Decoding cognitive states and motor intentions from intracranial EEG: How promising is high-frequency brain activity for brain-machine interfaces?

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Whether the future of Brain-Computer Interface (BCI) technology will be predominantly based on non-invasive recordings of brain signals or, on the contrary, on invasive electrophysiological recordings is still a matter of debate. Yet, it is conceivable that the nature of the optimal recordings that are needed will depend on the application and the context. For example, while intracranial EEG (iEEG) might turn out to be irreplaceable with scalp EEG in the case of certain specific clinical or therapeutic BCI applications (e.g., restoring skilled motor behavior to tetraplegic patients), other applications such as neurofeedback-based cognitive remediation or enhancement strategies will most probably continue to rely on non-invasive brain recordings. In addition, it is a safe bet that the BCI-oriented video gaming industry is unlikely to require in the future that its customers undergo surgery to be able to play their games. We contend therefore that research into invasive and non-invasive methods for BCI research will remain complementary and, most importantly, will serve different purposes.

In humans, reports of invasive BCI systems are less numerous than in non-human primates and signal selection for optimal control is still in its early days (Andersen, Musallam et al. 2004). Furthermore, most reports of invasive BCI studies have relied on electrocorticography (ECoG) subdural grids and strips; however, insights on the putative utility of stereotactic-EEG (SEEG) recordings for BCI applications are scarce (Lachaux, Jerbi et al. 2007; Jerbi, Freyermuth et al. 2009; Hamame, Vidal et al. 2012).

We performed a series of studies to evaluate the possible utility of intracerebral recordings obtained via SEEG depth electrodes for the development of novel Brain-Computer Interfaces. In particular, we set out to investigate the efficiency of local broadband high-gamma (approx. 50-150 Hz) neuronal activity as a reliable BCI feature. This hypothesis stems from accumulating evidence across both human and animal studies indicating that broadband high-gamma activity is a reliable marker of local neuronal processing (Logothetis, Pauls et al. 2001; Mukamel, Gelbard et al. 2005; Crone, Sinai et al. 2006; Lachaux, Fonlupt et al. 2007).

To test the ability of patients to control various parameters of their intracranial recordings in real-time we used the *Brain TV* set-up, a custom-design online signal analysis system that computes and displays the ongoing power variations at various frequencies, including the high-gamma band (Lachaux, Jerbi et al. 2007). Combining the findings of task-related power modulations observed with this system with that of classical offline analysis paves the way for the development of novel strategies for BCI and real-time functional mapping. In addition, we used offline analysis of SEEG data acquired during various delayed motor tasks (hand and eye movements) that directly address the question of whether motor intentions can be decoded in the brain, not only at execution but prior to execution during the planning phase.

Our results suggest that BCI performance may be improved by using signals recorded from various neuronal systems such as the oscillatory activity recorded in the motor and oculomotor systems as well as higher cognitive processes including attention and mental calculation networks (Jerbi, Freyermuth et al. 2009). We also found that gamma- and alpha-band activity play a key role in motor intention decoding, providing high decoding accuracy even during the delay period preceding movements. Of further interest to invasive BCI applications, is our finding that gamma-band power modulations in prefrontal cortex are differentially modulated by positive and negative feedback on one's performance (Jung, Jerbi et al. 2010). Moreover, we recently found using SEEG data that goal-directed behavior is associated with transient suppressions of broad-band gamma power in neuronal structures that closely match the so-called default-mode network (Jerbi, Vidal et al. 2010; Ossandon, Jerbi et al. 2011).

Beyond advancing our knowledge of the electrophysiological underpinnings of resting-state networks observed with fMRI, these recent results suggest that real-time monitoring of gamma power fluctuations in the resting state might be key to assessing a subject's attention state, and possibly also for tracking pathological alteration of finegrained spatio-temporal network dynamics in patients with epilepsy.

In conclusion, our SEEG findings suggest that local modulations of gamma-band activity can be reliably used to infer the subject's intentions or cognitive states provided that the electrodes are implanted in the involved sites. A small methodological note of caution has to be raised, however, because of the vulnerability of SEEG to eye-movement artifacts. This previously unsuspected phenomenon consists of gamma-range contamination of the SEEG signal caused by the activity of extra-ocular eye muscles during saccade executions. Several techniques (such as bipolar re-referencing) can be applied to minimize or rule out the contribution of such artifacts (Jerbi, Freyermuth et al. 2009; Worrell, Jerbi et al. 2012).

Taken together, our findings suggest that SEEG depth recordings of high-gamma activity provide an extremely promising feature to decode motor intentions and cognitive states and that non-invasive techniques such as electroencephalography and magnetoencephalography (MEG) might also need to improve their ability to target such high-frequency modulations in order to improve their decoding power. High-gamma activity has been reported with MEG (e.g., (Dalal, Baillet et al. 2009)) but its sensitivity can be improved by adequate task design (Jerbi, Ossandon et al. 2009) and putatively by improved source modeling approaches (e.g., (Cottereau, Jerbi et al. 2007; Dalal, Guggisberg et al. 2008)). Finally, while we have focused here on the utility of gamma-band activity for future BCI application, we contend that lower-frequency oscillations (e.g., in the alpha and beta range) will continue to be very useful features for decoding, both separately and in combination with high-gamma activity.

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REFERENCES

Andersen, R. A., S. Musallam, et al. (2004). "Selecting the signals for a brain-machine interface." Curr Opin Neurobiol **14**(6): 720-6.

Cottereau, B., K. Jerbi, et al. (2007). "Multiresolution imaging of MEG cortical sources using an explicit piecewise model." Neuroimage **38**(3): 439-51.

Crone, N. E., A. Sinai, et al. (2006). "High-frequency gamma oscillations and human brain mapping with electrocorticography." Prog Brain Res **159**: 275-95.

Dalal, S. S., S. Baillet, et al. (2009). "Simultaneous MEG and intracranial EEG recordings during attentive reading." Neuroimage **45**(4): 1289-304.

Dalal, S. S., A. G. Guggisberg, et al. (2008). "Five-dimensional neuroimaging: localization of the time-frequency dynamics of cortical activity." Neuroimage **40**(4): 1686-700.

Hamame, C. M., J. R. Vidal, et al. (2012). "Reading the mind's eye: online detection of visuo-spatial working memory and visual imagery in the inferior temporal lobe." Neuroimage **59**(1): 872-9.

Jerbi, K., S. Freyermuth, et al. (2009). "Saccade related gamma-band activity in intracerebral EEG: dissociating neural from ocular muscle activity." Brain Topogr **22**(1): 18-23.

Jerbi, K., S. Freyermuth, et al. (2009). "Watching brain TV and playing brain ball exploring novel BCI strategies using real-time analysis of human intracranial data." Int Rev Neurobiol **86**: 159-68.

Jerbi, K., T. Ossandon, et al. (2009). "Task-related gamma-band dynamics from an intracerebral perspective: review and implications for surface EEG and MEG." Hum Brain Mapp **30**(6): 1758-71.

Jerbi, K., J. R. Vidal, et al. (2010). "Exploring the electrophysiological correlates of the default-mode network with intracerebral EEG." Front Syst Neurosci **4**: 27.

Jung, J., K. Jerbi, et al.(2010) "Brain responses to success and failure: Direct recordings from human cerebral cortex" Hum Brain Mapp **31**(8): 1217-32.

Lachaux, J. P., P. Fonlupt, et al. (2007). "Relationship between task-related gamma oscillations and BOLD signal: new insights from combined fMRI and intracranial EEG." Hum Brain Mapp **28**(12): 1368-75.

Lachaux, J. P., K. Jerbi, et al. (2007). "A blueprint for real-time functional mapping via human intracranial recordings." PLoS One **2**(10): e1094.

Logothetis, N. K., J. Pauls, et al. (2001). "Neurophysiological investigation of the basis of the fMRI signal." Nature **412**(6843): 150-7.

Mukamel, R., H. Gelbard, et al. (2005). "Coupling between neuronal firing, field potentials, and FMRI in human auditory cortex." Science **309**(5736): 951-4.

Ossandon, T., K. Jerbi, et al. (2011). "Transient suppression of broadband gamma power in the default-mode network is correlated with task complexity and subject performance." J Neurosci **31**(41): 14521-30.

Worrell, G. A., K. Jerbi, et al. (2012). "Recording and analysis techniques for high-frequency oscillations." Prog Neurobiol **98**(3): 265-78.