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Chapter

Cerebral Spectral Perturbation during Upper Limb Diagonal Movements

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Abstract

While it has been suggested that diagonal rhythmical bilateral movements promote improvement in motor and cognitive functions, no study that we are aware of has actually examined electrophysiological changes during diagonal movements. Therefore, we aimed to study cerebral activity during the performance of diagonal and vertical movements (DM and VM, respectively), through EEG recording focusing on theta, alpha, and beta frequency bands. Following independent component analysis, we computed time-frequency and source localization analysis. We found that (1) increased frontal theta during the initiation of DM was possibly related to the computational effort; (2) a biphasic pattern of frontoparietal alpha/beta modulations was found during VM; and in addition, (3) source localization showed increased frontal theta during DM generated in the middle frontal cortex. We will discuss the current results and their implications in relation to task difficulty, spatial and temporal computation.

Keywords: diagonal movement, ERSP, source localization, time-frequency analysis

1. Introduction

1.1 Diagonal movement overview

Diagonal arm movements are upper limb movements performed along the sagittal plane that implies the vertical body midline in order to reach the opposite hemispace. For this reason, diagonal movements are inherently different from movements performed along either the transverse or vertical planes. In fact, during vertical and horizontal movements, upper limbs cross the transverse and vertical body midline, respectively, but not both of these axes at the same time. In fact, Adele Diamond [1] has suggested the idea that rhythmical, diagonal, bilateral coordinated arm movements and eye-hand coordination could play a role in cognitive rehabilitation as well, providing a framework that could reduce the distance between the idea that motor activity cannot influence cognition and that cognitive rehabilitation requires only pure cognitive-related protocols.

At the beginning of the twenty-first century, Diamond summarized different scientific evidence to highlight the fact that movement and cognition are linked in terms

of development timing and that these two domains activate shared brain regions such as the prefrontal cortex and cerebellum [2]. Specifically, it was observed that activity in the prefrontal cortex increases when a motor task requires the maintenance of movement information through execution, selection of relevant task-related motor information, and inhibition of automated behavior that could compromise motor performance.

Yet very few studies have examined this issue. A rare exception regards the studies related to a rehabilitation protocol based on stretching exercise and joint mobility called proprioceptive neuromuscular facilitation (PNF) [3]. This rehabilitation protocol also includes diagonal arm movements in order to promote strength, coordination, functional motoricity, and movement initiation [4]. More recently, Moreira et al. [5] studied cerebral electrophysiological activity after the performance of unimanual diagonal arm movements as presented in the original PNF protocol. They observed an increase of beta and alpha power within a frontoparietal network after performance. They showed that this kind of motor activity could improve motoricity through modulation of cerebral plasticity over frontoparietal regions, suggesting that improved motor execution is directly linked to motor control in the central nervous system.

Over the last few years, we studied another motor task that involves diagonal movements, named Quadrato Motor Training (QMT) [6–8]. QMT is a sensorimotor training based on step-by-step, whole-body movement in vertical, horizontal, and diagonal directions. From the electrophysiological point of view, pre- and post-EEG recording showed acute and chronic increase of theta and alpha power and coherence over frontal, parietal, and temporal regions [9–11]. We hypothesized that it is especially the planning of diagonal movement which plays a crucial role in the establishment of such a modulation of theta and alpha band activity. However, it is difficult to disentangle and isolate the contribution of diagonal from vertical and horizontal movement, and further studies in which EEG is recorded during the execution of QMT should be performed. Thus, as a first step, in order to examine the effects of diagonal movements, in the current study, we measured cerebral activity during the performance of diagonal and vertical movements (DM and VM, respectively), using EEG recording. Given the aforementioned literature, particular focus was addressed to the theta, alpha, and beta frequency bands.

1.2 Brain oscillations, movement, and cognition

Theta (4–7 Hz) activity seems to be involved in different cognitive functions such as sustained attention [12], spatial navigation [13], memory [14], meditative states/internalized attention [15], and creativity [16]. Importantly, all these cognitive functions require integration from different cerebral regions in order to produce effective outcomes. In fact, it was suggested that there is an inverse relationship between the extent of a recruited cortical network and the elicited oscillatory frequency during task performance [17]. For these reasons, theta is also thought to support long-range integration and promotion of mental states related to absorption and concentration [18–20].

Alpha activity (8–12 Hz) is considered a fundamental brain rhythm produced in the occipital cortex which reflects cortical inactivity during relaxed wakefulness with closed eyes and reduced sensory and motor processing [21, 22]. Alpha desynchronization has been observed during a task that requires the deployment of attention toward specific targets or locations in space, suggesting that alpha could play an important role in the management of attentional resources and sensory perception [23–26]. Moreover, similar to theta, increased parietal alpha power has been related to internal-directed attention [27].

Beta frequency (13–30 Hz) is classically related to active wakefulness. It was observed as an oscillatory activity replacing alpha waves when individuals opened

their eyes [28–30]. Beta desynchronization has been typically observed during the execution of voluntary movement [31, 32] and during sensorimotor processing [33]. After the conclusion of a voluntary movement, beta synchronization called "post-movement beta rebound" has been observed over the sensorimotor cortex [34, 35]. Other studies have suggested that beta is also involved in a large range of cognitive, emotional, and attentional processing [36–39].

1.3 Aim of this study

Despite the fact that movement along the diagonal axis has been seen as a benefit in different motor and cognitive rehabilitation protocols, none of the studies we are aware of have investigated the neural correlates of diagonal movement during the actual movement performance. Therefore, we aimed to observe the electrophysiological correlates of diagonal movements and compare them to a control condition such as vertical movement. We hypothesized that diagonal movements compared to vertical movements require more computational effort and motor control to be well executed. This should result in increased theta, in decreased alpha due to an increase in internalized attention, and finally in a modulation of beta tied to the start and the end of each movement.

2. Methods

2.1 Participants and design

Eleven right-handed healthy participants (six males; mean age 40.3 years; SD 9.22) volunteered to take part in the study. All participants had normal or corrected-to-normal vision, and they declared to not suffer from any psychiatric or physical disease that could interfere with their performance.

The research took place in the Research Institute for Neuroscience, Education, and Didactics of the Patrizio Paoletti Foundation. The participants signed an informed consent. The study was approved by the ethics committee of Bar-Ilan University.

Before each experimental session, participants performed a training phase in which they learned to perform correctly the movements required for the experiment. During the experimental session, EEG recording was conducted during the performance of diagonal and vertical movements with both arms at the same time in an antiphase movement (i.e., each arm moved jointly with the other arm starting from the opposite side of the body and moving toward the opposite direction along the same axis; for a clear explanation, see **Figure 1**).

2.2 Paradigm

Participants performed a total of 320 rhythmical movements with both arms while sitting in a chair. Movements were divided into eight blocks. Each block consisted in 40 rhythmical continuous movements paced by an external sound. We used a 440 Hz tone with a duration of 100 ms, presented with the pace of 1 Hz (i.e., one sound each second), in order to guide the movements.

At the beginning of each block, participants had to keep one arm in the upper position and the other one in the lower position (see **Figure 1**). Then, in line with the start of the pacing sounds, they had to move their arms along the vertical or diagonal axis, according to the condition of the block. A total of 20 consecutive trials were used in each block. Each trial lasted 2 s. Therefore, each trial was composed of two sounds (i.e., two movements). The participants were instructed to perform
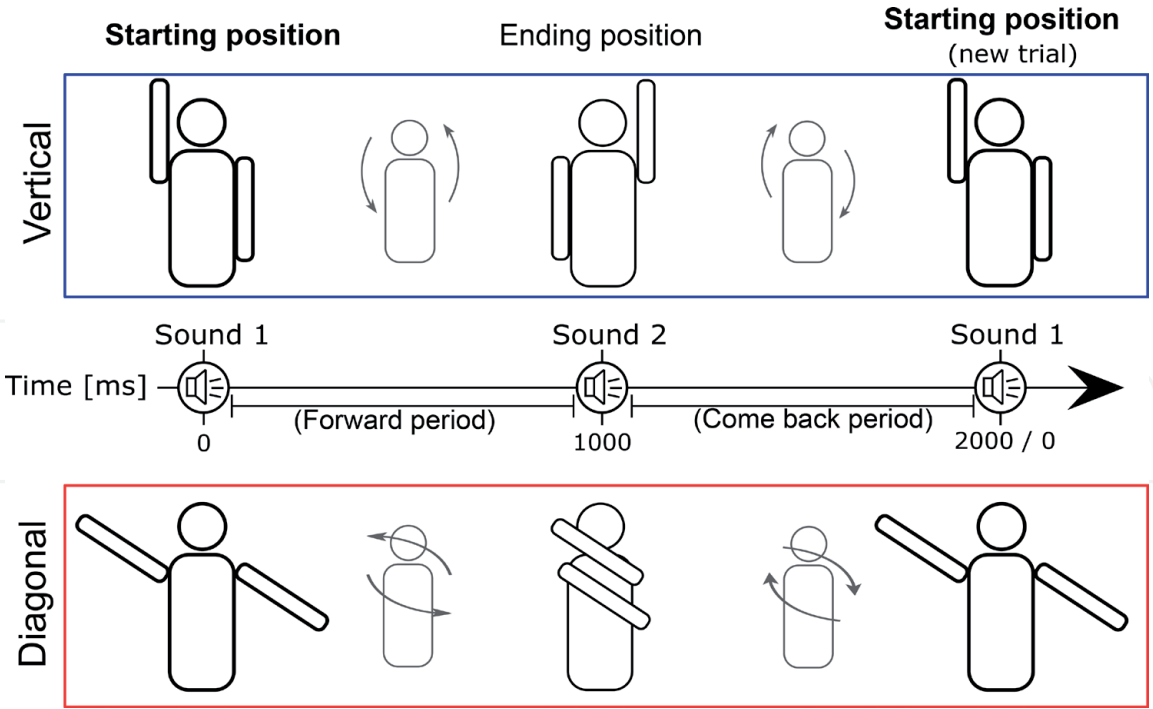
Figure 1.
Examples of the structure of a single trial. Each trial lasts 2 s and is composed of two sounds played at 0 and 1000 ms. Since each block was composed of 20 continuous movements, the sound at 2000 ms of the represented trial is indeed the sound at 0 ms of the next trial. Here vertical and diagonal conditions are both depicted with the right arm in the upper position.

the movement between each sound in order to be in the starting position or in the ending position whenever a sound occurred.

Four experimental conditions (movement (diagonal, vertical) and hand (right, left)) were used: (1) vertical movement starting with the right hand above head, (2) diagonal movement starting with the right hand above head, (3) vertical movement starting with the left hand above head, (4) and diagonal movement starting with the left hand above head. Each condition was repeated twice.

2.3 EEG

2.3.1 EEG recording

EEG was recorded using the eego sports system from ANT Neuro (Enschede, Netherlands). We recorded electrophysiological brain activity from 32 scalp sites with a 10/10 electrode layout. In addition, we used a three-dimensional accelerometer placed on the right arm in order to record movements along x, y, and z axes. Recording was conducted with a sample rate of 1000 Hz, and impedance was kept below 10 kohm. Online reference was CPz.

The experiment was conducted in a dimly lighted room and implemented in E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). We used a standard computer monitor for visual output and two speakers placed below the screen for sound presentation.

2.3.2 EEG analysis

EEG signals were preprocessed and analyzed using EEGLAB toolbox [40] for time-frequency analysis and eLORETA for source localization analysis. First, data were preprocessed using a 50 Hz notch filter and filtered between 1 and 40 Hz with

a second-order infinite impulse response (IIR) Butterworth filter. The first two trials from each block were rejected in order to avoid transient activity related to the start of the continuous movement.

We then performed independent component analysis (ICA) using the Infomax algorithm implemented in EEGLAB, over the whole set of electrodes along the whole recording. Through ICA, we deconstructed the signal into 34 independent components, allowing us to identify and reject ocular and major motion artifacts. After labeling and rejection of non-brain-derived activity, we projected the components back into the channel domain to obtain clear EEG time course and to perform further analysis (for ICA methodological information, see [41]). EEG was finally offline referenced against the mean of all derivations.

2.3.2.1 Time-frequency analysis

Two-second time windows were extracted, locking t0 with the first sound of each trial.

Time-frequency analysis was conducted for both single electrodes and four different region of interests (ROIs): frontal (electrodes F3, Fz, F4), fronto-central (electrodes FC1, FC2), parietal (electrodes P3, Pz, P4), and POz. These ROIs were selected on the base of a previous experiment [5] in which an increase in alpha and beta activity was found along the frontoparietal axis after the performance of diagonal movements. We extracted time-frequency courses for theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) frequency bands.

First, we computed event-related spectral perturbation (ESRP) on the whole trial period in EEGLAB. In this way, we obtained one matrix for each electrode, hence a total of 32 matrices. Each 100 by 200 matrix was composed of 100 frequency values (from 1 to 50 Hz with frequency values distributed logarithmically over the total amount of rows) × 200 time points (from 1 to 2000 ms). A similar analysis was conducted by Cohen and colleagues [42].

Then, in order to analyze power value change in each frequency band of interest, we extracted and averaged data for each desired frequency band, comparing vertical and diagonal arm movement-related spectral perturbation over time.
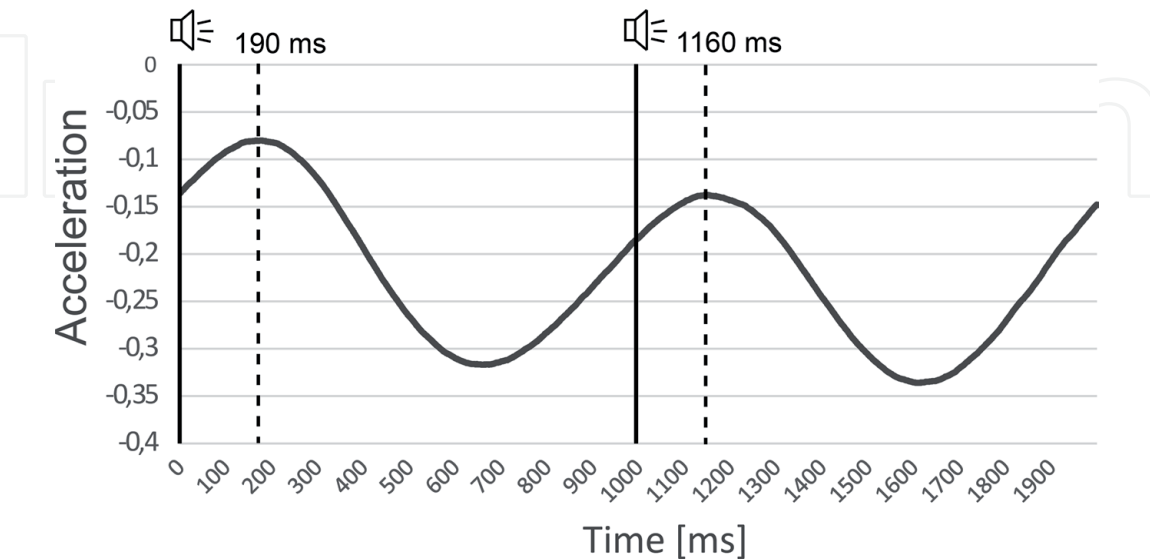

Figure 2.
Accelerometer data representing peaks of movement as a function of time (resulting from the movement). We averaged data from all trials in vertical and diagonal conditions in order to identify the time points in which the arm reached the starting and the ending point of each movement. Bold lines represent presentation of the pacing sounds.

The trial period was split into two time windows: forward period (1000 ms after the first sound (1–1000 ms)) and comeback period (1000 ms after the second sound for each trial (1001–2000 ms)). These two time windows represent two distinct movements in each trial. Forward period includes the movement from the starting position to the ending position, while comeback period includes the movement back from the ending position to the starting position (see **Figure 1**).

Statistical analysis was performed on specific time windows in both forward period and comeback period. Time windows were first defined by the accelerometer data. Our accelerometer can detect not only the acceleration but also the position in space starting from a baseline reference position. We observed that the participants reached the starting point and ending point slightly after the actual sound presentation. We extracted data from the accelerometer from each trial and observed that the delay between sound presentation and actual start of the movement from the starting point was 190 ms while between sound presentation and start of actual movement from the ending point was 160 ms (see **Figure 2**).

Finally, statistical analysis was performed using STATISTICA software (StatSoft, Inc., Tulsa, OK, USA).

2.3.2.2 Source localization

Using low-resolution brain electromagnetic tomography (LORETA) [43], it is possible to solve the inverse problem in EEG and localize generators of electrophysiological components of EEG signal in a specific frequency band.

After time-frequency analysis, we performed source localization analysis using LORETA in order to observe differences between vertical and diagonal movements for theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) activity. Source localization analysis was conducted in specific time windows using a data-driven approach, according to what we observed in the time-frequency analysis.

More specifically, we focused on the time windows previously observed in time-frequency analysis for each specific frequency band. Therefore, we compared the generator of theta in diagonal and vertical movements during the planning of movement in forward period (between 100 and 300 ms), of alpha during the two peaks of activity in comeback period (200–400 ms; 650–850 ms) and of beta in forward period (320–520 ms) and comeback period (220–420 ms). Specifically, analyzed frequencies were theta (7 Hz), alpha (11 Hz), and beta (two frequencies, 19 and 23 Hz).

We performed one-tailed t-test comparisons based on the time-frequency observed activity pattern (i.e., diagonal-related activity greater than vertical-related activity or vice versa). Therefore, for theta, we expected diagonal > vertical; for alpha, we expected diagonal > vertical in P1 and vertical > diagonal in P2; and for beta, we expected diagonal > vertical in both time windows.

Statistical analysis was conducted using subject-wise normalization, and results are expressed as a t-test on the logarithmically transformed data. Nonparametric randomized permutation and probability threshold corrections were performed [44].

3. Results

3.1 Time-frequency results

3.1.1 Theta (4–7 Hz)

We selected a time window ranging from −100 to +100 ms around the peaks recorded by accelerometer and then extracted and analyzed the activity. We

identified the two peaks in forward period and comeback period as peak forward (190 ms) and peak comeback (1160 ms), respectively.

We performed a 2 × 2 ANOVA with condition (vertical, diagonal) and peak (peak forward, peak comeback) as factors. ANOVA was performed for specific ROIs: frontal ROI (F3, Fz, F4), Fz, and parietal ROI (P3, Pz, P4). We performed analysis on Fz separately because we know that this region is particularly relevant for the generation of frontal midline theta [12, 15].

For the frontal ROI, none of the main effects was significant (all $p > 0.14$). The condition-peak interaction was significant [$F(1, 10) = 5.21$; $p < 0.05$; $\eta 2 = 0.34$]. Fisher LSD post hoc analysis showed that peak forward in the diagonal condition was significantly higher than peak forward in the vertical condition ($p < 0.03$) and from peak comeback in the diagonal condition ($p < 0.05$) (see **Figure 3**).

For channel Fz, none of the main effects was significant ($p > 0.11$). The condition-peak interaction was significant [$F(1, 10) = 5.15$; $p < 0.05$; $\eta 2 = 0.34$]. Fisher LSD post hoc analysis showed that peak forward in the diagonal condition was significantly different from peak forward in the vertical condition ($p < 0.03$) and from peak comeback in the diagonal condition ($p < 0.03$) (see **Figure 3**).

For the parietal ROI, none of the main effects or their interaction was significant (all $p > 0.14$).

3.1.2 Alpha (8–12 Hz)

First, we analyzed the same time window previously analyzed for the theta band (Peak1 = 90–290 ms, Peak2 = 1060–1260 ms) in the same clustered ROIs (frontal ROI, parietal ROI) and POz (see **Figure 4**).

For all ROIs, no main effects or their interaction was significant (all $p > 0.15$).

In order to conduct a more specific analysis, we observed the time course and performed qualitative assessment by visual inspection. In this way, we were able to divide each period into time windows to be used for analysis. We used this manual selection method to identify specific time windows of interest in a data-driven approach
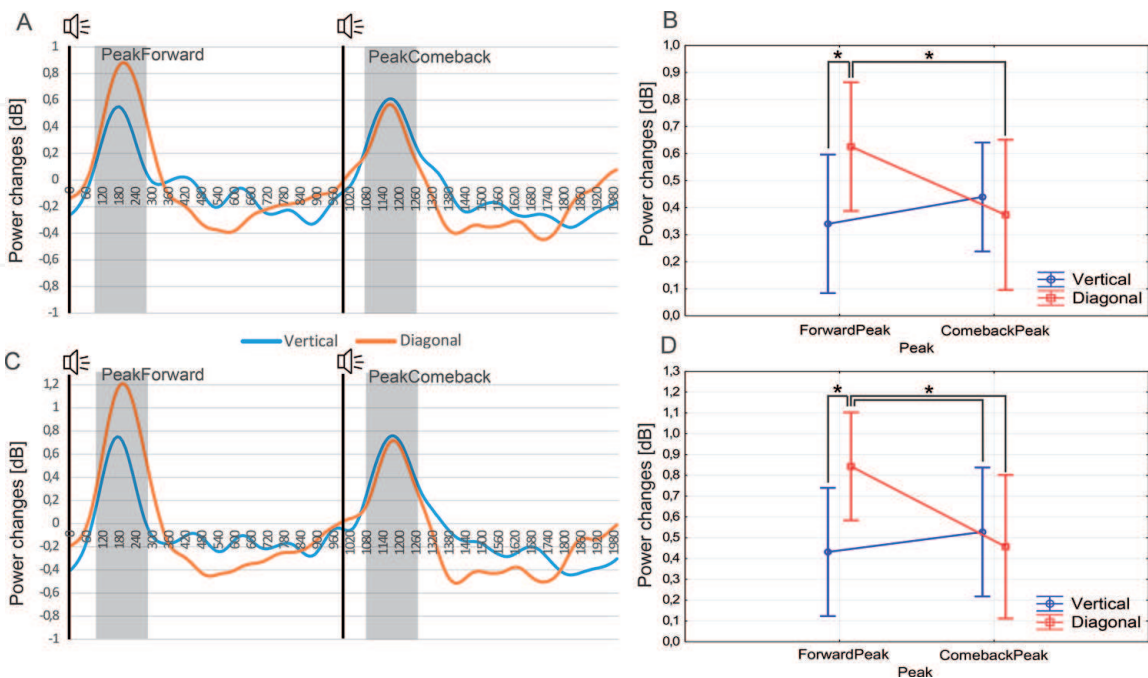

Figure 3.
Theta (4–7 Hz) time-frequency plot (left panels) and analysis (right panels) of the 2 × 2 ANOVA with condition and peak as factors in frontal ROI (A, B) and Fz (C, D). In A and C, highlighted rectangles represent time windows used for analysis. In B and D, bold lines represent significant differences (p < 0.05).
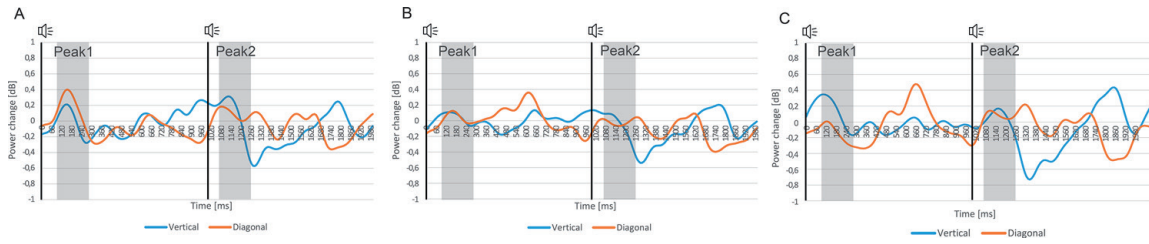
Figure 4.
Alpha (8–12 Hz) time-frequency plot with time windows of interest for frontal ROI (A), parietal ROI (B), and POz (C).

(a similar approach was used by Missonnier et al. see [45]). Maclin et al. [46] used a similar approach to manually select specific noncanonical frequency bands of interest. After visual inspection, we decided to adopt different approaches for each period, basing our criterion on specific parameters that will be explained later.

3.1.2.1 Alpha: forward period

After visual inspection, since we did not have an a priori hypothesis, we decided to analyze forward period adopting an exploratory approach. We divided the forward period into four time windows of 250 ms each in order to analyze the computation of the movement (0–250 ms; t1), the start of the movement (250–500 ms; t2), the crossing of body midline (500–750 ms; t3), and the final part of the movement execution (750–1000 ms; t4) (see **Figure 5A**, **C** and **E**).

We employed a 2 × 4 ANOVA using condition (vertical, diagonal) and time window (t1, t2, t3, t4) as factors. We performed analysis on frontal and parietal ROIs.

None of the main effects or their interaction were significant for frontal ROI (all $p > 0.09$), for parietal ROI (all $p > 0.18$), and for POz (all $p > 0.13$).

3.1.2.2 Alpha: comeback period

Observing the time course during comeback period in the alpha range, we noticed two distinct peaks of activity both in frontal and parietal regions, located at 1290 and 1790 ms, respectively, after the start of the comeback period.

First, we segmented the comeback period into three main stages in order to analyze the two main peaks and the activity between them. The external time windows last 200 ms and fell around the two main peaks. Between these two time windows, we identified a central additional one. Therefore, we identified the three time windows as follows: p1 = 200–400 ms, p2 = 400–700 ms, p3 = 700–900 ms (see **Figure 5B**, **D** and **F**).

We performed a 2 × 3 ANOVA using condition (vertical, diagonal) and time window (p1, p2, p3) as factors. We performed the analysis on frontal and parietal ROIs and POz.

For the frontal ROI, none of the main effects were significant (all $p > 0.30$). The condition-time window interaction was significant $[F(2, 20) = 4.37; p < 0.05; \eta2 = 0.30]$. Fisher LSD post hoc revealed that p1 in vertical was significantly different from p3 in vertical ($p < 0.05$), while all other comparisons were not significant (see **Figure 6A**).

For the parietal ROI, none of the main effects were significant (all $p > 0.59$). The condition-time window interaction was significant $[F(2,20) = 6.13; p < 0.01; \eta2 = 0.38]$. Fisher LSD post hoc revealed that p1 in vertical was significantly different from p3 in vertical ($p < 0.05$), p1 in diagonal ($p < 0.05$), and p2 in diagonal ($p < 0.05$), while all other comparisons were not significant. Comparison between vertical and diagonal condition was significant in p1 ($p < 0.05$) and p3 ($p < 0.05$) (see **Figure 6B**).
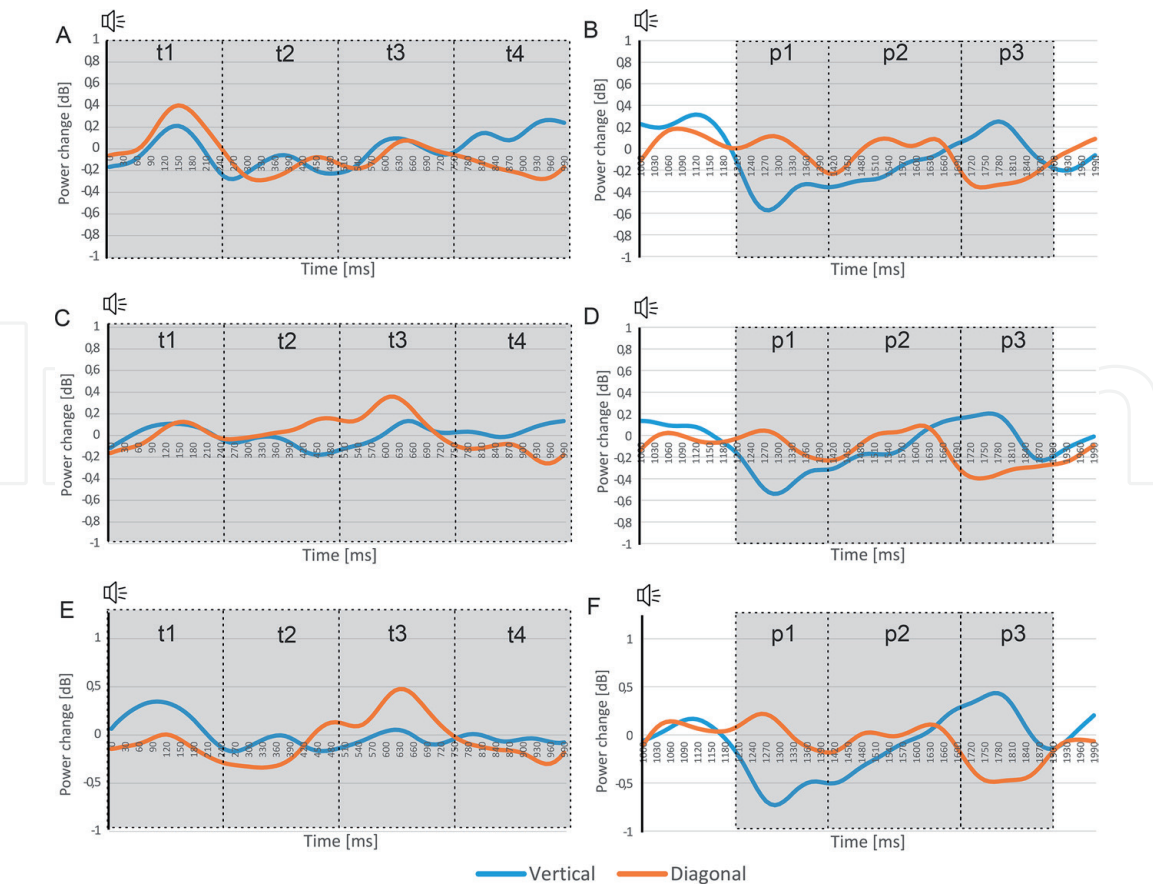
Figure 5.
Alpha (8–12 Hz) time-frequency plot with time window segmentation of forward period (left side) in frontal ROI (A), parietal ROI (C), and POz (E) and comeback period (right side) in frontal ROI (B), parietal ROI (D), and POz (F).
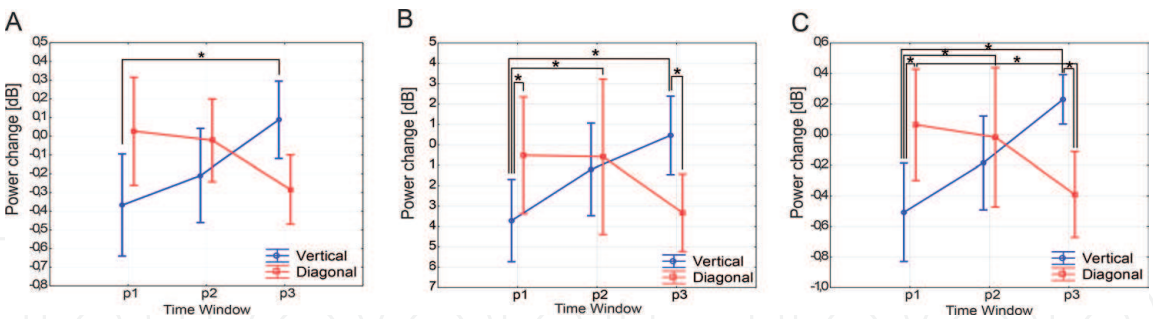

Figure 6.
Alpha (8–12 Hz) analysis of time windows p1, p2, and p3 during comeback period in frontal ROI (a), parietal ROI (B), and POz (panel C).

For POz, none of the main effects were significant (all p > 0.57). The condition-time window interaction was significant [F(2, 20) = 8.64; p < 0.01; η2 = 0.46]. Fisher LSD post hoc revealed that p1 in vertical was significantly different from p3 in vertical (p < 0.01), p1 in diagonal (p < 0.05), and p2 in diagonal (p < 0.05); p3 in diagonal was significantly different from p3 in vertical (p < 0.01) and p1 in diagonal (p < 0.05) (see **Figure 6C**).

3.1.2.3 Alpha: single peaks

To refine our analysis, we extracted the activity in the two main peaks using a time window of 50 ms around the maximum value (Peak1 = 240–340 ms; Peak2 = 740–840 ms) and performed a 2 by 2 ANOVA with condition (vertical, diagonal) and peaks (peak forward, peak comeback) as factors (see **Figure 7**).

For the frontal ROI, none of the main effects were significant (all $p > 0.32$). The condition-time window interaction was found [$F(2,20) = 7.66$; $p < 0.05$; $\eta2 = 0.43$]. Fisher LSD post hoc revealed that Peak1 in vertical was significantly different from Peak2 in vertical ($p < 0.05$). No differences between vertical and diagonal were found (see **Figure 7A**).

For the parietal ROI, the condition-time window interaction was significant [$F(2, 20) = 28.72$; $p < 0.001$; $\eta2 = 0.74$]. Fisher LSD post hoc revealed that vertical and diagonal were significantly different in both Peak1 and Peak2 ($p < 0.01$) (see **Figure 7B**). Peak1 and Peak2 were also significantly different for both vertical ($p < 0.001$) and diagonal ($p < 0.05$). None of the main effects were significant (all $p > 0.07$).

For POz, the condition-time window interaction was significant [$F(2, 20) = 28.52$; $p < 0.001$; $\eta2 = 0.74$]. Fisher LSD post hoc revealed that vertical and diagonal were significantly different in both Peak1 and Peak2 ($p < 0.01$) (see **Figure 7C**). Peak1 and Peak2 were significantly different in both vertical ($p < 0.001$) and diagonal ($p < 0.05$). None of the main effects were significant (all $p > 0.19$).
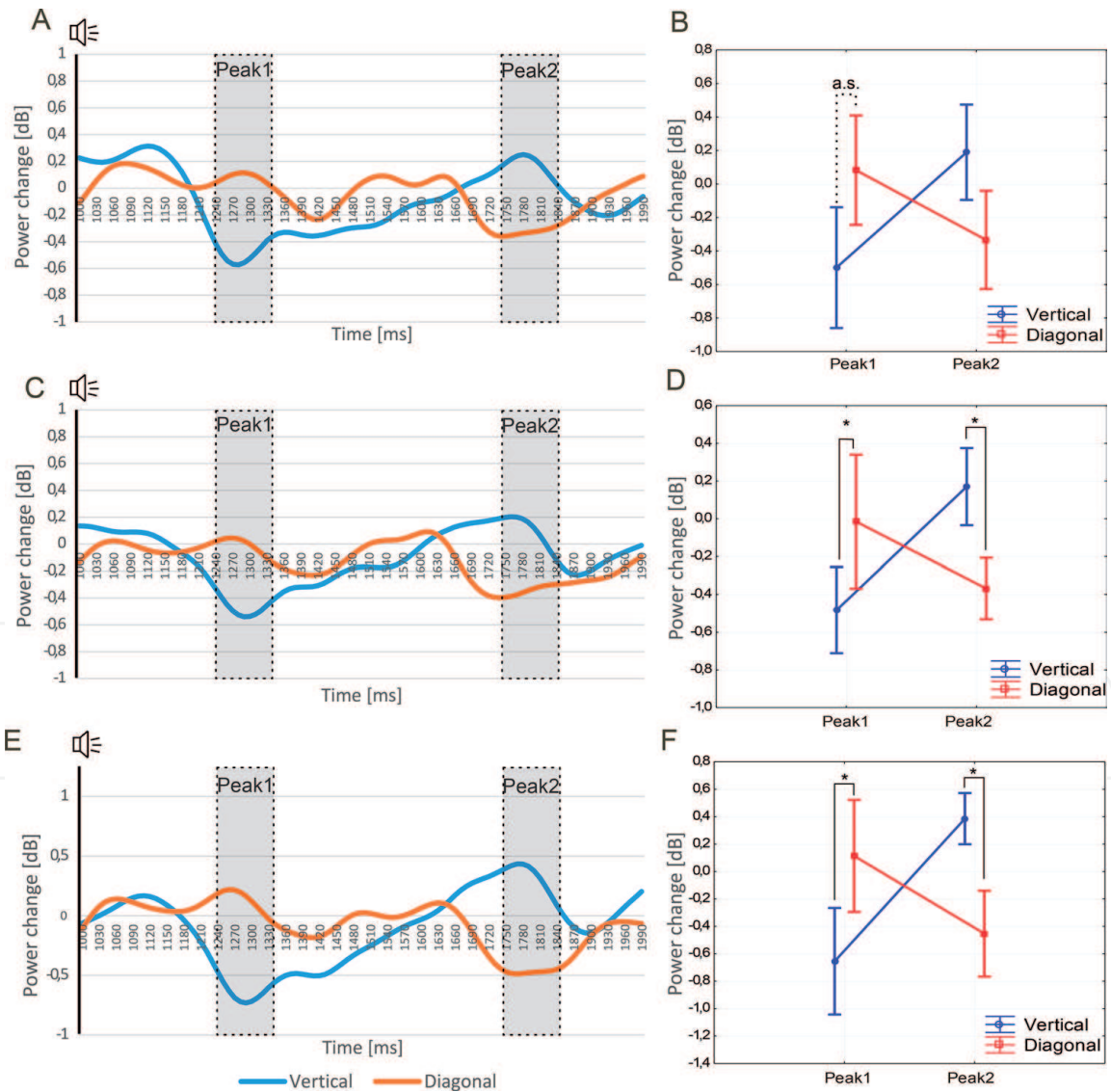

Figure 7.
Alpha (8–12 Hz) time-frequency plot with peak segmentation during comeback period in frontal ROI (A), parietal ROI (C), and POz (E). Analysis of peaks p1 and p2 during comeback period in frontal ROI (B), parietal ROI (panel D), and POz (panel F). In A, C, and E, highlighted rectangles represent time windows used for analysis. In B, D, and F, only significant or almost significant comparisons between vertical and diagonal are displayed. Bold lines represent significant differences ($p < 0.05$), and the dashed line represents a difference that approaches statistical significance.

3.1.2.4 Alpha1 vs. Alpha2

Since lower and upper alphas have previously been reported to have different roles, lower alpha being related to general attentional processes and upper alpha being more sensitive to perceptual and semantic processing during task performance [51], we further wanted to explore the possibility that lower and upper alpha could have different involvement in the modulation of alpha biphasic activity during vertical movements. Therefore, we analyzed POz, where we have found the maximum alpha modulation.

We divided the alpha band into Alpha1 and Alpha2 (8–10 Hz and 11–12 Hz, respectively) and performed a two-way ANOVA with alpha (Alpha1, Alpha2) and peak (Peak1, Peak2) as factors.

The main effect of peak was significant [$F(1, 10) = 11.42$; $p < 0.01$; $\eta2 = 0.53$], suggesting that Peak2 (mean, 0.432 dB) was significantly higher than Peak1 (mean. -0.689 dB). The alpha-peak interaction was significant [$F(1, 10) = 14.5$; $p < 0.01$; $\eta2 = 0.59$]. Fisher LSD post hoc revealed that comparison between Alpha1 and Alpha2 approached significance in Peak1 ($p = 0.07$) and was significant in Peak2 ($p < 0.05$) (see **Figure 8**).

3.1.3 Beta (13–30 Hz)

For analysis in the beta frequency, we used the same time window already used for the alpha band. In forward period (M1), we therefore used four consecutive time windows lasting 250 ms each, while in the comeback period, we used three time windows: p1 = 200–400 ms, p2 = 400–700 ms, p3 = 700–900 ms (see **Figure 9**).

3.1.3.1 Beta: forward period

A 2 × 4 ANOVA using condition (vertical, diagonal) and time window (t1, t2, t3, t4) as factors was conducted. We performed analysis on the frontal and parietal ROIs. For the frontal ROI, none of the main effects or interaction were significant (all $p > 0.25$). For the parietal ROI, none of the main effects were significant (all $p > 0.38$).
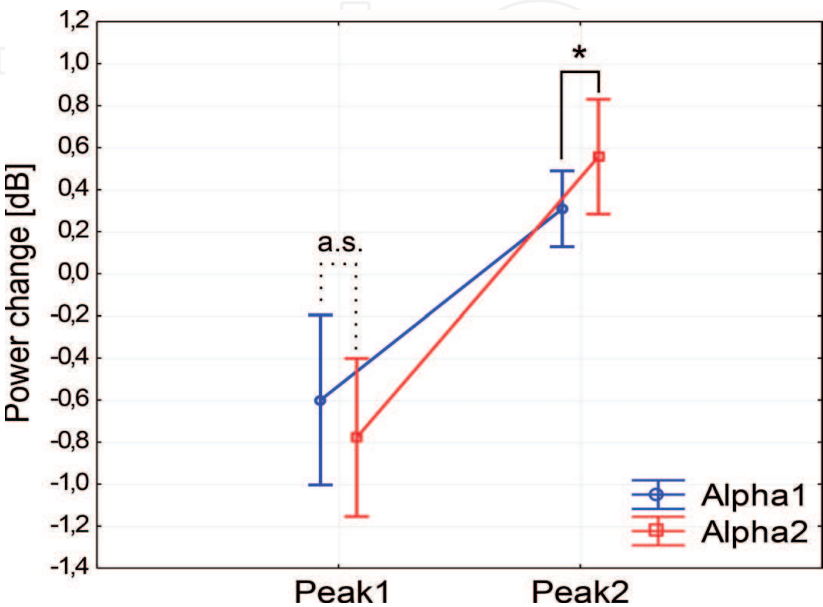

Figure 8.
Comparisons between Alpha1 and Alpha2 in Peak1 and Peak2. The bold line represents a significant difference (p < 0.05), and the dashed line represents a difference that approaches statistical significance.
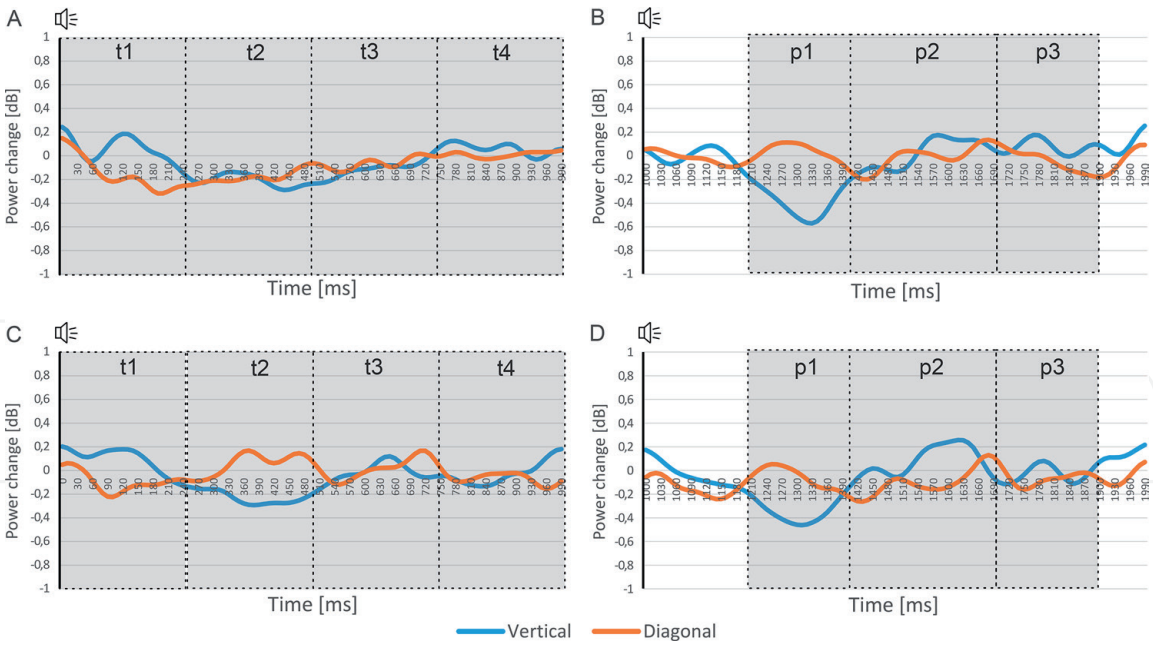
Figure 9.
Beta (13–30 Hz) time-frequency plot with peak segmentation during forward period (left panels) and comeback period (right panels) for frontal ROI (A, B) and parietal ROI (C, D).
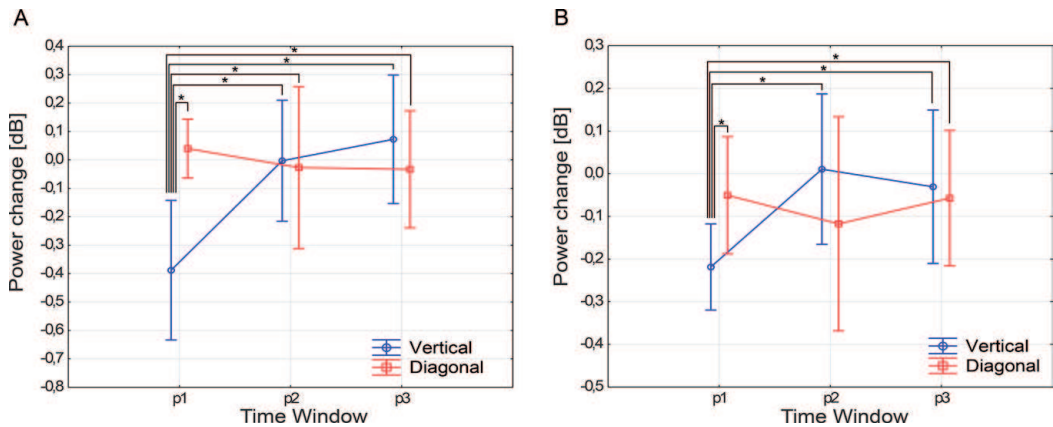

Figure 10.
Beta (13–30 Hz) analysis of time windows p1, p2, and p3 during comeback period for frontal ROI (A) and parietal ROI (B). Bold lines represent significant differences (p < 0.05).

3.1.3.2 Beta: comeback period

We performed a 2 × 3 ANOVA using condition (vertical, diagonal) and time window (p1, p2, p3) as factors. We performed the analysis on frontal and parietal ROIs.

For the frontal ROI, none of the main effects were significant (all $p > 0.12$). The condition-time window interaction was significant [$F_{(2, 20)} = 4.07$; $p < 0.05$; $\eta 2 = 0.28$]. Fisher LSD post hoc revealed that p1 in vertical was significantly different from all other factors ($p < 0.05$) (see **Figure 10A**).

For the parietal ROI, none of the main effects were significant (all $p > 0.55$). The condition-time window interaction was significant [$F_{(2, 20)} = 5.45$; $p < 0.05$; $\eta 2 = 0.35$]. Fisher LSD post hoc revealed that p1 in vertical was significantly different from p2 in vertical ($p < 0.01$), p3 in vertical ($p < 0.01$), p1 in diagonal ($p < 0.05$), and p3 in diagonal ($p < 0.05$), while all other comparisons were not significant (see **Figure 10B**). For the parietal ROI, none of the main effects were significant (all $p > 0.55$).

3.2 Source localization

After observing modulation of theta, alpha, and beta frequency, we observed the difference between diagonal and vertical movement in the generation of such frequency band activity in specific time windows (see Methods section for more details).

3.2.1 Theta

We analyzed theta during the peak in the forward period at the start of each trial, specifically between 100 and 300 ms. Significantly higher theta was found in the left middle frontal gyrus during diagonal movement compared to vertical movement ($p < 0.05$) (see **Figure 11**).

3.2.2 Alpha

We analyzed alpha in two time windows corresponding to the positive and negative activity peaks during the comeback period. These two time windows were P1 at 1200–1400 ms and P2 at 1650–1850 ms.

For P1, significant higher alpha was found in the posterior cingulate cortex during diagonal movement compared to vertical movement ($p < 0.05$). For P2, significantly higher alpha was found in the left inferior parietal lobule during vertical movement compared to diagonal movement ($p < 0.05$) (see **Figure 11B**).

3.2.3 Beta

We analyzed beta during the second time window in forward period (t2) and in the first time window (p1) during comeback period. These two time windows were t2 at 320–520 ms and p1 at 1220–1420 ms. None of the comparisons was significant (all $p > 0.52$).
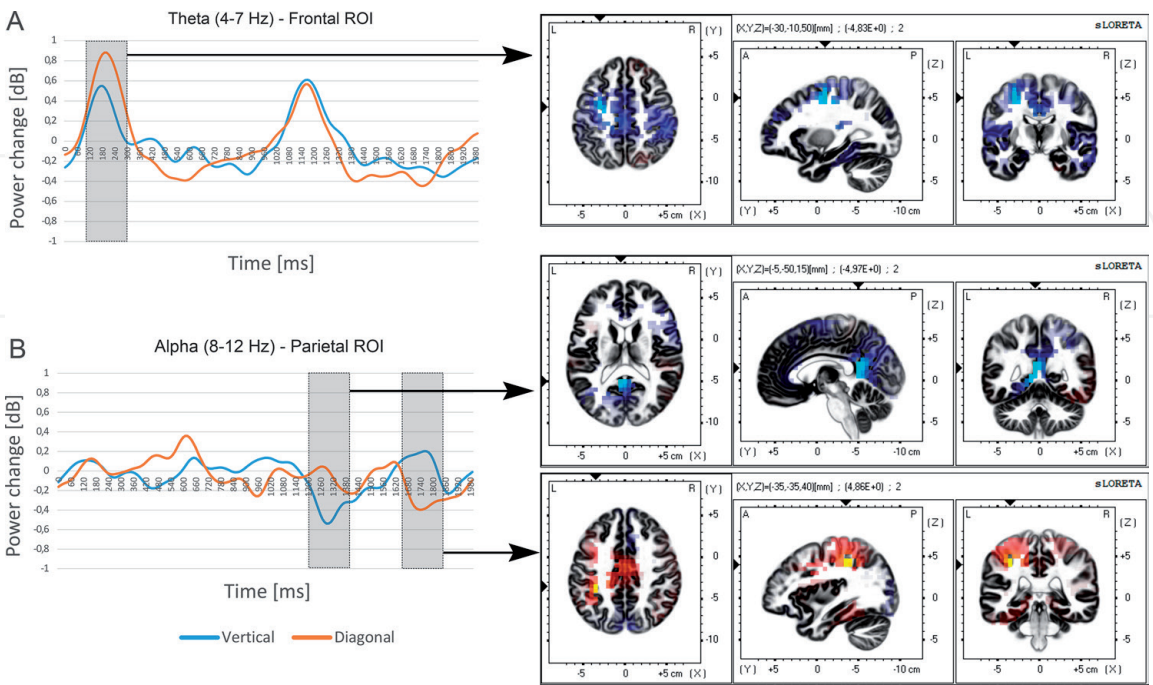

Figure 11.
Source localization of theta (A) and alpha (B) activity. Theta has been analyzed in the 100–300 ms time window. Alpha activity has been analyzed in two time windows: 1200–1400 and 1650–1850 ms (B). Blue blobs mean that activity during diagonal movement is higher than during vertical movement and vice versa for yellow blobs.

4. Discussion

Diagonal rhythmical bilateral movements have previously been suggested to promote improvement in motor and cognitive functions [1, 3]. The diagonal axis has the role of a metaphorical rule breaker in relation to the way of thinking, as suggested by the definition of "diagonal thinking" as a mixture of logical (i.e., vertical) and creative (i.e., lateral) thinking [47]. Diagonal movements are widely used in disciplines based on whole-body movements such as Asian martial arts (i.e., aikido, Tai Chi, Qigong) or modern and contemporary dance.

Yet, no study that we are aware of has actually examined electrophysiological changes during diagonal movements. Consequently, in the present study, we wanted to examine cerebral activity during diagonal arm movements in comparison to vertical arm movements. Previous literature has suggested that diagonal movements promote neuroplasticity along frontoparietal pathways through an increase in alpha and beta power [5]. For this reason, we focused our analysis on spectral power changes during the actual execution of movements in the theta, alpha, and beta bands.

Time-frequency analysis was conducted in order to observe how power in specific frequencies changes over time during movement execution.

4.1 Theta: attention, navigation, and computation

Comparing vertical to diagonal movement, we observed an increase of theta power during the first stage of diagonal movement over frontal electrodes, especially over Fz. This increment of frontal theta can be explained in three interrelated ways, including attentional effort [12, 19], navigational computation [13], and integration of information from different brain regions [16, 17]. First, it reflects greater attentional effort required for diagonal movement. In fact, diagonal movements are more complex and less automatic than vertical movements, and subjects must be more focused and pay more attention in order to perform correctly the movement. Second, it could reflect navigational computation. In both diagonal and vertical movements, the arms swing in peripersonal space, requiring the computation of the trajectory of both arms. However, it is only in diagonal movements that the arms go across the sagittal body midline and reach the other peripersonal hemispace. This kind of crossing requires more complex spatial computation than during movements that do not involve both hemispaces. Third, theta has previously been related to the integration of different information from distant cerebral regions [17]. Other studies have suggested that theta increase is related to a general mechanism of recall and integration of information from different domains supported by a central executive module [19, 48].

Finally, the state of focused attention on movement execution, together with the navigational computation necessary for the performance and the external sound, could evoke an absorption state in subjects. In fact, the role of *frontal midline theta* has been previously related to meditation, internalized attention, and integration of sensory information into executive control components of complex motor behavior [12, 15, 49].

4.2 Alpha: internalized attention and movement

While greater theta activity was related to the diagonal movements, we observed a biphasic modulation of alpha activity during the second part of vertical movements. Keeping in mind that each movement was composed of two parts (forward period and comeback period), we observed a biphasic response in the comeback period during vertical movement.

In fact, we observed first a decrease of alpha power immediately after the start of the comeback period and, consequently, an increase in the same frequency band tied to the end of the movement.

The decreased alpha activity observed immediately after the end of the second movement could reflect a decrease in internalized attention.

The decrease in alpha is classically related to a decrease of focusing on internal states and an amplified processing of information from the environment through sensorial inputs, especially from the visual system [17, 50].

Thus, this alpha decrease supports an increased attentional focus on the environment and a contextual decrease of internalized attention. Probably, after the forward period, subjects consider the movement ended, and this could represent an attentional disengagement related to the movement performance.

For those reasons, vertical movements in the comeback period do not require particular cognitive effort, but, immediately before the next trial, subjects must re-engage cognitive resources and focus on the internal state causing the significant increase of alpha observed at the end of the whole trial.

Klimesch [51] suggested that alpha is not a unitary frequency band but it would be better described as a union of two sub-bands named lower and upper alpha. These two sub-bands seem to support different functions: lower alpha would be more modulated by general attentional processes, while upper alpha would be more sensitive to perceptual and semantic processing during task performance.

Our result suggests that during vertical movement, Alpha1 and Alpha2 were significantly different in Peak2 and approached significance in Peak1. This means that during vertical movements, in Peak1, Alpha2 is slightly lower than Alpha1 and vice versa and in Peak2 Alpha2 is higher than Alpha1. Since Alpha2 has been associated with perceptual processing during task performance [51], we can hypothesize that the activity pattern observed over alpha power could reflect not a pure movement-related attentional engagement/disengagement but rather an inhibition/enhancement of environmental sensory input processing.

4.3 Beta

In the beta band, we observed a desynchronization during comeback period only in vertical movements, around 1300 ms after the start of the trial. The timing and the shape of the time course follow as observed in Peak1 in the alpha band. Contrary to our expectations, we did not find a similar desynchronization during diagonal movements. Probably, higher attentional demand during diagonal movement could address this issue, but further research will be performed.

Between consecutive trials (from 1900 to 100 ms of the next trial), we can observe a small increase in beta activity both in diagonal and vertical movements. This enhanced beta activity represents the post-movement beta rebound [35]. The presence of this activity suggests that subjects perceive the end of the trial as the conclusion of the movement, indexing the new trial as a new movement.

4.4 Source localization

A theta generator during the first stage of diagonal movements has been located in the middle frontal gyrus of the left hemisphere. The location of this generator supports the aforementioned frontal midline theta hypothesis in which the increase of theta during diagonal movement could increase internalized attention and integration of information from different regions such as frontal, sensorimotor, and parietal cortices.

Alpha generators during Peak1 and Peak2 in comeback period were found to be located in the posterior cingulate cortex and the left inferior parietal lobule,

respectively. The posterior cingulate cortex is a region involved in directing attention toward internal or external cognition [52]. In our case, we observed a decrease of alpha during vertical movement. This result is in line with our hypothesis about the increase of external sensory input during Peak1 in vertical movement and the consequent inhibition in order to reallocate attention to the execution of the movement. In Peak2 we observed higher alpha activity during vertical compared to diagonal movement execution. The inferior parietal cortex is classically involved in spatial attention (for a review, see [53]), body perception [54], and motor functions [55]. Fu et al. [56] suggested that increase in alpha power over the inferior parietal cortex could underlie integration of sensory cues in order to redirect attention. This explanation fits well with our hypothesis of attentional fluctuations related to the end of vertical movements. In fact as already hypothesized before, the selective increase in alpha at the end of the movement could represent a re-engagement of attention toward sensorimotor information in order to perform correctly the next trial.

5. Conclusions

Results from time-frequency analysis and source localization converge to support our initial hypothesis. We observed that diagonal movements increase theta activity over the middle frontal gyrus during the first stage of movement execution, suggesting that they are indeed more complex than vertical movements. This complexity could be reflected in more computational resources being allocated at the start of the movement and to a reduced focus on the external environment during the whole performance. Moreover, the higher complexity of diagonal movement is addressed also by the biphasic alpha activity that involves the posterior cingulate cortex and inferior parietal lobule reflecting attentional fluctuations on internal vs. external environment during the execution of vertical movements.

Taken together, these results suggest that diagonal movements have indeed an effect on the ability to inhibit external input and to induce a mental mindset oriented to an increase in internalized attention.

Since theta has been related to a great variety of cognitive functions, one of our future aims is to understand whether motor training, which involves diagonal movement, could produce a reliable and prolonged enhancement of theta activity in order to enhance cognitive functioning on a long time scale.

We intend to examine whether the integrative role of theta could help healthy cognitive and motor development or be helpful in reducing symptoms of psychiatric disease based on psychological fragmentation, such as post-traumatic stress disorder or schizophrenia.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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