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What are the Causes of Performance Variation in Brain-Computer Interfacing?

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Abstract. While research on brain-computer interfacing (BCI) has seen tremendous progress in recent years, performance still varies substantially between as well as within subjects, with roughly 10 - 20% of subjects being incapable of successfully operating a BCI system. In this short report, I argue that this variation in performance constitutes one of the major obstacles that impedes a successful commercialization of BCI systems. I review the current state of research on the neuro-physiological causes of performance variation in BCI, discuss recent progress and open problems, and delineate potential research programs for addressing this issue.

Keywords: *brain-computer interfaces, bci-illiteracy, motor imagery, sensorimotor-rhythm, gamma-oscillations.*

1. Introduction

In recent years, the tremendous progress in brain-computer interfacing (BCI) has prompted the development of BCI for purposes other than communication, such as driving a wheelchair [Galan et al., 2008] or browsing the Internet [Bensch et al., 2007]. However, the arguably most significant promise of BCI, communication with completely locked-in subjects, has not yet been fulfilled. Furthermore, there exists a large variation in performance within as well as across subjects, which renders BCI-control rather unreliable. While most studies aim to address this issue by advanced machine-learning techniques, I argue here that these efforts should be complemented by a thorough investigation into the neuro-physiological causes of good or bad BCI performance. Only an understanding of what determines a subject's capacity to operate a BCI system will enable us to devise experimental paradigms and signal processing methodologies that may fulfill the (sometimes distressingly exaggerated) expectations raised by media reports. In this report, I review the current state-of-the-art of this research program, discuss some recent progress by our group, and delineate potential approaches to open problems.

2. Performance variation in brain-computer interfacing

After a brief calibration period, most healthy subjects are capable of utilizing a BCI system for basic communication [Grosse-Wentrup et al., 2009a; Blankertz et al. 2008; Sellers et al., 2006]. Furthermore, subjects in early to middle stages of amyotrophic lateral sclerosis (ALS) have been shown to be capable of operating a BCI system [Kübler et al., 2005]. However, a substantial percentage of subjects appears incapable of achieving performance levels sufficient for reliable communication [Popescu, et al., 2008; Guger et al., 2009], and to date no communication with a completely locked-in subject has been reported. Interestingly, these observations appear to be independent of the experimental paradigm.

Unfortunately, the causes of this performance variation remain largely unknown. While intensive training is known to improve performance in most subjects [Curran & Stokes, 2003], and the specific feedback design may also play a role [Barbero & Grosse-Wentrup, 2010], to date there is very little work on the neuro-physiological causes of performance variation. Recently, evidence has been presented that the amplitude of the sensorimotor-rhythm (SMR) at rest, i.e., the power of mu- (12-14 Hz) and beta-rhythms (20-30 Hz) over sensorimotor areas, is a good predictor of subsequent BCI-performance in motor-imagery paradigms [Blankertz et al., 2010]. This marks a substantial advance, as it relates resting-state properties of the brain to BCI-performance. It should be noted, however, that multiple areas beyond sensorimotor cortex are known to be involved in motor imagery, including prefrontal- and premotor-cortex, supplementary motor area, anterior cingulate cortex and the cerebellum [Decety, 1996]. Surprisingly, none of these areas have been found to provide information on a subject's intention in BCI, raising the question on their specific roles in motor imagery.

Motivated by this apparent contradiction, we have investigated connectivity patterns between brain regions involved in motor imagery. In a first study, we provided evidence that motor-imagery reduces connectivity between frontal regions and sensorimotor areas in the gamma-frequency range (roughly above 40 Hz) [Grosse-Wentrup, 2009b]. In a second study, we further explored the relation of gamma-range oscillations and motor-imagery performance [Grosse-Wentrup et al., 2010]. We first derived a trial-wise measure of motor-imagery performance by computing the certainty of a support vector machine (SVM) in classifying EEG trials as motor-imagery of either the left- or the right hand, based on bandpower features over sensorimotor areas. We then correlated this performance measure with gamma-range oscillations across the scalp, thereby uncovering a wide-spread network of gamma-range oscillations that correlate with motor-imagery performance. Interestingly, we again found this effect to be most prominent over frontal areas, thereby presenting the first empirical evidence for the relevance of cross-frequency correlations over large distances for explaining performance variations in BCI. Taken together, these two studies suggest a prominent role of prefrontal areas in the process of motor imagery, that may be of particular relevance for addressing performance variations in BCI.

3. Open problems

In general, performance variations may be investigated on multiple levels: across experimental paradigms, within subjects, and across subjects. While within-subject variations have been addressed in [Grosse-Wentrup et al., 2010] and across-subject variations in [Blankertz et al., 2010], both studies only consider BCI based on motor imagery. It remains to be seen whether similar results can be obtained for BCI systems not based on motor paradigms. Furthermore, current research has been carried out on healthy subjects only. In order to be of potential benefit to subjects actually in need of a BCI system, these results need to be reproduced on subjects with ALS and other patient groups that stand to benefit from BCI technology. As the purpose of investigating the causes of performance variation is to identify the most promising approaches for teaching subjects how to operate a BCI system, the benefit of the obtained insights needs to be validated in randomized controlled trials. Such interventional studies may consist of neuro-feedback programs, e.g., providing feedback on the state of frontal gamma-oscillations or the resting-state SMR, in order to teach subjects how to induce a state of mind beneficial for BCI performance. More invasive approaches may also be considered, e.g., involving transcranial alternating current stimulation (TACS) in order to artificially induce the brain states found to be beneficial for BCI performance in [Grosse-Wentrup et al., 2010].

References

Barbero A, Grosse-Wentrup M. Biased feedback in brain-computer interfaces. *Journal of Neuroengineering and Rehabilitation*, 7(34), 2010.

Bensch M, Karim AA, Mellinger J, Hinterberger T, Tangermann M, Bogdan M, Rosenstiel W, Birbaumer N. Nessi: an EEG-controlled web browser for severely paralyzed patients. *Computational Intelligence and Neuroscience*, Article ID 71863, 2007.

Blankertz B, Tomioka R, Lemm S, Kawanabe M, Müller KR. Optimizing spatial filters for robust EEG single-trial analysis. *IEEE Signal Processing Magazine,* 25(1): 41-56, 2008.

Blankertz B, Sannelli C, Halder S, Hammer EM, Kübler A, Müller KR, Curio G, Dickhaus T. Neurophysiological predictor of SMR-based BCI performance. *NeuroImage*, 51(4): 1393-1309, 2010.

Curran EA, Stokes MJ.Learning to control brain activity: a review of the production and control of EEG components for driving brain-computer interface (BCI) systems. *Brain and Cognition,51*(3):326-36, 2003.

Decety J. The neurophysiological basis of motor imagery. *Behavioral Brain Research,* 77(1-2): 45-52, 1996.

Galan F, Nuttin M, Lew E, Ferrez PW, Vanacker G, Philips J, Millan JDR. A brain-actuated wheelchair: asynchronous and non-invasive brain–computer interfaces for continuous control of robots. *Clinical Neurophysiology*, 119(9):2159-2169, 2008.

Grosse-Wentrup, M, Liefhold C, Gramann K, Buss M. Beamforming in noninvasive brain-computer interfaces. *IEEE Transactions on Biomedical Engineering,* 56(4): 1209-1219, 2009a.

Grosse-Wentrup M. Understanding brain connectivity patterns during motor imagery for brain-computer interfacing. In *Advances in Neural Information Processing Systems (NIPS) 21, 561-568, 2009b.*

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

Guger C, Daban S, Sellers E, Holzner C, Krausz G, Carabalona R, Gramatica F, Edlinger G. How many people are able to control a P300-based brain–computer interface (BCI)? *Neuroscience Letters*, 462(1); 94-98, 2009.

Kübler A, Nijboer F, Mellinger J, Vaughan TM, Pawelzik H, Schalk G, McFarland DJ, Birbaumer N, Wolpaw JR. Patients with ALS can use sensorimotor rhythms to operate a brain-computer interface. *Neurology*, 64(10): 1775-1777, 2005.

Popescu F, Blankertz B, Müller KR. Computational challenges for noninvasive brain computer interfaces, *IEEE Intelligent Systems,* 23(3): 78–79. 2008.