brain-computer interfaces (BCIs). Volitional modulation of the SMR by means of motor imagery is a frequently used paradigm in BCI-research. If γ-oscillations act as modulatory variable on the SMR, as implied by our results, then a subject's capability to operate a motor-imagery BCI depends (at least partially) on the subject's state of γ-oscillations. This insight might open up a new approach to understanding and addressing the problem of so-called „BCI-illiteracy", i.e., the incapability of about 20% of healthy subjects to operate a BCI. In particular, our results suggest that subjects should receive neuro-feedback on their current state of γ-power in order to learn how to volitionally induce a state of γ-oscillations beneficial for BCI-performance.

In our study, we used four BrainAmp amplifiers, manufactured by Brain Products, to record a 128-channel EEG at 500 Hz while subjects performed motor imagery of either the right or left hand. We recorded data from ten subjects without known neurological conditions, with all but one subject being naive to motor imagery and BCIs. Using a machine learning procedure, we then estimated each subject's capability to volitionally modulate their SMR on a trial-wise basis. Specifically, we trained a linear support vector machine (SVM) to discriminate left vs. right hand motor imagery from log-bandpower features in 2 Hz frequency bands ranging from 7-40 Hz. The resulting SVM decision value of each trial is subsequently termed the SMR lateralization score, as its sign reflects the inferred type of motor imagery and its absolute value represents the extent of SMR lateralization. In a next step, we multiplied the SMR lateralization score by the true class label of each trial (+/-1 for trials of right/left hand motor imagery). In this way, we obtained a trial-wise performance measure, whose absolute value reflects the certainty of a classification, and whose sign is indicative of whether a trial is correctly or incorrectly classified. We then correlated this performance measure, subsequently termed the SMR quality score, with band-power in the γ-range (55-85 Hz) across electrodes. On the group level, this revealed a distinct correlation structure shown in

Figure 1: Topography of the correlation between the SMR quality score and γ-power (group-level data).

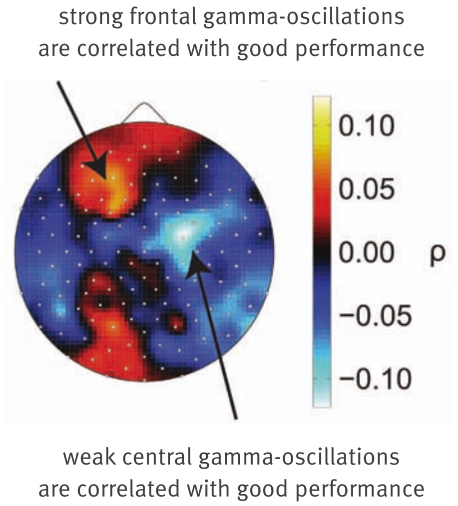


Figure 2: Relation of the SMR lateralization score and γ-power, spatially averaged according to the subject-specific correlation map analogous to Figure 1 (best performing subject). Green and red dots denote trials of right and left hand motor imagery, respectively.

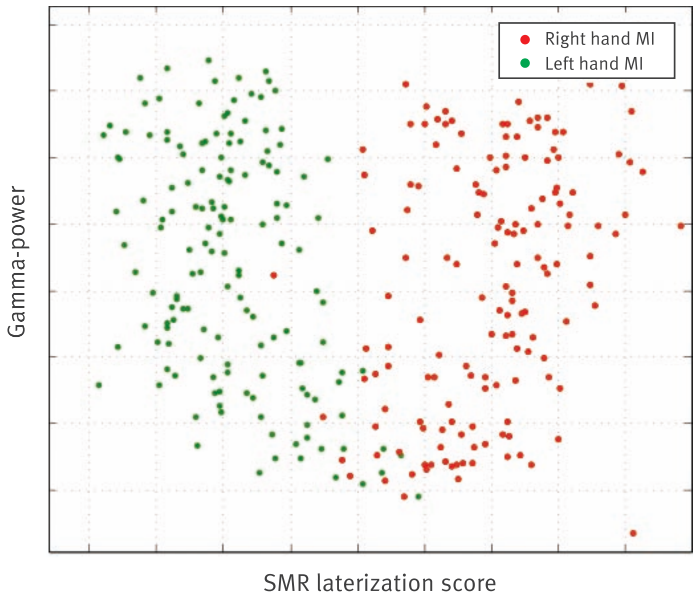


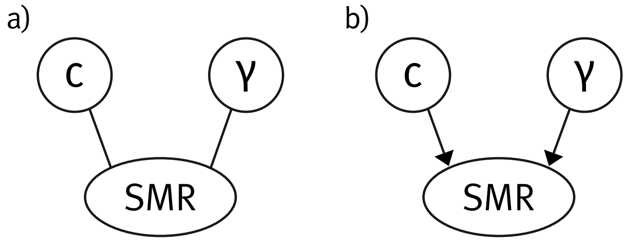
Figure 1, which was found to be highly significant ($p < 0.00001$). While we found centro-parietal γ-power to be negatively correlated with the extent of SMR modulation, frontal and occipital γ-power showed a positive correlation with performance. To better illustrate this effect, Figure 2 shows the relation of the SMR lateralization score and γ-power for each trial recorded from our best-performing subject. Here, green and red dots denote trials in which the subject was asked to perform motor imagery of the right and left hand, respectively. The x-axis displays the subject-specific estimate of the SMR lateralization score, with a negative/ positive value indicating motor imagery of the left/right hand. The y-axis shows the state of γ-power within each trial, averaged according to the subject-specific correlation map (shown in Figure1 for the group level). As can be seen from this figure, the SMR lateralization score takes on rather small absolute values for the low γ regime, with red and green dots intermingled. Accordingly, it is difficult to infer the type of motor imagery performed by this subject from the SMR lateralization score for these trials. An increase of γ-power, however, can be seen to be associated with a separation of the SMR lateralization scores of both classes. In fact, for high values of γ the red and green dots are well separated, indicating excellent BCI-performance.

While these results demonstrate a close connection between γ-oscillations and the SMR, they do not yet provide information on their causal relation. To further investigate this relation, we employed the framework for causal inference developed by J. Pearl and co-workers [3]. This framework is based on two principles. First, given a set of observed variables, all causal structures not capable of generating the observed (in-)dependencies between these variables are rejected. Second, Occam‘s razor is invoked to select from the remaining potential causal structures the most simple one (in terms of explanatory power).

In our study, we chose to investigate the dependencies between *c*, the instruction given to the subject which type of motor imagery to perform, the SMR lateralization score (simply denoted by SMR), and γ-power (averaged according to the subject-specific correlation map). Employing non-linear independence tests on the group-level data, we found strong evidence for a dependence between *c* and SMR as well as for a dependence between SMR and γ. We did not find any evidence, however, for a dependence between *c* and γ. Accordingly, we propose the dependency structure between these variables to be the one depicted in Figure 3.a. It then remains to investigate which causal structures are capable of generating this dependency structure. First, it should be noted that our prior knowledge of the experimental paradigm allows us to conclude that *c* is a cause of the SMR, as *c* was the instruction given to the subject. Second, a causal link from SMR to γ is unlikely, as this would imply a dependence between *c* and γ via SMR, for which we found no evidence. Third, any direct causal relation between *c* and γ is unlikely for the same reason, i.e., the lack to find any evidence for a dependence between *c* and γ. Accordingly, we interpret the data as providing evidence for the causal structure depicted in Figure 3.b, with γ acting as a modulatory variable on the SMR.

While this result provides further insight into the role of γ-oscillations, several issues require further investigation. First, as our data was recorded by EEG, it is conceivable that the observed γ-range oscillations are not directly generated by neuronal processes, but that the reported effect is due to a systematic variation of muscle tone with BCI-performance. This question may be settled by a source localization approach, in which sources of non-cortical origin are excluded from the analysis. Second, it is presently unclear whether the observed γ-range oscillations are a genuine cause of the SMR, or whether both share a hidden common cause. While in principle this can be inferred from empirical data as well [3], this requires conditional non-linear independence tests. As these are at present difficult to apply with limited amount of data, either new approaches to testing conditional independencies need to be developed, or interventional tests should be explored for experimentally testing the causal relation proposed in [2], e.g., by Transcranial Alternating Current Stimulation (TACS). Third, the behavioral correlate of the effect reported in [2], i.e., the thought pattern associated with the state of γ-power beneficial for BCI-performance, remains unknown. Hopefully, research into this behavioral correlate will result in more precise instructions to subjects how to successfully operate a BCI. Finally, while the effect reported in [2] was found to be significant not only on the group-level data but also for several subjects on the single-subject level, it remains to be determined whether it is strong enough to be of actual value to subjects in need to a BCI. ●

Figure 3: Inferred dependency- and causal structure.



References

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2) *M. Grosse-Wentrup, B. Schölkopf, and J. Hill, Causal influence of gamma-oscillations on the sensorimotor-rhythm. NeuroImage, 2010 (in press). Online version at doi:10.1016/j.neuroimage.2010.04.265.*

3) *J. Pearl, Causality: Models, Reasoning, and Inference, Cambridge University Press (2000).*