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Electrophysiological analysis of the perception of passive movement

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ABSTRACT

The goal of the present study was to determine the electrophysiological correlate of the threshold of perception of passive motion (TPPM) in a group of healthy individuals. We expect a different pattern of activation over the frontoparietal network produced by the conscious perception of the passive movement. Ten right-handed male volunteers, between 20 and 30 years of age, were submitted to the threshold of perception of passive motion (TPPM) task in a proprioception testing device (PTD). The device was designed to passively move the arm in internal and external rotations about the shoulder joint. Participants were instructed to press a hand-held switch every time movement of the shoulder was detected. Electromyographic (EMG) and electroencephalographic (EEG) activities were acquired during the task. Passive movement of the shoulder joint was followed by a clear and prolonged decrease in the signal magnitude of the electroencephalogram. The electrophysiological correlate of the TPPM was characterized by the establishment of a frontoparietal network, during the processing of somatosensory information.

The somatosensory system processes multiple sensations from the body, including pain, pressure, temperature, and proprioception [23]. Proprioception is a specialized form of the sense that encompasses the ability to detect movement (kinesthesia) [21]. Moreover, proprioception is the sensation of the relative position of neighbouring parts of the body. Contrarily, the exteroceptive senses, by which we perceive the outside environment, and interoceptive senses, by which we perceive the pain and movement of internal organs, proprioception is a third distinct sensory modality that provides feedback solely on the status of the body internally. The assessment of kinesthesia has been traditionally conducted by measuring the threshold of perception of passive motion (TPPM) [7,15,21]. In this context, given that proprioceptive signals contribute to the formation of a conscious (i.e., having an awareness of one's sensations) perception of joint position and motion [8,14,24], the TPPM quantifies one's ability to consciously detect joint movement.

Electrophysiology has also been employed in the study of proprioception. Specifically, electrophysiological studies have investigated the cortical representation of passive motion [1,2,30–32,36]. However, these studies aimed exclusively at contrasting patterns of brain activation between disabled individuals and healthy control subjects, without considering the perception of limb movement. In this sense, there are still gaps to be filled in our understanding of the patterns of neural activity related to somatosensory perception [9,29].

The general goal of the present study was to develop an experimental paradigm that would combine EEG activity and the TPPM, taking a psychophysical approach to the investigation of proprioception. The specific aim was to determine the electrophysiological, event-related spectral perturbation (ERSP), correlate of the threshold of perception of passive motion (TPPM) in a group of healthy individuals, using an attention-demanding task, and examining the cortical representation (i.e., quantitative electroencephalogram—qEEG) of different stages of proprioceptive information processing, from motion perception until motor response. The present study is relevant because propose a novel psychophysical approach to the study of kinesthetic perception by developing an experimental paradigm that integrates EEG acquisition and a proprioceptive task. Moreover, we expect that the conscious perception of the passive movement could generate a new pattern of the frontoparietal network's activation.

The sample consisted of 10 male volunteers, with ages ranging from 20 to 30 years (mean = 25; SD = 1.92). All participants were healthy, free of cognitive deficits, and were not using any medication or psychoactive substance at the time of the test. Participants

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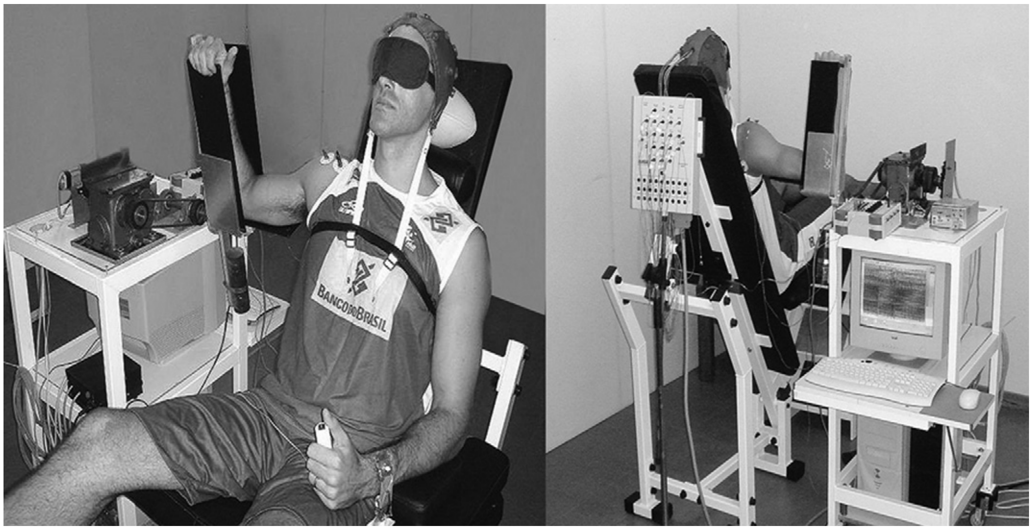

Fig. 1. The apparatus and participant position. The device was designed to passively move the arm in internal and external rotations about the shoulder joint.

included in the study had no previous history of musculoskeletal injuries or shoulder pathologies and had not participated in any systematic long-term activities to improve upper limb abilities. To identify and exclude from the experiment any participant who could contaminate future results, a questionnaire was administered and a neuropsychiatrist performed a clinical evaluation. The Edinburgh Handedness Inventory was used to assess laterality and exclude left-handed individuals from the experiment [27]. Participants signed a consent form, where the experimental condition was thoroughly described. The ethics committee of the Psychiatric Institute of the Federal University of Rio de Janeiro approved the experiment (N^0 55-liv.02/08).

A motor-driven, proprioception-testing device (PTD), which was developed at the Brain Mapping and Sensorimotor Integration Laboratory, was used to assess the threshold of perception of passive motion (TPPM). The PTD comprised: (1) a motor reducer driver that included an electric motor (12 V, 12 W, 7 A, 14 N m torque) and a reducer; (2) synchronized pulleys and belt that moved a lever arm; (3) an u-shaped lever arm for limb placement; (4) air splints around the lever arm and the participant's arm to provide uniform compression within the device, stabilize the upper extremity, and reduce cues from cutaneous mechanoreceptors [3]; (5) a button-switch for the participant to indicate a response. The device was designed to passively move the arm in internal and external rotations about the shoulder joint. A potentiometer connected to the shaft of the lever arm and interfaced with a PC converted angular movement into electric signals that were stored on the computer.

Electroencephalographic (EEG) activity was acquired during the task with a 20-channel Braintech-3000 (EMSA-Medical Instruments, Brazil). The International 10/20 System [18] for electrode placement (referenced to linked earlobes) was used and the 20 monopolar electrodes were arranged in a nylon cap, which was also developed at the Brain Mapping and Sensorimotor Integration Laboratory.

Electromyographic (EMG) activity of the infraspinatus and pectoralis major muscles was recorded concurrently with the EEG by an EMG device (Lynx-EMG1000) (Fig. 1).

A light and sound-attenuated room was prepared for data acquisition, which was always performed in the afternoon (between 2 p.m. and 5 p.m.). Participants were comfortably seated on a reclining chair attached to the PTD, with the dominant arm abducted at the shoulder by 90° and rotated forward by 30° so that the arm was in the same plane as the scapula. The elbow was flexed at 90°. Participants were instructed to relax and to avoid imagining movement of the shoulder during the task. The task involved internal and external rotations of the upper arm about its longitudinal axis. Auditory and visual cues were attenuated using ear-plugs and a blindfold. The initial test position, established at 80° of the external rotation, was chosen to avoid extreme positioning of the joint. Each trial started with 15 s of EEG and EMG recording without motor movement. After these baseline measurements, the motor shaft was engaged to rotate the shoulder at the rate of 0.4°/s in the direction of the internal rotation. Participants were instructed to respond by pressing the hand-held switch when movement of the shoulder was detected. Participants performed five blocks of four trials each. Threshold of perception of passive motion was measured by recording the response latency, i.e., the time to detect the passive movement and press the button-switch after stimulation onset.

The software (Delphi 5.0) used to acquire the EEG signal was developed at the Brain Mapping and Sensorimotor Integration Lab-

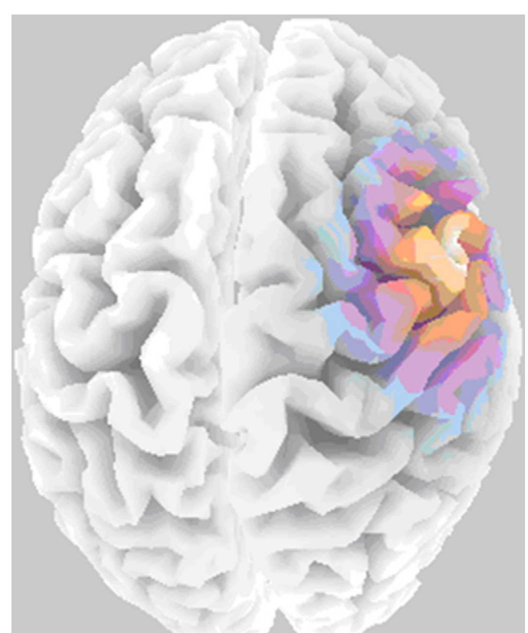

Fig. 2. ICA component 7 corresponding to the moment of motor response. Maximum activation was observed in Broadman area 6 (precentral gyrus), during movement execution ($x = 50$, $y = -3$, $z = 50$).

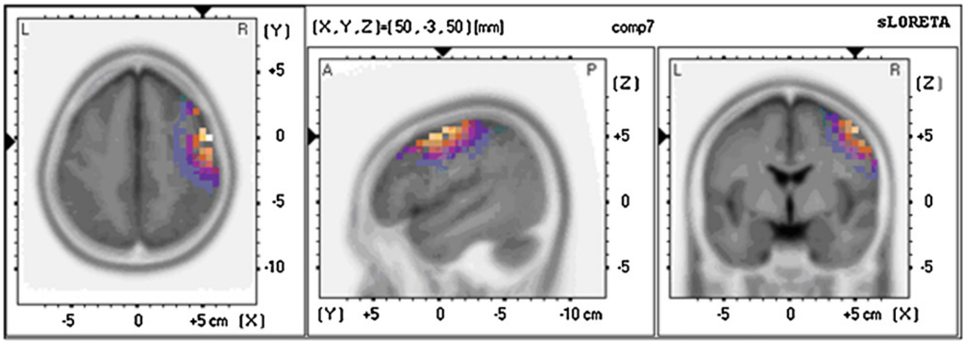

Fig. 3. Activation of Broadman area 6 during movement execution.

oratory. Visual inspection was used to detect and eliminate artifacts in the recordings. The data acquired had total amplitude of less than 100 μV. The EEG signal was amplified with a gain of 22,000 and digitally filtered with a 60-Hz notch filter. Eye-movement (EOG) artifact was monitored with a bipolar electrodes (9-mm diameter) attached above and on the external canthus of the right eye. Impedance for EEG and EOG electrodes were under 5 kΩ and 20 kΩ, respectively. EMG activity was sampled at 1,000 Hz.

Data collected during the experiment (EEG and EMG) were processed with Matlab 5.3. The EEG epochs were aligned to the pressing of the button-switch (trigger). Root mean square (RMS) value for the EMG was calculated [20] and used to assess possible resistance to the motion by the participant. The presence of EMG activity was used as an exclusion criterion.

The data were first averaged for each participant and then across participants. Continuous EEG data were epoched in 9-s windows time-locked to the trigger. The baseline was set between −2 s and 0 s, the analysis period of interest between 0 and 7 s, and the trigger at 3 s. The data were filtered between 0.10 and 50 Hz to remove artifacts, such as those due to eye movements. A visual inspection and independent component analysis (ICA) were applied to remove as many sources of artifacts 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 artifacts (±100 μV) were also deleted. ICA was then applied to identify and remove any remaining artifacts after the initial visual inspection. ICA is an information maximization algorithm that is derived from spatial filters through the blind source separation of EEG signals into temporally independent and spatially fixed components. Independent components resembling eye-blink or muscle artifacts 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 was then re-inspected 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.). We removed 12% of the trials, all of them were contaminated with artifacts.

To assess event-related changes in data recorded from the 20 electrode derivations, EEGLAB employed custom spectral decomposition techniques for the following event-related time/frequency measure: event-related spectral perturbation (ERSP), indicating the mean event-related changes in the power spectrum [11].

ERSP was calculated by computing the power spectrum over a sliding window and then averaging across trials. The color of each image pixel indicates signal magnitude (in dB) at a given frequency and latency relative to the trigger. Typically, for n trials, if $F_k(f,t)$ is the spectral estimate of trial k at frequency f and time t:

$$\text{ERSP}(f, t) = \frac{1}{n}\sum_{k=1}^{n}\left|F_k(f, t)\right|^2$$

$F_k(f,t)$ was computed by using a short-time Fourier transform that provides a specified time and frequency resolution. To visualize power changes across the frequency range, the mean baseline log power spectrum was subtracted from each spectral estimate, producing the baseline-normalized ERSP. Significance of deviations from baseline power was assessed using a bootstrap method.

Response latencies were averaged across trials for each participant individually and then across participants.

Mean response latency and standard deviation for the sample of the study were 3.18 s and 1.84 s, respectively.

Source localization was applied using sLORETA (standardized low resolution electromagnetic tomography). Maximum activation was observed in Broadman area 6 (precentral gyrus), during movement execution ($x = 50$, $y = -3$, $z = 50$). Figs. 2 and 3 illustrate ICA component 7, corresponding to the moment of motor response (pressing of the button-switch), and the areas activated around 3 s.

Neural activity related to the stages of somatosensory information processing was observed. Event-related responses comprise both induced and evoked potentials. Fig. 4 illustrates mean event-related changes in signal magnitude over time in a broad frequency range. Only significant changes in power ($p \leq 0.01$) are displayed.

Approximately 3 s before pressing of the button-switch, shoulder movement was accompanied, at all electrode sites, by a clear and prolonged decrease in signal magnitude. This pattern became more evident and intense at 3 s, i.e., the moment of the motor response, and lasted for a few seconds. The observed activity at F4, C3, and C4 occurred mainly in the alpha and beta frequency bands (8–30 Hz). In contrast, the pattern of suppression at F3 and P3 was more restricted to the alpha band.

Fig. 5 provides topographic maps in different latencies at 8 Hz. It illustrates the activation of different cortical areas during passive movement of the shoulder until pressing of the button-switch at 3 s. During passive movement, there was a decrease in signal magnitude that was localized to the parietal region of the left hemisphere, and this was followed by a pronounced decrease in the bilateral frontal area (1.7 s before the trigger). A lateralized decrease in signal magnitude was observed in the right hemisphere between 1.5 and 1.3 s before the trigger. From 1.0 s until 0.7 s before the motor response, there was a decrease in signal magnitude in the frontal and parietal areas in the left hemisphere. Around 0.6 s before the trigger, the right-central area was activated. About 0.5 s and 0.3 s, parietal activation in the left hemisphere was reduced and left-frontal and right-central activities became more prominent. Just

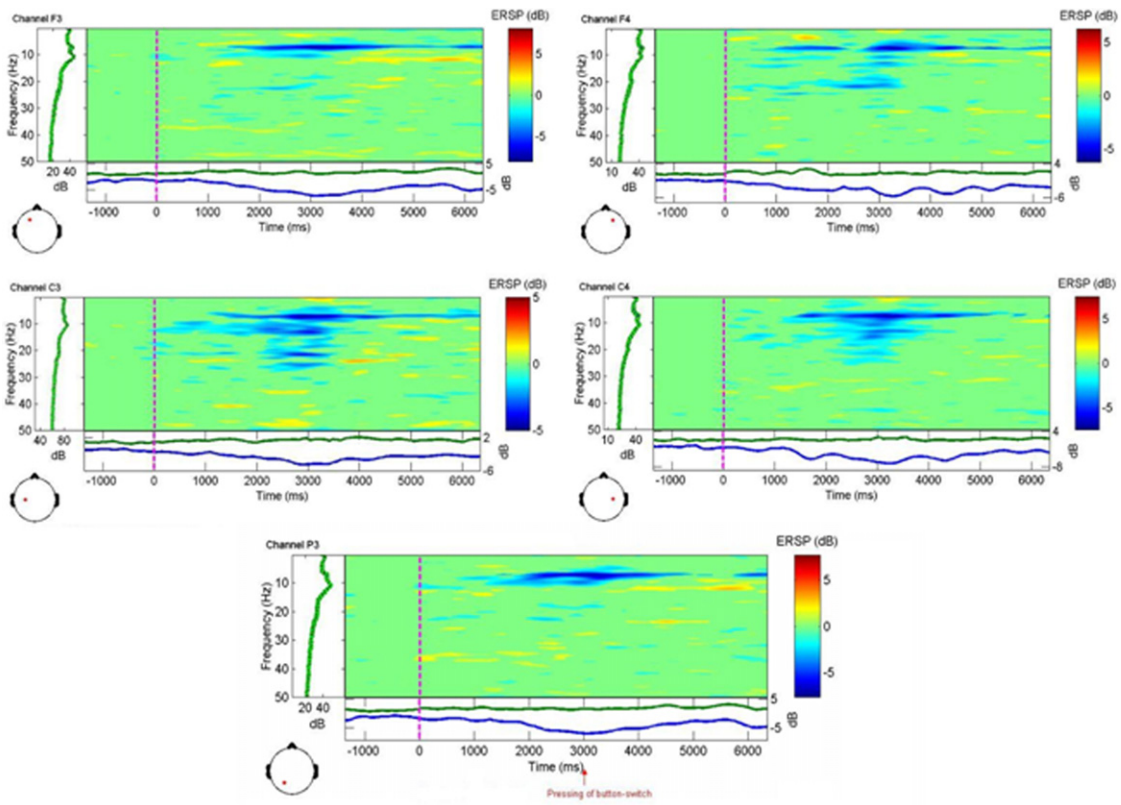

Fig. 4. Time–frequency ERSP maps obtained during the passive movement task (TPPM) in F3, F4, C3, C4, and P3. Only significant changes in power ($p \leq 0.01$) are displayed. The red arrow indicates the time-point of interest: pressing the button-switch (trigger) at 3 s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

before pressing the button switch, changes were maximal at the contralateral primary hand area. At 3.0 s, the decrease in signal magnitude was focused over the right hemisphere, likely overlying the primary motor area.

The goal of the present study was to propose a new approach to the analysis of kinesthetic perception, through the characterization of the electrophysiological correlate of the TPPM, and, consequently, to broaden the possibilities for the interpretation of this phenomenon. Our findings illustrate the cortical dynamics underlying kinesthetic perception and the establishment of a frontoparietal network during the processing of somatosensory information in a passive movement task. As illustrated in Fig. 4, signal magnitude suppression in the alpha and beta bands became evident during passive movement. A growing body of evidence suggests that oscillations in alpha and beta bands may be involved in higher cognitive functions and sensorimotor processing [5,26,29]. The magnitude suppression that occurred concurrently with passive movement suggests that the cerebral cortex began to actively process sensory information as soon as the task was initiated, even though the participant had not yet perceived the onset of the passive rotation [34]. Our results are similar in some sense with [25] that found instantly after the beginning of the Functional electrical stimulation (FES) movement, a high up ERD was seen, followed by a beta ERS comparable to that observed after active or passive wrist actions. Both changes were maximal over the contralateral primary hand area. This stage of processing involved activation of the frontal, central, and parietal cortical areas, as indicated by the activities from the different electrode sites. This result is similar to other studies that have demonstrated that stimuli that do not reach awareness may still generate activity in corresponding sensory cortices [6,10,22].

Our results also illustrate that cortical activity related to the perception of passive motion was characterized by the formation of a frontoparietal network, as indicated by the simultaneous activation of specific cortical areas (as seen in Fig. 5). Approximately 3 s before motor response, the parietal lobe was activated. The parietal lobe is an important region involved in the conscious perception. It is an area responsible for the multisensory processing of bodily signals for self-consciousness. A recent study has demonstrated that integration of multisensory bodily signals is crucial for bodily self-consciousness, specially to self-location, first-person perspective, and self-location [17,19]. This was followed by a bilateral frontal engagement at around 1.7 s before the trigger and then a central activation at the right hemisphere (1.5–1.3 s prior to the pressing of the button-switch). Engagement of the frontal lobe is related to the activation of the association area responsible for the brain's executive functions: judgment (stimulus recognition), planning, maintenance and organization of events in memory for future action [4,16]. Thus, this first stage seems to correspond to a transient phase during which different perceptual and decisional processing possibly occurred [28]. The period from 1.0 s to 0.3 s before the trigger marked the establishment of the frontoparietal cortical network per se. Posterior, frontal, and central areas were activated in this time period, establishing an integrated communication system between distinct brain regions. This pattern of cortical activation is in accordance with the functional organization of perception and movement widely described in the literature by different experimental paradigms [6,29]. Posterior association areas are highly connected with frontal association areas and are crucial for the integration of different sensory modalities. Frontal areas, in contrast, transform sensory information into planned movement, by identifying motor programs and sending this information to the premotor and motor

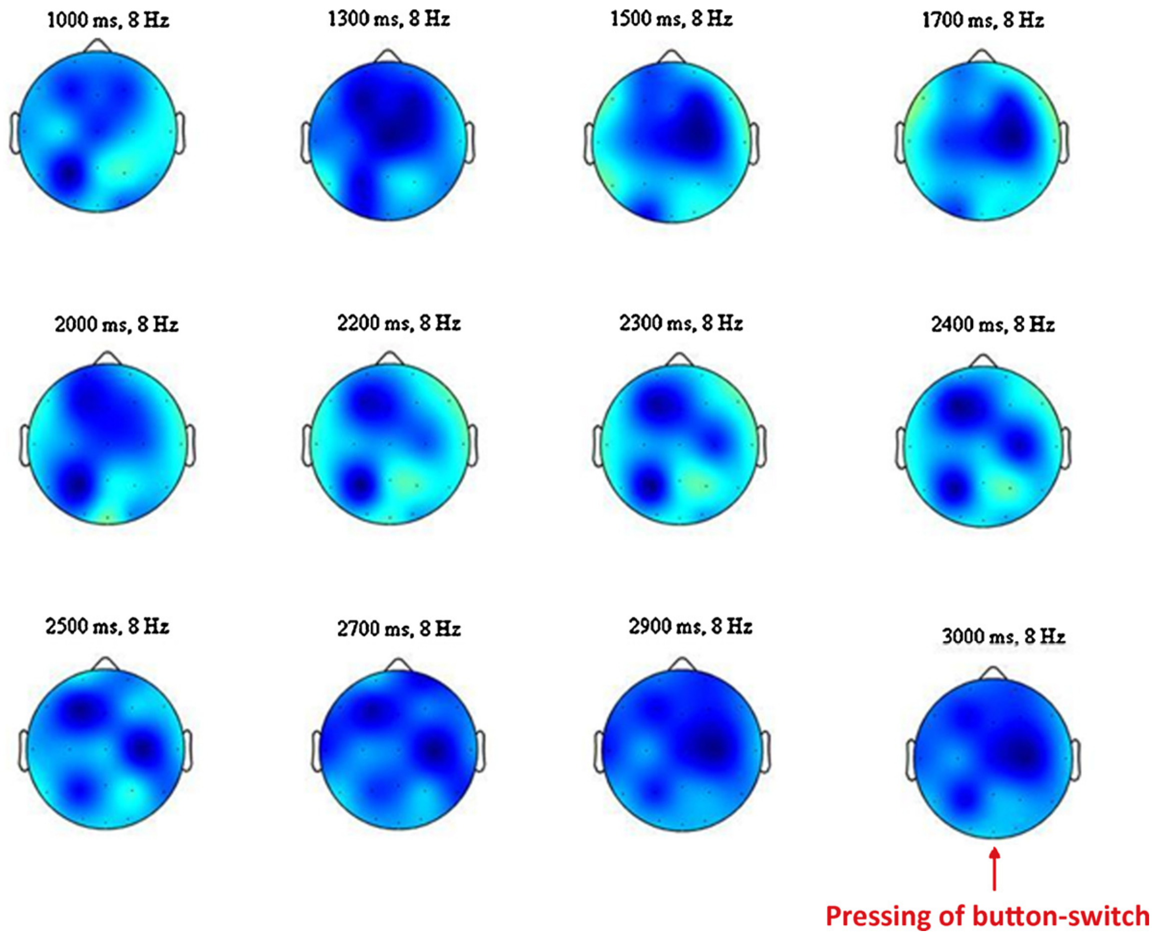

Fig. 5. Maps of cortical activation during the passive movement task. Maps are representative of the whole sample of the study. Maps are representative of the whole sample of the study. Time length observed varies between 1000 and 3000 ms, and the presented frequency was 8 Hz.

cortices to be implemented. Thus, the integration between frontal and posterior association areas is crucial for directed behaviors [33]. In this context, we believe that the establishment of such frontoparietal network characterizes the electrophysiological correlate of the TPPM. In other words, the co-activation of frontal and parietal areas marks the moment awareness is reached and, therefore, the moment of motion perception. As expected, 0.1 s before pressing of the button switch, and then at 3.0 s, a region overlying the primary motor cortex was activated, contralateral to the hand that executed the movement, characterizing the moment of motion response.

Our findings corroborate the finding of previous electrophysiological and functional imaging studies that showed that the processing of consciously perceived stimuli involves a widespread network that includes the primary sensory cortex, as well as several areas higher in the processing hierarchy [6,13,22,35]. Specifically, studies that investigated the neural mechanisms underlying conscious perception employing different experimental paradigms have shown that attention and working memory are essential components of conscious perception and entail the activation of a frontoparietal network [12,22]. Overall, studies have demonstrated that awareness is a product of large-scale interactions between different regions of the brain.

Our experiment proposes a novel psychophysical approach to the study of kinesthetic perception by developing an experimental paradigm that integrates EEG acquisition and a proprioceptive task. The results indicated that conscious perception of passive movement is related to a specific pattern of cortical activation that involves the formation of a frontoparietal network. Particularly, the approach adopted in the present study proposes that such network is what ultimately defines the TPPM. Although distinct methodologies yield specific results, a key difference between the present study and others using the TPPM is the attentional engagement embedded in the paradigm. In this sense, the association between EEG, passive movement and the attentional component of the paradigm enables a broader understanding of the mechanisms involved in kinesthetic awareness [31,32]. Future studies are still necessary to further explore the issue of cortical representation of kinesthetic perception, especially in populations where sensory deficits are present.

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