Effects of functional electro-stimulation in the theta-band coherence: a qEEG study

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Introduction. Functional electrical stimulation (FES) is a technique used for rehabilitation of motor and sensory dysfunction and consisted in the application of neuromuscular electrical stimulation concurrently with a functional activity. Previous studies suggest that sensory motor processing during FES stimulation of hand is similar to that of voluntary hand movement.

Aim. To examine the changes in theta band (4-8 Hz) coherence in the centro-parietal and temporo-parietal junction during a FES task. Our hypothesis is that different conditions of electro-stimulation can produce changes in the theta band coherence in the sensory-motor and multisensory integration.

Subjects and methods. The sample was composed of 24 students, male (n =14) and female (n =10), between 25 and 40 years old. Subjects were randomly distributed in three groups: control group (n = 8), G24 (n = 8) and G36 (n = 8). The control group simulated four blocks without electrostimulation been applied. The G24 group was exposed to four blocks of electrostimulation. The G36 group was exposed to six blocks of electrostimulation. We employed FES equipment to stimulate the extension of the right index finger and the electroencephalographic signal was simultaneously recorded.

Results. A main effect was found for the condition, block and electrode in the centro-parietal junction, although we only found a main effect for condition and electrode in the temporo-parietal junction.

Conclusion. Our results suggest that the functional coupling between the central and parietal areas is directly connected to the priming memory function, although the coupling between temporal and parietal areas is related to the working memory.

Key words. Coherence. Electroencephalography. Functional coupling. Functional electro-stimulation. Sensory-motor integration. Theta band.

Introduction

Functional electrical stimulation (FES) is a technique used for rehabilitation of motor and sensory dysfunction and consisted in the application of neuromuscular electrical stimulation concurrently with a functional activity [1]. Previous studies suggest that sensory motor processing during FES stimulation is similar to that of voluntary hand movement [2]. The Quantitative Electroencephalograph (EEGq) is a temporal high definition electrophysiological technique that measures cortical alterations during motor, sensory and cognitive tasks [3-5]. The use of EEGq in the investigation of electrical stimulation is rendering findings of cortical function during sensory motor integration [2,6-8]. Of the several frequency bands observed in EEGq, theta (4-8 Hz) is typically associated with cognitive processing [4] as an information processing error [9], and sensory stimulus identification and codification [4,10,11]. Theta can be evoked spontaneously or by a deterministic sensory or cognitive stimulus [12]. Studies have demonstrated that theta oscillations are related to underlying mechanisms of voluntary sensory-motor integration [13]. Despite these findings, little is known about the influence of passive movement tasks in the theta wave.

Coherence is a parameter extracted from the EEGq that represents the inter- communication between two distinct areas. The dynamic between these areas demonstrates changes in the coupling of the two during the task [14,15]. The analysis of coherence can provide information about which signal was selected and activated during the sensory-motor integration process [16-18]. Therefore, the present study analyzes the changes in theta band coherence frequency in the centro-parietal and temporo-parietal junction during a functional electro-stimulation task. We hypothesize that different electro-stimulation conditions elicit changes in theta band coherence in the sensory-motor and multisensory integration areas.

Subjects and methods

Sample

Sample was composed of 24 students (14 male and 10 female), ages varying 25 and 40 years old (32.5 ± 7.5), right-handed [19]. Inclusion criteria were absence of mental or physical impairments (screened by a previous anamnesis and clinical examination) and absence of the use of psychoactive or psychotropic substances. All subjects signed a consent form and were aware of all the experimental protocol. The experiment was approved by the Ethics Committee of Federal University of Rio de Janeiro (IPUB/UFRJ).

Experimental procedures

The subjects were randomly distributed in three groups: control group (n = 8), G24 (n = 8) and G36 (n = 8). All subjects seated comfortably in a sound and light-attenuated room during the task accomplish. The subjects sat in a chair, with arms supported on a table right in front of them, aiming to reduce muscle's artifacts. The participants were blindfolded to reduce potential visual stimuli and eyes blink. We used an eight channel microcomputer-controlled stimulator (Ibramed, Neuro Compact-2642), with biphasic (fixed pulse width of 320 μs for each phase), rectangular with constant-current pulses to stimulate the hands' muscle of participants. The frequency of the stimulation pulses was set in 48.8 Hz to achieve a sufficiently smooth and strong contraction of the muscles without extensive fatigue. The current amplitude was set at 2×10^{-3} A. The device consists on a current source and was used to stimulate the right index finger extension. The hand was fixed on a table and a velcro's strip was used to immobilize all other fingers, leaving only the index finger free of stimulation. Skin's resistance was measured by a multimeter (ohmmeter) and ranged from 800 to 1500 Ω. The skin was scraped and cleaned with alcohol, it was also used a gel between the electrodes and the skin. The electrodes were set up at 5 cm from the lateral epicondylus on the lateral forearm side, and the other 12 cm from the first one, occupying the posterior forearm side, following the index finger extensor tendon's trajectory.

Task procedures

The experiment consisted of trials and blocks. Each trial was determined by stimulation moment (i.e., time on) with 4.86 s of current passage, added to a resting moment (time off) with 8.39 s without current passage. Each block was composed of six trials. The control group simulated four blocks (i.e., 24 trials) with 1-min period between each block without electrostimulation been applied. The current intensity for this group was naught. The G24 group was exposed to four blocks (i.e., 24 trials) of electrostimulation with 1-min interval between each block, obeying the device conditions described before. Only the G36 group was exposed to six blocks (i.e., 36 trials) of electrostimulation with 1-min interval between each block under the same conditions of G24. For G24 were applied 5,693 pulses with a total time of 116.64 s. For G36 were delivered 8,539 pulses with a total time of 174.96 s. The control group only simulated the electrostimulation procedures as described above. Simultaneously with the electrostimulation of the extensor muscle's finger, electroencephalographic signals were acquired.

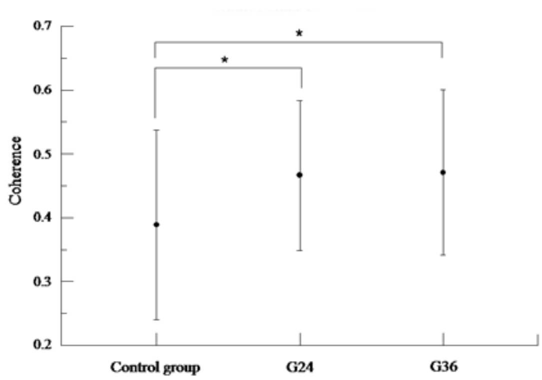
Data acquisition

EEG - the International 10/20 System for electrodes [20] was used with the 20-channel EEG system Braintech-3000 (EMSA Medical Instruments, Brazil). The 20 electrodes were arranged in a nylon cap (ElectroCap, 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 5-10 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) 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.

Data processing and analysis

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

Figure 1. Mean and standard deviation of coherence in theta band for centro-parietal junction. The result showed a main effect for condition ($p < 0.001$). The Scheffer's test demonstrated a significant difference between control group and G24 ($p < 0.001$), and control group and G36 ($p < 0.001$)



the square modulus of the FT (Fourier transform), which was performed by MATLAB 5.3 (Matworks, Inc.). The number of samples was 800 (4 s × 200 Hz) with rectangular windowing. Quantitative EEG parameters were extracted from 8-s periods time-locked with movement-offset or stimulation (the selected epoch started 4 s before and ended 4 s after the trigger, i.e., moment 1 and moment 2, respectively). Thereafter, all raw EEG trials were visually controlled and trials contaminated with ocular or muscle artifacts were discarded. The Fast Fourier Transform (FFT) resolution was 1/4 s-0.25 Hz. To examine stationary, the Run Test and Reverse-Arrangement Test were applied. Specially, the stationary was accepted for each 4 s (epoch's duration in this period). 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 integrated in the analysis.

Statistical analysis

Theta band coherence was the dependent variable of interest. The statistical analyses of theta band coherence was performed using a four-way repeated measures ANOVA with the factors condition (control group, G24 and G36), electrode (C3/P3, C4/P4, T3/P3 and T4/P4), moment (pre and post stimulation) and block (first and last block of stimulation) as the four within-subject factors. We performed the analysis using SPSS v. 17.0.

Results

Two ANOVA four-way (factors: electrode × condition × block × moment) were done: one to analyze the centro-parietal junction (C3-P3 and C4-P4) and another to analyze the temporo-parietal junction (T3-P3 and T4-P4). In the first analysis, we found a main effect for condition ($p < 0.001$) (Fig. 1), block ($p = 0.016$) (Fig. 2) and electrode ($p < 0.001$) (Fig. 3). Observing the main effect for condition, the Scheffer's test showed a significant difference between control group and G24 ($p < 0.001$), and between control group and G36 ($p < 0.001$). The main effect for block demonstrated that the last block is greater than the first. In terms of the main effect for electrode, we found a difference between C4-P4 and C3-P3. The coherence value was higher in the C4-P4 electrode combination. We performed an ANOVA three-way (factors: electrode, bloc and moment for each condition) for each group. For the control group we found a significant difference for electrode ($p = 0.004$), for the G24 we observed a significant difference for electrode ($p = 0.025$) and for the G36 we found a significant difference for block ($p = 0.05$) and electrode ($p = 0.001$).

In the second analysis, a main effect was found for condition ($p < 0.001$) (Fig. 4) and electrode ($p < 0.001$) (Fig. 5). Examination of main effect for condition (Scheffer's test) demonstrated a significant difference between control group and G24 ($p = 0.008$), and between control group and G36 ($p < 0.001$). Regarding the main effect for electrode, we found a difference between T4-P4 and T3-P3, with a higher coherence value for T4-P4. We realized an ANOVA three-way to analyze each condition separately. The control condition demonstrated a main effect for electrode ($p < 0.001$), for G24 we found main effect for electrode ($p < 0.001$), and for G36 we observed a main effect for block ($p = 0.003$) and electrode ($p < 0.001$).

Discussion

The aim of this study was to analyze the alterations of the theta band coherence in the centro-parietal and temporo-parietal regions under different electro-stimulation conditions. Our experimental hypothesis is that different conditions of electro-stimulation generate different variations in the theta coherence of the centro-parietal and temporo-parietal junction. These regions are involved in the reception of sensory information and the execution of motor responses [21]. The present discussion involves the interhemispheric comparison of the centro-parietal and temporo-parietal regions. The two analyses verified a main effect for condition and electrode, and a main effect was also found for block in the centro-parietal junction analysis.

Centro-parietal junction: sensorimotor integration

The experiment consisted of applying electro-stimulation to the forefinger, and we evaluated the process of sensory-motor integration through electrocortical analysis of the EEGq. Our results demonstrated a main effect for condition, block and electrode. A significant difference between the control group and the two experimental groups (G24 and G36) was found; however, a main effect was not found between G24 and G36. This demonstrates that electro-stimulation causes alterations in theta coherence; however, the amount of electro-stimulation, represented by the number of blocks in each group, did not change the intensity of communication between the central and parietal regions. In relation to the main effect for block, an increase in the theta coherence was verified for the first to the last block. This indicates that the functional coupling between the central and parietal cortices increased during the experiment, which can be interpreted as a learning effect. Regarding the main effect for electrode, this study verified an increase in coherence in the right centro-parietal junction, demonstrating greater participation of this region in the task compared to the left centro-parietal junction.

The somatosensory region is an area related to sensory information processing and sensorimotor integration, when the parietal cortex participates in multisensory integration [14,22]. Therefore, somatosensory and sensorimotor events can induce the centro-parietal junction activation [14]. The results presented in this study point to greater involvement of the right centro-parietal junction, or rather the ipsilateral region to the stimulation. Evidence has demonstrated that the representation of the body in the somatosensory cortex is mainly contralateral, but many studies have indicated a similar function in the ipsilateral region [23-25]. Previous studies have shown that the electro-stimulation of a finger on one hand can change the perception of the opposite hand, suggesting a function model for the processing of somatosensory information [24,25]. Thus, our study strengthens the idea of the functional importance of the ipsilateral somatosensory cortex, because using the coherence data verified that it is not simply the activation of the determined area, but rather a coupling of the two areas, which characterizes a procedural function.

Figure 2. Mean and standard deviation of coherence in theta band for centro-parietal junction. The result showed a main effect for block ($p = 0.018$).

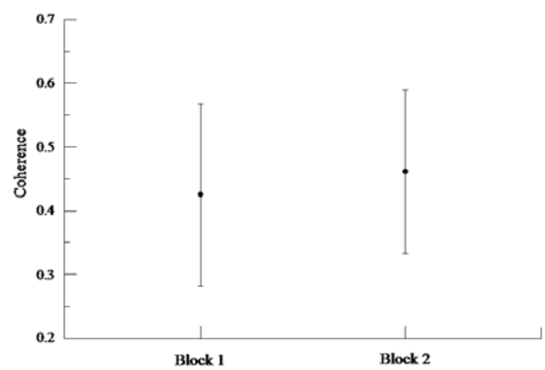
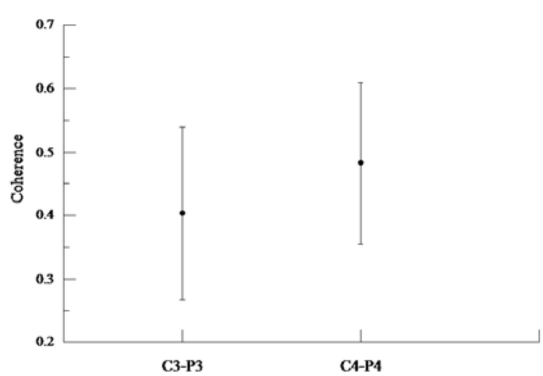


Figure 3. Mean and standard deviation of coherence in theta band for centro-parietal junction. The result showed a main effect for electrode ($p < 0.001$).



In a recent study, Babiloni et al [14] investigated if the centro-parietal functional coupling, analyzed through the coherence between C3 and P3, increased during the anticipation of somatosensory events. With this objective, they used an experiment involving two tasks: the go/no go paradigm with a presentation of visual stimuli, and intracutaneous electro-stimulation of the forefinger. The experiment included two conditions: one where visual stimuli occurred at the same time as the electro-stimulation, and another with an interval of 1.5 s

Figure 4. Mean and standard deviation of coherence in theta band for temporo-parietal junction. The result showed a main effect for condition ($p < 0.001$). The Scheffer's test demonstrated a significant difference between control group and G24 ($p = 0.005$), and control group and G36 ($p < 0.001$).

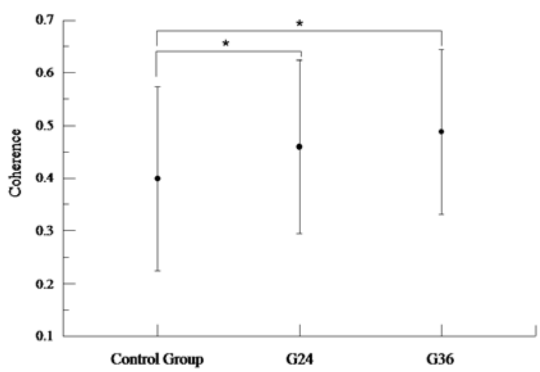
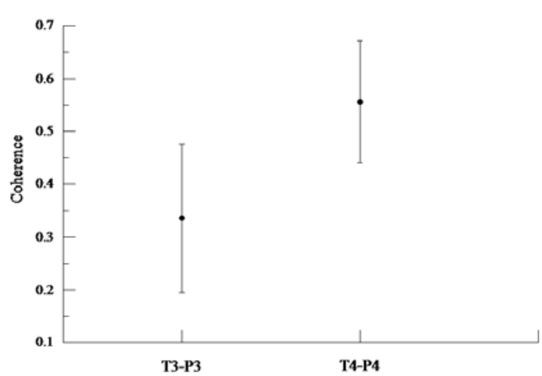


Figure 5. Mean and standard deviation of coherence in theta band for temporo-parietal junction. The result showed a main effect for electrode ($p < 0.001$).



between the visual stimuli and the electro-stimulation. The results pointed to a bilateral connection increase between the central and the parietal areas under all the frequencies during the pre-stimulation period in the simultaneous condition, and a contralateral increase when the visual stimuli occurred before the electro-stimulation. Our results agree with previous studies that demonstrated a strengthening of the coupling between the central- and right-parietal areas during the electro-stimulation of the forefinger. This finding corroborates the importance of communication of these areas in sensorimotor integration. Even though our findings do not verify a main effect in the moment factor, the increase in coherence in all blocks suggests an expression of the priming memory, as this functions as a pre-stimulation that assists in the manifestation of a future response. Thus, we understand that the priming memory functions as a modulator of the somatosensory system serving as a base for each new block, making the system recognize the stimuli in a more integrated form. Consequently, we suggest that the coupling between the central and the parietal regions in the theta band have a direct correlation with the priming memory.

Temporo-parietal junction: multisensory integration

The analysis of the temporo-parietal junction demonstrated a main effect for condition and electrode factors. The main effect found for condition, was between the control group and the two experimental groups (G24 and G36); however, a main effect was not found between G24 and G36. This indicates that the intensity of coupling between the temporal and the parietal regions does not directly depend on the quantity of electro-stimulation blocks presented. Moreover, the electrode main effect demonstrated an increase in the right temporo-parietal junction coherence, signifying the greater involvement of this region in the task compared with the left temporo-parietal junction.

The principal function of the temporo-parietal junction is multisensory integration and the sense of one's own body [21,26]. We chose this area for our study due to the sensory character of the experiment. Our findings demonstrated that under the experimental conditions, the coherence between these areas increased indicating the importance of this coupling in a electro-stimulation task. Thus, these results signify that this region is activated by unimodal stimulation, even though it is well known that this area is responsible for multi-sensory integration. In a recent study, Balslev et al [27] analyzed the cortex areas involved in the coordination of conflicting stimuli. They asked their subjects to reproduce a determined movement with the forefinger of the left hand, based on one shown on a screen placed in front of the subject. Two different conditions were introduced. In the first one, the experimenter conducted the subject's right forefinger in the same pattern shown on the screen, generating congruent information. In the second, the right forefinger was conducted in a pattern incongruent with the image. The area more activated in the incongruent situation was the right temporo-parietal junction, reflecting the importance of this region in the sensory disorientation situations. Even though our study does not directly analyze sensory incongruence, we found an increase in the theta coherence of the right temporo-parietal junction. Therefore, we could surmise that when electro-stimulation is applied, part of the motor control process for the central system is replaced by an external electrical current that produces a response independent of the central process and in some way confuses the peripheral control system. In other words, producing an involuntary movement generates incongruence between central and peripheral control.

In a recent study, Hegner et al [28] investigated the cortical oscillation related to the memory of tactile work using magnetoencephalography. Fourteen right-handed participants were asked to determine if both of the tactile stimuli applied sequentially to the fingertip of the right middle finger at an interval of 3 seconds each were the same or different. This experiment demonstrated that the ipsilateral temporo-parietal cortex plays an important role in maintaining tactile information in the working memory. We found greater theta coherence in the ipsilateral temporo-parietal cortex in the experimental group (G24 and G36), demonstrating that the task generated a response from this area. Moreover, no main effect was found between the first and the last block, nor between the pre- and post-stimulation, suggesting that the information stayed in the system during the entire experiment indicating the performance of memory. Thus, our findings are in agreement with those of Hegner et al [28] in that working memory is characterized not just as short term memory, where data needed for quick utilization is stored, but also as a memory that stays in the cortex during the execution period of a task in order to guarantee its efficiency. Therefore, our experiment strengthens the function of the ipsilateral temporo-parietal junction in tactile working memory from its activation throughout the entire experiment. We also verified that such information can stay in the memory for more than a few seconds much like Hegner et al [28] demonstrated, because the intervals between blocks were one minute in our study. This suggests that more research about the somestetic working memory is needed with the objective of investigating the time of permanence and its capacity.

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Efectos de la electroestimulación funcional en la coherencia de la banda theta: estudio con electroencefalografía cuantitativa

Introducción. La estimulación eléctrica funcional (EEF) es una técnica utilizada para la rehabilitación de la disfunción motora y sensorial que consiste en aplicar una estimulación eléctrica neuromuscular al tiempo que se lleva a cabo una actividad funcional. Estudios precedentes sugieren que el procesamiento sensoriomotor que tiene lugar durante la estimulación de la mano con EEF es similar al generado con su movimiento voluntario.

Objetivo. Examinar los cambios de la coherencia de la banda theta (4-8 Hz) en la unión centroparietal y temporoparietal durante la ejecución de una tarea con EEF. La hipótesis planteada es que diferentes condiciones de electroestimulación pueden producir cambios en la coherencia de la banda theta durante la integración sensoriomotora y multisensorial.

Sujetos y métodos. La muestra se compuso de 24 estudiantes, 14 varones y 10 mujeres, de 25 a 40 años de edad. Los participantes se distribuyeron al azar en tres grupos: grupo control (n = 8), grupo G24 (n = 8) y grupo G36 (n = 8). El grupo control simuló cuatro bloques sin recibir electroestimulación. El grupo G24 se expuso a cuatro bloques de electroestimulación, y el G36, a seis bloques. La electroestimulación aplicada con el equipo de EEF consistió en estimular la extensión del dedo índice derecho al tiempo que se registraba la señal electroencefalográfica.

Resultados. Se halló un efecto principal de la condición, el bloque y el electrodo en la unión centroparietal, a diferencia de la unión temporoparietal, en la que únicamente se constató un efecto principal de la condición y del electrodo.

Conclusión. Los resultados parecen indicar que el acoplamiento funcional entre las zonas central y parietal está vinculado directamente con la función de la memoria de preparación (*priming*), aunque el acoplamiento entre las zonas temporal y parietal se relacione con la memoria de trabajo.

Palabras clave. Acoplamiento funcional. Banda theta. Coherencia. Electroencefalografía. Electroestimulación funcional. Integración sensoriomotora.