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Camille Jeunet

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Training Users' Spatial Abilities to Improve Brain-Computer Interface Performance: A Theoretical Approach

Camille Jeunet
Laboratoire Handicap & Système Nerveux – University of Bordeaux
Project Team Potioc – Inria Bordeaux Sud-Ouest
200 Avenue de la Vieille Tour, 33400 Talence, France
Email: camille.jeunet@inria.fr

***Abstract*—Mental-Imagery based Brain-Computer Interfaces (MI-BCIs) allow their users to send commands to a computer using their brain activity alone (typically measured by ElectroEncephaloGraphy - EEG), which is processed while they perform specific mental tasks. While very promising MI-BCIs remain barely used outside laboratories because of the difficulty encountered by users to control them. Indeed, although some users obtain good control performances after training, a substantial proportion remains unable to reliably control an MI-BCI. This huge variability in user performance led the community to look for predictors of MI-BCI control ability. Mainly, neurophysiological and psychological predictors of MI-BCI performance have been proposed. In this paper, a newly-depicted lever to increase MI-BCI performance is introduced: namely a spatial ability training. The aims of this paper are to clarify the relationship between spatial abilities and mental imagery tasks used in MI-BCI paradigms, and to provide suggestions to include a spatial ability training in MI-BCI training protocols.**

I. INTRODUCTION

A brain computer interface (BCI) is a hardware and software communication system that enables its user to interact with surroundings without the involvement of peripheral nerves and muscles, i.e., by using control signals generated from electroencephalographic (EEG) activity [1]. More specifically, this paper focuses on BCIs for which these control signals are sent via the execution of *mental tasks* (e.g., motor imagery): so-called Mental-Imagery based BCIs (MI-BCIs). MI-BCIs represent a new, non-muscular channel for relaying users' intentions to external devices such as computers, assistive appliances or neural prostheses [2]. Unfortunately, most of these promising BCI-based technologies cannot yet be offered on the public market since a notable portion of users (estimated to be between 15 and 30%) does not seem to be able to learn to control such a system [3]: this phenomenon is often called "BCI illiteracy" or "BCI deficiency". This high "BCI illiteracy" rate could be due on the one hand to several EEG-related flaws like non-stationarity, poor signal/noise ratio or imperfect classification algorithms [3]. On the other hand, standard training protocols [4] have also been questioned [5] as they do not follow recommendations from instructional design and psychology. Nonetheless, although there is a large proportion of "illiterates", some users perform excellently [6] and the EEG-related flaws and unsuitable protocols do not explain the important variability in performance . From this observation emerged the idea of a relation between users' characteristics and their ability to control an MI-BCI, which led the community to look for predictors of MI-BCI performance (i.e., the rate of correctly recognised MI tasks). The training process to learn to control an MI-BCI being time- and resource-consuming, being able to predict users' success (or failure) could avoid important loss of time and energy for both users and experimenters. From another perspective, knowing these predictors could guide the design of new training protocols that would be adapted to users' characteristics. In this paper, a newly-depicted lever to increase MI-BCI performance is introduced: namely a spatial ability training. This factor seems to be a very promising predictor of MI-BCI performance as it appeared to be stable and reliable. The aims of this paper are to clarify the relationship between spatial abilities and mental imagery tasks used in MI-BCI paradigms, and to provide suggestions to include a spatial ability training in MI-BCI training protocols.

II. PREDICTORS OF MI-BCI PERFORMANCE

A. Neurophysiological Predictors

Recently, evidence was presented that the amplitude of sensorimotor-rhythms (SMRs) at rest is a good predictor of subsequent BCI-performance in motor-imagery paradigms [7]: a correlation (r=0.53) was found between a new neurophysiological predictor based on the μ (about 9-14 Hz) rhythm over sensorimotor areas and BCI performance (N = 80). Moreover, Grosse-Wentrup et al. [8] demonstrated that the modulation of SMRs was positively correlated with the power of frontal and occipital γ-oscillations, and negatively correlated with the power of centro-parietal γ-oscillations. Besides, Grosse-Wentrup and Schölkopf [9] showed that high-frequency γ-oscillations originating in fronto-parietal networks predicted variations in performance on a trial-to-trial basis. This finding was interpreted as empirical support for an influence of attentional networks on BCI performance via the modulation of SMRs. Furthermore, Ahn et al. [10] found that BCI-illiterate show higher θ- and lower α-power levels than BCI-literate. Statistically significant areas were frontal and posterior-parietal regions for the θ-band and the whole cortex area for the α-band. A high positive correlation between γ-activity and motor-imagery performance was also shown in the prefrontal area [11]. Finally, [12] demonstrated that having higher frontal θ and lower posterior α prior to performing motor-imagery, which reflects a high attentional level, may enhance the BCI classification performance. While the search for neurophysiological predictors seems to be a promising approach, some studies showed that the user's psychological profile could also be an important factor influencing BCI-control performance.

B. Psychological Predictors

Mood and motivation [13], as well as the locus of control score related to dealing with technology [14], have been shown to be correlated with motor-imagery based BCI performance. Fear of the BCI system has also been shown to affect performance [14][15]. In [16], attention span, personality and motivation play a moderate role for one-session motor-imagery based BCI performance, but a significant predictive model of performance, including the visuo-motor coordination and the degree of concentration, is depicted. In a recent study [6], this model has been tested in a 4 session experiment within a neurofeedback paradigm. Results show that these parameters explain almost 20% of the BCI performance within a linear regression, even if visuo-motor coordination failed significance. While offering interesting perspectives, none of these studies proposes a highly reliable model. Also, most of these studies determine predictors based on one MI-BCI session. Yet, no evidence shows that this performance is representative of long-term MI-BCI control performance. Finally, these studies only considered motor-imagery, while it has been shown that the best combination of tasks for users was composed of both motor and non-motor MI-tasks [17]. In the next section, a study proposing to overcome these limitations is introduced.

III. SPATIAL ABILITIES PLAY A MAJOR ROLE IN MI-BCI PERFORMANCE

Recently, Jeunet et al. [18], proposed a study aiming at determining a predictive model of MI-BCI performance. This study presented three major novelties. First, users were asked to learn to perform three MI-tasks: one motor (left-hand motor imagery) and two non-motor (mental rotation and mental subtraction), based on Friedrich et al's study [17]. Including these MI-tasks increased the ecology of the study. Indeed, these tasks are more likely to be used in "real-life" applications as they are associated with the best performances on average over subjects [17]. Second, users' mean performance at performing these 3 MI-tasks was measured across 6 sessions, spread over 6 different days. It enabled to get a better idea of their longer-term MI-BCI control ability. Finally, neurophysiological and psychological factors were both considered as potential predictors in the model. Until now, these two kinds of predictors were always considered separately (except in one study [16]). Here, the authors considered that the information provided by these two kinds of predictors could be complementary. During the experiment, participants were asked to perform the 3 MI-tasks and to complete several psychometric questionnaires which enabled to determine aspects of their cognitive and personality profiles. Results unveiled three major findings. The first is a predictive model of MI-BCI performance composed of 4 factors: tension, abstractness abilities, self-reliance (all three assessed by the 16-PF 5 questionnaire [19]) and the "active/reflective" dimension of the Learning Style [20]. The second concerns the absence of neurophysiological patterns among the selected predictors. Finally, the third is the strong correlation between MI-BCI performance and Mental Rotation test scores [21]. The Mental Rotation test is known to evaluate Spatial Abilities (SA). This result emphasizes the potential important role of SA in mental imagery abilities. Given this potential important role of SA, it is worth exploring SA training possibilities in the aim of improving MI-BCI performance.

IV. SPATIAL ABILITIES

A. Definition & Relationship with Mental-Imagery

SA can be defined as mental capacities involving the construction, transformation and interpretation of mental images [22]. They reflect the use of MI to manipulate spatial representations. Many studies have been led in order to determine the different factors composing SA (for a review, see [22]). Numerous models of these SA factors have been proposed, the relevance of many of them being still discussed. Nonetheless, some factors are redundant in most studies: *Visualisation, Orientation and Spatial Relations*. *Visualisation* is the ability to mentally manipulate a pictorially presented object. *Orientation* corresponds to the ability to comprehend the arrangement of elements. Finally, the *Spatial Relation* ability corresponds to the capacity to rapidly and accurately rotate a mental image. Considering the BCI experiment described in the previous section, one can notice that SA are linked with the three MI tasks proposed. First, the mental rotation task and the *Spatial Relation* factor are intimately related as participants had to "rapidly rotate a mental image" while performing this task. Second, Rourke and Finlayson [23] showed a significant correlation between SA and arithmetics abilities: children confronted to difficulties to perform arithmetics also had low SA. This result could explain the relationship between SA and the subtraction task. Third, the mental rotation test, used here to assess SA, is also used to evaluate motor imagery abilities in healthy subjects and patients with brain injuries [24]. This last result emplhasizes the relationship between SA and the left-hand motor-imagery task. These links between SA and the three MI tasks led to consider the potential positive impact an SA training could have on MI-BCI performance. In the next section, some SA trainings of interest are thus introduced.

B. Spatial Ability Training

SA training has been shown to be efficient in many different areas such as surgery, mathematics or engineering education. A large majority of these SA training are based on the Vanderberg and Kuse [21] Mental Rotation test. This test is composed of two sets of 10 items. Each set has to be completed in 3 minutes maximum. An item consists in a 3D shape on the left and four 3D shapes on the right. Among the four 3D shapes, two are similar to the left one with a rotation of 60^o, 120^o or 180^o around the vertical axis. The other two are mirrored reversed and rotated images of the left 3D shape. For each item, the participant has to find the two 3D shapes similar to the left one. Hoyek et al. [25] used a computerised version of this Mental Rotation test to train students' SA and showed an improvement in their ability to learn anatomy. Indeed, SA were shown to impact capacities in scientific learning [26]. This is why Wiedenbauer and Jansen-Osmann [27] developped a manual version of the Mental Rotation test for children. This manual version appeared to be efficient to improve children SA. On the other hand, Mental Rotation test scores have also been shown to be improved through different activities such as sport [28], juggling [29] or engineering courses [30]. Training SA abilities through the administration of Mental Rotation tests is considered as a *specific* training (as it enables to train one aspect of SA: the *Spatial Relations*) by opposition to *general* trainings (focusing on several aspects of SA) and *indirect* trainings (i.e., improving SA through different activities such as sport of engineering classes). In a meta-analysis, Baenninger et al. [30] revealed that to obtain the best performances, the SA training should be *specific* and have a medium duration, i.e., 3 to 5 sessions spread over at least 3 weeks.

V. PROPOSING A SPATIAL ABILITY TRAINING TO IMPROVE USERS' MI-BCI CONTROL PERFORMANCE

In the study of Jeunet et al. [18], participants followed a standard training protocol composed of 6 identical sessions during which they had to learn to perform 3 MI-tasks: mental rotation, mental subtraction and left-hand motor imagery. On the one hand, no improvement in performance was noticed between the 1^{st} and 6^{th} session on average. It suggests that despite the large number of sessions, participants did not learn during this experiment. On the other hand, the mean MI-BCI performance appeared to be strongly correlated with users' mental rotation scores. This correlation added to the relationship between SA and the MI-tasks suggests that an increase in mental rotation scores might be associated with an improvement of MI-BCI performance. In accordance with the literature, it thus seems worth exploring the effect of the inclusion of a specific and medium duration SA training, based on 3 to 5 sessions of Mental Rotation tests [21], in standard MI-BCI training protocols. These SA training sessions could replace some of the MI-BCI training sessions.

VI. CONCLUSION

In this paper, one potential lever for BCI reliablity enhancement was developped: the inclusion of a spatial ability training in MI-BCI training protocols. This new approach is expected to be responsible for a great improvement of users MI-BCI performance: this hypothesis will be tested in a future experiment. In addition to a spatial ability training, other levers, such as taking users' personality into account and improving the feedback content and visualisation, should be explored in the aim of improving MI-BCI performance. One could expect this work to have a significant impact on BCI reliability, and thus acceptability and usability of BCI-based technologies such as smart wheelchairs or neuroprostheses.

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