Study of cerebral cortico-cortical coherence during motor practice

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HIGHLIGHTS
• Coh increases areas related to motor execution and decreases in those that are less related.
• The motor practice related to reduced cortico-cortical communication in cognitive brain regions.
• Upsurge in neural plasticity in motor-related area during practice.

ABBREVIATIONS
AE   Absolute timing error
Coh   Coherence
d   Cohen's d
EEG   Electroencephalogram
FIR   Finite impulse response
Fz   Frontal region
IQR   Interquartile range
LTP   Long-term potentiation
M1   Primary motor cortex
PLV   Phase Locked Value
q1   First quartile
q3   Third quartile
RE   Relative timing error

BACKGROUND: Coherence is one of the neural mechanisms related to communication and plasticity. The literature presents two divergent results regarding coherence and motor practice. One result suggests a decrease in coherence during practice, while the other indicates an increase in coherence throughout practice.
AIM: Considering these two divergent results in the literature, this study aimed to examine the role of coherence in motor practice. We hypothesize that electrode pairs related to C3 (C3-P3 and C3-F3) show an increase of coherence during practice, while electrodes less related to motor action (F4, C4, and P4) may exhibit decreased.
METHOD: Twenty-four right-handed participants practice 120 trials of a sequential key-pressing task.
RESULTS: The results indicated, in the alpha upper and theta bands, from initiation to end of practice, the coherence increased in the F3-C3 electrode pair and decreased in the C3-C4, C3-P3, P3-P4, F3-P3, and C4-P4 electrodes pairs.
CONCLUSION: The results partially confirmed the hypothesis. The coherence increases in the electrode pairings related to the motor execution and decreases between the lesser related. During the motor learning process, communication reduction occurred in groups of neurons not associated with the stimulus, and the potentiation of synaptic plasticity within groups of neurons associated with the stimulus occurred.

KEYWORDS: Motor learning | Motor control | Implicit learning | Neurophysiology

INTRODUCTION

The practice itself is the most critical variable in motor skill acquisition [1], whether in music, rehabilitation, or sports. With practice, the learner improves performance, becomes more speedy and accurate, and decreases errors [2]. Within a single practice session, it is already possible to observe performance improvement, with much of this improvement depending on error detection and correction mechanisms [3].

A series of psychophysiological studies using electroencephalogram (EEG) have shown mechanisms underlying the modification of brain activity due to practice (Reuter, Booms and Leow [4] for review). The EEG, via scalp, records the electrical signals produced by the neurons, neurons are embedded in assemblies in which they influence mutually through excitatory and inhibitory synaptic connections [5]. Neuronal assemblies refer to a group or ensemble of neurons that exhibit synchronized activity to perform a specific function or represent certain information within the brain [6]. Individual neurons communicate with each other through synaptic connections, forming complex networks [7]. Within these networks, the neuronal assemblies are functional units that require coordinated activity of multiple neurons to accomplish specific tasks, such as motor response [8]. These assemblies are dynamic and flexible, reconfiguring themselves according to demands [9]. The execution of motor actions *per se* generates perceptual-motor demands that reconfigure neuronal assemblies [10].

With practice, neurons are expected to change synchronization levels, increasing or decreasing specific neural response patterns within neuronal assemblies [11]. This synchronized activity among neurons constitutes one of the principal mechanisms of memory formation

for two principal reasons: cortico-cortical communication and mechanisms of plasticity [12]. In cortico-cortical communication terms, synchronization may support neural communication by establishing transient associations between different brain areas [13]. For example, when performing a throw, information regarding the ball's weight and color, the opponent's position vision, and the arm's speed are processed in distinct brain regions. These pieces of information must be connected through a mechanism has ensured that the brain associates them with the same action. The synchronization enables communication among the different brain regions. The mechanisms of plasticity function of synchronization are associated with a classical concept of Hebbian learning [6]. Hebbian learning suggests that when two neurons are repeatedly activated together, the strength of the synaptic connection between them is increased [6]. In this logic, the increased synchronization results from several synaptic inputs arriving at postsynaptic neurons simultaneously (spatial summation), enabling rapid depolarization [14]. This rapid depolarization increases the postsynaptic membrane potential above the firing threshold, triggering the neural plasticity processes [15].

Two main results about synchronization and motor practice are found in the literature. The first result shows that synchronization decreases with practice, reflecting the refinement of cortical resources [16]. Refinement of cortical resources refers to perfecting the available resources within the brain's cortical areas to maximize their efficiency and capacity to perform specific functions. During motor practice, reduced activity in frontal regions characterizes the refinement of cortical resources [17]. A series of processes occur through practice, leading to decreased cognitive demand [18,19]. The frontal regions' activity is traditionally associated with cognitive processes [20]. Gentilli et al. [10] showed a reduction of synchronization in the early to late practice. This reduction occurred among electrode pairs considering the frontal (Fz) region as the reference [Fz–F3, Fz–C3, Fz–C4, Fz–T4 (...)]. As mentioned above, the frontal regions' activity would be more related to the cognitive processes [20], and the decreasing synchronization during practice would indicate movements less dependent on cognitive processes [17]. In this rationale, synchronization is seen as cortico-cortical communication among brain areas [21]. As movements are less dependent on cognitive processes with the advancement of practice [18,19], the cortico-cortical communication between the frontal and other areas could be decreased. Thus, the authors explain the reduction of synchronization as a decrease in cortico-cortical communication due to a decrease in cognitive demand, typical of the motor learning process [10,22].

On the other hand, the previous results claim that with the practice, there is an increase in synchronization and not a decrease [23,24]. In this case, the increased synchronization during practice is an effect of the mechanisms of plasticity [11]. Kranczioch et al. [3] showed better performance is related to increased synchronization between contralateral fronto-central and ipsilateral parieto-occipital brain regions. The tenet here is that synchronous activity in the brain, precisely presynaptic and postsynaptic neurons, can lead to long-lasting changes [25].

At first glance, one would consider these two kinds of results divergent. In the study of Gentilli et al. [10], the synchronization decreased considering reference to the frontal areas (Fz). While in the Kranczioch et al. [23] study, the synchronization was increased in the local motor more related to movement. Perhaps, there is no divergence between results. The motor learning process may be associated with a decrease in cortico-cortical communication among brain areas associated with cognitive processes [10] and a simultaneous increase in neural plasticity processes in the brain areas related to movement [23].

Most often, researchers infer synchronization by observing coupling between different points. In animal experiments, researchers record extracellular action potentials and analyze the local field potentials in the same or different regions. Human scalp EEG studies do not measure action potentials. Here, synchronization refers either to the phase relation of EEG oscillations between two regions or coherence. This way of inferring synchronization is similar to the one used by other studies in motor practice [10,22,23,26,27].

Considering this divergence in literature, there is a need to further examine the role of coherence in motor practice. We hypothesize that, from initiation to end of practice, the coherence will increase in the electrode pairings more related to the motor execution and decrease among less related electrode pairings to the motor execution. The primary motor cortex of the contralateral hemisphere predominantly originates the descending projections that control unilateral movements [28]. In the present study, we used the right hand to control movement. The C3 is equivalent to the M1 contralateral hemisphere for our motor task. Thus, we expect electrode pairs related to C3 (C3-P3 and C3-F3) to exhibit increased coherence. On the other hand, electrodes less related to motor action, such as F4, C4, and P4, may exhibit a decrease in coherence. Researchers have highlighted that brain activity in the theta and alpha frequency bands highly responds to cognitive processing [29]. As is well known, the process of motor practice involves cognitive processing [18,19]; thus, using these two frequency bands could indicate cognitive processing. Our study aims to shed light on this matter by exploring the potential coexistence of two explanations for coherence results. Specifically, we investigate the possibility that the system operates in both ways, with increased coherence observed in areas more closely associated with motor action. In contrast, areas less relevant to the task exhibit decreased coherence.

METHODS

Participants

Twenty-four right-handed participants (12 men and 12 women), ranging from 18 to 35 years old (mean = 26.07; standard deviation = 5.58), participated in this experiment. All participants had normal or corrected-to-normal visual acuity in both eyes and no prior motor task experience. The sample size was defined using the Power Analysis package from r (the official release of the package: http://cran.r-project.org/web/packages/pwr/). The analysis indicated a sample size of 23.51 subjects, considering an effect size of 0.7, the power of the test as 0.95, and alpha as 5%. A local ethics committee approved the study (CAAE 24116513.2.0000.5149). All participants provided written informed consent after receiving a full explanation of the study.

Apparatus

A computer, color monitor, and numeric keypad were positioned on a standard table in the laboratory room. A custom-made software program (https://github.com/edftercio/pressing_sequential_keys) was used to control the experimental task in the LabVIEW software (National Instruments, Texas, EUA). Participants were asked to sit on a chair in front of the computer monitor and to adjust the numeric keypad position to use it comfortably. They used it with their right hand.

The B-Alert×10 sensor headset (Advanced Brain Monitoring Inc., Carlsbad, CA, USA) was used to acquire the electroencephalography (EEG). Nine Ag/AgCl EEG electrodes were located at F3, Fz, F4, C3, Cz, C4, P3, POz, and P4, according to the international 10–20 system. The pairs of electrodes were chosen based on the same positioning as previous studies [3,22, 27,26,30]. Two electrodes on the mastoid bones (left and right) were used as the reference and ground. The sampling rate was 1,024 samples/s for all channels and transferred in real-time via Bluetooth link to a host computer where the B-Alert software (Advanced Brain Monitoring Inc., Carlsbad, CA) is stored. All electrode impedances were maintained below 5 kΩ.

Task

Participants were instructed to use their right hand's index finger to sequentially press four keys (2, 8, 6, and 4) on the numeric keypad [31,32]. In this task, the learner needs to press a sequence of keys with two goals: (a) learn the partial (or relative) timing between key-pressed and (b) learn the total (or absolute) time between the first and the last key of the sequence. The partial time between each key was (1) 22.2% (key 2 to 8), (2) 44.4% (key 8 to 6), and (3) 33.3% (key 6 to 4) and total time was 900 ms [33,34,35,36]. Partial time is relative to the total time executed. Thus, the two task goals are dissociated, meaning it is possible to achieve the partial goal without achieving the total goal. For instance, the learner executed a total time of 1000 ms with partial times of 22.22% (key 2 to 8), 44.4% (key 8 to 6), and 33.3% (key 6 to 4). In this example, there was a total time error of 100 ms (absolute timing error) and no error in the partial time (relative timing error). After each trial, the knowledge of the results was displayed on the screen immediately. The knowledge of results included the partial time between each key, the relative timing error (highlighted in Figure 1), and the total time performed.
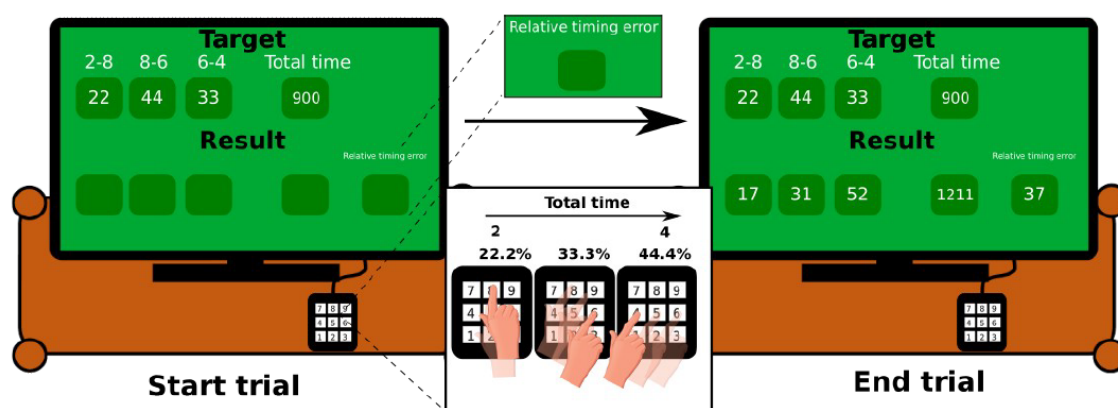
Figure 1. Motor Task. On the left side of the figure, it is possible to observe the monitor screen before the execution, indicating goals (partial times and the total time). On the right side, the completion of the task is shown, indicating the feedback at the bottom of the partial times (total relative error and error for each segment) and the total time. In this example, the learner produced a relative error of 37% (|22-17|+|44-31|+|33-52|) and a total time of 1211. In the figure's center is a highlight of the relative error and an example of the execution of the sequence 2, 8, 6, and 4.

Procedures and Experimental Design

The exact instructions were given to each participant about the information displayed on the computer screen. All subjects were required to be as accurate as possible regarding partial and total time goals. Before each trial, partial and total time goals were displayed on the computer screen. After the task execution, the results were presented on the screen for at least six seconds. Participants were instructed to spend the time they needed to compare their results with the goals. After six seconds, a sign requiring the initiation of the next trial was presented. Participants were instructed to start whenever they wanted the next trial after receiving the sign to start. When a participant pressed the keys incorrectly, a warning was displayed, and the trial was repeated. No participant pressed the keys incorrectly. The experiment consisted of all participants performed 120 trials at the time goals, 22.2% (key 2 to 8), 44.4% (key 8 to 6), and (3) 33.3% (key 6 to 4) and total time goal of 900 ms.

Measurements

We used relative timing error (RE) and absolute timing error (AE) as task performance measures. We used RE to measure proficiency in learning the relative timing dimension and AE to measure proficiency in learning the absolute timing dimension [37]. The RE was determined as the sum of differences between the partial time performed and the partial time goal for each segment. It was computed as the following:

$$RE_n = (|S1_n - 22.22|) + (|S2_n - 44.44|) + (|S3_n - 33.33|)$$

S1, S2, and S3 are the values in each segment (S1 key 2 to 8, S2 key 8 to 6, and S3 key 6 to 4) performed in each trial (n). The values of each segment were relativized by total time, as the following:

$$S1_n = ts/0.01 * T \;;\; S2_n = ts/0.01 * T \;;\; S2_n = ts/0.01 * T$$

ts is the time (in ms) in each segment and T is the total time (in ms) in each trial n. We computed AE as the difference between the total time performed (time spent between pressing keys 2 and 4) and the total time goal.

We used the Phase Locked Value (PLV) according to the method previously described in Lachaux [38] to measure Coherence (Coh) between two pairs of EEG electrodes. This method quantification of frequency-specific synchronization (i.e., transient phase-locking) between two electrodes signals [38]. We computed the following:

$$PLV_t = \frac{1}{2}\left| \sum_{N}^{n=1<exp} (j\theta(t,n)) \right|$$

where θ(t, n) is the phase difference [i.e., φ1(t, n)- φ(t, n)]. Although a complex Gabor wavelet can be used, we computed the phase value using the Hilbert transform. We used the following electrodes combination: F3-F4, C3-C4, P3-P4, F3-C3, F3-P3, F4-C4, F4-P4, C3-P3, and C4-P4.

EEG signal processing

We applied the 60 Hz notch filter to the signal. Then, the zero-phase pass-band filter (lower cutoff of 0.1 Hz and an upper cutoff of 100 Hz) and the zero-phase high-passed filter (lower cutoff of 1 Hz) were applied to the signal to remove the DC offset. Finally, the multidimensional median filter was used with a window size of 10 ms.

Subsequently, all electrodes were filtered in the interest bands using a finite impulse response (FIR) filter using the window method. The bands were theta (4–7 Hz), alpha lower (8–10 Hz), and alpha upper (10–12 Hz).

Posteriorly, we computed the phase value through the Hilbert transform. After, the signals were separated (epoch) in three moments: (1) planning - the interval between the sign for initiation of trial and key press 2; (2) execution - the interval between pressing keys 2 and 4; (3) processing - the interval between key press 4 and the sign for initiation of the subsequent trial. Data from the motor task and EEG were synchronized offline by an algorithm developed in Python (https://osf.io/q8yjp/). The details of offline synchronization are provided in Nogueira et al. [27].

Statistical analysis

Outlier analyses (intra-group, trial-by-trial) were performed for all measurements (RE, AE, and Coh). It was computed as the following:

$$ref = IQR*1.5$$

$$threshold\_up = q1 + ref$$

$$threshold\_down = q3 + ref$$

where IQR represents the interquartile range, q1 denotes the first quartile, and q3 represents the third quartile. In the presence of outlier data, we initially removed the outliers. We then calculated a new average value and replaced the outlier value with the updated average value. In addition, the data were filtered through the median filter and moving average with a windows size of 12 trials to ER and EA and Coh with a windows size of 12 ms.

We did a t-test for dependent samples for EA, ER, and Coh (for each electrodes combination separately). We organized all measurements into two blocks of 12 trials for analysis: the first block of the first 12 trials and the last block of the last 12 trials.

A significant difference at the level of α = 0.05 was adopted for all statistical analyses. Effect sizes were calculated using Cohen's (d).

RESULTS

Performance

Descriptive analyses of absolute timing error and relative timing error are shown in Figure 2. Inferential analysis detects the difference between the initial and final parts of practice in the absolute timing error [t(23) = 2.59, p = 0.01, d = 0.52] and relative timing error [t(23) = 8.76, p < 0.01, d = 1.79]. In both measures, the first block of practice showed more errors than the last.
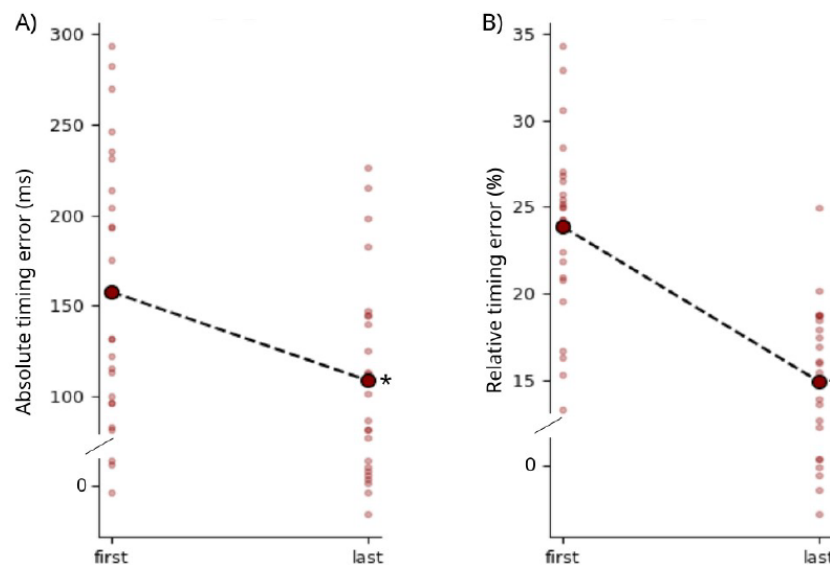

Figure 2. Performance analyses between the initiate and end of practice. (A) absolute timing error and (B) relative timing error of two blocks of 12 trials - 12 first trials (first) and 12 last trials (last). circle = mean of blocks. dots = individual means of blocks. * = p < 0.05.

EEG coherence
Alpha lower

Descriptive analyses of the first 12 trials and last 12 trials of practice are shown in Figure 3. As principal results, the analysis revealed differences between the initial and final part of practice during execution at the C3-C4 and during the planning and processing at the P3-P4 (Table 1). In all situations above, the Coh decreased from initiate to end of practice.
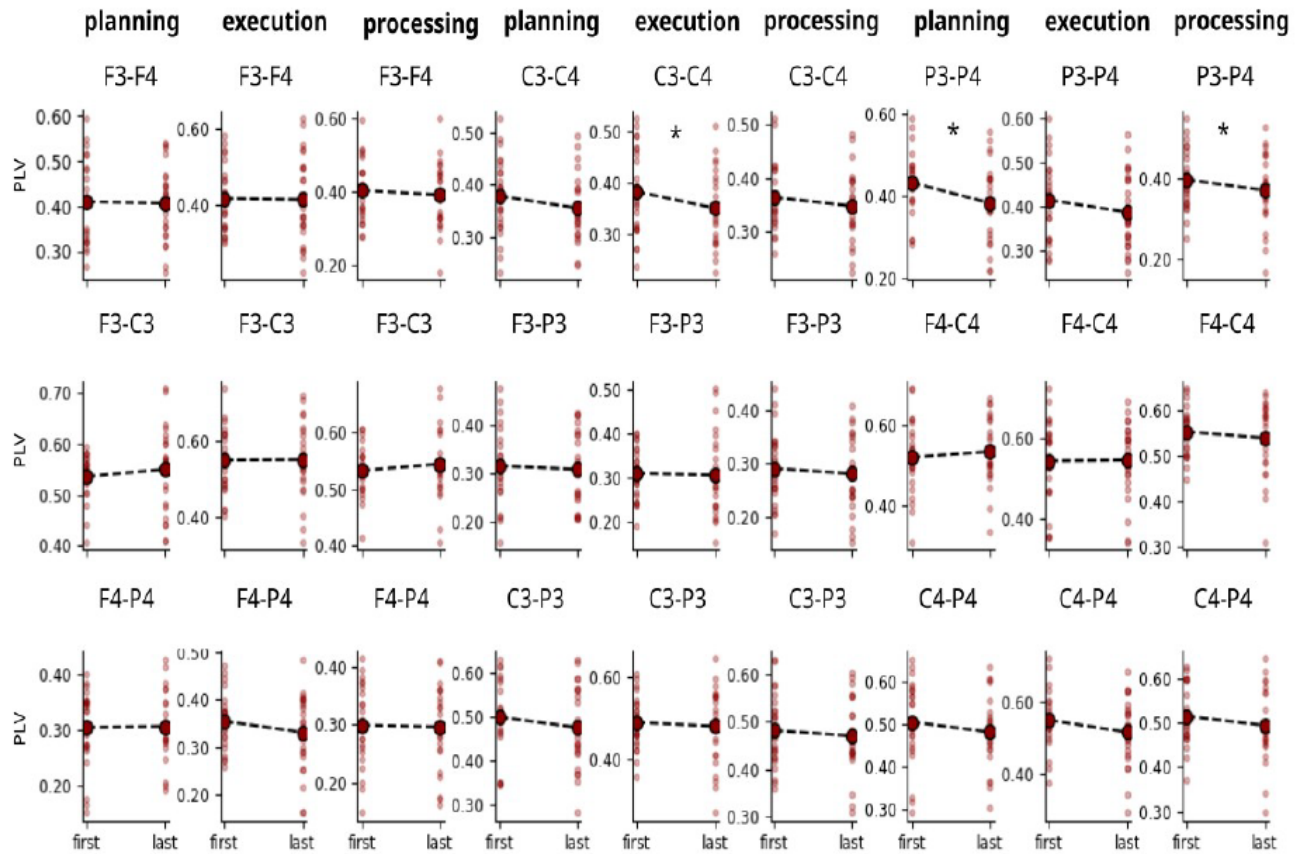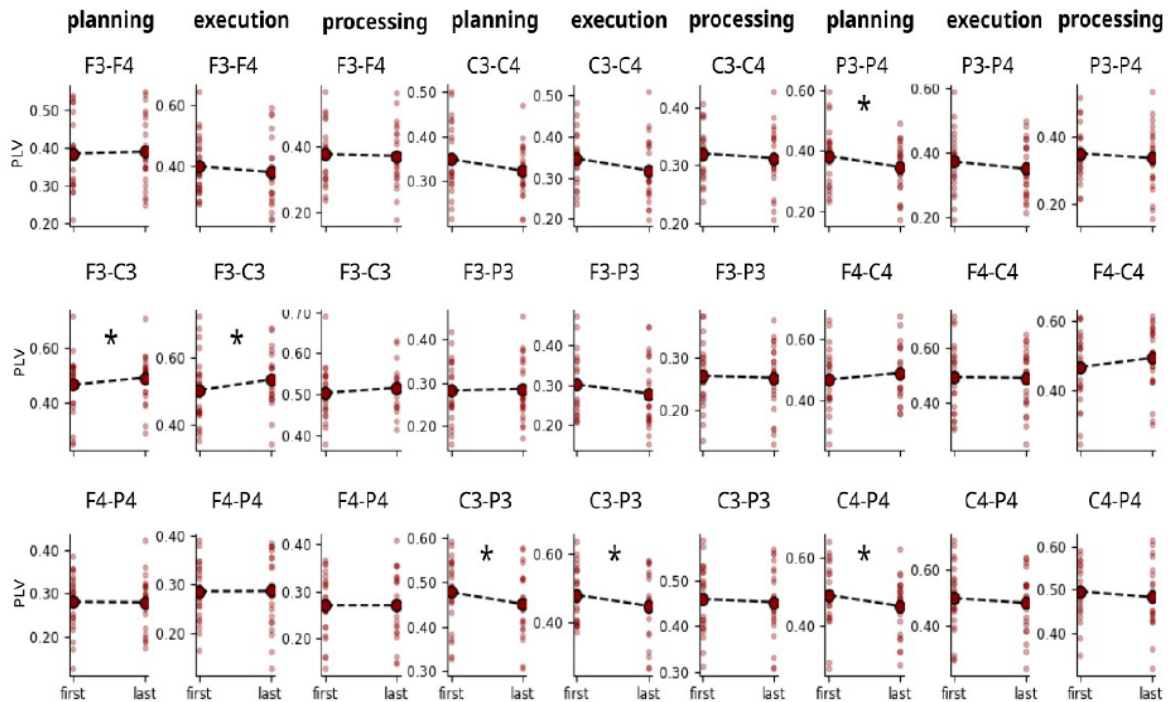
Figure 3. Alpha lower. circle = mean of blocks. dots = individual means of blocks. * = p < 0.05.

Table 1. EEG coherence in the alpha lower.

	moment	t	df	p	d		moment	t	df	p	d
	planning	0.24	23	0.80	0.04		planning	-0.8	23	0.43	0.16
F3-F4	execution	0.15	23	0.87	0.03	F4-C4	execution	-0.15	23	0.87	0.02
	processing	1.27	23	0.21	0.13		processing	0.85	23	0.4	0.19
	planning	1.84	23	0.07	0.33		planning	-0.17	23	0.86	0.02
C3-C4	execution	2.81	23	<0.01	0.41	F4-P4	execution	1.61	23	0.12	0.32
	processing	1.86	23	0.07	0.25		processing	0.52	23	0.6	0.04
	planning	3.68	23	<0.01	0.56		planning	1..77	23	0.08	0.26
P3-P4	execution	1.86	23	0.07	0.30	C3-P3	execution	0.55	23	0.58	0.11
	processing	2.91	23	<0.01	0.32		processing	1.30	23	0.20	0.14
	planning	-1.00	23	0.32	0.20		planning	1.55	23	0.13	0.25
F3-C3	execution	-0.09	23	0.92	0.01	C4-P4	execution	1.95	23	0.06	0.38
	processing	-1.12	23	0.27	0.20		processing	2.03	23	0.05	0.27
	planning	0.56	23	0.57	0.09						
F3-P3	execution	0.32	23	0.74	0.54						
	processing	1.43	23	0.16	0.14						

Alpha upper

Descriptive analyses of the first 12 trials and last 12 trials of practice are shown in Figure 4. As principal results, the analysis revealed differences between the initial and final part of practice during planning at the P3-P4, during planning and execution at the F3-C3, during planning and execution at the C3-P3, and during planning at the C4-P4 (Table 2). In the P3-P4, C3-P3, and C4- P4, the Coh decreased from initiate to end of practice. On the other hand, in the F3-C3, the Coh increase from initiate to end of practice.
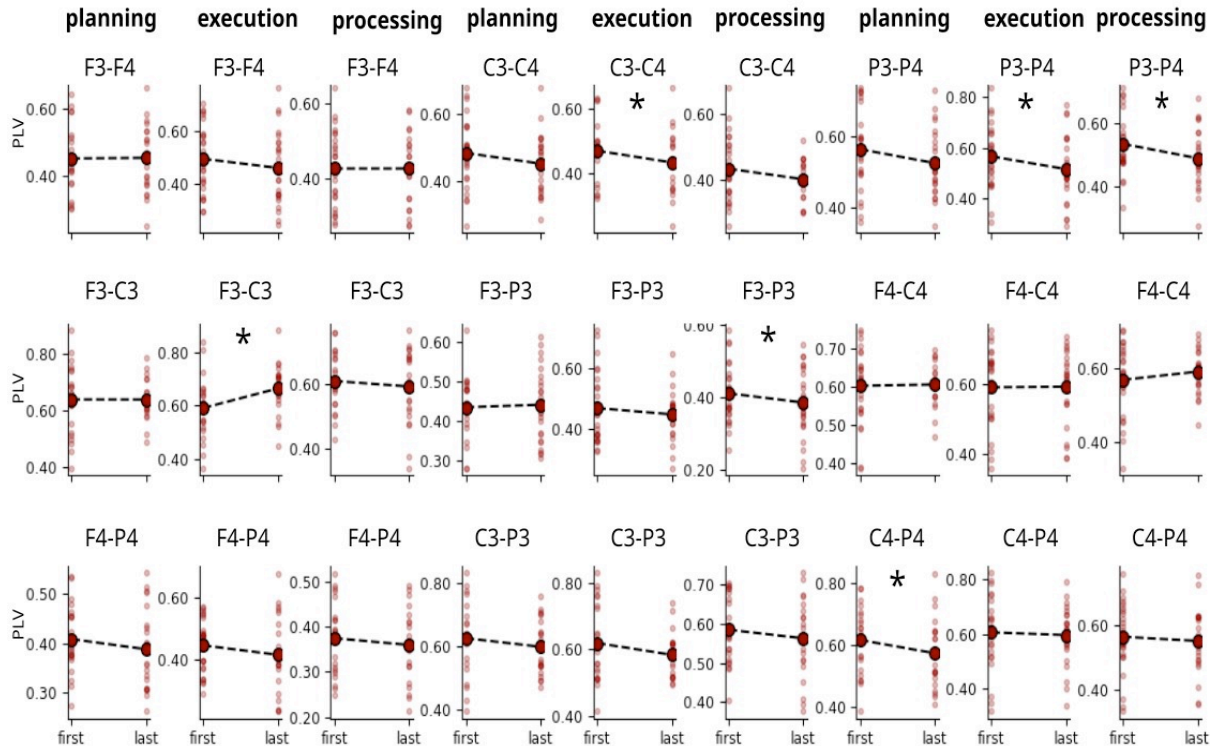

Figure 4. Alpha upper. circle = mean of blocks. dots = individual means of blocks. * = p < 0.05.

Table 2. EEG coherence in the alpha upper.

	moment	t	df	p	d		moment	t	df	p	d
F3-F4	planning	0.37	23	0.70	0.05	F4-C4	planning	-1.24	23	0.22	0.23
	execution	0.12	23	0.23	0.18		execution	0.15	23	0.87	0.02
	processing	0.63	23	0.52	0.05		processing	-1.63	23	0.11	0.26
C3-C4	planning	1.71	23	0.10	0.38	F4-P4	planning	0.11	23	0.91	0.01
	execution	1.74	23	0.09	0.42		execution	-0.03	23	0.97	<0.05
	processing	0.88	23	0.38	0.16		processing	<0.05	23	0.99	<0.05
P3-P4	planning	2.48	23	0.02	0.40	C3-P3	planning	2.33	23	0.02	0.35
	execution	1.50	23	0.14	0.26		execution	2.20	23	0.03	0.36
	processing	1.29	23	0.20	0.15		processing	0.71	23	0.48	0.09
F3-C3	planning	-2.29	23	0.03	0.26	C4-P4	planning	2.16	23	0.04	0.36
	execution	-2.15	23	0.04	0.35		execution	0.87	23	0.38	0.15
	processing	-1.49	23	0.14	0.21		processing	1.78	23	0.08	0.19
F3-P3	planning	-0.39	23	0.70	0.05						
	execution	1.98	23	0.05	0.28						
	processing	0.62	23	0.54	0.06						

Theta

Descriptive analyses of the first 12 trials and last 12 trials of practice are shown in Figure 5. As principal results, the analysis revealed differences between the initial and final part of practice during execution at the C3-C4, during execution and processing at the P3-P4, during execution at the F3-C3, during processing at the F3-P3, and during planning at the C4-P4 (Table 3). In the C3-C4, P3-P4, F3-P3, and C4-P4, the Coh decrease from initiate to end of practice. On the other hand, in the F3-C3, the Coh increase from initiate to end of practice.

Figure 5. Theta. circle = mean of blocks. dots = individual means of blocks. * = p < 0.05.

Table 3. EEG coherence in the theta.

	moment	t	df	p	d		moment	t	df	p	d
F3-F4	planning	-0.10	23	0.91	0.01	F4-C4	planning	-0.18	23	0.85	0.04
	execution	1.63	23	0.11	0.25		execution	-0.09	23	0.92	0.01
	processing	<0.01	23	0.99	<0.01		processing	-1.33	23	0.19	0.27
C3-C4	planning	1.69	23	0.10	0.32	F4-P4	planning	1.37	23	0.18	0.28
	execution	2.09	23	0.04	0.40		execution	1.78	23	0.08	0.29
	processing	1.74	23	0.09	0.39		processing	1.37	23	0.18	0.19
P3-P4	planning	1.99	23	0.05	0.36	C3-P3	planning	1.20	23	0.24	0.27
	execution	2.36	23	0.02	0.38		execution	1.62	23	0.11	0.38
	processing	3.67	23	<0.01	0.47		processing	1.98	23	0.05	0.24
F3-C3	planning	0.01	23	0.98	<0.01	C4-P4	planning	2.36	23	0.02	0.40
	execution	-2.86	23	<0.01	0.72		execution	0.48	23	0.63	0.08
	processing	1.11	23	0.27	0.17		processing	1.02	23	0.31	0.12
F3-P3	planning	-0.31	23	0.75	0.07						
	execution	0.79	23	0.43	0.20						
	processing	2.40	23	0.02	0.28						

DISCUSSION

We analyzed the role of coherence in motor practice. From the initial to the end of practice, we hypothesize that the coherence will increase in the electrode pairings more related to the motor execution and decrease among lesser related electrode pairings to the motor execution. Specifically, we expected electrode pairs related to C3 (C3-P3 and C3-F3) to exhibit increased coherence. On the other hand, electrodes less related to motor action, such as F4, C4, and P4, would decrease coherence. Overall, the results confirm the study's hypotheses. In the alpha upper and theta bands, from initiation to end of practice, the coherence increased in the F3-C3 electrode pair and decreased in the C3-C4, P3-P4, F3-P3, and C4-P4 electrodes pairs.

As expected, from initiation to end of practice, the coherence increased in the electrode pairings more related to the motor execution. Our results show, at the alpha upper and theta bands, the F3-C3 electrode pars increase the coherence from initiation to end of practice. These results corroborate the literature showing the increased coherence in the brain areas associated with the stimulus [39,40]. It is well-established that motor practice induces plastic changes in the brain [41]. Most specifically, studies have been showing that when a new motor skill is learned, there is a shift of activity from the prefrontal regions to the premotor, such as the primary motor cortex (M1) [42,43]. Unilateral movements are controlled by descending projections originating, predominantly, in the primary motor cortex of the contralateral hemisphere [20]. In the present study, the right hand was used to control movement. Thus, the C3 is equivalent to the M1 contralateral hemisphere for our motor task. It is possible to speculate that the motor learning process strengthened the connection between M1 and prefrontal areas via plasticity mechanisms [44]. The literature has indicated that phase synchronization may be related to long-term potentiation (LTP) [11]. LTP is one of the mechanisms of synaptic potentiation that produces long-lasting synaptic strengthening [45], characterized by postsynaptic neurons firing after presynaptic neurons (10-20 ms), generating the strengthening of synapses [25]. It is possible that during the motor learning process, the practice produces stimuli to induce LTP in brain areas related to movement execution [44].

Also, we expected, throughout practice, the coherence decrease in the electrode pairings less related to the motor execution. Our results show that at the alpha upper and theta bands, the C3-C4, P3-P4, F3-P3, and C4-P4 electrodes pairs decreased the coherence from initiation to end of practice. Refining neural areas is possible to explain this result [46]. One of the characteristics of skilled performance is movement efficiency; this efficiency can be described in different terms [47]. In the muscular energy cost terms, it would be characterized by the prime mover muscles (or agonist) tensioning and the absence of antagonist muscles tension [48]. In neural terms, neural efficiency can be characterized by deactivating regions associated with irrelevant information processing [46]. This notion is supported by previous studies examining power-spectral EEG [16,26,49]. It is possible to speculate that the coherence between frontal, posterior, and ipsilateral-motor areas is associated with irrelevant information processing in the motor task of study [16,46]. Thus, the practice may be led to a refinement of neural areas, decreasing the participation of brain areas less related to movement.

Finally, neural communication and plasticity may support each other. Two brain areas communicating through phase synchronization will probably induce synaptic plasticity between these areas [11]. Likewise, if connections between two brain areas have been strengthened, these regions will be more likely to communicate with each other [5]. Our results suggest that communication and plasticity mutually support each other. Namely, the increase or decrease of coherence reflects the dynamic of strengthening brain areas more related to movement and weakening less related. It is possible to speculate that during the process of motor learning, the reduction of synaptic transmission in groups of neurons not associated with the stimulus and the potentiation of synaptic transmission within groups of neurons associated with the stimulus [50].

Some results challenge the logic of the study. For example, the C3-P3 electrode pair in the upper alpha band showed increased coherence from initiation to the end of practice. Since these electrode pairs are related to motor execution, we expected an increase rather than a decrease. It is possible to speculate that the time of the feedback presentation may have impacted this result. A minimum interval of 6 seconds was provided between each trial. However, participants could have extended this interval as there was no time constraint for initiating the subsequent trial. In other words, participants could take as much time as they deem necessary to process the feedback. Parietal regions, where the P3 electrode is located, are more associated with information integration via feedback [51, 52]. It is speculated that this time interval may have been crucial in increasing the demand for cognitive feedback processing, resulting in a non-essential type of processing. Thus, similar to frontal regions, reducing communication between these two regions could be an important mechanism for refining cortical resources. However, this issue awaits further studies with specific design.

Limitations and Directions for Further Research

A possible limitation of this study was the motor task duration. In the study, the planning moment duration was around 1.5 seconds, the execution moment duration was around 0.930, and the processing moment was 6 seconds. Except for the processing moment, all moments we have had short circles of EEG signals in each trial because we used high-frequency bands (4-12 Hz) for analysis. One

problem in short circles is the edge effect of specific epochs. However, we avoid edge effects purely, first, bandpass filtering and Hilbert transforming the continuous signal, then epoch afterward (as described in the "2.6 EEG signal processing section"). Thus, we suggest that future studies use a task with more duration for each epoch. Another limitation of the study was the number of task subjects. As can be observed, there was a wide dispersion of data in the EEG measure. As indicated in the methods section, sample size calculation was performed using common parameters for behavioral data. However, it is suggested that future studies modify the parameters, taking into account this variability in the EEG measure.

CONCLUSION

The results of our study suggest that the motor learning process may be a decrease in cortico-cortical communication among brain areas associated with cognitive processes [30], also an increase in neural plasticity processes in the brain areas related to movement [3]. It is possible that neural communication and plasticity may support each other. Two brain areas communicating through phase synchronization will probably induce synaptic plasticity between these areas [11]. Likewise, if connections between two brain areas have been strengthened, these regions will be more likely to communicate with each other [5]. Thus, our results suggest that communication and plasticity mutually support each other.

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