



Event-related (De)synchronization (ERD/ERS) during motor imagery tasks: Implications for brain–computer interfaces

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ABSTRACT

The primary aims of this research were to examine (1) mu and beta event-related desynchronization/synchronization (ERD/ERS) during motor imagery tasks with varying movement duration and (2) the potential impacts of movement duration on ERD/ERS patterns. Motor imagery tasks included brief and continuous imagined hand movements. During an imagery task, participants imagined an indicated movement for 1 s (i.e., brief movement imagery) or 5 s (i.e., continuous movement imagery). The results of the study support (1) that mu and beta ERD/ERS patterns are elicited during imagined hand movements and (2) that movement duration affects ERS and does not affect ERD patterns, during motor movement imagery. Additionally, brief movement imagery had a greater impact on mu and beta ERD; continuous movement imagery had a greater impact on mu and beta ERS. This research will be useful for designing future brain–computer interfaces as it provides valuable insight into the dynamics of electroencephalographic (EEG) oscillatory changes during motor imagery tasks with varying movement duration.

Relevance to industry: Brain–computer interfaces (BCIs) have gained considerable interests by both research and industry communities who want to improve the quality of life for those who suffer from severe motor disabilities, such as amyotrophic lateral sclerosis (ALS), brainstem stroke, and cerebral palsy (CP). The results of this study should be applied to EEG-based BCI system design in order to enhance accuracy and classification performance for BCI system control.

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1. Introduction

As a non-muscular communication and control system (Wolpaw et al., 2002; Morash et al., 2008; Nam et al., 2009; Blankertz et al., 2010), brain–computer interface (BCI) has shown emerging possibilities for people who have lost all voluntary muscle control, but are cognitively intact, by allowing them to write sentences (Birbaumer, 1997; Donchin et al., 2000; Scherer et al., 2004; Nijboer et al., 2008; Kübler and Birbaumer, 2008), move a cursor on the computer screen (Wolpaw et al., 2002), play an electronic ping-pong game (Babiloni et al., 2003), control an orthosis that provides hand grasp (Obermaier et al., 2001), or operate a brain-actuated wheelchair (Galán et al., 2008). During the last two

decades, BCI systems have used a variety of electrophysiological signal components (Wolpaw et al., 2002; Parasuraman and Rizzo, 2008; Graftmann et al., 2010): visual evoked potentials (Sutter and Tran, 1992; Middendorf et al., 2000), slow cortical potentials (Rockstroh et al., 1989; Birbaumer, 1997), P300 evoked potentials (Farwell and Donchin, 1988; Donchin et al., 2000; Li et al., 2011), mu and beta rhythms (Pfurtscheller and Lopes da Silva, 1999; Neuper and Pfurtscheller, 2006; Neuper et al., 2009), and cortical neuronal action potentials (Kennedy et al., 2000).

The change in amplitude of specific cortical mu and beta rhythms during self-paced voluntary movements has gained considerable interests as a potential electrophysiological signal for EEG-based brain–computer interfaces (Cheyne et al., 2003; Neuper and Pfurtscheller, 2006; Parasuraman and Rizzo, 2008; Morash et al., 2008). These variations of synchronization of cortical rhythms are referred to as an ‘event-related desynchronization/synchronization’ (ERD/ERS; Neuper and Pfurtscheller, 2001). For example, when a self-paced finger movement is performed, the 8–14 Hz alpha band

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(mu ERD) and the 15–25 Hz beta band (beta ERD) exhibit a decrease in amplitude prior to the actual movement. This pre-movement suppression over sensorimotor areas can be attributed to motor preparation and execution (Pfurtscheller and Berghold, 1989; Leocani et al., 1997; Kaiser et al., 2003). Conversely, when the finger movement ceases, the 15–25 Hz beta band (beta ERS) over the precentral region of the brain exhibits an increase in amplitude (Pfurtscheller et al., 1981; Gaetz and Cheyne, 2006). It is assumed that this post-movement rebound reflects an 'idling' deactivated motor cortex (Pfurtscheller et al., 1997b; Alegre et al., 2003). As an indicator of cortical activation/deactivation, event-related (de)synchronization (ERD/ERS) has been extensively investigated during various motor tasks utilizing finger (Stancák and Pfurtscheller, 1995; Cassim et al., 2000; Haeger-Ross and Schieber, 2000; Li et al., 2004; Erbil and Ugan, 2007), hand (Pfurtscheller et al., 2000, 2005; Neuper and Pfurtscheller, 2001; Bai et al., 2007), foot (Neuper and Pfurtscheller, 2001; Müller-Putz et al., 2007), and tongue movements (Pfurtscheller et al., 1994; Morash et al., 2008). These studies indicate that ERD/ERS patterns can be differentiated in various frequency bands by different kinds of physical movements. These patterns can then be interpreted by an EEG-based BCI system as different control channels. To utilize this type of control, a minimum of two different patterns must be analyzed and classified for different movement types (Pfurtscheller et al., 1997a).

A question has been raised as to whether or not motor imagery tasks would also produce similar ERD/ERS patterns as those observed during physical movements. Motor imagery has been considered as an integral method of BCI system operation (Neuper et al., 2006; Parasuraman and Rizzo, 2008; Nam et al., 2011) to assist those who have highly limited motor functions, such as amyotrophic lateral sclerosis (ALS) or spinal cord injury. Motor imagery tasks can lead to cortical rhythm amplitude suppression (ERD) and enhancement (ERS) over primary sensorimotor areas (Taniguchi et al., 2000; Neuper et al., 2005). For example, hand movement imagery by non-disabled people (Neuper and Pfurtscheller, 1999) as well as people with severe motor disabilities (Neuper and Pfurtscheller, 1998) caused a desynchronization of mu rhythms (8–12 Hz) and central beta rhythms (13–28 Hz). Different ERD/ERS patterns have been identified among imagined hand movements (Pfurtscheller et al., 1997a; Neuper et al., 1999) as well as different motor imagery tasks involving the tongue (Spiegler et al., 2004) as well as a single hand or foot (Pfurtscheller et al., 2006; Morash et al., 2008). These studies strongly indicate that the same cortical areas activated during physical movements would be engaged in the mental imagery of motor actions (Jeannerod, 2001). Salvaris and Sepulveda (2010) also found in their imagery movement BCI experiments that multiple trial classification results of imaginary movement were similar to those of real movement.

However, it is of significance to note that the dynamics of ERD/ERS phenomena during motor tasks still remain unclear. First, not all studies have shown the expected imagery-related EEG changes. Pfurtscheller et al. (2005), who studied beta rebound after three different types of motor imagery (hand, foot, and tongue), found that only foot imagery produced a clear beta rebound for the majority of subjects. In contrast, only two out of nine subjects displayed a significant short-lasting beta power increase after one-handed imagery. Likewise, tongue motor imagery did not exhibit any beta rebound. On the other hand, Pfurtscheller et al. (2006) found a significant mu ERD in all subjects during hand motor imagery, but less clear patterns occurred during foot motor imagery. Second, although movement-related power changes in the alpha and beta bands are known to be affected by movement duration, conflicting results have been reported in physical movement studies. For example, Erbil and Ugan (2007) found that alpha amplitude, which decreased shortly before movement onset,

gradually - but not fully - recovered toward the baseline during sustained and continuous movements over a span of 30 s. However, Stancák and Pfurtscheller (1995) did not distinguish slow (0.4 s) and brisk (1.7 s) movements in beta ERD before the onset of finger movement, yet found significant differences after movement onset. Cassim et al. (2000), who investigated ERD/ERS patterns during brief (1 s) and sustained (10 s) physical finger movements, also found that movement duration had little effect on both pre and post-movement periods, although powers in the alpha and beta bands during sustained movements returned to baseline values within a relatively short amount of time (1 s and 5 s, respectively). Finally, even though several studies have been conducted to assess movement duration effects during physical movements (e.g., Stancák and Pfurtscheller, 1995; Cassim et al., 2000; Erbil and Ugan, 2007), little research has been conducted on the effects of movement duration during motor imagery tasks on ERD/ERS patterns. Different movement durations may lead to different motor commands involving different sub-cortical structures (Desmedt, 1983; Stancák and Pfurtscheller, 1995), which can be an important control mechanism for users with severe motor disabilities to operate ERD/ERS-based brain-computer interfaces (BCIs). It has also been assumed that ERD/ERS patterns can be altered by different movement durations, which affect classification accuracy in the BCI systems (e.g., Parasuraman and Rizzo, 2008). For instance, several physical movement-related studies have reported that longer movement duration (sustained movement) produces delays in ERS patterns as well as a longer recovery time after motor movement (Cassim et al., 2000; Erbil and Ugan, 2007). However, there has been a general lack of understanding of, or inattention to, issues related to movement duration effects during motor imagery tasks.

The brief literature review above shows that more studies should be conducted on the changes in electroencephalographic (EEG) alpha and beta amplitudes in order to (1) ascertain predictable changes in the sensorimotor alpha and beta bands during motor imagery tasks and (2) investigate the effects of different imagined movement durations on ERD/ERS patterns. As illustrated in Fig. 1, the main goal of this study was to systematically investigate event-related (de)synchronization (ERD/ERS) patterns elicited by motor imagery tasks with varying movement durations (i.e., brief hand movement imagery for 1 s vs. continuous hand movement imagery for 5 s). Although the electrophysiological mechanism has been useful in explaining ERD/ERS patterns, particularly during imagery movement, it is still not entirely understood. Therefore the results of this study should aid in the understanding of human cortical activity and movement imagery-related rhythms in association with the mental imagery of motor actions or behaviors. In the present study, two motor imagery tasks (brief vs. continuous) were compared to address the following two questions: (1) are mu and beta ERD/ERS patterns during imagined hand movements indicative of those previously observed in physical movements?; and (2) do brief and continuous hand movement imageries produce differing ERD/ERS patterns?

2. Methods

2.1. Participants

Fifteen able-bodied volunteers (11 men and 4 women) participated in the study, whose mean age (M) was 20.1 years (Standard Deviation, $SD = 0.35$). No participants had any medical or neurological disorders. All but one of the participants were right handed as assessed by Edinburgh Inventory (Oldfield, 1971). Participants provided informed consent after the experimental procedure had been explained. Participants were rewarded extra course credit for their participation.

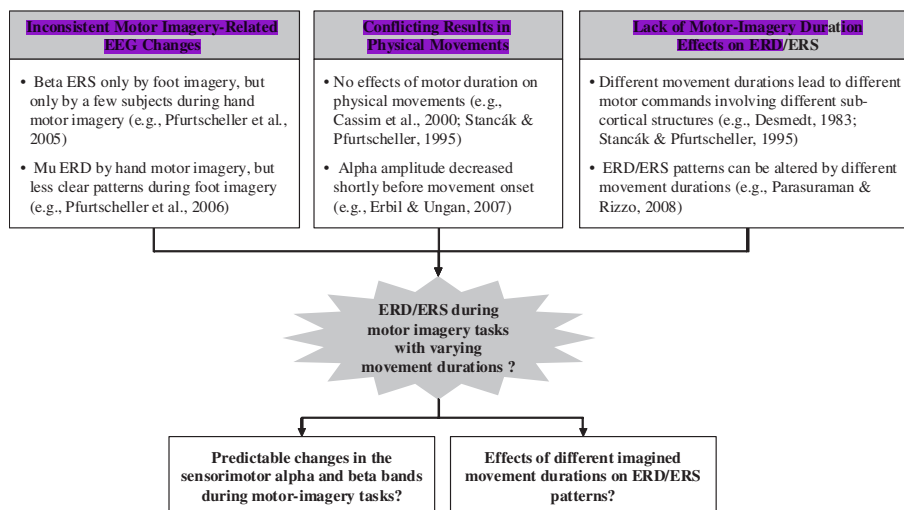


Fig. 1. Schematic representation of research goal and questions drawn from previous studies.

2.2. Task procedures and design

Two types of motor imagery tasks were performed that included both brief and continuous movements with one's dominant hand. During the brief imagery task, participants imagined the indicated movement for 1 s. During the continuous imagery task, participants were asked to imagine the indicated movement for 5 s. As seen in Fig. 2, an ERD time course was computed utilizing three time periods before movement onset (P3: 2–3 s, P2: 3–4 s and P1: 4–5 s) and a 1 s period after movement onset (P0₁: 5–6 s). Additionally, an ERS time course was computed utilizing a 1 s period before movement offset (P0₂: brief = 5–6 s; continuous = 9–10 s) and four 1 s periods after movement offset (brief = P1: 6–7 s, P2:

7–8 s, P3: 8–9 s and P4: 9–10 s; continuous = P1: 10–11 s, P2: 11–12 s, P3: 12–13 s and P4: 1–14 s).

Before the experiment, all the participants were given both written and verbal instructions regarding how to perform the experimental tasks while remaining relaxed and avoiding any motion (see Fig. 3). A number of training trials were also presented in order for participants to get familiar with the respective tasks that they would perform. During the experiment, participants were asked to sit in a comfortable armchair at a distance of about 80 cm from a 17" computer monitor in a noise-controlled, dimly lit room. Each trial started with a blank screen at second 0 (see Fig. 2). At second 5, an indicator pointed to one of two different motor imagery tasks onscreen for either 1 s (brief movement imagery) or

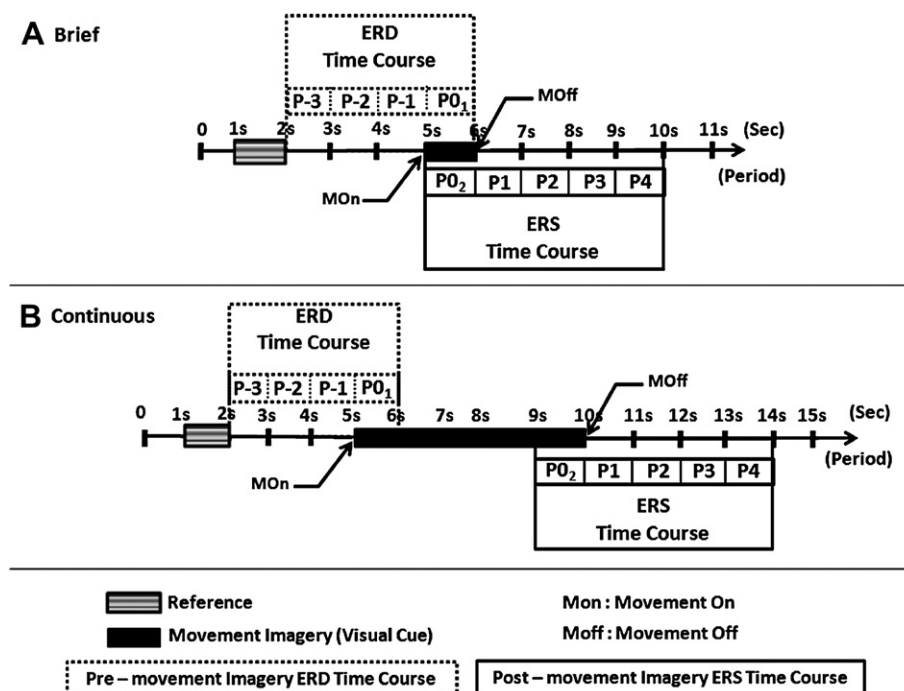


Fig. 2. Experiment protocol of brief (A) and continuous (B) movement imagery.

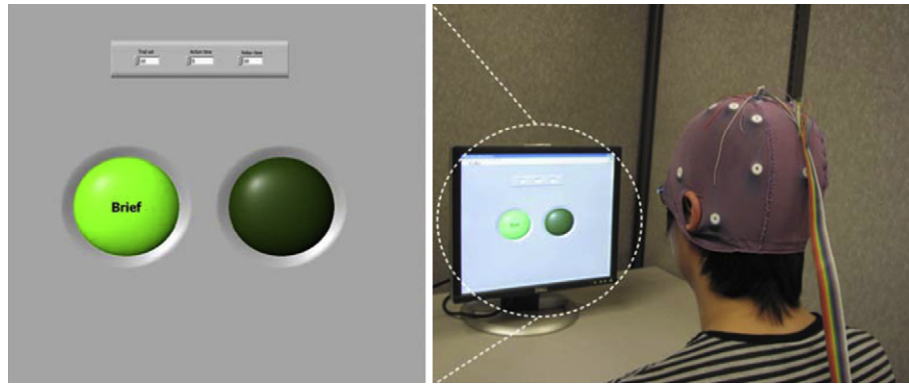


Fig. 3. Screenshot of experimental environment.

5 s (continuous movement imagery), which were determined by considering the results of previous studies (e.g., Stancák and Pfurtscheller (1995); Cassim et al., 2000; Erbil and Ungan, 2007) as well as the experimental data of our preliminary research. Since motor imagery is defined in the present study as “the mental rehearsal of a motor act without overt movements by muscular activity” (Neuper et al., 2009, p. 240), participants were instructed to imagine the kinesthetic experience (Neuper et al., 2005) of movement (e.g., grasping an object placed in their hand). In order to detect a reliable value of power during rest time, the time interval between the end of one movement and the onset of the next movement was set to 10 s (Niedermeyer and Lopes da Silva, 2004). The whole sequence was repeated 20 times. The tasks (i.e., brief or continuous movement imagery) were randomized to minimize the effect of task familiarity.

2.3. EEG recordings and preprocessing

EEG signals were recorded using an EEG cap (Electro-Cap International, Inc.) from electrodes C₃ and C₄, which are the most important electrode locations for different motor task discrimination (Ramoser et al., 2000), based on the modified 10–20 system of the International Federation (Sharbrough and Chatrian, 1991). All channels were referenced to the right mastoid and grounded to the left mastoid, while keeping the electrode impedance less than 5 kΩ. The EEG signal was amplified with a g.USBamp amplifier (g.tec Medical Engineering) and digitized by using the BCI2000 system (Schalk et al., 2004). The signal analysis was performed using a LabVIEW™ program. These EEG trails were bandpass filtered at 8–30 Hz and digitally sampled at a rate of 256 Hz.

2.4. Quantification of ERD/ERS

To compare changes in electroencephalographic (EEG) alpha and beta amplitudes elicited by different motor imagery tasks, this study measured the ERD/ERS in the 8–13 Hz mu bands and 14–30 Hz beta bands. By following the standard ERD/ERS calculation of Pfurtscheller and Aranibar (1979), ERD/ERS was quantified through: (1) bandpass filtering of all event-related trials, (2) squaring of the amplitude samples to obtain power samples, (3) averaging of power sample across all trials, and (4) averaging over time samples to smooth the data and reduce the variability (Pfurtscheller and Lopes da Silva, 1999, pp. 1844–1845).

The ERD/ERS was here defined as percentage power decrease (ERD) or power increase (ERS) in relation to a 1 s reference interval before the movement imagery. Mathematically, quantifying the ERD/ERS as relative amplitude (RA) can be expressed as follows:

$$Act_{(j)} = \frac{1}{N} \sum_{i=1}^N y_{ij}^2$$

$$R = \frac{1}{k+1} \sum_{j=r_0}^{r_0+k} Act_{(j)}$$

$$RA_{(j)}(\%) = \left(\frac{Act_{(j)} - R}{R} \right) \times 100(\%)$$

where N is the total number of trials and y_{ij} is the j th sample of the i th trial of the band pass filtered data. $Act_{(j)}$ is the averaged power value at the j th sample squared. R is the average power in the reference interval $[r_0, r_0 + k]$ (Grimm and Pfurtscheller, 2006).

2.5. Statistical analysis

An analysis of variance (ANOVA) for repeated-measures was used to investigate (1) ERD/ERS patterns elicited by motor imagery tasks and (2) any differences in ERD/ERS patterns between brief and continuous motor imagery. Independent variables included movement duration (brief vs. continuous) and period (represented by four 1 s averages for ERD and five 1 s averages for ERS). A 2 (duration of movement imagery) \times 4 (time period before and after imagery movement) within-subjects design was used to assess ERD patterns in mu and beta bands. As seen in Fig. 2, an ERD time course was computed for three 1 s time periods before movement (P3: seconds 2–3, P2: seconds 3–4, P1: seconds 4–5) as well as the 1 s time period after movement onset (P0₁: brief = seconds 5–6; continuous = seconds 5–6). To investigate ERS changes in mu and beta bands, a 2 (duration of movement imagery) \times 5 (time period before and after imagery movement) within-subjects design was used. An ERS time course was computed for a 1 s time period before movement termination (P0₂: brief = seconds 5–6; continuous = seconds 9–10) as well as four 1 second time periods after movement imagery (brief = P1: seconds 6–7, P2: seconds 7–8, P3: seconds 8–9, P4: seconds 9–10; continuous = P1: seconds 10–11, P2: seconds 11–12, P3: seconds 12–13, P4: seconds 13–14) were selected.

Post hoc comparisons were also carried out with Duncan's multiple range test at $p < 0.05$ to identify significant period(s) indicating event-related desynchronization (ERD) or synchronization (ERS). Finally, a paired t -test was performed to compare differences in maximum amplitude (%) and latency (second) for the mu and beta ERD/ERS between brief and continuous movement imagery (see Table 2). Latency was defined as the time from movement onset (ERD) or movement offset (ERS) to the maximum amplitude.

Table 1
Summary of ANOVA results for ERD/ERS parameters.

Parameter	Effect		F-value	P-value
Mu	ERD	Duration	$F(1,14) = 3.73$	0.0740
		Time Period	$F(3,42) = 6.97$	0.0007
	ERS	Duration	$F(1,14) = 5.31$	0.0370
		Time Period	$F(4,56) = 12.88$	<0.0001
Beta	ERD	Duration	$F(1,14) = 4.18$	0.0602
		Time Period	$F(3,42) = 8.16$	0.0002
	ERS	Duration	$F(1,14) = 8.02$	0.0133
		Time Period	$F(4,56) = 13.39$	<0.0001

3. Results

A series of a two-way analysis of variance was performed to assess ERD/ERS patterns in mu and beta bands along with post hoc comparisons using Duncan's multiple range test. Table 1 is a summary of the significant effects for ERD/ERS parameters.

3.1. Pre-movement event-related desynchronization in the 8–13 Hz band (mu ERD)

Grand average mu and beta ERD/ERS power time courses for fifteen subjects during self-paced brief and continuous movement imagery are displayed in Fig. 4. All values are relative to the baseline (0) in ERD and ERS patterns. A smaller ERD value denotes a more desynchronized status in the pre-movement ERD, while a larger value indicates a more synchronized status in the post-movement ERS. In this study, relative powers were smaller during brief movement imagery than during continuous movement imagery in the mu and beta pre-movement ERD, indicating a more desynchronized status during brief movement imagery. However,

the relative powers were larger during continuous movement imagery than during brief movement imagery in the mu and beta post-movement ERS, indicating a more synchronized status during continuous movement imagery.

Grand average mu ERD power time courses during brief and continuous movement imagery are displayed in Fig. 4A. The period effect was found to be significant for the amplitude decrease in the 8–13 Hz mu band, $F(3, 42) = 6.97$, $p = 0.0007$, indicating a significant pre-movement ERD pattern. Post hoc analysis also showed that the average mu rhythm ERD values were significantly larger at P0₁ (i.e., movement onset), compared to other time periods ($p < 0.05$ with Duncan's multiple range test).

A repeated-measures ANOVA for mu pre-movement ERD showed no significant main effect of movement duration, although the relative amplitude in brief movement imagery ($M = -4.96$, $SD = 26.22$) was lower than in continuous movement imagery ($M = -1.05$, $SD = 39.02$), indicating that the relative amplitude was more desynchronized in brief movement imagery than in continuous movement imagery. The paired t -test showed that the maximal mu ERD value was, on average, smaller during brief movement imagery than during continuous movement imagery (see Table 2). However, the difference was not statistically significant. On the other hand, the mu ERD reached its maximum value more quickly during continuous movement imagery than during brief movement imagery, $t(14) = 2.238$, $p = 0.042$.

3.2. Post-movement event-related synchronization in the 8–13 Hz band (mu ERS)

A significant period effect was found on the mu post-movement ERS values, $F(4,56) = 12.88$, $p < 0.0001$, indicating a significant post-movement ERS pattern. Post hoc analysis showed that the average

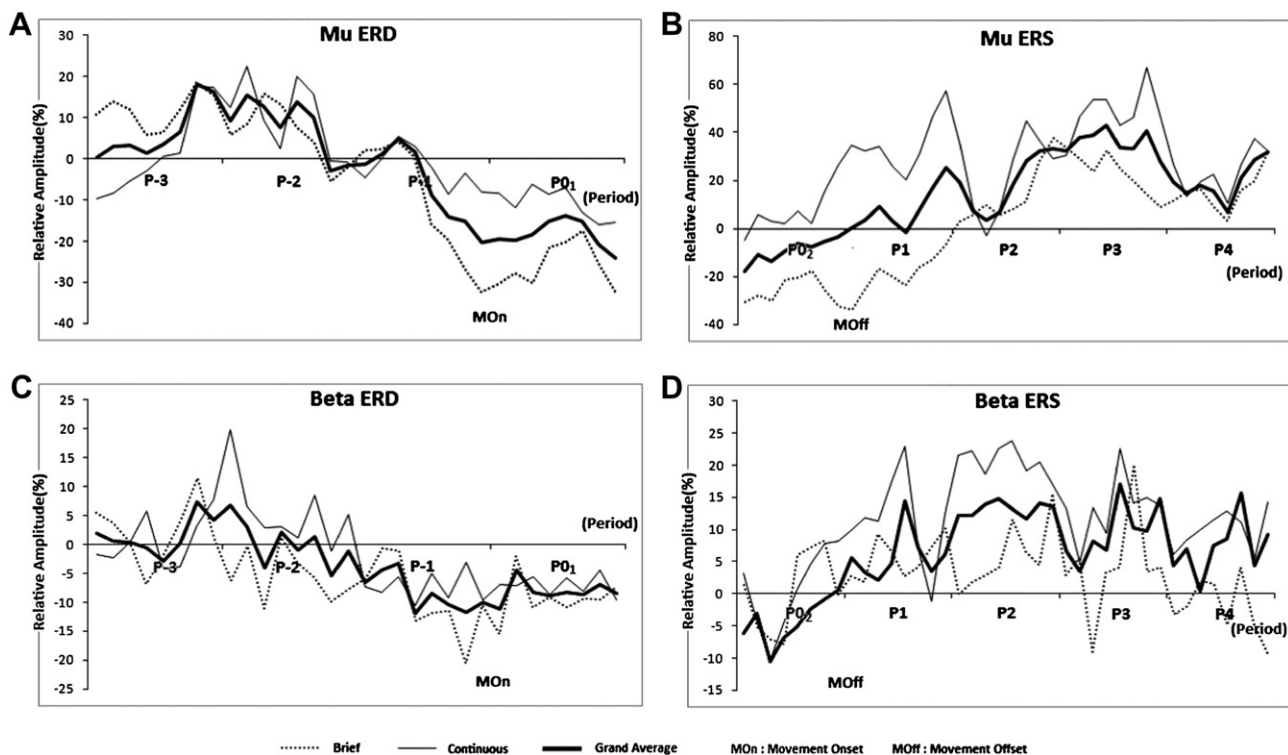


Fig. 4. ERD/ERS patterns over the central region (C₃ and C₄) during imagery movements in mu and beta bands. Thirty-two consecutive points (i.e., 8/sec of sampling rate) were only averaged in order to reduce the number of power values. The trend was drawn as a thick (grand average), dotted (brief movement imagery), and thin (continuous movement imagery) line.

Table 2

Maximum amplitude (%) and latency (s) of mu and beta ERD/ERS for each participant in brief and continuous movement imagery.

Participant	Mu ERD				Mu ERS				Beta ERD				Beta ERS			
	Brief		Continuous		Brief		Continuous		Brief		Continuous		Brief		Continuous	
	max	latency	max	latency	max	latency	max	latency	max	latency	max	latency	max	latency	max	latency
1	−67.50	−0.375	−48.16	0.250	262.93	2.250	234.57	−0.375	−60.27	−0.625	−11.36	−0.625	48.18	1.5	107.00	1.500
2	−69.87	−0.500	−69.05	0.375	108.71	2.125	101.96	0.125	−55.92	−0.625	−42.75	−0.750	59.97	0.625	87.80	2.000
3	−60.10	0.500	−69.55	0.250	101.21	2.500	26.71	3.250	−36.82	0.125	−63.36	−0.250	77.70	1.000	25.23	0.250
4	−87.24	0.250	−91.11	0.375	180.03	3.875	72.48	2.500	−58.52	0.500	−43.60	0.125	59.89	1.500	77.53	2.625
5	−82.86	0.750	−76.02	−1.500	0.84	4.000	214.31	3.125	−32.68	0.875	−44.15	−1.125	42.59	1.000	69.41	1.000
6	−78.88	0.250	−51.94	0.500	37.99	3.750	306.59	1.875	−54.45	0.500	−57.45	0.125	8.08	−0.125	81.97	1.625
7	−69.73	0.625	−48.82	0.000	181.75	3.125	134.23	0.875	−40.50	0.250	−48.40	−2.500	93.92	2.000	60.05	0.750
8	−60.01	0.000	−71.88	−1.250	195.41	2.125	149.53	2.125	−54.61	0.000	−47.91	−1.375	52.90	1.750	114.45	3.250
9	−56.10	0.875	−79.28	−1.375	110.64	2.625	103.75	0.500	−24.50	0.750	−41.80	−0.750	67.12	1.875	297.27	0.000
10	−82.31	0.250	33.74	−1.000	42.68	3.000	838.77	1.000	−46.40	0.500	−8.85	−1.125	69.01	2.625	195.48	1.125
11	−68.86	−0.750	−61.36	−0.375	172.06	2.125	353.87	0.250	−43.39	−1.000	−56.20	−1.750	92.74	−0.375	47.47	3.875
12	−36.81	0.125	−29.15	0.125	91.87	2.750	246.89	2.750	−38.88	−1.125	−53.17	0.125	74.50	2.875	84.84	0.500
13	−28.60	0.625	−75.90	−1.250	99.62	1.125	96.18	2.375	−27.30	0.375	−48.20	−1.500	29.76	1.125	91.73	1.375
14	−70.23	0.750	−78.01	0.125	161.07	4.000	56.47	2.500	−55.08	0.250	−57.79	−0.375	70.16	1.125	66.53	3.500
15	−70.79	0.875	−78.69	0.250	184.85	2.000	45.57	1.750	−44.05	0.875	−54.67	−0.375	44.82	1.875	106.92	0.250
Mean	−65.99	0.283	−59.67	−0.300	128.77	2.758	198.79	1.641	−44.89	0.108	−45.31	−0.808	59.42	1.358	100.91	1.575

Latencies were calculated with respect to the maximum ERD/ERS at each frequency band.

mu rhythm ERS values were significantly higher 2 s after movement offset as compared to other periods ($p < 0.05$ with Duncan's multiple range test). As seen in Fig. 4B, an increase in amplitude began about 1 s before movement termination in the 8–13 Hz mu band, peaking at about 3 s after movement termination.

A significant main effect of movement duration on mu ERS was found, $F(1,14) = 5.31$; $p = 0.0370$. That is, the relative amplitude was larger for continuous movement imagery ($M = 29.40$, $SD = 47.78$) than for brief movement imagery ($M = 0.87$, $SD = 33.80$), indicating that the relative amplitude was more synchronized during continuous movement imagery than during brief movement imagery. The results of the paired t -test results showed that continuous movement imagery had, on average, a significantly shorter latency in mu ERS than brief movement imagery, $t(14) = 3.628$, $p = 0.003$. However, there was no significant difference in peak amplitude between the two movement conditions.

3.3. Pre-movement event-related desynchronization in the 14–30 Hz band (beta ERD)

Grand average beta power time courses during the two different motor imagery tasks are displayed in Fig. 4C. The amplitude in the 14–30 Hz beta band decreased shortly before movement onset, $F(3, 42) = 8.16$, $p = 0.0002$, indicating a significant pre-movement ERD in the beta band. Post hoc analysis showed that the beta ERD value was significantly larger 1 s before movement imagery, compared to other periods ($p < 0.05$ with Duncan's multiple range test).

The repeated-measures ANOVA showed no significant main effect of movement duration on pre-movement ERD in the 14–30 Hz beta band. However, beta ERD showed a stronger power suppression

during brief movement imagery ($M = -5.42$, $SD = 12.58$) compared to continuous movement imagery ($M = -1.55$, $SD = 16.53$). The paired t -test showed significant difference in latency, as peak ERD occurred more quickly during continuous movement imagery than during brief movement imagery, $t(14) = 3.580$, $p = 0.003$. However, there was no significant difference in peak beta ERD between the two movement conditions.

3.4. Post-movement event-related synchronization in the 14–30 Hz band (beta ERS)

Results showed a post-movement power increase in 14–30 Hz beta band, $F(4, 56) = 13.39$, $p < 0.0001$ (see Fig. 4D), indicating a significant beta post-movement ERS pattern. Further inspection on period effect showed that beta ERS values were significantly higher 1 s after termination of imagery of hand movement, compared to other periods ($p < 0.05$ with Duncan's multiple range test).

Similar to mu ERS, a significant main effect was found for movement duration on beta ERS, $F(1, 14) = 8.02$; $p = 0.0133$. Continuous movement imagery ($M = 13.63$, $SD = 21.23$) showed a larger relative amplitude than brief movement imagery ($M = 0.81$, $SD = 14.95$), indicating that the relative amplitude was more synchronized in the continuous condition than in brief condition. The paired t -test for the maximum beta ERS showed that continuous movement imagery had, on average, a significantly larger maximum value than brief movement imagery, $t(14) = -2.250$, $p = 0.041$. Latency was found to be non-significant, although it took longer for continuous movement imagery to reach its maximum value than brief movement imagery.

4. Discussion

The primary aims of the present study were to examine (1) mu and beta ERD/ERS patterns elicited by motor imagery tasks and (2) the effect of movement duration (brief vs. continuous) on motor imagery-induced ERD/ERS patterns. Results from the current study indicate that (1) similar mu and beta ERD/ERS patterns were exhibited during imagined hand movements, compared to those previously observed during physical movements and (2) ERD patterns during motor movement imagery were unaffected by movement duration, whereas ERS patterns were influenced by movement duration; brief movement imagery had a greater impact on mu and beta ERD, whereas continuous movement imagery had a greater impact on mu and beta ERS.

4.1. Mu and beta ERD/ERS patterns in hand movement imagery

This study found that hand movement imagery blocks mu rhythms (8–13 Hz), which is consistent with the previous observations that a decrease in amplitude of the sensory motor rhythm (SMR) is related to the planning and execution of physical movements (Erbil and Ungan, 2007), as well as motor imagery (Neuper and Pfurtscheller, 1999; Neuper et al., 2005). Furthermore, results showed a power decrease occurring about movement onset (see Fig. 4A), which provides additional evidence that the same cortical areas that are activated during physical movements would be involved in performing the mental imagery of motor actions (Jeannerod, 2001).

We also found an amplitude enhancement or event-related synchronization of mu rhythms (mu ERS) during imagined hand movements. As seen in Fig. 4B, a power increase in the 8–13 Hz mu band starts at about 1 s before movement offset, and peaks at about 3 s after movement termination. This result is not consistent with the findings reported by Pfurtscheller et al. (2006), who found few significant mu rhythms (mu ERS) during hand movement imagery. One possible explanation for this discrepancy is difference in movement duration. Pfurtscheller et al. (2006) used a fixed movement duration of 3 s, whereas this study assessed two different types of movement durations (i.e., 1 s and 5 s). We found both pre-movement suppression and enhancement in mu rhythms during motor imagery tasks. Such simultaneous mu ERD and ERS patterns can be interpreted via the so-called “focal ERD/surround ERS” phenomena (Suffczynski et al., 2001), in which desynchronization of the mu rhythm does not occur in isolation, but is accompanied by an increase in synchronization in neighboring cortical areas.

A significant pre-movement suppression was found in the 14–30 Hz beta band (beta ERD). As seen in Fig. 4C, a power decrease occurred 1 s before movement onset. This result is consistent with that of Stancák and Pfurtscheller (1995) study, who found significant beta ERD patterns in both brisk and slow finger movements. Beta rhythms, similar to the mu rhythms, would also be desynchronized during the preparation and execution of physical motor movements, as well as movement imageries involving the sensorimotor cortex (Stancák and Pfurtscheller, 1995; Neuper and Pfurtscheller, 2001). A short-lasting beta burst (i.e., beta ERS) was found in the majority of subjects after termination of the imagery process. This beta rebound showed a faster recovery than mu ERS after movement termination: maximal synchronized values observed about 1 s in the beta band and about 2 s in the mu band. This finding clarifies one of the questions posed in the introductory section: an amplitude increase in the beta band (beta ERS) can also be generated by movement imagery without an overt motor action. This finding indicates that subjects were able to activate the primary motor area and supplementary motor area (SMA) during imagined actions similar to the robust activation observed during

physical motor tasks (Pfurtscheller et al., 2005). Also, the beta rebound occurring after hand movement imagery in this study is consistent with Pfurtscheller et al. (1996), who reported a significant beta ERS after hand motor imagery.

4.2. Effects of movement duration on mu and beta ERD/ERS patterns

Movement duration did not have any effect on the pre-movement attenuation in the mu rhythm (i.e., mu ERD). This finding is consistent with the results reported by Cassim et al. (2000), who concluded that motor preparation remains unchanged in spite of movement duration. The relative amplitude decrease in the present study was larger in brief movement imagery than in continuous movement imagery. A power decrease began shortly before movement onset during brief movement imagery and a peak desynchronization occurred about 1 s after movement onset. During continuous movement imagery, amplitude decreased shortly before movement onset. Mu desynchronization reached peak ERD more quickly during continuous movement imagery than during brief movement imagery. On the other hand, movement imagery duration had a significant effect on mu ERS. The increase in relative amplitude was larger during continuous movement imagery than during brief movement imagery. Also, maximum amplitude values were higher during continuous movement than during brief movement for the majority of participants. However, maximum peak amplitude for mu ERS showed no significant differences between the two movement durations.

Similar to mu ERD, beta rhythm attenuation was not affected by movement duration in the present study, even though the relative amplitude suppression during brief movement imagery was larger than during continuous movement imagery. Maximum ERD values were reached more quickly during continuous movement imageries than during brief movement imageries. However, the peak amplitude for beta ERD showed no significant differences between the two movement durations. A decrease in power occurred before movement imagery onset in both brief and continuous movements. This result is consistent with Stancák and Pfurtscheller (1995), who did not find significant movement duration effect between slow (0.4 s) and brisk (1.7 s) in the beta ERD before the onset of physical finger movement. The results of the present study showed that movement duration had a significant effect on the beta rebound after a motor imagery task, consistent with Erbil and Ungan (2007) results that rapid beta recovery occurs during continuous physical hand movements. Similar to mu ERS, a significant power increase occurred during both movements, with continuous movement imagery yielding a larger power increase over brief movement imagery. The maximum peak amplitude in continuous movement was higher than in brief movement for the majority of participants. However, the time to reach its max value (latency) was not significantly different between the movement durations.

The results reported here support the view that relative power on pre-movement desynchronization (ERD) in the mu and beta rhythms is not affected by movement duration, whereas motor imagery-induced power changes on the post-movement synchronization (ERS) in the mu and beta bands are differentially affected by movement durations. This result indicates that the type of movement duration may influence the performance in EEG-based BCI systems using the post-movement synchronization (ERS) in the mu and beta bands. This study also found that brief movement imagery had a larger impact on the mu and beta ERD, whereas mu and beta ERS values were more greatly affected by continuous movement. However, this finding differs from Cassim et al. (2000), who concluded that movement duration has little effect on both pre and

post-movement periods. One possible explanation may be due to a functional difference in motor preparation between physical movement and imagined movement. For example, motor imagery preparation involves less primary motor cortex activity than physical movement preparation (Morash et al., 2008). However, it is also known that movement imagery affects neurons in the primary sensorimotor area (Pfurtscheller et al., 1997b) and can modify sensorimotor rhythms in a way that can be observed during the preparatory phase of physical movement (Parasuraman and Rizzo, 2008). Therefore, more studies should be conducted to unravel the underlying effects of the movement duration on motor imagery-induced ERD/ERS, and to further investigate any differences in ERD/ERS patterns between physical and imagined movements.

4.3. Implication for designing brain–computer interfaces

A typical EEG-based BCI system consists of input (i.e., EEG signals), output (i.e., device commands), signal processing to translate input into output, and an operation protocol (e.g., timing of operation) (Wolpaw et al., 2002). Designing EEG-based brain–computer interfaces requires input signals that are “reliable and significantly related to specific states of the brain” (Pfurtscheller et al., 1997a, p. 643). It is well known that BCI input signals and signal features (e.g., ERD/ERS) can be affected by a cognitive process or a control strategy the BCI user performs, which subsequently would affect movement classification as well as accuracy (Pfurtscheller et al., 1997a; Morash et al., 2008; Neuper et al., 2009). Therefore, it is of importance to investigate and utilize the relationship between individual cognitive processes (e.g., motor movement imagery) and accompanying changes in BCI signal features when designing brain–computer interfaces (Müller-Putz et al., 2005).

Some of ERD/ERS-based BCI studies suggest the use of brief motor imagery tasks for effective BCI operation (e.g., Morash et al., 2008). However, we suggest a different approach for better accuracy of BCI operation; brief movement imagery for pre-movement desynchronization (ERD) and continuous movement imagery for post-movement synchronization (ERS). In the present study, motor imagery-induced power changes on the post-movement synchronization (ERS) in mu and beta bands were affected differently by movement durations. That is, mu and beta post-movement ERS patterns were susceptible to different movement durations during motor movement imagery. However, pre-movement desynchronization (ERD) in mu and beta rhythms was not affected by movement duration. In addition, brief movement imagery had a larger impact on mu and beta ERD than continuous movement, indicating a more desynchronized status in the pre-movement ERD. Conversely, mu and beta ERS values were more greatly affected by continuous movement, indicating a more synchronized status in the post-movement ERS.

5. Conclusion

Results from the current study indicate that (1) electroencephalographic (EEG) oscillatory changes in sensorimotor mu and beta bands can be induced by motor imagery tasks and (2) ERS patterns can be affected by different imagined movement durations, whereas ERD is unaffected by movement durations. Moreover, this study found that brief movement imagery had a larger impact on pre-movement mu and beta ERD, whereas post-movement mu and beta ERS values were more affected by continuous movement imagery.

The results of present empirical study on ERD/ERS patterns in association with imagery tasks with varying movement durations (i.e. brief and continuous movement imagery) would provide important implications when designing an EEG-based brain–computer interface (BCI) for people with severe motor disabilities (e.g., ALS, CP, etc.) to use motor imageries coupled with different

movement durations as a BCI control method (Wolpaw et al., 2002; Morash et al., 2008). This study also has clear implications for neuroergonomics concerning the neural basis of human cognition and performance in relation to the use of technology (e.g., Parasuraman and Rizzo, 2008) and augmented cognition with an emphasis on the automatic assessment of the instantaneous cognitive state of the user to enhance user performance and cognitive capabilities (e.g., Schmorow and Stanney, 2008).

To develop effective BCI applications, more studies are required regarding ERD/ERS patterns. First, enhancement or suppression of human EEG rhythms can be reinforced through training and feedback (Pfurtscheller et al., 1997a; Neuper and Pfurtscheller, 2001; Morash et al., 2008). For example, Neuper et al. (2009) found that visual feedback on motor imagery in the context of BCI use modulates sensorimotor EEG rhythms. Future research, in which neural efficiency is compared after subjects receive feedback about the performed mental task, is also needed. In addition, it is of significance to investigate ERD/ERS patterns as the relative amplitude with different reference (baseline) values selected in the EEG periods (Cassim et al., 2000). Different ERD/ERS patterns might occur, depending on different EEG periods as reference, even if the same power value is detected and used to calculate relative amplitude (Erbil and Ugan, 2007). The effects of different references and/or the optimized reference period(s) on motor imagery-induced ERD/ERS patterns should be investigated in future studies.

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