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Gamma-band oscillations in fronto-central areas during performance of a sensorimotor integration task: A qEEG coherence study

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This study aimed to elucidate electrophysiological and cortical mechanisms involved in anticipatory actions when 23 healthy right-handed subjects had to catch a free falling object by qEEG gamma-band (30–100 Hz). It is involved in cognitive processes, memory, spatial/temporal and proprioceptive factors. Our hypothesis is that an increase in gamma coherence in frontal areas will be observed during moment preceding ball drop, due to their involvement in attention, planning, selection of movements, preparation and voluntary control of action and in central areas during moment after ball drop, due to their involvement in motor preparation, perception and execution of movement. However, through a paired *t*-test, we found an increase in gamma coherence for F3–F4 electrode pair during moment preceding ball drop and confirmed our hypothesis for C3–C4 electrode pair. We conclude that gamma plays an important role in reflecting binding of several brain areas in a complex motor task as observed in our results. Moreover, for selection of movements, preparation and voluntary control of action, motor preparation, perception and execution of movement, the integration of somatosensory and visual information is mandatory.

The practice of a motor task promotes several changes in the cortical activity relative to the intention and the movement execution aiming to adapt, retain and consolidate the motor act [2]. Catching an object is a complex movement which involves not only programming but also effective motor coordination. Such behavior is related to the activation and recruitment of cortical regions which take part in the sensorimotor integration process that integrates information coming from the environment and the performed motor task in order to prepare motor acts and to enhance the execution of goal-directed tasks [9,8]. Within this context, the cortical areas are recruited to promote a self-organization (i.e., the functional reorganization of circuits) of neural networks for the constitution of a functional group (binding problems) [16,6] to improve the coordination and the motor control due to the instability induced by the task [31].

The gamma-band corresponds to a frequency varying from 30 Hz to 100 Hz and it is involved in the cognitive process, memory, and spatial/temporal and proprioceptive integration factors [4,5]. In line with that, the gamma activity has been related to the sensorimotor process during performance of tasks involving visual discrimination and motor preparation [26,25]. Several laboratories have reported an increase in amplitude of gamma-band during sensory and cognitive processes [27,19]. Particularly, the results of our group are interesting due to the coupling among cortical areas in gamma coherence. Contrary to other experiments, our group explored the relevant role of gamma expressing cortical coupling among different regions. Therefore, this study aimed to elucidate electrocortical mechanisms involved in anticipatory actions when individuals had to catch a free falling object by qEEG gamma-band. Our hypothesis is that an increase in gamma coherence in frontal areas will be observed during moment preceding ball drop, due to their involvement in attention, planning, selection of

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movements, preparation and voluntary control of action [31] and in central areas during moment after ball drop, due to their involvement in motor preparation, perception and execution of movement [9].

Sample was composed of 23 healthy subjects (13 male and 10 female), right handed [12], with ages varying between 25 and 40 years (mean = 32.5; SD = 7.5). Inclusion criteria were absence of mental or physical impairments, no history of psychoactive substances and no neuromuscular disorders (screened by a previous anamnesis and 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 experiments [9,8,31].

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 every 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 experiments had six blocks that lasted 2 min and 30 s with 1 min intervals between them.

Electroencephalography – The International 10/20 System for electrodes 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 monopole 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 under 5–10 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 Sensorimotor Integration Laboratory was employed to filter the raw data: notch (60 Hz), high-pass of 0.3 Hz and low-pass of 100 Hz.

Electromyography – Electromyographic (EMG) 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 500 ms from the trigger point.

To quantify reference-free data, a visual inspection and independent component analysis (ICA) were applied to identify and remove any remaining artifacts, i.e., eye blinks and ocular movements produced by the task. Data from individual electrodes exhibiting loss of contact with the scalp or high impedances (>10 kΩ) were deleted and data from single-trial epochs exhibiting excessive movement artifact (±100 μV) were also deleted. Independent component analysis (ICA) was then applied to identify and remove any remaining artifacts after the initial visual inspection. ICA is an information maximization algorithm that derives spatial filters by blind source separation of the EEG signals into temporally independent and spatially fixed components. Independent components resembling eye-blink or muscle artifact were removed and the remaining components were then back-projected onto the scalp electrodes by multiplying the input data by the inverse matrix of the spatial filter coefficients derived from ICA using established procedures. The ICA-filtered data were then reinspected for residual artifacts using the same rejection criteria described above. Then, a classic estimator was applied for the power spectral density (PSD), or directly from the square modulus of the FT (Fourier transform), 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). The analyzed electrophysiological variable was gamma (35–60 Hz) coherence. It represents a measurement of linear covariation between two signals in the frequency domain. It is mathematically bounded between zero and one, whereby one signifies a perfect linear association and zero denotes that the signals are not linearly related at that particular frequency. The premise is that when activities from spatially remote events covary they tend to interact, also denoted as functional connectivity. Standard coherence as a measure of functional coupling provides a link between two signals but no directional information. To this end, estimators can be constructed, such as a directed transfer function, which examines asymmetries in inter-regional information flow and establishes a direction of drive between the coupled sites [22,21].

The F3, FZ and F4 electrodes represent the premotor cortex, functionally responsible for selection of movements, preparation and voluntary control of action [9,31]. The F7 and F8 electrodes represent the prefrontal cortex, functionally responsible for executive functions, such as attention and planning [8]. The C3 and C4 electrodes are placed on the pre-central and central gyri, representing the primary sensory motor cortex (SM1) in each hemisphere that is functionally linked to motor preparation, perception and execution of movement [28]. The CZ electrode represents the SM1 of both hemispheres and the supplementary motor area (SMA), which is functionally related to temporal organization and coordination of sequential movements [30]. The gamma-band was chosen to explore its associations with the binding for cognitive process, memory, and spatial/temporal and proprioceptive integration factors [4,5].

The statistical design allowed for examination of functional connectivity and directionality of the communication between the sensorimotor areas in each hemisphere, with respective regions related to sensory, motor execution, and integrative or associative functions. For statistical analysis SPSS 17.0 was used. All results are given as mean values and standard deviation. A paired *t*-test was used to analyze the within subject's factor moment (i.e., preceding and after ball drop) for each pair of electrodes: F3–F4, F7–F8, F3–FZ, F4–FZ, F7–FZ, F8–FZ, C3–C4, C3–CZ, C4–CZ, F3–C3, F4–C4, FZ–CZ. Moreover, we used the Bonferroni correction to address the problem of multiple comparisons. The outcome of statistical calculations were declared significant if $p \leq 0.05$.

The first statistical analysis with regard to frontal region demonstrated a significant difference in the F3–F4 electrode pair ($p = 0.011$). It was found a significant increase in the gamma coherence when compared the moments preceding (mean = 0.46; SD = 0.093) and after (mean = 0.48; SD = 0.098) ball drop as observed in Fig. 1. Moreover, the second analysis demonstrated a significant difference in the C3–C4 electrode pair ($p = 0.046$). It was found a significant increase in the gamma coherence when compared the moments preceding (mean = 0.56; SD = 0.007) and after (mean = 0.57; SD = 0.007) ball drop as observed in Fig. 2. No other significant result was found.

The current experiment is an attempt to elucidate electro-cortical mechanisms regarding anticipatory actions involved in voluntary movements. In particular, subjects had to catch a free falling object (i.e., a ball). Our hypothesis is that an increase

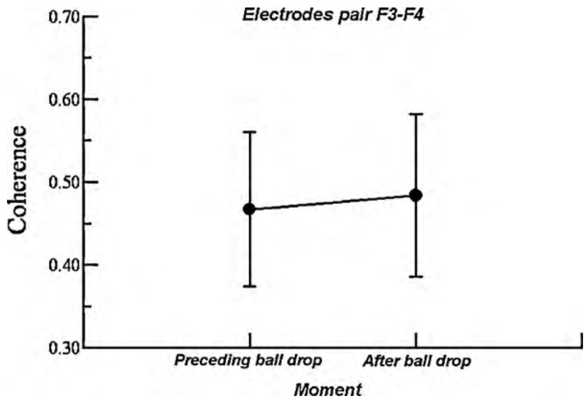

Fig. 1. Mean and standard deviation for coherence on gamma-band. Significant difference between moments observed by *t*-test ($p < 0.046$).

in gamma coherence in frontal areas would be observed during moment preceding ball drop, due to their involvement in attention, planning, selection of movements, preparation and voluntary control of action [31] and in central areas during moment after ball drop, due to their involvement in motor preparation, perception and execution of movement [9].

Gamma-band represents a large scale approach to study sensorimotor integration mechanisms and binding. Moreover, the application of coherence and associated measures provides a valuable analytical tool to investigate functional connectivity between neural sites and changes that occur due to several factors such as task complexity, context and learning [20,23]. Within this context, the increase in gamma coherence can be seen when an organization of somatotopic information happens [29], when neural networks are involved parallelly in motor act improvement, mainly, due to the projections of the corpus callosum in transmission of sensorimotor information [7]. Within this context, the discussion is divided into two parts, where we will discuss the significant result for F3–F4 and C3–C4 pairs of electrodes and their relationship with the gamma-band.

It was demonstrated a significant difference in gamma coherence between moment preceding and after ball drop for F3–F4 electrode pair, i.e., an increase in coherence in the moment after ball drop, in opposition to our expectation. It seems only in this moment, the CNS was capable to integrate relevant information about the task, the so-called binding phenomena, like a consequence of task demands, i.e., the preparation and voluntary control of action, and the selection of movements [31]. It is likely that binding occurs in many different kinds of brain processes and may

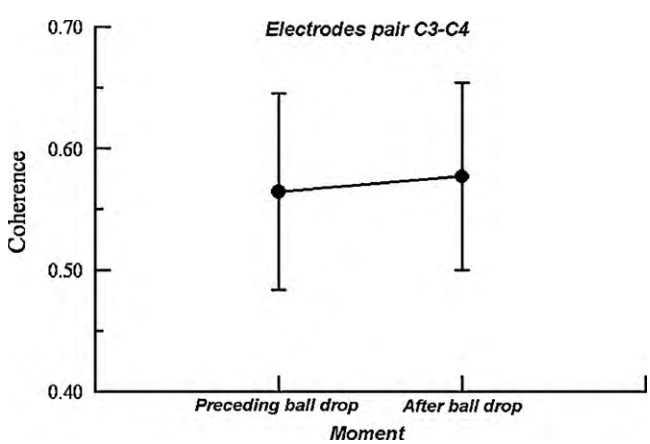

Fig. 2. Mean and standard deviation for coherence on gamma-band. Significant difference between moments observed by *t*-test ($p < 0.011$).

represent a diverse set of functions [4]. In our task, subjects had to catch a free falling object (i.e., a ball). In the moment preceding ball drop, subjects received an amount of stimuli which seemed not to be sufficient to prepare them for catching the ball. In line with this, Pfurtscheller et al. [14] argued that the sensorimotor system works in idling state for lack of somatosensory information processing or motor response generated, like for lack of visual information processing. Such fact can justify the lower values of coherence during moment preceding ball drop when compared with moment after ball drop. Such explanation can be also applied to F7–F8 results, besides these electrodes represent areas responsible for different functions, such as attention and planning, which are not required in the moment after ball drop.

In relation to moment after ball drop, our findings suggest that the increase in cortical communication across left and right premotor areas happened due to the visual and somatosensory information related to the motor execution. It is knowledge that the control of movement is distributed over neural populations which encode movement-related information, that is, the neural network has to transform the sensory information into an appropriate command for motor system operation [3]. Regarding this, visual and somatosensory information clearly make an important contribution to the selection and voluntary preparation of the catching task and to its 'on-line' control [15]. We argue that subjects had to integrate visual feedback of the ball dropping with the synchronous coordination of finger movements. Moreover, to maintain an 'on-line' control of the task (i.e., on-line visuospatial information used to control and to correct ongoing movements), an adjustment of posture and position of the hand must be maintained by subjects to task performance [18,32].

In our task, the visual feedback of the ball vertically dropping happens in a short space of 40 cm above the floor, what would justify the activation of premotor areas, responsible for selecting and voluntarily preparing movements based on spatial cues [1]. In this context, our finding agree with some studies that reported an augmentation of premotor activity after the appearance of a spatial cue as an arrow in a certain position of a computer screen indicating a direction to make a particular response [1], indicating these areas can direct movements based on sensory information, which is relevant for goal-directed tasks [3,15]. In our task, subjects had to attend to an object (i.e., the ball) while prepared for catching it, requiring a visual guidance for hand movements which need a set of somatosensory information to control the movements, more specifically, the manipulation of the ball that involves a synchronous coordination of finger movements [11]. Moreover, it is necessary adjusting the hand to the shape and to the fall line of the ball (i.e., posture and position of the hand related to the ball). As a result, premotor areas provide the transformation of the visual and somatosensory information into motor commands in order to send that information to SM1 [17]. In line with that, we interpret our findings as if the increase in coupling of premotor areas happened to integrate and to send the relevant information to SM1 in order to enable subjects performing the task. Therefore, the requirement of those sensory feedback commands would explain the higher coherence values in the moment after ball drop.

It was demonstrated a significant difference in gamma coherence between moment preceding and after ball drop for C3–C4 electrode pair, i.e., an increase in the moment after ball drop. As expected, our hypothesis was confirmed. It might be explained due to the sufficient amount of sensory stimuli provided by task in this moment in contrast to moment preceding ball drop according to the same discussion regarding F3–F4 results [14]. Therefore, our finding points out to an increase of interhemispheric communication in central areas in the moment after ball drop [29]. Cortically, we assume that this enhance of the coherence values reflects the necessity of the cooperation of both SM1 to perform the task (i.e., catching the ball dropped). SM1 receive visual and somatosensory information from speed, trajectory and spatial position of the limb of premotor areas, which are important in the execution of movements and in addition, receive somatosensory information from temporal organization and coordination of sequential movements of SMA [24]. It is suggested that gamma promoted the binding of information through the coupling of these sites, to supply task demands (i.e., motor preparation, perception and execution of movement). According to Pfurtscheller and Lopes da Silva [13], beta and alpha frequency bands are too slow to be used as signal carriers for the binding in high levels of processing. In contrast, gamma-band is considered to be ideal for establishing rapid synchronization between neural sites. The relationship between a higher level of complexity and an elevation of coherence values receives support from findings in other studies that use the coherence function in manual tasks [10].

With regard to our results, a more intense sensorimotor integration process happened in the moment after ball drop, due to integration of both visual and somatosensory information related to motor execution. Such information would be available on an implicity memory elaborated by constant motor execution along the task [9]. For this reason, we suggest that the implicity memory was elaborated by integration of premotor and primary motor areas, demonstrating that binding problem happens continually in the neural networks through sensory feedback from premotor areas to SM1.

We proposed that gamma plays an important role in reflecting binding of several brain areas in a complex motor task as observed in our results. Moreover, for selection of movements, preparation and voluntary control of action, motor preparation, perception and execution of movement, the integration of somatosensory and visual information is mandatory. In line with that, further experiments that utilize the same variables with new populations and paradigm are necessary to expand the knowledge about gamma and coherence behavior and better understanding the processes involved in cortical functions and in binding problem.

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