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Integration of cortical areas during performance of a catching ball task

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ABSTRACT

The study aimed to elucidate electrophysiological and cortical mechanisms involved in anticipatory actions when healthy subjects had to catch balls in free drop; specifically through quantitative electroencephalography (qEEG) alpha absolute power changes. Our hypothesis is that during the preparation of motor action (i.e., 2 s before ball's drop) occurred integration among left medial frontal, left primary somatomotor and left posterior parietal cortices, showing a differentiated activity involving expectation, planning and preparedness. This hypothesis supports a lateralization of motor function. Although we contend that in right-handers the left hemisphere takes on a dominant role for the regulation of motor behavior. The sample was composed of 23 healthy subjects (13 male and 10 female), right handed, with ages varying between 25 and 40 years old (32.5 ± 7.5), absence of mental and physical illness, right handed, and do not make use of any psychoactive or psychotropic substance at the time of the study. The experiment consisted of a task of catching balls in free drop. The three-way ANOVA analysis demonstrated an interaction between moment and position in left medial frontal cortex (F3 electrode), somatomotor cortex (C3 electrode) and posterior parietal cortex (P3 electrode; $p < 0.001$). Summarizing, through experimental task employed, it was possible to observe integration among frontal, central and parietal regions. This integration appears to be more predominant in expectation, planning and motor preparation. In this way, it established an absolute predominance of this mechanism under the left hemisphere.

Motor behavior is the product of a fine integration between cortical and peripheral components associated to afferent information. It has acknowledged the relevance of identifying, acquiring and processing sensory stimuli during the execution and control of a motor task [15]. Such factors are the elementary components of the preparation and adjustment of a motor gesture, and they take part in the integration among different specialized centers in the final production of the movement [18]. This process occurs through sensorimotor integration, when sensory information is integrated by central nervous system to attend to motor programs. The possibility of adjusting a certain action to the different environmental demands provides a variety of movements and skills essential to the improvement of the desired motor execution [17]. Catching an object is a complex movement which involves not only programming but also effective motor coordination. Such behavior is related with the activation and recruitment of cortical regions which take part in the integration process that occurs between the information coming from the environment and the performed motor task [6].

The quantitative electroencephalogram (qEEG) might be well suited to the task of monitoring the changes in brain state that occur when an individual performing a task comes to adopt an effective strategy and to develop appropriate skills. Spectral features of the electroencephalography (EEG) in the alpha (8–12 Hz) band are sensitive to variations in perception, cognition or motor action [3]. In this manner, the assessment of EEG would be informative as it could address how the brain organizes and integrates sensory information, performs cognitive operations and achieves motor control

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during the performance of multiple complex tasks. Identification of such cortical dynamics could be useful in the future with the appropriate technologies for assessment of these processes [14]. This study aimed to elucidate electrophysiological/cortical mechanisms involved in anticipatory actions when individuals had to catch balls in free drop; specifically through qEEG alpha absolute power changes. Our hypothesis is that during the preparation of motor action (i.e., moment preceding balls drop) occurred integration among left medial frontal, left primary somatomotor and left parietal posterior cortices, showing a differentiated activity involving expectation, planning and preparedness. This hypothesis supports a lateralization of motor function. Although we contend that in right-handers the left hemisphere takes on a dominant role for the regulation of motor behavior.

Sample was composed of 23 healthy subjects (13 male and 10 female), right handed [20], with ages varying between 25 and 40 years old (32.5 ± 7.5). Inclusion criteria were absence of mental or physical impairments, no history of psychoactive substances and no neuromuscular disorders (screened by a previous clinical examination). All subjects signed a consent form and were aware of the whole experimental protocol. The experiment was approved by the Ethics Committee of Federal University of Rio de Janeiro (IPUB/UFRJ). This experimental paradigm has been already used in other experiment [26].

The task was performed in a sound and light-attenuated room, to minimize sensory interference. Individuals sat on a comfortable chair to minimize muscular artifacts, while electroencephalography and electromyography (EMG) data were collected. An electromagnetic system, composed of two solenoids, was placed right in front of the subject and released 8-cm balls, one at each 11 s, at 40 cm above the floor, straight onto the subject's hand. The right hand was placed in a way that the four medial metacarpi were in the fall line. After its catch, the ball was immediately discharged. Each released ball composed a trial and blocks were made of 15 trials. All experiment had six blocks that lasted 2 min and 30 s with 1 min intervals between them.

EEG The International 10/20 System for electrodes [12] was used with the 20-channel EEG system Braintech-3000 (EMSA-Medical Instruments, Brazil). The 20 electrodes were arranged in a nylon cap (ElectroCap Inc., Fairfax, VA, USA) yielding monopolar derivations referred to linked earlobes. In addition, two 9-mm diameter electrodes were attached above and on the external corner of the right eye, in a bipolar electrode montage, for eye-movement (EOG) artifacts monitoring. Impedance of EEG and EOG electrodes was kept between 5 and 10 KΩ. The data acquired had total amplitude of less than 100 μV. The EEG signal was amplified with a gain of 22,000, analogically filtered between 0.01 Hz (high-pass) and 100 Hz (low-pass), and sampled at 240 Hz. The software Data Acquisition (Delphi 5.0), developed at the Brain Mapping and Sensory Motor Integration Lab, was employed with the following digital filters: notch (60 Hz), high-pass of 0.3 Hz and low-pass of 25 Hz.

EMG Electromyographic activity of the flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi radialis (ECR) and extensor carpi ulnaris (ECU) was recorded by an EMG device (Lynx-EMG1000), to monitor and assess any voluntary movement during the task. Bipolar electrodes (2-mm recording diameter) were attached to the skin. The reference electrode was fixed on the skin overlying the lateral epicondyle near the wrist joint. The skin was cleaned with alcohol prior to electrode attachment. The EMG was amplified (1000×), filtered (10–3000 Hz), digitized (10,000 samples/s), and recorded synchronously to the EEG onto the computer's hard drive. In each trial, the EMG signal was rectified and averaged over the 500 ms starting from the trigger onset. EMG was used in order to detect and remove possible artifacts related to the ball's fall that could affect the electroencephalographic signal.

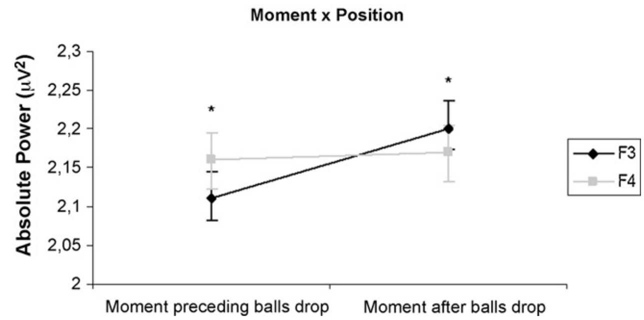

Fig. 1. Interaction between moment and position factors on F3–F4 electrode combination observed through mean and standard deviation values. (*) Significant difference, $p < 0.001$.

To quantify reference-free data, a visual inspection and independent component analysis (ICA) were applied to remove possible sources of artifacts produced by the task. A classic estimator was applied for the power spectral density (PSD), or directly from the square modulus of the Fourier transform (FT), which was performed by MATLAB 5.3 (Matworks, Inc.). Quantitative EEG parameters were reduced to 4-s periods (the selected epoch started 2 s before and ended 2 s after the trigger, i.e., moment preceding balls drop and moment after balls drop), for consecutive (non-overlapping) artifact-free, 4 s EEG epochs (spectral resolution: 0.25 Hz), with rectangular windowing. In this manner, based on artifact-free EEG epochs, the threshold was defined by mean plus three standard deviations and epochs with total power higher than this threshold were not integrating the analysis.

The F3 and F4 electrodes represent medial frontal cortex, functionally related to motivation, planning and motor programming [19]. The C3 and C4 represent the primary somatomotor cortex, functionally related to motor execution [25]. Lastly, P3 and P4 electrodes represent the posterior parietal cortex, functionally related to sensorimotor orientation [24]. The alpha band (8–12 Hz) was chosen due to its association with perception, cognition or motor action [21].

In statistical analysis, the EEG absolute power values were $\log_{10}$-transformed by *SPSS* software (version 15.0) to approximate a normal distribution. A three-way ANOVA and a post hoc test (Scheffé) were performed to analyze the factors moment (moment preceding balls drop and moment after balls drop) and blocks (1–6) for each electrode combination: (a) F3/F4; (b) C3/C4 and (c) P3/P4 ($p < 0.05$).

The statistical analysis demonstrated an interaction between the moment and position factors for each electrode combination ($p < 0.001$). It was found a significant decreasing in absolute power values in moment preceding balls drop in F3 electrode (mean = 2.11; s.d. = 0.036) when compared with F4 electrode (mean = 2.16; s.d. = 0.034). On the other hand, it was noted an increasing in absolute power values in moment after balls drop in F4 electrode (mean = 2.17; s.d. = 0.038) when compared with F3 electrode (mean = 2.2; s.d. = 0.027), as observed in Fig. 1. In relation to C3 electrode, it was found a significant decreasing in absolute power values in moment preceding balls drop (mean = 3.21; s.d. = 0.43) when compared with C4 electrode (mean = 3.47; s.d. = 0.56). In moment after balls drop, it was noted an increasing in absolute power values in C4 electrode (mean = 3.57; s.d. = 0.47) when compared with C3 electrode (mean = 3.87; s.d. = 0.52), according to Fig. 2. Lastly, it was found a significant decreasing in absolute power values in moment preceding balls drop in P3 electrode (mean = 3.34; s.d. = 0.07) when compared with P4 electrode (mean = 3.51; s.d. = 0.068). In moment after balls drop, it was noted an increasing in absolute power values in P4 electrode (mean = 3.58; s.d. = 0.048) when compared with P3 electrode (mean = 3.68; s.d. = 0.037), as observed in Fig. 3.

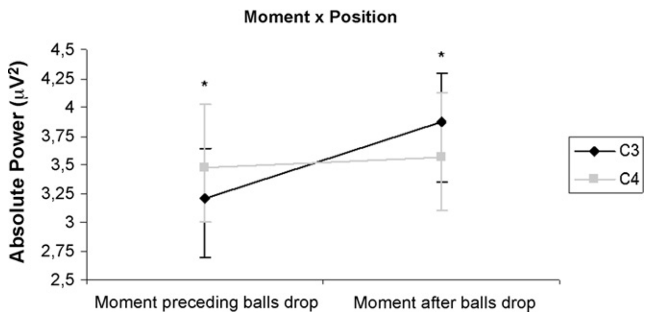

Fig. 2. Interaction between moment and position factors on C3–C4 electrode combination observed through mean and standard deviation values. (*) Significant difference, $p < 0.001$.

The current experiment is an attempt to understand cortical/electrophysiological mechanisms regarding anticipatory actions involved in voluntary movements, specifically, when subjects had to seize free falling balls. Our hypothesis is that during the preparation of motor action (i.e., moment preceding balls drop) occurred integration among left medial frontal, left primary somatomotor and left posterior parietal cortices, showing a differentiated activity involving expectation, planning and preparedness. This hypothesis supports a lateralization of motor function. Although we contend that in right-handers the left hemisphere takes on a dominant role for the regulation of motor behavior. In this manner, through qEEG, changes in the alpha absolute power were examined. We observed the interaction between moment (i.e., moment preceding balls drop and moment after balls drop) and different scalp's position (medial frontal, primary somatomotor and posterior parietal cortices). It suggests that moment and position would better explain alpha power expression instead of the main effects isolated. Our findings presented a reduction in alpha absolute power values in electrodes F3, C3 and P3 when compared with homologous electrodes (i.e., F4, C4 and P4). Such behavior occurred during the period of expectancy and promptness before the motor action (i.e., moment preceding balls drop) which is relating to contralateral arm's movement [19]. Traditionally, alpha power is considered to have an inverse relationship with neural activation. It can be seen in different experiments involving perception, cognition or motor action [21]. In our results, the reduction of power, i.e., observed in alpha band, expresses an increment of activity in pyramidal neuron's population at these sites, in the moment that precedes the balls drop [3], which seems to reflect an increase in neural activity [19], suggesting an increased expectation, alertness and readiness.

In relation to F3 results, our data is supported by Szurhaj et al. [25] which has demonstrated the involvement of the frontomedial cortex (i.e., contralateral arm's movement) during the planning and preparation of a motor action. Moreover, a power decrease was observed by Szurhaj, seen from the ERD/ERS paradigm, indicating a differentiated activation of these areas, which initiated in average between 0 and 375 ms before the movement. Szurhaj examined μ (i.e., 6–9 Hz) and β (i.e., 13–30 Hz) rhythms. Differently, our data presented alpha as a whole (i.e., 8–12 Hz). Other findings have described the participation of the prefrontal and pre-motor cortices during the judgment, planning and organization of future actions and during the planning and organization of acts that are adequate [7]. In this sense, it was demonstrated for Ajemian et al. [1] that the pre-motor cortex orchestrates the sensorial orientation of the members before the execution of a movement. The association between our results and the gotten ones in other experiments suggests a close integration between the functions of the prefrontal (i.e., actions selection) and pre-motor areas (i.e., organization and command of the action) [8].

Our results related to C3 electrode, suggest a phenomenon known as sensory facilitation. Brunia suggested a neurophysiological model, i.e., thalamocortical gating, to explain preparatory behavior [5]. This model expects that preparatory attention expresses a cortical activation which occurs before stimuli's presentation. According to Brunia, such activation is narrowed to the cortical area related to the modality of the stimulus. Our results are in agreement with those experiments, C3 site was substantially activated during movement preparation phase (e.g., considering the inverse relation of the alpha band). One suggests that this region is related to the planning and preparation of motor gestures of the contra-lateral member [25]. In this manner, a possible explanation is that during the motor preparation (i.e., moment preceding balls drop) occurred a comparison between elements pre-stored in medial frontal cortex (i.e., implicit memory) on the somatomotor cortex and new parameters of the upcoming motor action. Similar results were seen in experiments by Zang et al. [29] and Kansaku et al. [13] which demonstrated that pre-motor and primary motor cortex are activated like an integrated form during the preparatory moment. Taken together these and our results suggest that the involvement of the somatomotor cortex seems to be direct with implicit memory processes. Such processes simulate internally operations of "pre-established neural networks" which occur before the motor action. Internal simulations of motor commands have also been observed in experiments which make use of motor imagery [23] and mirror neurons paradigms [11]. Therefore, the increase in activity perceived by the decrease in alpha power suggests an involvement of two cortical regions (i.e., prefrontal cortex and somatomotor cortex) on the processing of sensory information related to motor execution (i.e., catching) like a parallel process.

Additionally, our results indicate an increase in cortical activation on P3 electrode during motor planning and preparation phase of contra-lateral limb. Previous experiments report that the posterior parietal cortex is responsible by initiation and sensorimotor guidance, preparing limb movement and handling of objects, via visual and proprioceptive information, assisting in motor planning. In relation to balls drop task, there is a considerable proprioceptive and visual demand of this experiment, which justifies the activation of the left posterior parietal cortex [4]. Therefore, in moment preceding balls drop, the data suggest a strong integration between proprioceptive information (hand's position) and visual information at the beginning of balls drop (spatial-temporal coordination regarding the ball's contact with the hand). These activities regarding to sensory modalities explain the higher activation of the left posterior parietal cortex, specially in moment preceding balls drop. The results obtained by Wheaton et al. [28] support our data. An alpha power decreased in left posterior parietal cortex during movement preparation in healthy subjects was found. Similarly, the

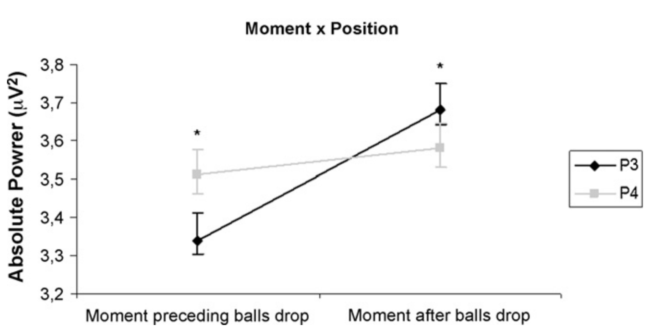

Fig. 3. Interaction between moment and position factors on P3–P4 electrode combination observed through mean and standard deviation values. (*) Significant difference, $p < 0.001$.

subjects were able to exploit, additionally, the visual information available on the brief time period during early ball's drop period. In this moment, the correspondent area to electrode P3 may provide information about coordination of arm and finger movements when moved to visual targets [22] and also anticipatory coordination of grip and load forces to maintain grasp stability during object manipulation [9], which occurs before the motor action as a basis for the movement organization.

On the other hand, the moment after balls drop revealed an increase in alpha power values of the electrodes F3, C3 and P3 when compared with homologous electrodes (i.e., F4, C4 and P4), which seems to reflect a diminished neural activity [3], suggesting a decreased expectation, alertness and readiness subsequent to the balls drop. It could be interpreted as a deactivation of the involved cortical areas. It could be verified due to task being performed in open circuit, i.e., the movements are fast enough to allow the use of this feedback information in real time [2], which could leave a decrease in these specific cortical activation. Other justify that the right hemisphere specialization in spatial functions might be related to (spatial) attention control of visual representation [16], or a regulation function in conflict situations [27], as when experiencing a bad interaction between motor and proprioceptive interaction and/or visual feedback [10].

Summarizing, through the experimental task employed, it was possible to observe integration among medial frontal, primary somatomotor and posterior parietal cortices. These areas demonstrated a differentiated activity involving expectation, planning and preparedness in the balls drop task. Thus, an absolute predominance of this integration mechanism was observed over the left hemisphere. We recommend, new investigations should replicate these findings, maybe, utilizing new paradigms, different objects and randomization time. Moreover, different population, other than healthy subjects, should also be considered for new experiments, for example, healthy elderly subjects and patients suffering from mild cognitive impairment and Alzheimer disease, in an attempt to observe specific variables such as attention, episodic memory, anticipatory movements, reaction time and motor planning and execution.

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