Please cite this article in press as: Athanasiou A et al. Investigating the role of alpha and beta rhythms in functional motor networks. Neuroscience (2016), http://dx.doi.org/10.1016/j.neuroscience.2016.05.044

Neuroscience xxx (2016) xxx–xxx

INVESTIGATING THE ROLE OF ALPHA AND BETA RHYTHMS IN FUNCTIONAL MOTOR NETWORKS

ALKINOOS ATHANASIOU, [a,b]* **MANOUSOS A. KLADOS,** [a] **CHARIS STYLIADIS,** [a] **NICOLAS FOROGLOU,** [b] **KONSTANTINOS POLYZOIDIS** [b] **AND PANAGIOTIS D. BAMIDIS** [a]

[a] *Lab of Medical Physics, School of Medicine, Faculty of Health Sciences, Aristotle University of Thessaloniki (AUTH), 54124 Thessaloniki, Greece*

[b] *First Department of Neurosurgery, ≪AHEPA≫≫ University General Hospital, 54634 Thessaloniki, Greece*

Abstract—It is recognized that lower electroencephalographic (EEG) frequencies correspond to distributed brain activity over larger spatial regions than higher frequencies and are associated with coordination. In motor processes it has been suggested that this is not always the case. Our objective was to explore this contradiction. In our study, seven healthy subjects performed four motor tasks (execution and imagery of right hand and foot) under EEG recording. Two cortical source models were defined, model ≪A≫ with 16 regions of interest (ROIs) and model ≪B≫ with 20 ROIs over the sensorimotor cortex. Functional connectivity was calculated by Directed Transfer Function for alpha and beta rhythm networks. Four graph properties were calculated for each network: characteristic path length (CPL), clustering coefficient (CC), density (D) and small-world-ness (SW). Different network modules and in-degrees of nodes were also calculated and depicted in connectivity maps. Analysis of variance was used to determine statistical significance of observed differences in the network properties between tasks, between rhythms and between ROI models. Consistently on both models, CPL and CC were lower and D was higher in beta rhythm networks. No statistically significant difference was observed for SW between rhythms or for any property between tasks on any model. Comparing the models we observed lower CPL for both rhythms, lower CC in alpha and higher CC in beta when the number of ROIs increased. Also, denser networks with higher SW were correlated with higher number of ROIs. We propose a non-exclusive model where alpha rhythm uses greater wiring costs to engage in local information progression while beta rhythm coordinates the neurophysiological processes in sensorimotor tasks.

This article is part of a Special Issue entitled: Neurofeedback.

Key words: brain waves, electroencephalography, functional connectivity, motor imagery, motor network, sensorimotor cortex.

*Correspondence to: A. Athanasiou, Lab of Medical Physics, School of Medicine, Faculty of Health Sciences, Aristotle University of Thessaloniki, PO Box: 376, 54124 Thessaloniki, Greece. Tel: +30-2310-999310, mobile: +30-6947-811621.
E-mail addresses: athalkinoos@auth.gr (A. Athanasiou), klados@cbs.mpg.de (M. A. Klados), cstyliadis@auth.gr (C. Styliadis), nforoglou@auth.gr (N. Foroglou), polyzoik@auth.gr (K. Polyzoidis), bamidis@med.auth.gr (P. D. Bamidis).

Abbreviations: BCIs, Brain-Computer Interfaces; CC, clustering coefficient; CCD, Cortical Current Density; CPL, characteristic path length; D, density; DTF, Directed Transfer Function; EEG, electroencephalographic; FME, foot motor execution; FMI, foot motor imagery; HME, hand motor execution; HMI, Hand motor imagery; MNI, Montreal Neurological Institute; MRI, Magnetic Resonance Imaging; MVAR, multivariate autoregressive; PCC, Pearson's Correlation Coefficient; ROIs, regions of interest; SW, small-world-ness.

http://dx.doi.org/10.1016/j.neuroscience.2016.05.044

INTRODUCTION

The *performance of physical motor tasks* (also known as motor execution) involves the activation and communication of many cortical regions. The mental rehearsal or execution of a motor task that does not actually lead to physical execution is often referred to as motor imagery (Decety and Ingvar, 1990). Motor imagery has drawn a lot of attention especially due to the similar (to motor execution) activation patterns that it elicits in the human brain (Pfurtscheller and Neuper, 1997; Avikainen et al., 2002; Järveläinen et al., 2004) and it has been extensively utilized in rehabilitation practices and sports training. More importantly, motor imagery has been employed in cases of severe neurological disability (such as those caused by strokes or spinal cord injury) as a control modality of Brain-Computer Interfaces (BCIs) to promote communication or functional mobility restoration (Wolpaw et al., 2002; Birbaumer, 2006).

Recently, interest has been drawn to the functional characteristics of cortical regions, especially the way that each region communicates with each other and the neurophysiological observations that actually better represent their activation and communication patterns. In a number of electroencephalographic (EEG) studies, neural oscillations within the range of alpha (8–12 Hz) and beta (13–30 Hz), as well as gamma activity (30–90 Hz), have been identified as the EEG bandwidth more commonly associated with the sensorimotor processes (Neuper et al., 2006; Sabate et al., 2011, 2012; Lopes da Silva, 2013). Alpha rhythm when recorded over the sensorimotor regions is also known as the mu or sensorimotor rhythm and alpha modulation has drawn attention with regards to its physiological role in motor execution and motor imagery (Sabate et al., 2011). An attentional role to both local neuronal processes and wide interactions has been attributed to alpha rhythm (Palva and Palva, 2011). While traditionally alpha has been shown to decrease in amplitude in response to movement (Arroyo et al., 1993), more active task-centric roles have since also been attributed to this range of oscillations (von Stein and Sarnthein, 2000; Palva and Palva, 2011; Sabate et al., 2011, 2012).

The beta rhythm has also been known to be voluntarily modulated during motor execution (Salmelin et al., 1995; Willemse et al., 2010). Yet some researchers suggested that beta does not represent an independent process or physiological role (Jurgens et al., 1995; Sugata et al., 2014), that is phase locked to the alpha rhythm and, as such, not offered as independent control feature (Krusienski et al., 2007). It has been also suggested that alpha and beta rhythms could be considered components of a wider range of the mu rhythm (Pineda, 2008). Nonetheless, beta rhythm has some unique properties including an inhibitory state native to primary motor cortex or an underlying cortical network baseline activity (Neuper and Pfurtscheller, 2001), as well as an active state related to limb movement (Salmelin et al., 1995; Neuper and Pfurtscheller, 1996, 2001). Beta rhythm (especially high beta band or 20–30 Hz) has also been reported to be a good physiological predictor of motor skill acquisition when compared to other frequency ranges, including the alpha range of the sensorimotor mu rhythm (8–12 Hz) (Wu et al., 2014). The beta band desynchronization has also been reported to be the most robust EEG localized feature during motor execution of the hand (Kuo et al., 2014).

Alpha and beta oscillation patterns cannot be considered temporally and spatially static (Varela et al., 2001; Astolfi et al., 2007; Ioannides, 2007). Instead, the actual mechanics and dynamics of cortical interactions and information flow can be portrayed and studied by means of functional connectivity (Ioannides, 2007; Athanasiou et al., 2012) which has the ability to estimate significant temporal correlations and dynamic networks that are formed across spatially separated cortical activations (Astolfi et al., 2007; Athanasiou et al., 2012). In motor skills acquisition, connectivity is more suited to depict the dynamic cortical processes than more "static" traditional methods (Wu et al., 2014). Furthermore, cross-frequency coupling is an important property of brain activity that has been recognized to significantly contribute, not only to cognitive functioning (Fitzgerald et al., 2013), but sensorimotor processes as well, serving intercommunication between cortical activity of different spatial and frequency characteristics (Canolty and Knight, 2010).

A number of studies suggests that lower frequencies tend to modulate brain activity over larger spatial regions and are therefore associated to top-down control and coordination functionality (Canolty and Knight, 2010; Fitzgerald et al., 2013). In contrast, higher frequencies tend to form more spatially focused modulation and are associated with processing within local neuronal clusters (von Stein and Sarnthein, 2000; Achard et al., 2006; Canolty and Knight, 2010). Though similar observations apply for motor processes (Crone et al., 1998), this is not always the case. Such evidence (Willemse et al., 2010; Athanasiou et al., 2014; Zhang et al., 2014) suggests that the alpha band presents high modulation in spatially focused connectivity flows while higher frequency bands handle distant connectivity interactions. Observations implying a role of beta rhythm in distant information flow have also been reported by De Vico Fallani et al. (2013) and Strens et al. (2004). Such an exemption, possibly non-mutually exclusive (Palva and Palva, 2011), has also been observed in other neurophysiological processes, such as visual working memory (Palva et al., 2010). It has also been reported during processes intrinsic to visual cortical areas where higher frequency components (gamma) could present modulation across separated areas and over lower, locally nested, frequency components (delta) (Bruns and Eckhorn, 2004).

In our previous work (Athanasiou et al., 2012, 2014) we investigated the formation and properties of networks of alpha and beta rhythms in motor imagery and execution using graph analysis of functional connectivity over the sensorimotor cortex and surrounding cortical areas. We identified patterns of properties unique to each rhythm, namely an increased clustering of the alpha networks or an increased density combined with more effective path lengths of the beta networks (Athanasiou et al., 2014). Such observations led us to hypothesize and propose a functional model regarding the distinct physiological roles of those rhythms in sensorimotor processes. According to this proposed model, alpha rhythm seems to carry and modulate elaborate information on the neurophysiological process that is being executed; using greater wiring costs to achieve this task, and assumes the role of local neuronal processing. Similarly beta rhythm carries and disperses coordinative information among different clusters of nodes and modulates activity over larger spatial regions.

The goal of the current paper is to present and further elaborate the observations of our previous study, as well as subject the aforementioned proposed scenario to a different model of cortical regions of interest (ROIs) and compare those findings to what we have already suggested. We examine the possibility that the role of beta rhythm, in specific context, may be the coordination of sensorimotor information and that of alpha rhythm may be related to local processing. Furthermore, we discuss our findings in the light of the relevant literature and what functional models other authors propose or suggest regarding the formation of sensorimotor cortical networks. Ultimately, we make mention of the significance of these observations not only towards a more profound understanding of how brain activity is modulated in the motor system but also towards the possible implementation of such knowledge in the design and development of connectivity-based BCIs (Goel et al., 2011; Benz et al., 2012; Zhang et al., 2014; Hamedi et al., 2016; Kabbara et al., 2016).

EXPERIMENTAL PROCEDURES

Subjects

Seven healthy, right-handed individuals participated in this study. The study was performed in accordance with