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Full Paper

Time-varying Brain Potentials and Interhemispheric Coherences of Anterior and Posterior Regions during Repetitive Unimanual Finger Movements

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Abstract: Previous brain electrophysiological research has studied the interregional connectivity during the tapping task and found that inter-hemispheric alpha coherence was more significant under bimanual task conditions than that under unilateral conditions, but the interregional connectivity situation in the unilateral tapping condition was not explored clearly. We have designed a unilateral repetitive finger-tapping task to delineate the anterior and posterior cortex contributions to unilateral finger movement. Sixteen right handed college students participated in this study. Event related potentials (ERPs) and the strength of event related coherence (ERCoh) were analyzed to examine the antero-postero dominance of cortical activity in the phase of early visual process (75-120ms), pre-execution (175-260ms), execution (310-420ms) and post-execution (420-620ms). Results showed that the occipital (Oz, O1 and O2), frontal (Fz, F3, and F4), fronto-central (Fz, Cz, F3 and C3), and parietal regions were the most pronounced in the early visual, pre-execution, execution, and post-execution phases, respectively. Moreover, among four inter-hemispheric pairs only the Coh (C3 and C4) was significantly correlated to reaction time (RT) of tapping in the execution phase. In conclusion, the aforementioned variability of electrophysiological data (ERPs and coherence) and the change of antero-postero regional dominance with time reflect the relative importance of different mechanisms in different phases. The mechanisms of visual processing, motor planning, motor execution and feedback reward were operational, respectively.

Keywords: Lateralization, event-related potential, cortical connectivity, unilateral movement

1. Introduction

Previous electrophysiological brain research has studied the interregional connectivity during the tapping task and found that the inter-hemispheric interaction was more significant in the bimanual task condition than that of unilateral tasks [1-5]. Knyazeva *et al.* [2] found that the inter-hemispheric alpha coherence of C3-C4 and P3-P4 in 7-8 year-old children increased while conducting bimanual rhythmic tasks. Both coherence values were negatively correlated with the time difference between the left and right hand intertap intervals. Knyazeva *et al.* [1] further found the inter-hemispheric coherence of acallosal children were shown to be smaller comparing with those of normal children in frontal, central and parietal pairs in both right-hand tapping and bimanual tapping. Rissman *et al.* [4] used the general linear model to survey the inter-regional interaction. They compared their data with the previous findings of EEG and fMRI studies and further concluded that greater bimanual coordination induced stronger connectivity between motor regions of left and right hemisphere.

Similar to the effect of bimanual finger task on brain mechanism, sequential finger movements can also result in more bilateral activation of sensorimotor areas than single-step movements. Many researchers have mentioned that the greater intercommunication between bilateral and mesial central and prefrontal regions could be enhanced by sequential finger movements [3,4,6,7] .

Different from the aforementioned studies, the reported study explored the brain mechanism during execution of unilateral finger movements. Although we know sequential and bimanual finger movements might result in bilateral activation, the mechanism of unilateral finger movement has not been explored clearly. The coherence and synchronization in alpha band have been studied often while surveying the effect of unilateral finger movement on brain mechanisms. Stancak *et al.* [5] found a coherence between the left and right S1/M1 areas after movement onset in the lower alpha band (7.8-9.8 Hz) correlated with the size of the callosal body in both unilateral and bilateral movement in normal right handed adults. Pfurtscheller *et al.* [8] conducted en experiment to justify the maximal event related desynchronization happening in the 10-12 Hz band close to C3 and C4 electrodes during voluntary finger movement. Sailer and coworkers [9] found a pronounced bilateral activation of sensorimotor regions for the alpha band in the elderly while executing a simple finger task. Interestingly, Andrew and Pfurtscheller [10] found the relationship of intrinsic mu rhythm between sensorimotor (mu rhythm) and supplementary motor was more desynchronized during the unilateral finger movement than the resting state.

Besides these coherence and synchronization studies, other studies of the alpha band have also been conducted. For example, the ratio of alpha and tapping frequencies was close to 2:1 during the tapping movement in most habitual smokers [11]. Moreover, Deiber and colleagues [12] found the 7.8-9.8 Hz task related power of EEG for right tapping movement was more prominent than comparing with those for left and bimanual movements; therefore, the sensitivity of lower alpha band to task difficulty was inferred.

Moreover, the aforementioned studies neglected the tapping effect on activities in the occipital region. The occipital region was not the main area of interest in studies related to the brain mechanism of finger tapping, but in fact, the occipital region might occupy an important role during finger movement [1,13,14]. The occipital activation was pronounced while conducting precise movements [13]. Van der Lubbe *et al*. [14] suggested that the occipital component reflected the process of direction code and the following parietal-temporal component reflect a link between visual perception to action. Furthermore, while observing complex or simple movements the occipital regions were obviously activated [15,16]. Therefore, we inferred if the goal directed movements guided by visual information would activate the occipital regions. This present study will also substantiate this important issue. In this study we only focused on the issue of unilateral and simple finger movement. All the participants conducted one-step and unilateral tapping task without bimanual and sequential characteristics.

2. Methods

2.1. Participants

Sixteen right handed college students (2 males and 14 females) aged 19 to 24 (mean= 20.19, SD=1.38) without any neuromuscular or cerebral disease voluntarily participated in the present study. The averaged handedness quotient of self reported Edinburgh handedness inventory [17] was 95.56 (±8.19). The averaged eyedness quotient of five tasks was 76.25%. The tasks included (1) to look through a small opening formed by crossed index fingers and thumbs of both hands (Miles test); (2) to look through a kaleidoscope; (3) to look through a hole in a card (Dolman method); (4) to cover one eye with one hand; and (5) to close one eye. Item 4 and 5 were decided by us and item 1, 2 and 3 were cited from related articles [18,19].

2.2. Variables

We took the individual finger (the index, middle, or 4th finger) which is used to press a computer key as an independent variable. Dependent variables included the reaction time (the period between seeing the number and the action of pressing the corresponding key) and the mean amplitude of event related potentials at four anterior-posterior electrodes over midline, left and right scalp locations in early visual, pre-execution, execution, and post-execution phases. Besides, the brain coherence strength (value from 0 to 1) between electrodes F3 and F4 [Coh(F3, F4)], C3 and C4 [Coh(C3, C4)], P3 and P4 [Coh(P3, P4)], as well as O1 and O2 [Coh(O1, O2)] in the alpha band (8-12 Hz) was treated as the indication of inter-hemispheric integration.

2.3. Experimental Design

Participants were presented with the three Arabic numerals 2, 3, and 4. Their responsibility was to look at the center of the screen and respond to these stimuli by pressing the corresponding keys on the keyboard with their index, middle and 4^{th} finger respectively [20,21]. There were 600 attempts in total, and the inter-stimulus interval was set as 2000 ms. Therefore, it took 20 minutes to complete the task (please see Figure 1). Their EEGs and reaction times were recorded during the process for later analyses.

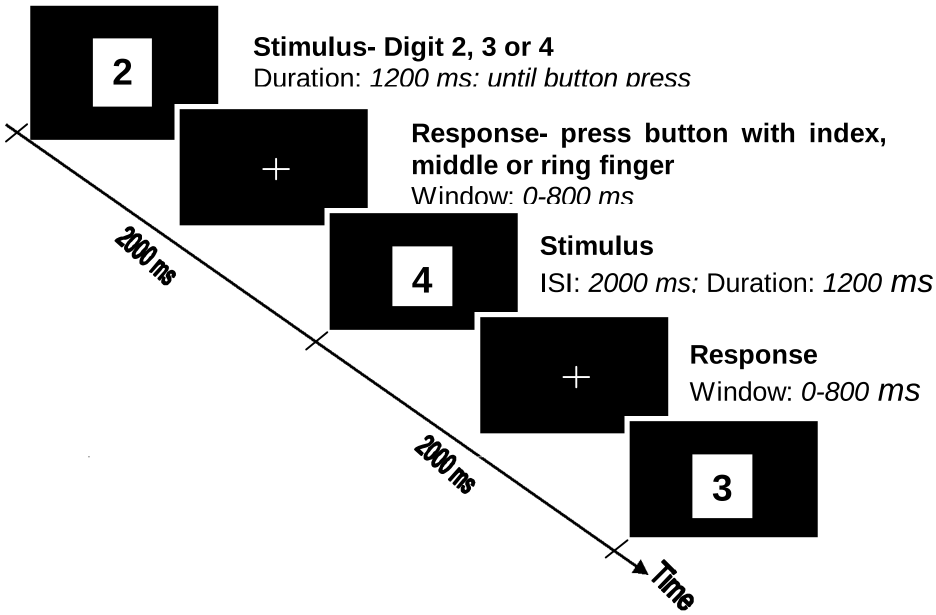
2.4. Stimulus presentation and key pressing performance

The timing of the stimulus presentation was controlled and subject responses (accuracy and reaction time) were recorded using Stim II Software (Neuroscan, Inc. Sterling, VA, USA). The stimuli included the Arabic numerals 2, 3, and 4.

2.5. Experimental Procedure

Each participant was required to respond by pressing the specified keys on the keyboard with their right-hand fingers. When the number 2 appeared on the screen, the participants pressed the corresponding key with their index finger as soon as possible. Likewise, participants pressed the corresponding keys using their middle or 4th fingers if they saw the numbers 3 or 4, respectively [20,21]. There were 200 attempts each of these three conditions, and the order of these 600 attempts was totally randomized (Figure 1).

Figure 1. Experimental procedure. Digits 2, 3 or 4 were presented on the center of screen until a button press or automatically disappeared after 1200 ms. Subjects were required to respond by pressing a key with their right-hand index finger when "2" appears, the middle finger when "3" appears, and the ring finger when "4" appears. 2000 ms from the last stimulus, a new stimulus comes up. The order of 600 attempts was totally randomized.

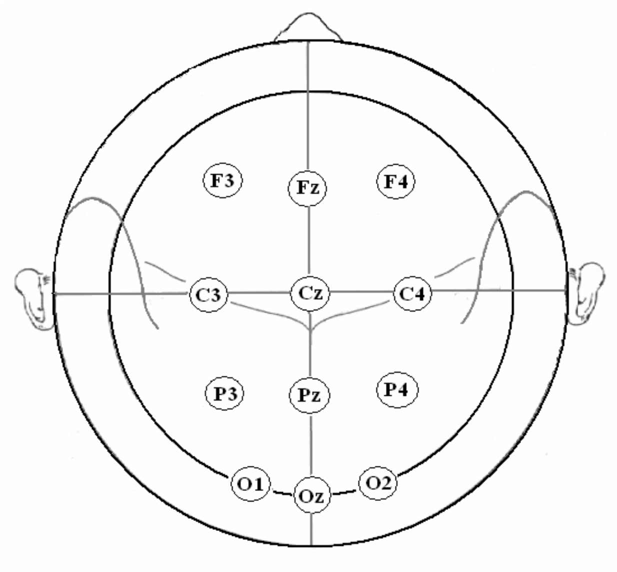


2.6. Electroencephalogram (EEG) acquisition and ERP recording

EEGs were recorded from 17 Sintered electrodes (Fz, FCz, Cz, Pz, Oz, F4, FC4, C4, P4, O2, F3, FC3, C3, P3, O1, Heog, and Veog; 12 of them were of interest in this study as shown in Figure 2) attached according to the standard 10-20 system, using a Brain-Amp-MR amplifier (Brain Products

GmbH) and the software Brain Vision Recorder Version 1.01 (Brain Products GmbH). All electrode impedances were brought to below 10 kΩ. The EEG was band pass filtered (1-30 Hz) and digitized at a sampling rate of 1000 samples/s. The baseline for ERP measurements was the mean voltage of a 100ms pre-stimulus interval. Attempts exceeding ± 100μV at horizontal and vertical electro-oculogram (EOG) were excluded immediately. Furthermore, attempts with eye blinks, eye movement deflections, and over ± 60μV at any electrode were also excluded from ERP averages.

Figure 2. Electrode positions of interest.



2.7. Calculating the coherences

According to the Brain Vision Analyzer User Manual Version 1.04 [22], the correlation/autocorrelation was the coherence method obtained in the frequency domain. The formulas are described as follows. "*The first method calculates the coherence using the following formula. In the second formula, totaling is carried out via the segment number i. Formation of the average also relates to segments with a fixed frequency f and a fixed channel c*".

$$\mathrm{Coh}(c1, c2)(f)=|\mathrm{Cov}(c1, c2)(f)|^2 / (|\mathrm{Cov}(c1,c1)(f)|\ |\mathrm{Cov}(c2,c2)(f)|),$$

in conjunction with

$$\mathrm{Cov}(c1,c2)(f)=\Sigma(c1,i(f))-\mathrm{avg}(c1(f)))\ (c2,i(f)-\mathrm{avg}(c2(f)))$$

The aforementioned words appeared in Italics and the formulas were all adapted from the cited reference [22].

2.8. Statistics

One-way repeated measure ANOVAs were used to compare the differences of event related potentials among anterior-posterior electrodes over midline scalp locations (Fz, Cz, Pz, and Oz), right hemispheric locations (F4, C4, P4, and O2) and left hemispheric locations (F3, C3, P3, and O1) in four different phases (early visual, pre-execution, execution, and post-execution). The coherence strengths in alpha band among inter-hemispheric pairs (F3-F4, C3-C4, P3-P4, and O1-O2) were also compared by one-way repeated measure ANOVAs. The Greenhouse-Geisser correction was applied where appropriate to correct for violations of sphericity [23]. After the difference reaching the significant level ($p < .05$), the least significant difference (LSD) post hoc test was used to compare between electrodes or between coherence pairs. LSD is an adjustment equivalent to no adjustment for multiple comparisons after the result of repeated ANOVA reaching the significant level. Furthermore, *Spearman's r* correlations were conducted between the reaction time and the inter-hemispheric coherence of combinations of channels in four phases. The nonparametric *Spearman's r* was used because of the lack of normal distribution in reaction time and coherence strength within the 16 subjects.

3. Results

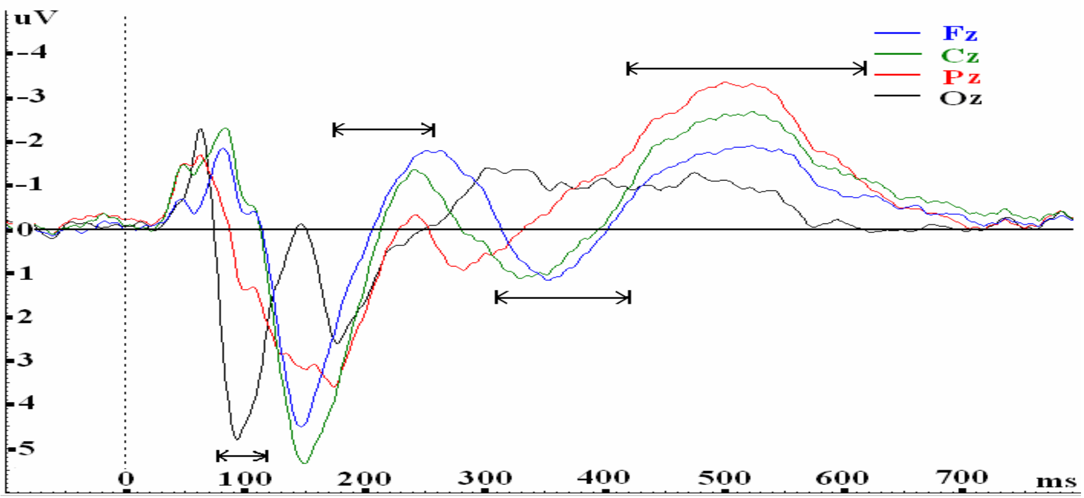
3.1. Behavioral results

The mean accuracy of all 12 subjects was 97.03%. The mean reaction time of correct responses ranged from 412.27 ms to 599.69 ms (mean=476.91, SD=48.69).

3.2. Event related potentials

The ERPs were reported according to the order of four sequential time windows including early visual phase (75-120 ms), pre-execution phase (175-260 ms), execution phase (310-420 ms) and post-execution phase (420-620 ms). All those four phases demonstrated obvious and meaningful waveforms (Figure 3).

Figure 3. Averaged ERP curves of 16 subjects recorded from the mid-line electrodes.



3.2.1. Over midline scalp locations

In the early visual phase (P75-120), the strongest mean amplitude was found at Oz (see Figure 3). The one-way repeated-measures ANOVA revealed a statistically significant difference existed among Fz, Cz, Pz, and Oz (F (1.246, 18.695) = 23.376, p = 0.000) (Table 1). The LSD post hoc test (Table 2) revealed that the mean amplitude of Oz was significantly higher than that of the Pz (mean difference = 2.673, p = 0.001), Cz (mean difference = 4.474, p = 0.000), and Fz (mean difference = 4.232, p = 0.000). Furthermore, the mean amplitude of Pz was significantly higher than that of Cz (mean difference = 1.801, p = 0.000) and Fz (mean difference = 1.559, p = 0.001). Conversely, there was no significant difference between Cz and Fz (mean difference = -0.243, p = 0.202).

In the pre-execution phase (N175-260), Fz was the most pronounced amplitude (see Figure 3). The one-way repeated-measure ANOVA revealed a statistically significant difference existed among Fz, Cz, Pz, and Oz (F (1.634, 24.513) = 6.833, p = 0.007) (Table 1). The LSD post hoc test (Table 2) revealed that the mean amplitude of Pz was not significantly different from that of Oz (mean difference = 0.417, p = 0.250). However, it was significantly more pronunced than the mean amplitude of Cz (mean difference = 0.819, p = 0.005) and Fz (mean difference = 1.643, p = 0.001). Furthermore, the mean amplitude of Fz was more pronounced than that of Oz (mean difference = -1.226, p = 0.034) and that of Cz (mean difference = -0.823, p = 0.001). Nevertheless, the mean amplitude of Oz was not significantly different from that of Cz (mean difference = 0.402, p = 0.403).

In the execution phase (P310-420), the mean amplitudes of Cz and Fz were the stronger (see Figure 3). The one-way repeated-measure ANOVA revealed a statistically significant difference existed among Fz, Cz, Pz, and Oz (F (1.991, 29.860) = 11.496, p = 0.000) (Table 1). The LSD post hoc test (Table 2) revealed that the mean amplitude did not show significant differences between Cz and Fz (mean difference = -0.024, p = 0.925), and between Oz and Pz (mean difference = -0.473, p = 0.138). Moreover, the mean amplitude of Fz was larger than that of Oz (mean difference = 1.612, p = 0.002) and Pz (mean difference = 1.139, p = 0.014). The mean amplitude of Cz was larger than that of Oz (mean difference = 1.588, p = 0.000) and Pz (mean difference = 1.116, p = 0.000).

In the post-execution phase (N420-620), the mean amplitude of Pz was the strongest (see Figure 3) among the four electrodes. The one-way repeated-measures ANOVA revealed a statistically significant difference existed among Fz, Cz, Pz, and Oz (F (1.522, 22.837) = 15.670, p = 0.000) (Table 1). The LSD post hoc test (Table 2) revealed that the mean amplitude of Pz was significant pronounced than that of Oz (mean difference = -1.790, p = 0.000) and Fz (mean difference = -1.113, p = 0.003). Moreover, the mean amplitude of Cz was more pronounced than that of Oz (mean difference = -1.276, p = 0.001). There was no significant difference between Oz and Fz (mean difference = 0.676, p = 0.096). However, the mean amplitudes demonstrated significant differences between Pz and Cz (mean difference = -0.514, p = 0.032) and between Fz and Cz (mean difference = 0.600, p = 0.001).

Table 1. The one-way repeated measures ANOVAs were used to compare the mean amplitudes among anterior-posterior electrodes in different phases over midline, left and right scalp locations.

	Early visual	Pre-execution	Execution	Post-execution
Mid-line				
Fz	-0.791	-0.654	0.487	-1.410
Cz	-1.033	0.169	0.464	-2.010
Pz	0.768	0.989	-0.652	-2.523
Oz	3.441	0.571	-1.124	-0.734
F-value	F(1.246, 18.695) = 23.376; p=.000	F(1.634, 24.513) = 6.833; p=.007	F(1.991, 29.860) = 11.496; p=.000	F(1.522, 22.837) = 15.670; p=.000
Left				
F3	-0.174	-0.485	0.375	-1.129
C3	-0.460	0.459	0.562	-1.805
P3	1.467	1.741	-0.061	-2.203
O1	3.090	1.161	-1.004	-0.907
F-value	F(1.269, 19.035) = 16.094; p=.000	F(1.461, 21.910) = 19.628; p=.000	F(1.636,24.534) = 8.637; p=.002	F(1.608, 24.124) = 13.453; p=.000
Right				
F4	-0.147	-0.424	-0.112	-1.243
C4	-0.433	1.163	-0.200	-2.104
P4	1.436	2.063	-1.165	-2.129
O2	3.687	1.284	-1.669	-0.975
F-value	F(1.113, 16.700) = 16.896; p=.001	F(1.919, 28.781) = 18.599; p=.000	F(1.840, 27.594) = 7.127; p=.004	F(1.414, 21.210) = 13.543; p=.001

Table 2. LSD post-hoc tests to compare the differences of mean amplitudes between the pairs of electrodes on the midline during the four phases.

	Early visual		Pre-execution		Execution		Post-execution	
	Mean Difference	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*
Oz vs. Pz	2.673**	.001	-0.417	.250	-0.473	.138	1.790***	.000
Oz vs. Cz	4.474***	.000	0.402	.403	-1.588***	.000	1.276**	.001
Oz vs. Fz	4.232***	.000	1.226*	.034	-1.612**	.002	0.676	.096
Pz vs. Cz	1.801***	.000	0.819**	.005	-1.116***	.000	-0.514*	.032
Pz vs. Fz	1.559**	.001	1.643**	.001	-1.139*	.014	-1.113**	.003
Cz vs. Fz	-0.243	.202	0.823**	.001	-0.024	.925	-0.600**	.001

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

3.2.2. Over left and right hemispheric locations

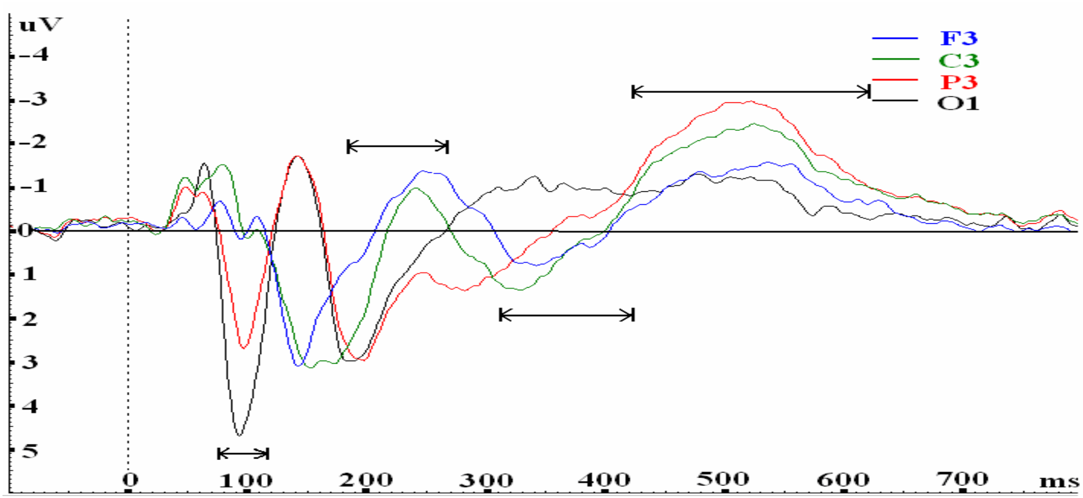
The most significant or non-significant findings of the anterior-posterior comparisons at left and right hemispheric electrodes were similar to those of midline electrodes. Both of the left and the right scalp locations had only two findings which were different from those of midline scalp locations. At the left hemispheric electrodes, the mean amplitude of O1 was more pronounced than that of P3 (mean difference = -0.580, p = 0.028) in the pre-execution phase (N175-260) and the P3 was greater than the O1 (mean difference = 0.942, p = 0.002) in the execution phase (Table 3 and Figure 4).

Table 3. LSD post-hoc tests to compare the differences of mean amplitudes between the pairs of electrodes in the left hemisphere during the four phases.

	Early visual		**Pre-execution**		**Execution**		**Post-execution**	
	Mean Difference	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*
O1 vs. P3	1.623*	.021	-0.580*	.028	-0.942**	.002	1.296***	.000
O1 vs. C3	3.550**	.001	0.702	.114	-1.566**	.001	0.898**	.005
O1 vs. F3	3.265**	.001	1.646**	.001	-1.379*	.011	0.222	.485
P3 vs. C3	1.927***	.000	1.282***	.000	-0.623*	.014	-0.398*	.042
P3 vs. F3	1.641***	.000	2.226***	.000	-0.437	.231	-1.074**	.001
C3 vs. F3	-0.285	.147	0.944***	.000	0.187	.453	-0.676***	.000

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Figure 4. Averaged ERP curves of 16 subjects recorded from the left-hemisphere electrodes.



3.2.3. Over right hemispheric locations

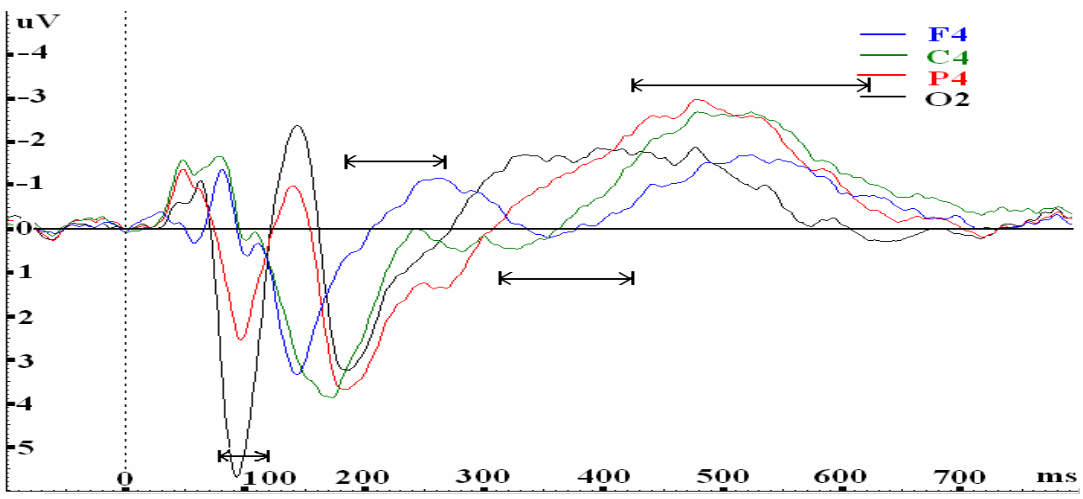
At the right electrodes, the mean amplitude of O2 was more pronounced than that of P4 (mean difference = -0.779, p = 0.011) in the pre-execution phase (N175-260) and the P4 was not significantly different from the C4 (mean difference = -0.026, p = 0.873) in the post-execution phase (Table 4 and Figure 5).

Table 4. LSD post-hoc tests to compare the differences of mean amplitudes between the pairs of electrodes in the right hemisphere during the four phases.

	Early visual		**Pre-execution**		**Execution**		**Post-execution**	
	Mean Difference	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*
O2 vs. P4	2.251**	.004	-0.779*	.011	-.504	.111	1.155***	.000
O2 vs. C4	4.120***	.000	0.121	.752	-1.469**	.003	1.129***	.000
O2 vs. F4	3.835**	.001	1.708**	.002	-1.556*	.013	0.268	.431
P4 vs. C4	1.870***	.000	0.900**	.002	-.965**	.002	-0.026	.873
P4 vs. F4	1.584**	.001	2.488***	.000	-1.053*	.038	-0.887**	.004
C4 vs. F4	-0.286	.170	1.587***	.000	-.088	.802	-0.861***	.000

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Figure 5. Averaged ERP curves of 16 subjects recorded from the right hemisphere electrodes.



3.3. A comparison of coherence strength between inter-hemispheric pairs

The strength values of all coherence pairs are listed in Appendix 1. The four inter-hemispheric coherence pairs (O1-O2, P3-P4, C3-C4, and F3-F4) in four phases were compared by one-way repeated measure ANOVAs (Table 5) and *post hoc* comparisons (Table 6).

Table 5. The one-way repeated measure ANOVAs applied to compare the coherence strength among inter-hemispheric pairs during the different phases.

	Early visual	**Pre-execution**	**Execution**	**Post-execution**
Coh(F3, F4)	.102	.163	.175	.105
Coh(C3, C4)	.223	.342	.319	.275
Coh(P3, P4)	.229	.319	.303	.272
Coh(O1,O2)	.243	.258	.249	.230
F-value	F(1.818,27.274) =5.553; p=.011	F(1.816,27.243) =5.167; p=.015	F(2.133,31.991) =3.362; p=.044	F(1.461,20.459) =5.689; p=.017

Table 6. LSD *post-hoc* tests applied to compare the difference of coherence strength between anterior posterior inter-hemispheric electrode pairs.

	Early visual		Pre-execution		Execution		Post-execution	
	Mean Difference	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*	*Mean Difference*	*p*
O1-O2 vs. P3-P4	.014	.784	-.061	.174	-.053	.304	-.042	.382
O1-O2 vs. C3-C4	.020	.697	-.084	.193	-.070	.254	-.046	.434
O1-O2 vs. F3-F4	.141**	.008	.095	.188	.075	.270	.125	.101
P3-P4 vs. C3-C4	.005	.836	-.023	.502	-.016	.606	-.003	.913
P3-P4 vs. F3-F4	.127***	.000	.156**	.002	.129**	.004	.167***	.000
C3-C4 vs. F3-F4	.121**	.001	.179**	.001	.145*	.012	.170***	.000

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

3.3.1. Early visual phase

The one-way repeated-measure ANOVA revealed a statistically significant difference existed among four pairs ($F(1.818,27.274)=5.553$, $p = 0.011$) (Table 5). The coherence of F3-F4 was the smallest. The LSD post hoc test (Table 6) revealed that the coherence of F3-F4 was significantly smaller than that of O1-O2 (mean difference = -0.141, $p = 0.008$), P3-P4 (mean difference = -0.127, $p = 0.000$), and C3-C4 (mean difference = -0.121, $p = 0.001$). Conversely, there was no significant difference among other pair comparisons.

3.3.2. Pre-execution, execution, and post-execution phases

The one-way repeated-measure ANOVA (Table 5) revealed a statistically significant difference existed among four pairs in the pre-execution ($F (1.816,27.243) = 5.167$, $p = 0.015$), execution ($F(2.133,31.991) = 3.362$, $p = 0.044$), and post-execution ($F(1.461,20.459) = 5.689$, $p = 0.017$) phases, respectively. The LSD post hoc test (Table 6) revealed the same statistical result in those three phases, which is the coherence of F3-F4 was significantly smaller than that of P3-P4 and C3-C4 and there was no significant difference among other pair comparisons. The detailed results were shown in Table 6.

Table 7. *Spearman's r* correlations between reaction time and the inter-hemispheric coherence of combinations of channels in four phases. Only the pair of C3-C4 in the execution phase significantly correlated to reaction time (highlighted in bold).

Coherence pairs	**Early visual**		**Pre-execution**		**Execution**		**Post-execution**	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Coh(F3, F4)	-.115	.672	-.306	.249	-.047	.863	.021	.940
Coh(C3,C4)	-.418	.107	-.306	.249	**-.585***	**.017**	-.300	.259
Coh(P3, P4)	-.429	.097	-.376	.151	-.444	.085	-.300	.259
Coh(O1, O2)	-.088	.745	-.082	.762	-.432	.094	-.156	.564

Note. * $p < .05$

3.4. The correlation coefficients between RT and inter-hemispheric coherence pairs

Only the coherence strength of C3-C4 in the execution phase was negatively correlated to the reaction time (*Spearman's r* = -.585, *p* = 0.017). The coherence of other combinations of inter-hemispheric channels (O1-O2, P3-P4, and F3-F4) in any phase did not show any statistically significant relationship with reaction time (Table 7). Although the present study focused on the comparison of inter-hemispheric pairs, the detailed *Spearman's r* and *p* values of the relationship between reaction time and all combinations of channels were still listed in Appendix 2. Besides the aforementioned significant findings, the Coh(O1, P3) and Coh(O1, P4) in the early visual phase, Coh(C3, O1) in the pre-execution phase and Coh(C3, P3) in the execution phase were also negatively correlated with RT respectively (Appendix 2 & Figure 6).

4. Discussion and Conclusions

The findings of this study supported that even the simple unimanual movement is worked with the interactions of spatial and temporal aspects in the brain (Tables 1-4 and Figures 3-5). While considering the ERPs findings, we found the occipital regions activated dominantly in the early visual phase. After that, the frontal regions activated to plan the movement initiation and the ongoing process. Thirdly, the central and frontal regions worked together to execute the movement. Finally, the parietal regions were activated to give internal feedback for improving the performance the next time (also see Appendix 3). The similar findings and statements were also delineated by some researchers recently [4,24]. The major features of the brain potential signals were summarized in Table 8.

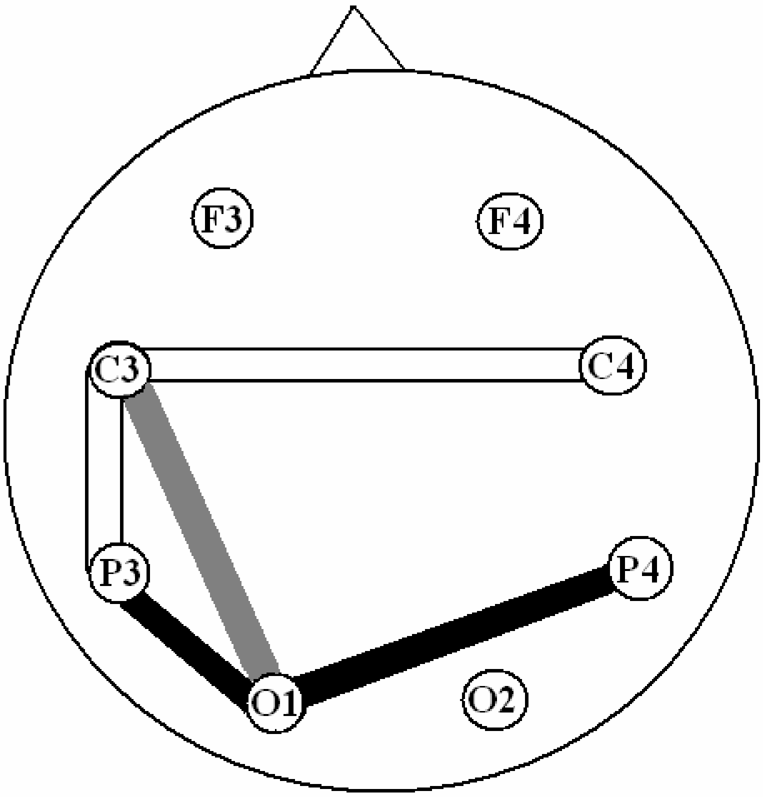
Table 8. Summarized major localized features of the brain potential signals.

Potentials & Coherences	Early visual			Pre-execution			Execution			Post-execution		
	L	M	R	L	M	R	L	M	R	L	M	R
P75-120	O1	Oz	O2									
N175-260				F3	Fz	F4						
P310-420							C3	Fz, Cz	F4, C4			
N420-620										P3	Pz	P4 , C4

Note. 1. L = left hemisphere electrodes (O1, P3, C3, F3), M = electrodes on midline location (Oz, Pz, Cz, Fz), R = right hemisphere electrodes(O2, P4, C4, F4).
2. The strongest electrode(s) in each phase were listed in the table according to the results of post hoc LSD statistics (also see Table 2, 3, 4, 6).

Few studies have substantiated the contributions of occipital regions to explain the brain mechanism of tapping movements, partly because their experimental tapping tasks lacked the visual characteristics [1,3-5]. In fact, the occipital-parietal regions can be activated during the observation of simple finger movements [15,16]. Therefore, it is reasonable to hypothesize that the occipital regions will activate while executing the task with both of visual and motor components. Consequently, in the present study, the occipital activation was obvious especially in the early phase.

Figure 6. Pairs of EEG electrodes where their coherences in the alpha band demonstrated significant correlations with reaction times (RT). Lines in *black* present the condition in the 'early visual phase'; the line in *grey* presents the condition in the 'pre-execution phase'; lines in *white* are in the condition of 'execution phase'. As there is no significant correlations found in the 'post-execution phase', there is no line for that phase. In this present study, only the inter-hemispheric pairs (O1-O2, P3-P4, C3-C4 and F3-F4) were discussed. The results demonstrated only the coherence strength of C3-C4 in the execution phase was negatively correlated to RT.



That the frontal regions are working dominantly in the pre-execution phase is also reasonable. Many studies found and mentioned the role of frontal areas during the movement planning process. The timing of pronounced frontal areas was compatible with those findings since movement planning mainly occurred in the stage after the visual processing and before the movement execution.

Pollok *at al.* [25] thought the coupling at 8-12Hz (alpha) in a cerebello-thalamic-cortical network reflects one possible mechanism of the motor system during the execution of simple motor tasks. The present study also explored brain issue in the alpha band and found the coherence of inter-hemispheric pairs in alpha band is a sensitive index that can be used to delineate the differences among different electrodes pairs. Besides, the negatively significant relationship between Coh(C3, C4) and RT found in this study is theoretically reasonable. Therefore, combining these results with other studies (e.g. [11,12]) to explore connectivity issues in alpha band is appropriate.

Kristeva *et al.* [26] studied a completely deafferented patient. The movement-evoked potential of this patient could not be observed during simple self-paced index finger flexion with or without visual feedback although the patient's motor behavioral performance was not worse than the controls that was being clear movement-evoked potential. The authors inferred this patient switched his learning strategy from a sensory feedback-driven to a feed-forward mode so that he can compete with the controls. In the experiment of this present study, the movements were guided by visual numbers and the participants were all with intact sensory. Therefore, we can figure out the participants might mainly use the feedback strategy to conduct the unimanual movement so that the movement related potentials were obvious in this present study (Figures 3, 4, and 5). Not surprisingly, in the final post-execution phase, the pronounced negative potentials observed in the parietal regions (Pz, P3, and P4). This also strongly suggests that the feedback mechanism might be run after the movement (execution phase) was conducted.

Obviously, the early positive peaks of Oz, O1 and O2 showed larger and occurred earlier than those of the electrodes in other regions (Figures 3, 4 and 5). Therefore, it is also interesting to further know the coherences during the time lags. We set the time interval of the lags from 100 ms to 150 ms (between the early visual and pre-execution phase). The one-way repeated-measure ANOVA revealed a statistically significant difference among four pairs in this time interval ($F(3, 45) = 4.951$, $p = 0.005$). The LSD post hoc test (Table 8) showed the coherence of O1-O2 (0.270) was significantly larger than that of C3-C4 (0.204) and F3-F4 (0.130) and the coherences of P3-P4 (0.222) and C3-C4 were respectively significantly larger than that of F3-F4. There was no significant difference between the pair of O1-O2 and P3-P4 and between the pair of P3-P4 and C3-C4. Similar to the early visual phase, the Coh (O1, O2) pair was the strongest. However, the Coh (O1, O2) pair did not show differences when compared with the pair Coh (P3, P4). This means that the inter-hemispheric connection activates in the occipitoparietal region before the pre-execution phase. After the pre-execution phase is initiated, the inter-hemispheric connection in the centroparietal region will be dominant (Table 5).

Table 9. LSD post-hoc tests applied to compare the difference of coherence strength between anterior posterior inter-hemispheric electrode pairs from.

To compare the coherence pairs	*Mean Difference*	*p*	To compare the coherence pairs	*Mean Difference*	*p*
O1-O2 vs. P3-P4	.048	.243	P3-P4 vs. C3-C4	.018	.554
O1-O2 vs. C3-C4	.066*	.039	P3-P4 vs. F3-F4	.092**	.008
O1-O2 vs. F3-F4	.141*	.010	C3-C4 vs. F3-F4	.074*	.043

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

In conclusion, the occipital regions functionally work in the early process of visually guided tapping movement. The frontal, central and parietal regions are also responsible for motor planning (pre-execution), motor execution, and action monitoring respectively. The brain potentials and inter-hemispheric coherences of anterior and posterior regions vary with times during visually guided unimanual movements.

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Appendix 1. Coherence values of all electrode pairs in four phases.

Coherence pairs	Early visual	Pre-execution	Execution	Post-execution
Coh(F3, F4)	.102	.163	.175	.105
Coh(F3, C3)	.177	.270	.252	.126
Coh(F3, C4)	.104	.192	.195	.110
Coh(F3, P3)	.100	.163	.161	.083
Coh(F3, P4)	.086	.170	.143	.073
Coh(F3, O1)	.021	.055	.051	.030
Coh(F3, O2)	.027	.062	.076	.036
Coh(F4, C3)	.126	.158	.142	.095
Coh(F4, C4)	.211	.283	.239	.189
Coh(F4, P3)	.062	.112	.098	.071
Coh(F4, P4)	.088	.176	.137	.100
Coh(F4, O1)	.019	.038	.035	.028
Coh(F4, O2)	.024	.044	.056	.039
Coh(C3,C4)	.223	.342	.319	.259
Coh(C3, P3)	.314	.454	.457	.388
Coh(C3, P4)	.146	.271	.254	.198
Coh(C3, O1)	.041	.112	.104	.090
Coh(C3, O2)	.029	.094	.111	.075
Coh(C4, P3)	.135	.253	.232	.206
Coh(C4, P4)	.394	.525	.510	.510
Coh(C4, O1)	.036	.097	.081	.090
Coh(C4, O2)	.052	.114	.131	.123
Coh(P3, P4)	.229	.319	.303	.264
Coh(P3, O1)	.276	.304	.288	.302
Coh(P3, O2)	.122	.173	.176	.143
Coh(P4, O1)	.112	.188	.184	.175
Coh(P4, O2)	.345	.359	.372	.360
Coh(O1, O2)	.243	.258	.250	.222

Appendix 2. Correlations between reaction time and the interhemispheric coherence of combinations of channels in four phases. The significant findings were highlighted in bold.

Coherence pairs	Early visual		Pre-execution		Execution		Post-execution	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Coh(F3, F4)	-.115	.672	-.306	.249	-.047	.863	.021	.940
Coh(F3, C3)	-.187	.488	-.359	.172	-.141	.602	-.347	.188
Coh(F3, C4)	-.206	.444	-.191	.478	-.329	.213	-.097	.721
Coh(F3, P3)	-.053	.846	-.247	.356	-.188	.485	-.209	.438
Coh(F3, P4)	-.087	.749	-.150	.579	-.228	.395	-.159	.557
Coh(F3, O1)	-.153	.571	-.361	.170	-.253	.345	-.305	.251
Coh(F3, O2)	.222	.408	-.475	.063	-.165	.542	-.156	.564
Coh(F4, C3)	.024	.931	-.097	.721	-.100	.713	-.206	.444
Coh(F4, C4)	-.053	.846	.388	.137	-.079	.770	-.383	.144
Coh(F4, P3)	-.215	.425	-.074	.787	-.174	.520	-.197	.464
Coh(F4, P4)	-.015	.957	.282	.289	.050	.854	-.288	.279
Coh(F4, O1)	-.477	.062	.001	.996	-.085	.753	-.241	.368
Coh(F4, O2)	-.397	.128	-.271	.311	.021	.940	-.285	.284
Coh(C3,C4)	-.418	.107	-.306	.249	**-.585***	**.017**	-.300	.259
Coh(C3, P3)	-.129	.633	-.012	.966	**-.506***	**.046**	-.388	.137
Coh(C3, P4)	-.344	.192	-.321	.226	-.432	.094	-.226	.399
Coh(C3, O1)	-.353	.180	**-.524***	**.037**	-.438	.090	-.397	.128
Coh(C3, O2)	-.015	.957	-.468	.068	-.366	.163	-.409	.116
Coh(C4, P3)	-.068	.803	-.197	.464	-.276	.300	-.071	.795
Coh(C4, P4)	.165	.542	.174	.520	-.050	.854	-.038	.888
Coh(C4, O1)	-.376	.151	-.285	.284	-.406	.119	-.129	.633
Coh(C4, O2)	-.159	.557	-.444	.085	-.282	.289	-.168	.535
Coh(P3, P4)	-.429	.097	-.376	.151	-.444	.085	-.300	.259
Coh(P3, O1)	**-.544***	**.029**	-.374	.154	-.218	.418	-.362	.169
Coh(P3, O2)	-.374	.154	-.388	.137	-.385	.141	-.394	.131
Coh(P4, O1)	**-.624***	**.010**	-.362	.169	-.318	.231	-.171	.528
Coh(P4, O2)	-.353	.180	-.315	.235	-.335	.204	-.238	.374
Coh(O1, O2)	-.088	.745	-.082	.762	-.432	.094	-.156	.564

Appendix 3. Topography maps. The head view from the top and the back in the four phases.