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Complexity and familiarity enhance single-trial detectability of imagined movements with electroencephalography

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HIGHLIGHTS

- We use machine-learning to classify EEG during motor imagery in samples of athletes, musicians, and age-matched controls.
- Imagery of complex actions and imagery of familiar actions can result in more robust brain responses in some cases.
- Our findings may be applied to improve brain-computer interfaces intended for use by behaviourally non-responsive patients.

ABSTRACT

Objective: We sought to determine whether the sensorimotor rhythms (SMR) elicited during motor imagery (MI) of complex and familiar actions could be more reliably detected with electroencephalography (EEG), and subsequently classified on a single-trial basis, than those elicited during relatively simpler imagined actions.

Methods: Groups of healthy volunteers, including experienced pianists and ice hockey players, performed MI of varying complexity and familiarity. Their electroencephalograms were recorded and compared using brain-computer interface (BCI) approaches and spectral analyses.

Results: Relative to simple MI, significantly more participants produced classifiable SMR for complex MI. During MI of performance of a complex musical piece, the EEG of the experienced pianists was classified significantly more accurately than during MI of performance of a simpler musical piece. The accuracy of EEG classification was also significantly more sustained during complex MI.

Conclusion: MI of complex actions results in EEG responses that are more reliably classified for more individuals than MI of relatively simpler actions, and familiarity with actions enhances these responses in some cases.

Significance: The accuracy of SMR-based BCIs in non-communicative patients may be improved by employing familiar and complex actions. Increased sensitivity to MI may also improve diagnostic accuracy for severely brain-injured patients in a vegetative state.

1. Introduction

Patients with disorders of consciousness (DOC) are behaviourally characterized by varying levels of arousal and awareness measured primarily by their ability to exhibit reliable responses to external stimulation (Jennett, 2002; Bernat, 2006; Owen, 2008). Of the various conditions included in the DOC (*e.g.*, coma, the minimally conscious state (MCS), *etc.*), the vegetative state (VS) is one of the most poorly understood (Jennett, 2002; Owen, 2008). After emerging from coma, VS patients retain cycles of eye opening and closing similar to the sleep-wake cycles of fully awake and aware individuals (Multi-Society Task Force on PVS, 1994a,b; Royal College of Physicians Working Group, 1996; *cf.* Cruse et al., 2013). Critically, despite producing spontaneous movements, VS patients are unable to exhibit any purposeful outward responses to verbal commands, and are thereby diagnosed as 'unaware' (Jennett, 2002; Owen, 2008). Many VS patients have diffuse brain injury that may include insult to the peripheral motor system; these circumstances could lead to an inaccurate diagnosis of VS in a patient who retains awareness and cognitive function, but lacks the ability to respond purposefully in a behavioural assessment (Owen, 2008).

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In fact, researchers have reported that some patients who are diagnosed as VS can follow (*e.g.*, Owen et al., 2006; Monti et al., 2010; Bardin et al., 2011; Cruse et al., 2011; Goldfine et al., 2011; Naci and Owen, 2013), or attempt to follow (*e.g.*, Bekinschtein et al., 2011; Cruse et al., 2012), commands by modulating their brain activity, despite being unable to follow commands with their external behaviour. These findings raise the possibility that assistive devices known as brain-computer interfaces (BCIs) could improve diagnostic accuracy in this group by detecting 'covert' signs of awareness, as well as by potentially offering the patient a means of communication (*e.g.*, Monti et al., 2010; Lulé et al., 2013).

BCIs are devices that can allow a person (the 'user') to operate a computer without producing a motor output. Using machine-learning techniques, subject-specific patterns of brain activity can be learned by a computer and subsequently classified into a predefined communicative output. For example, the computer may output the response "yes" when the user produces brain activity pattern A, and output the response "no" when the user produces brain activity pattern B (*e.g.*, Mason and Birch, 2003; Sorger et al., 2009; Lulé et al., 2013; Naci et al., 2013). The computer algorithm must be trained on a series of trials in which the desired output from the user is known (the 'training phase' of machine-learning classification), and then tested on trials in which the desired output from the user is not known (the 'testing phase' of machine-learning classification) based on predefined features of the data (*e.g.*, power in a given frequency band of the electroencephalogram, EEG). From the testing phase of classification, one can obtain an accuracy value based on the number of successfully identified brain responses and, by extension, correctly executed communicative outputs from the BCI. Crucially, from a clinical perspective, when classification accuracy is significantly above chance, the individual is demonstrably capable of producing consistent and appropriate patterns of brain activity in response to commands, thus providing a means to identify covert command-following in the absence of a behavioural response (Cruse et al., 2011; Owen, 2013). Since classification must be both accurate and reliable for successful communication and other BCI output functions, such as computer mouse cursor control, classification accuracy and task sensitivity are two of the most important measurements of any BCI.

A particular EEG signal called the sensorimotor-rhythm (SMR) is a practical option for BCIs intended for use by VS patients (Chatelle et al., 2012; Naci et al., 2012; Grosse-Wentrup and Schölkopf, 2013). Using as few as four surface electrodes placed on the head over the sensorimotor cortical areas (sites CP3, CP4, FC3, and FC4 from the modified international 10–20 system; Sharbrough et al., 1991), one can acquire the SMR as a person kinesthetically imagines moving a body part. Power decreases known as event-related desynchronizations (ERDs) and power increases known as event-related synchronizations (ERSs) in the mu (7–13 Hz) and beta (13–30 Hz) frequency bands are typically used as the signal features for classification with SMR-based BCIs (Pfurtscheller and Neuper, 1997; Neuper and Pfurtscheller, 2001; Neuper et al., 2009). Unlike other EEG-based BCI paradigms (*e.g.*, the P300 speller described in Farwell and Donchin (1988)), the imagination tasks used with SMR-based BCIs impose low sensory demands on the user. Furthermore, of particular importance for patients diagnosed as VS who, by definition, are unable to fixate their eyes, SMR BCIs need not involve visual stimulation (Chatelle et al., 2012; Naci et al., 2012; Grosse-Wentrup and Schölkopf, 2013). Finally, it is important to acknowledge that changes in the cortical motor system following prolonged immobility may prevent some behaviourally non-responsive patients from producing reliable SMRs. Nevertheless, there is evidence that individuals diagnosed with disorders of consciousness, including VS and MCS, can produce SMRs in motor tasks, even after several years of immobility (Goldfine et al., 2011; Cruse et al., 2011). Furthermore, patients with chronic and extensive motor impairments, including tetraplegia and advanced amyotrophic lateral sclerosis (ALS), have been successfully trained to control SMR-based BCIs (Pfurtscheller et al., 2000; Kübler et al., 2005). The SMR approach to BCI is therefore a viable option for patients who have been immobile for an extended period, including those with a disorder of consciousness.

Despite the potential benefits of bedside EEG-based BCIs for patients diagnosed as VS and their families, there is substantial intra- and inter-subject variability in BCI performance (Wolpaw et al., 2002; Pfurtscheller et al., 2006; Naci et al., 2012; Grosse-Wentrup and Schölkopf, 2013). In many studies of healthy volunteers and people with severe motor impairments, some individuals are simply unable to reliably regulate the brain signals necessary to operate a BCI without training (*e.g.*, Guger et al., 2003; Wolpaw and McFarland, 2004; Cruse et al., 2011; Hammer et al., 2012). In the current work, we propose modifications to the traditional SMR-based BCI design that may optimize BCI performance for behaviourally non-responsive patients in particular. These modifications apply to the nature of the task used to generate the SMR and the nature of the comparisons made during signal classification (see also Curran and Stokes, 2003; Curran et al., 2004).

In published SMR-based BCI research to date, users are typically instructed to imagine moving their hands, feet, or tongue to generate an SMR (*e.g.*, Neuper and Pfurtscheller, 2001; Kübler et al., 2005; Cruse et al., 2011). With only a few exceptions, users are asked to imagine very simple actions, such as repeatedly squeezing one of their hands into a fist. However, actions that are more complex could result in a more robust and consistent SMR (Curran and Stokes, 2003; Curran et al., 2004). Indeed, there is evidence that complex imagined actions are associated with more robust brain responses than simpler imagined actions. For instance, there is converging evidence from functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and transcranial magnetic stimulation (TMS) studies that complex motor imagery is associated with greater hemodynamic change and higher amplitude motor-evoked potentials than simple motor imagery (*e.g.*, Kuhtz-Buschbeck et al., 2003; Roosink and Zijdewind, 2010; Holper and Wolf, 2011). Similar to previous work, we define 'complex' motor imagery in this paper as tasks that involve both sequences of movements and more than one body part (*e.g.*, Kuhtz-Buschbeck et al., 2003; Roosink and Zijdewind, 2010; Holper and Wolf, 2011). We must also clarify that our complexity manipulations in this work always involve "common" complex action sequences; that is, we chose actions that participants would have previously encountered through overt practice (*e.g.*, Studies 2 and 3) or common knowledge (*e.g.*, clapping as in Study 1). We selected common action sequences to ensure that participants could draw from procedural memory or semantic knowledge in order to imagine each action. These sorts of known complex actions would therefore have lower cognitive demands than novel, complex action sequences that would need to be learned at the time of assessment (*e.g.*, tapping the fingers in a random sequence defined by the experimenter as in previous work; Kuhtz-Buschbeck et al., 2003; Roosink and Zijdewind, 2010; Holper and Wolf, 2011). We hypothesized that more complex actions would result in more robust SMRs and, consequently, higher classification accuracy than traditional SMR-based BCI imagery tasks.

Additionally, it has been proposed in previous work that asking users to imagine actions which they are familiar with could improve SMR classification (Curran and Stokes, 2003; Curran et al., 2004). In this paper, we chose to explore the role of action familiarity in modulation of the SMR by drawing from samples of experienced athletes and musicians, given that the effects of long-term motor learning have been studied extensively in these groups already (see Münte et al. (2002), and Nakata et al. (2010), for reviews). While imagining actions involving the sport or instrument of their expertise,