



Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge



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ABSTRACT

Cortical dynamics were examined during a cognitive-motor adaptation task that required inhibition of a familiar motor plan. EEG coherence between the motor planning (Fz) and left hemispheric region was progressively reduced over trials (low-beta, high-beta, gamma bands) along with faster, straighter reaching movements during both planning and execution. The major reduction in coherence (delta, low/high-theta, low/high-alpha bands) between Fz and the left prefrontal region during both movement planning and execution suggests gradual disengagement of frontal executive following its initial role in the suppression of established visuomotor maps. Also, change in the directionality of phase lags (delta, high-alpha, high-beta, gamma bands) reflects a progressive shift from feedback to feedforward motor control. The reduction of cortico-cortical communication, particularly in the frontal region, and the strategic feedback/feedforward mode shift translated as higher quality motor performance. This study extends our understanding of the role of frontal executive beyond purely cognitive tasks to cognitive-motor tasks.

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1. Introduction

Recently, the emergence of efficient cortical activity, as associated with a reduction in non-essential processing, was observed during the mastery of a task that required executive inhibition of a pre-existing motor plan (Gentili, Hadavi, Ayaz, Shewokis, & Contreras-Vidal, 2010; Gentili, Bradberry, Oh, Hatfield, & Contreras-Vidal, 2011; Gentili, Shewokis, Ayaz, & Contreras-Vidal, 2013; Shadmehr & Holcomb, 1999). Although changes in regional activity supported the notion that psychomotor efficiency contributed to the improvement in performance of such cognitive-motor adaptation tasks, changes in cortical network communications were not examined. Thus, there is a need to measure cortico-cortical communication in order to determine whether

the refinement of such cortical network communication occurs throughout the adaptation period. In this manner, additional support for the emergence of efficient neural processes as a result of learning would be provided by this metric (i.e., EEG coherence).

A number of studies that examined the cortical dynamics of motor skill at various stages of expertise have revealed reduction of non-essential cortical activity as a result of skill acquisition (e.g., Gentili, Bradberry, Hatfield, & Contreras-Vidal, 2009; Gentili et al., 2011, 2013; Kerick, Douglass, & Hatfield, 2004; for a review see Hatfield, Haufler, Hung, & Spalding, 2004). Most of these studies have focused on EEG spectral power and revealed a positive relationship between alpha power and expertise (e.g., Gentili, Bradberry, Hatfield, & Contreras-Vidal, 2008; Gentili et al., 2011; Hatfield, Landers, & Ray, 1984; Hatfield et al., 2004). In addition, some studies have reported contrasts of cortical network communications in novice and expert performers (Deeny, Haufler, Saffer, & Hatfield, 2009; Reiterer, Berger, Hemmelmann, & Rappelsberger, 2005). Such extreme contrasts clearly revealed lower coherence between several cortical regions with the motor planning area in experts, compared to novices, during a precision aiming task

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(Deeny et al., 2009). However, correlational studies are limited by the possibility of alternative explanations for the findings beyond the difference in motor skill level (i.e., expertise). Comparatively few studies have examined changes in cortico-cortical communication with practice (Andres et al., 1999; Busk & Galbraith, 1975; Gentili et al., 2009; Kranczoch, Athanassiou, Shen, Gao, & Sterr, 2008; Perfetti et al., 2011; Serrien, Cassidy, & Brown, 2003) and, collectively, the findings have been mixed. For instance, Busk and Galbraith observed a reduction in EEG coherence during practice of a pursuit-rotor tracking task, while Kranczoch et al., observed an elevation in coherence during a visually guided power-grip task. Also, previous studies involved practice of a skill for which no interference with previous motor experience existed and in which the analysis of the directionality of the cortico-cortical communications was generally ignored. Therefore, there is a need to further examine the role of cortico-cortical communications in motor adaptation.

We believe that the use of distortion of visual feedback during movement is particularly informative to examine cortical dynamics during learning in light of the effortful engagement initially required to negotiate such tasks. Such adaptation tasks require participants to integrate sensory (e.g., proprioceptive, visual) feedback in order to adapt the motor response to the task demand. During the early adaptation stage, movements are mainly guided by sensory feedback while such feedback is less important during late adaptation since the movements become automatic (Ashby, Turner, & Horvitz, 2010; Fitts & Posner, 1967; Seidler, Noll, & Thiers, 2004). In other words, the internal model of the new visuomotor transformation is gradually encoded throughout adaptation and the movement progressively shifts from feedback toward greater feedforward control. Such adaptation tasks also demand that the frontal executive regions would inhibit the pre-existing input–output relationships during the early adaptation stage and become less relevant as learning proceeds (Gentili et al., 2010, 2011, 2013). This idea is consistent with the results of previous imaging studies that suggested an important role for the prefrontal region in the inhibition of competing motor memories (Shadmehr & Holcomb, 1999).

Typically, the role of executive processes has been examined in the context of pure cognitive demand. Furthermore, relatively few studies have employed measures of cortico-cortical communication during such challenge (e.g., Müller & Anokhin, 2012; Schmiedt-Fehr & Basar-Eroglu, 2011; Shibata et al., 1998). The present study extends the examination of executive processes to the cognitive-motor domain while considering cortico-cortical communication between the frontal region and other cortical regions. Moreover, there is a need to investigate the relationship between the changes in cortico-cortical communication activity and the quality of the motor performance.

Therefore, we employed EEG to monitor the dynamics of cerebral cortical networking as participants suppressed a pre-existing neuromotor map and acquired a novel input–output relationship based on a visuomotor transformation. By investigating EEG coherence between electrode pairings that match well-known reciprocal anatomical connections between the premotor regions and the frontal, motor, temporal, parietal and occipital regions (Deeny, Hillman, Janelle, & Hatfield, 2003; Deeny et al., 2009; Gentili et al., 2009; Kaufer & Lewis, 1999; Rietschel et al., 2011) we predicted the emergence of an inverse relationship between cortico-cortical communication and the quality of performance as a result of practice such that reduction of cortico-cortical communication would translate as efficiency of movement. Specifically, such reduction of cortico-cortical communication should be particularly visible in the frontal areas. Since the left hemisphere has a critical role in the construction and storage of motor programs, integration of sensory feedback, learning, and the evaluation of the body

state (Fisk & Goodale, 1988; Grafton, Hazeltine, & Ivry, 2002; Kuitzbuschbeck et al., 2003; Wolpert, Goodbody, & Husain, 1998), it was also predicted that the degree of refinement in cortico-cortical communications will be prominent in this region relative to that in the right hemisphere throughout adaptation. Finally, it was predicted that the directionality of the information flow would change from the early to the late adaptation stage indicating a progressive shift from feedback to a feedforward control (automatization of the performance; Ashby et al., 2010; Fitts & Posner, 1967; Seidler et al., 2004). No comparable changes in performance or cortico-cortical communication were predicted for the control subjects who did not have to learn the visuomotor transformation.

2. Materials and methods

The variables extracted here (EEG coherence, EEG phase and kinematics) are derived from the re-analysis of a data set employed in a previous experiment (Gentili et al., 2011).

2.1. Task

Right-handed adults ($n=20$) were seated at a table facing a computer screen and drawn a line, using a pen, on a digitizing tablet (12 WACOM, InTuos) placed in front of them. Participants were seated facing a computer screen (14" display at eye level) at a distance of approximately 60 cm. Pen trajectories were displayed in real time on the computer screen by employing a custom Oasis v.8.29 software (Kikosoft, Nijmegen). Using their right arm/hand which the vision was prevented by a horizontal board, subjects performed "center-out" movements to draw lines from a center target circle (i.e., home target) to one of four peripheral targets. The home target circle (diameter 5 mm) represented the origin of a polar frame of reference where the four peripheral targets (5 mm diameter circles) were respectively located at 45°, 135°, 225°, and 315°, and each was positioned at 10 cm from the origin. A horizontal board prevented vision of the arm/hand moving on the digitizing tablet while movement trajectories were displayed as solid black lines on the screen (Fig. 1). Both EEG signals and pen kinematics were simultaneously recorded (for further details, see Gentili et al., 2011).

Upon completion of the familiarization stage (20 practice trials not analyzed) participants executed 20 trials (i.e., 1 block) under normal (i.e., unperturbed) visual feedback of cursor movement (pre-exposure). The learning and control groups each consisted of 10 participants. The learning group executed 180 drawing movements (9 blocks \times 20 trials) during which the screen cursor was rotated 60° counter-clockwise (exposure condition). The control group performed without any visual distortion. Lastly, a block of 20 trials was performed by all subjects once the distortion was removed to test for after-effects to assess if the internal model of the new visuomotor transformation was successfully acquired by the learning group. Participants self-selected the targets and self-initiated their movements (all targets were displayed) during each trial. The participants were allowed to move their eyes and instructed to distribute their movements toward all targets evenly to avoid privileging any particular target. They did not have any information regarding the perturbation (i.e., nature, magnitude and maintained constant throughout the experiment). Once a peripheral target was selected and the movement planned, participants drew a line as straight and fast as possible to link the home and the selected peripheral targets. The trial was terminated and restarted when movements were initiated earlier than 2 s after target presentation. Therefore, participants were provided the time to both select a target and plan their movement, allowing an extended time window to capture cortical activity related to movement planning and preparation (Contreras-Vidal & Kerick, 2004; Gentili et al., 2009, 2011). Once the peripheral target was reached all visual stimuli were erased from the screen, and the subject returned to the home target (self-paced with no speed/accuracy constraint or perturbation) in preparation for the next trial when a successful trial was performed (for further details, see Gentili et al., 2011) (see Fig. 1). The entire drawing task was completed in 45 min.

2.2. Data analysis

2.2.1. Movement kinematics

Movement planning and execution, movement time, movement length, and root mean squared error were computed in order to quantify the motor performance. All of the kinematic parameters (i.e., movement time and length; the root mean squared error) values were standardized with respect to the pre-exposure stage for each participant in order to account for any differences in participants' performance during the pre-exposure phase (i.e., baseline condition) and to focus on changes due solely to adaptation. As such, a standardization process was applied to the kinematic data, which were expressed in standard deviation units (i.e., sd units) relative to the baseline of each participant (for further details, see Gentili et al., 2011).

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