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Importance of baseline in event-related desynchronization during a combination task of motor imagery and motor observation

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Abstract

Objective. Event-related desynchronization (ERD) or synchronization (ERS) refers to the modulation of any EEG rhythm in response to a particular event. It is typically quantified as the ratio between a baseline and a task condition (the event). Here, we focused on the sensorimotor mu-rhythm. We explored the effects of different baselines on mu-power and ERD of the mu-rhythm during a motor imagery task. *Methods*. Eighteen healthy subjects performed motor imagery tasks while EEGs were recorded. Five different baseline movies were shown. For the imagery task a right-hand opening/closing movie was shown. Power and ERD of the mu-rhythm recorded over C3 and C4 for the different baselines were estimated. *Main Results*. 50% of the subjects showed relatively high mu-power for specific baselines only, and ERDs of these subjects were strongly dependent on the baseline used. In 17% of the subjects no preference was found. Contralateral ERD of the mu-rhythm was found in about 67% of the healthy volunteers, with a significant baseline preference in about 75% of that subgroup. *Significance*. The sensorimotor ERD quantifies activity of the brain during motor imagery tasks. Selection of the optimal baseline increases ERD.

S Online supplementary data available from stacks.iop.org/JNE/10/026009/mmedia

(Some figures may appear in colour only in the online journal)

1. Introduction

Event-related desynchronization (ERD) or synchronization (ERS) refers to the modulation of any EEG rhythm in response to a particular event. ERD was discovered by Gastaut and Bert in 1954, who described the attenuation of the alpha rhythm in adults watching movements (boxing) in films [1]. Pfurtscheller introduced ERD to explain the phenomenon of mu-power decrease, from high mu-power during rest to lower mu-power during movement execution and motor imagery [2–4]. Motor imagery based ERD may serve as a control signal in brain computer interface (BCI) applications, ranging from communication in locked-in patients to neurofeedback therapy [5, 6]. In 1999, Pfurtscheller and da Silva proposed to quantify ERD/ERS in this context as the percentage change of EEG-mu-band power between the relaxed condition (baseline) and the motor imagery or execution condition [7]. Here, we define 'baseline' as a particular condition that maximizes the

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mu-power throughout its duration. ERD/ERS can be observed at particular frequencies only, e.g. beta or gamma band frequencies. In this study we focus on mu-band-ERD/ERS, which is frequently observed during motor imagery.

Being a ratio, ERD or ERS measures depend on the magnitude and stationarity of the EEG signal in the baseline durations. When baseline power is absent the ERD measure loses its significance. Most previous studies focused on the mu-power suppression during motor imagery. For example Manganotti *et al* found a suppressive effect of task complexity [8]. Neuper *et al* reported the suppressive effect of four different motor imagery tasks: (i) kinesthetic motor imagery, (ii) visual motor imagery, (iii) motor execution (ME) and (iv) observation of movement (OOM) [9]. Their results showed that BCI classification accuracies were highest for ME and OOM. Orgs *et al* [10] and Del Percio *et al* [11] described the role of experience on mu attenuation for specific motor imagery tasks between professionals and amateurs. For instance, professional dancers showed larger mu-power decreases than non-professional dancers in dance movement, and lower ERD was found for elite karate athletes than for non-athletes.

However, little attention has been paid to the baseline duration. Recently, Blankertz *et al* [12] showed the importance of the sensorimotor rhythm during baseline conditions as a key factor to predict the accuracy of an ERD-based BCI. In that study, the power of sensory motor rhythms during the baseline duration (relaxed state, eyes open) was measured in 80 subjects. It was found that the power was directly proportional to the BCI accuracy: strong sensory motor rhythms (high mu-power) yielded high BCI accuracy. Because mu-power reaches its maximum during relaxed and motionless conditions, most of the previous studies suggested and implemented static baseline images, e.g. a static cross or a black screen [10, 12–15].

In this study, we explored if baseline mu-power could be maximized (or even just induced) by using various baseline movies (equivalent to five baseline conditions), ranging from static to dynamic. In addition, we quantified the associated ERD.

2. Methods

2.1. Subjects

All subjects were healthy young students or faculty members (all right-handed subjects with ten male and eight female) with no neurological diseases and normal or corrected-to-normal vision (mean age: 25.1 years, SD = 4.5). Each subject was informed about the experimental procedure and signed a written consent form.

2.2. EEG recording

EEGs were recorded using a 60 channel EEG amplifier (TMS-International, The Netherlands) with hardware low-pass cutoff frequency at 1350 Hz and Ag/AgCl electrodes positioned according to the international 5–10 system. The sampling frequency was set to 5000 Hz. All electrode impedances were kept below 5 kΩ. The ground electrode was attached to the nose of each subject. The left and right mastoids (similar to linked ears) were used as a reference. All data were stored to disk for further analysis.

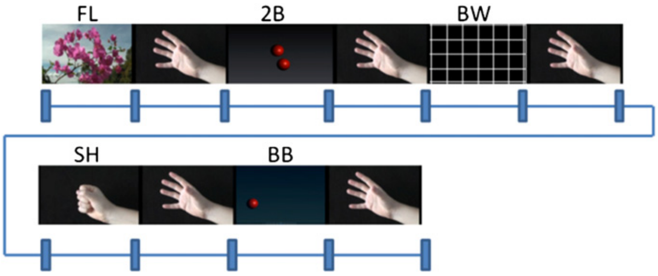

Figure 1. Time course of a typical run showing five different baseline movies (each 10 s in duration) and the five identical hand movies (with a duration of 8 s). Baselines are 'flower', 'two balls', 'white stripes on black screen', 'static right hand' and 'single bouncing ball'. Each baseline movie is regarded as a reference or idle state. Subjects were asked to relax but focus on the visual input. During display of the hand movies subjects were asked to observe and imagine (MI) the opening/closing hand.

2.3. Experimental design and procedure

Subjects observed six movies: one showing an opening/closing hand (H; motor imagery state, MI, duration of 8 s) and five different baseline movies (relax/reference state, durations of 10 s). During the motor imagery condition, subjects were asked to observe and imagine the hand motion with their right hand, and synchronize their imagery with the five hand closing/opening motions presented in this interval. The five hand motions filled up the 8 s without static intermissions.

During the five baseline movies, subjects were asked to relax but focus on the visual input. The five different baseline movies were: (1) a single bouncing ball (BB), (2) two moving balls (2B), (3) a slowly moving flower (FL), (4) a static right hand (SH) and (5) white stripes on a black screen (BW). In the BB movie, subjects observed one ball bouncing randomly all over the screen. In the 2B movie, subjects observed two balls hitting each other and moving only in the central part of the screen. In the FL movie, subjects observed slowly moving pink flowers against a panoramic background of sky and mountains. In the SH movie, subjects observed a static right hand on a black screen. In the last baseline movie, BW, subjects observed horizontal and vertical white stripes on a black screen. These five baselines can be classified in terms of movement as: (1) a static group (SH and BW), (2) a mildly- or quasi-static group (FL) and (3) a dynamic group (BB and 2B). ERD and baseline power of all different combinations of baseline and hand movies were studied, i.e. SH–H, BW–H, FL–H, BB–H and 2B–H.

Each measurement consisted of 15 runs; at each run, the subject watched five baseline movies and five (identical) opening/closing hand movies. Each time a baseline (or hand) movie was shown, it was counted as one trial. In two subjects (H110, H111), only 14 runs were repeated due to a technical problem. The order of five baselines was randomly presented throughout the experiment. An example is shown in figure 1.

Throughout the measurement, subjects sat in a comfortable chair and were asked to sit still and minimize eye blinking. The screen was located 1.2 m in front. To minimize environmental disturbances, all experiments were carried out in a shielded room. Light was turned off during measurements to keep subjects' attention to the screen. Six out of 18 subjects were asked to come back for a second measurement, which consisted of 7 runs. The second measurement was carried out between 2 weeks and 6 months later depending on the subject's schedules (average of 4.33 months (SD of 2.07 months)). Statistical analysis was limited to the C3 and C4 electrode position. For illustrative purposes, topographical ERDs (TopoERDs) are shown, as well.

2.4. Baseline power and stationarity

All EEG signals were digitally down sampled to 500 Hz and spatially filtered using a large Laplacian reference, which is a modified version of the method proposed by Hjorth [16, 17]. Subsequently, all data were filtered between 0.5 and 30 Hz using a fourth-order Butterworth filter. To prevent any transition effects from the previous active trial, every first second of all baseline trials was excluded from analysis. Furthermore, to avoid possible fatigue effects, every last second of all hand moving trials was also excluded. Each baseline (or each hand) duration was partitioned into nine (or seven) non-overlapping 1 s (500 samples) segments. The mu-power of each segment was estimated using Welch's method with a non-overlapping window length of 500 samples (1 s), integrating between lower and upper mu frequencies (8–13 Hz) obtained from the power density spectrum (PDS) using

$$\mathrm{Mu}_{k,\mathrm{ch}}^{i,j} = \int_{f=8\mathrm{Hz}}^{f=13\mathrm{Hz}} X(f)\,\mathrm{d}f, \tag{1}$$

where $\mathrm{Mu}_{k,\mathrm{ch}}^{i,j}$ denotes the mu-power of the ith trial at the kth segment in channel ch of baseline type $j = BB$, FL, SH, 2B and BW. $X(f)$ denotes the Fourier component at frequency f.

To ensure (weak) stationarity of the recorded EEG signals over 15 trials of each baseline condition, outlier analysis was performed. To this end, the average mu-power, $(\overline{\mathrm{Mu}}_{\mathrm{ch}}^{i,j})$, was computed from a total of nine mu-power segments for each trial according to

$$\overline{\mathrm{Mu}}_{\mathrm{ch}}^{i,j} = \frac{\sum_{k=1}^{k=\max(k)} \mathrm{Mu}_{k,\mathrm{ch}}^{i,j}}{\max(k)}. \tag{2}$$

Note that 'i', 'j', 'k' and 'ch' in equation (2) are similar to equation (1). Hereafter, the grand averaged mu-power and its standard deviation was computed from the 15 averaged mu-powers. We rejected any trial where the average mu-power exceeded twice the standard deviation of the grand average mu-power. This step was repeated for all five baselines and all hand movies. Note that if any baseline (or hand movie) trial was considered as outlier, we deleted that trial together with its subsequent hand movie trial (or its previous baseline trial).

Several researchers [18, 19] showed that the mu-power attenuation was mainly observed on the hemisphere contralateral to the hand of which the movement was imagined. However, some studies [20, 21] also reported bilateral modulations during motor imagery tasks. Therefore, in this study we investigated both C3 and C4.

2.5. Computation of ERD/ERS

The mu-ERD/ERS was computed according to [7]:

$$\text{ERD or ERS} = \frac{P_{\mathrm{MI}} - P_{\mathrm{BL}}}{P_{\mathrm{BL}}} \times 100, \tag{3}$$

where P_{MI} denotes the mu-power during the motor imagery (opening/closing hand movie) and P_{BL} denotes mu-power during the baseline. P_{MI} (or P_{BL}) of each channel was the grand averaged mu-power (see equation (1)) of the remaining trials.

2.6. Statistical analysis

Significance levels were calculated at C3 and C4 only. Welch's ANOVA and Dunnett's T3 post-hoc test were used to test for significant differences among average mu-power of five baselines (or five hand movies) both for single subjects and at group level. Note that the Welch's ANOVA and Dunnett's T3 post-hoc were employed instead of One-Way ANOVA and Tukey post-hoc, since the variances of mu-power in each baseline condition were unequal (see section 3.3).

At the single subject level, the 15 trials (or less, depending on how many outlier trials were removed) were divided in 1 s long segments and assembled as one long 105–135 s long time series. Note that 105 (or 135) s resulted from multiplying 7 (or 9) segments with 15 trials. For this series, we computed the mu-power of each segment. First, to classify subjects into groups, we employed a t-test to compare differences between baseline mu-power and hand movie mu-power. In any subject, if the mu-power of any baseline was significantly higher than that of the hand movie, we considered that subject as a member of the mu-suppressive group. If not, the average PDS in each baseline was visually inspected; the subject was considered as a member of the non-suppressive group (if a distinctive peak in mu-rhythm was found), or a member of the mu-absent group (otherwise). This resulted in three distinct groups. All members of the mu-absent group were rejected from any further analysis.

Second, to check the distribution of mu-power in each baseline, we first performed a homogeneity test to evaluate if variances for different baselines were similar. Subsequently, we employed Welch's ANOVA and Dunnett's T3 post-hoc test using SPSS to test for significant differences among the average mu-power of five baselines (or five hand movies); each baseline consisted of 105–135 mu-power segments. The significance levels were set at 0.05. Similar procedures were repeated for the analysis of five hand movies.

At the group level, only the non-suppressive and the mu-suppressive group were analyzed. At each group level, mu-powers of similar baseline from all group members were arranged into a single class regardless of their subject origins. Each class consisted of ≈1260–1620 segment mu-powers (for the mu-suppressive group or ≈210–270 for the non-suppressive group). Note that 1260 (or 1620) resulted from multiplying 105 (or 135) segments with 12 (the number of members in group 3). Similar to the single subject level, Welch's ANOVA and Dunnett's T3 were employed. The same procedures were also repeated for the five hand movies.

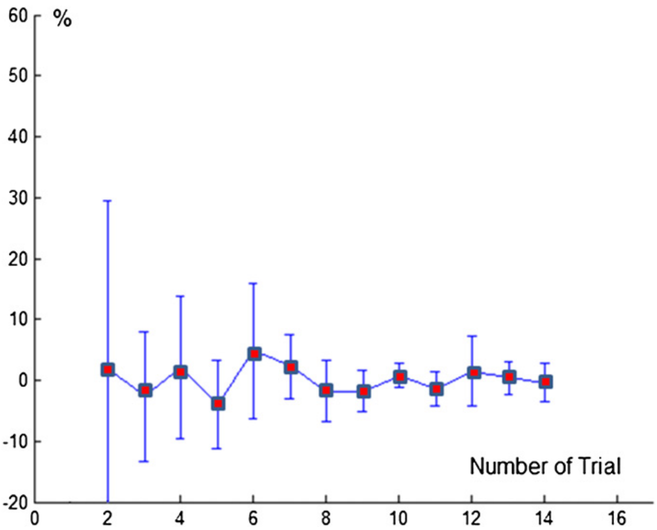

Figure 2. Progressive changes in mu-power as a function of increasing number of trials, averaged over all 14 subjects (all trials were selected randomly). The mu-power becomes (weakly) stationary after 6 to 7 trials. Square symbols indicate the mean, error bars indicate the standard deviation, averaged over 14 subjects. The progressive change in mu-power ($\mathrm{Mu}_{\mathrm{avg},k}$) was computed according to: $\mathrm{Mu}_{\mathrm{avg},k} = (\sum_{i=1}^{14} \frac{|\mathrm{Mu}_{i,k} - \mathrm{Mu}_{i,k-1}|}{\mathrm{Mu}_{i,k}} \times 100)/14$ where $\mathrm{Mu}_{i,k}$ is the mu-power of subject 'i' computed from 'k' trials; k is running from 2 to 14.

3. Results

3.1. Outlier percentage and stationarity

Outlier analysis resulted in an average of 1.4 (SD = 0.7) rejected trials (9.3%). For the remaining trials, mu-power was (weakly) stationary at the group level in group 1 and group 3 subjects (a total of 14 subjects), using six to seven trials or more, as shown in figures 2 (FL condition). A similar trend was also observed for other baselines and hand movies.

3.2. Baseline power

Subjects were classified into three groups according to their baseline power: (1) subjects who could not suppress their mu-rhythm during the motor imagery trials in all five baseline conditions (non-suppressive mu group), (2) subjects who did not show any mu-rhythm for all five baseline conditions (mu-absent group) and (3) subjects with significant mu-suppression in at least one of the five baseline conditions (mu-suppression group). The three groups represent about 11% (2/18), 22% (4/18) and 67% (12/18) of the study population, respectively. Figure 3 shows an example of each group.

3.3. Baseline power and ERD

Table S1 presents the ANOVA results for each of 18 subjects for C3 channel (see the supplementary section available at stacks.iop.org/JNE/10/026009/mmedia). Test for homogeneity showed that about 80% (10/12 subjects) of mu-power segments in the five baselines (60% (7/12 subjects) in the hand movies) were not homogeneous. Significant mu-power differences were found between the five baseline conditions in 75% (9/12) of group 3.

For each subject, the baselines that show consistently high mu-power are considered as optimal baselines. In figure 4, the group 3 subjects are divided into two subgroups: (i) a no preference subgroup, which represents the subjects who show clear contralateral ERDs in almost all baseline conditions (at least four out of five baselines), which represents ≈17% (3/18) of the study population and (ii) a preference subgroup, which represents the subjects who show a clear contralateral ERD in some particular baseline(s) (50% (9/18) of the study population). The inset in figure 4 shows the distribution of the optimal baseline (mu-power is high and a clear and significant contralateral ERD is observed) in the mu-suppressive group.

3.4. Group level analysis

Figure 5 shows the mu-power (C3) in each of the five hand movies and the five baselines from group 3. Significant mu-power differences were only found among the five baselines with $P < 0.01$, but not between the (identical) hand movies. Results are summarized in table 1. No significant mu-power differences between the five hand movies or baselines were found in group 1.

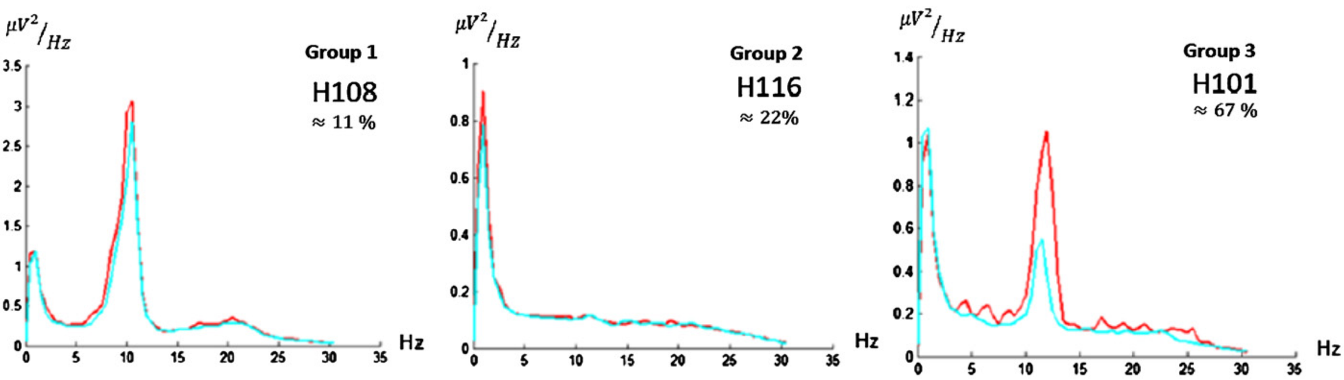

Figure 3. Three representative examples (H108, H116 and H101) of the grand averaged PDS of the three groups identified: (1) group 1 with a non-suppressive mu-rhythm during motor imagery, (2) group 2 with an absent mu-rhythm, (3) group 3 with a suppressive mu-rhythm during motor imagery. Spectra were calculated from the contralateral mu-rhythm (C3) of 15 trials of hand movies (blue) versus the 15 trials of BB baseline (red). Percentages denote the percentage of the population sharing a similar response.

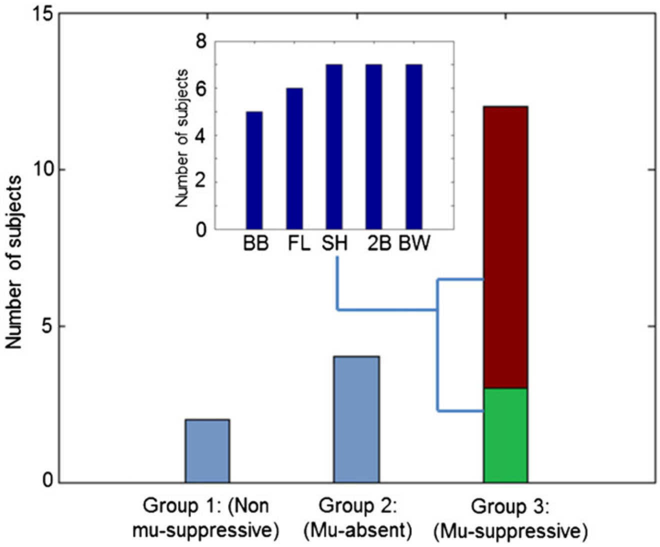

Figure 4. The number of subjects in the three groups (non mu-suppressive, mu-absent and mu-suppressive) using the contralateral mu recorded at C3. The last group is divided into the 'no preference baseline' subgroup (green) and the 'preference baseline' subgroup (brown). The inset represents the distribution of the optimal baseline in the mu-suppressive group.

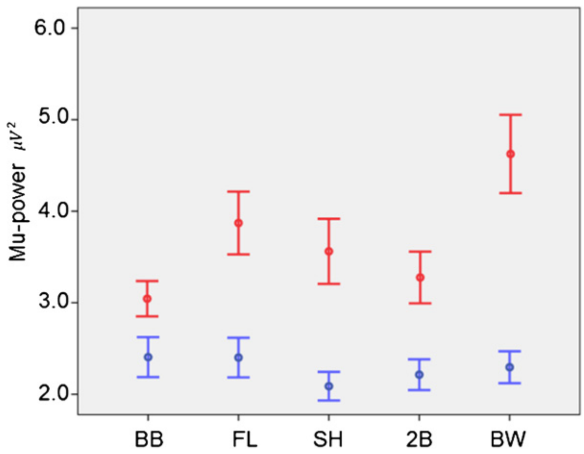

Figure 5. Mu-power (C3) in five hand movies (blue) and five baselines (red) from group 3. While baselines are all statistically different, hand movies are not.

Table 1. Summary of the results from Welch's ANOVA in the group levels.

	Group 1 (non-suppressive mu) *P*-value (Welch-ANOVA)		Group 3 (suppressive mu) *P*-value (Welch-ANOVA)	
Channel	5 hand movies	5 baselines	5 hand movies	5 baselines
C3	0.53	0.18	0.08	<0.001
C4	0.02	0.05	0.26	<0.001

3.5. Analysis of the baseline in subjects H109 and H111

We selected two subjects (H109 and H111) from group 3 as typical examples to show the detailed PDSs in the five baseline conditions and the effect of each baseline on topographical ERDs (TopoERDs).

In figure 6, PDSs during different baseline- versus motor imagery conditions are shown. In subject H109 (top row), the mu-power in the BB and 2B conditions is considerably higher than in the other conditions. However, in subject H111 (bottom row), the mu-power in FL, SH and BW is higher than in the other two conditions. Mu-powers in the different baseline conditions in both H109 and H111 are significantly different (see table S1 in the supplementary section available at stacks.iop.org/JNE/10/026009/mmedia).

3.6. Topographical ERDs of five baseline conditions in subjects H109 and H111

TopoERDs of subjects H109 and H111 are presented in figure 7. In subject H109, clear sensorimotor ERDs are observed only in BB and 2B conditions. This is in line with the PDSs in figure 6, where the baseline mu-power is high in the BB and 2B conditions. In subject H111, a clear sensorimotor ERD is observed in the TopoERD obtained for the BW condition; besides, smaller sensorimotor ERDs are observed for the FL and SH conditions. Thus, the BB and 2B conditions are the optimal baselines for subject H109, whereas the FL, SH and BW conditions are the optimal baselines for subject H111.

3.7. Long term stationarity of ERD

Comparing the TopoERDs from the first and second measurement, the ERDs in four out of six subjects (H101, H106, H107 and H111) are highly reproducible for almost all baselines. The results of the other two subjects show high reproducibility in three out of five baselines. Two examples of highly stationary TopoERDs are shown in figures 8(a) and (b). To compare the first and second measurement of mu-power in all six subjects, we tracked the changes of mu-power rank of each baseline. The results of the six repeated measurements are presented in table 2. In two cases, changes (Up or Down) are significant (bold and italic, see table 2). In table 2, for each baseline condition, the two columns represent the following: the first column represents the ranking of the mu-power in the first and second measurement (1 is highest, 5 is lowest). The second column represents the rank change: e.g. 1 Up or 1 Down. Significant changes in ranking are marked with red.

3.8. Analysis of ipsilateral (C4) mu-rhythm

The inter-trial outlier analysis using the ipsilateral mu-rhythm (from C4) showed that 1.2 trials (SD 0.7) were outliers. The three groups, found using analysis of the ipsilateral mu (C4), were similar to those found using the contralateral (C3) modulation of the mu-rhythm: group 1 (≈17% (3/18)), group 2 (≈17% (3/18)) and group 3 (67% (12/18)); see supplementary figure S1 available at stacks.iop.org/JNE/10/026009/mmedia for more details. In the mu-suppressive group (group 3), 75% (9/12) of the group members were baseline preference subjects (50% of the study population). At group level, significant differences were found among the five baselines ($P < 0.001$) in this group. In sum, no significant differences

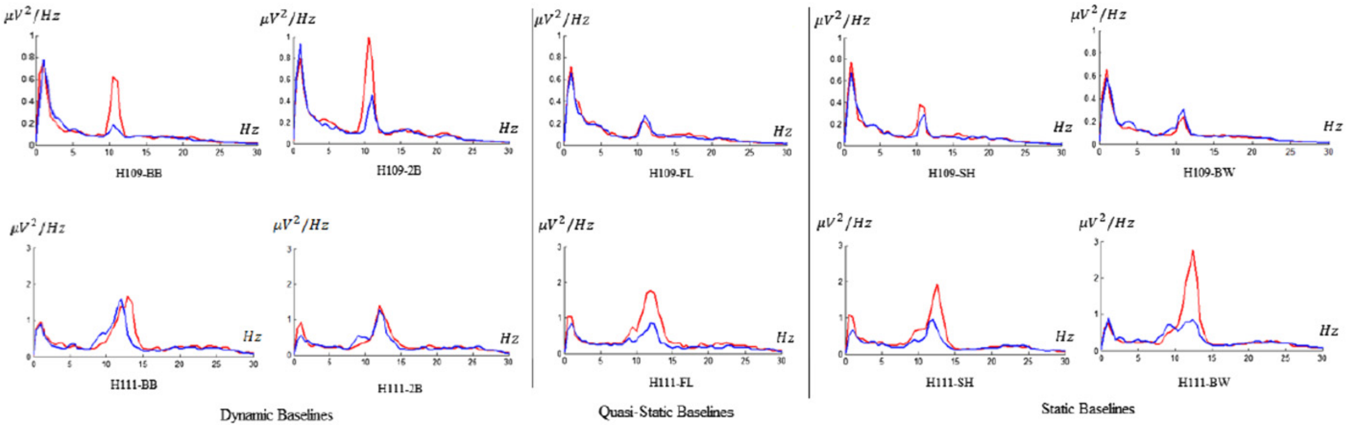

Figure 6. Effects of baseline on PDSs (red) in subjects H109 and H111. PDSs during the MI are shown, as well (blue). All data were from contralateral mu (C3).

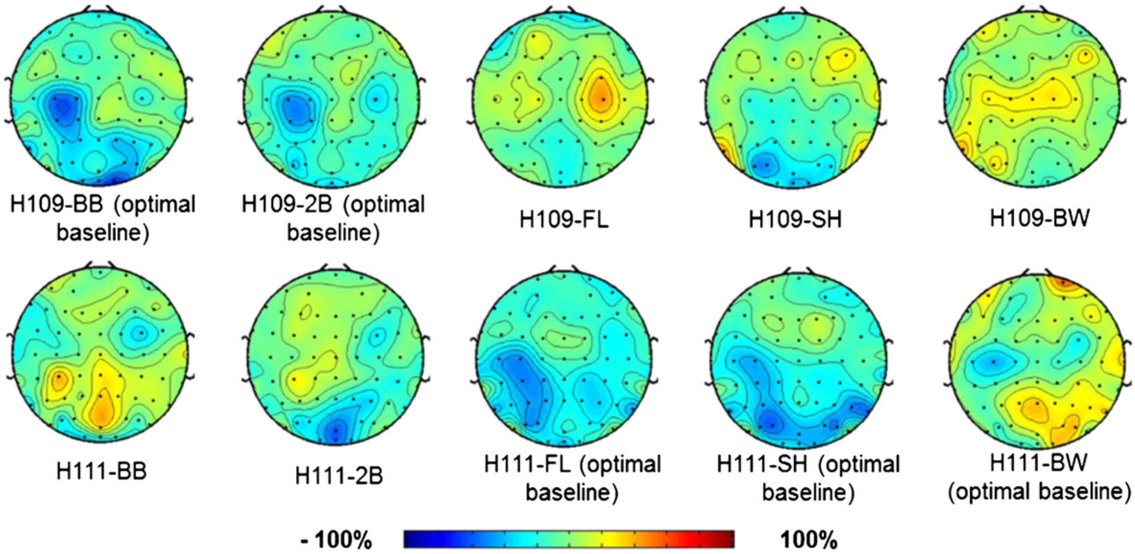

Figure 7. TopoERDs of two subjects H109 and H111. Blue indicates desynchronization of mu-power; red indicates synchronization of mu-power during MI. The BB and 2B conditions are the optimal baselines for subject H109 while the FL, SH and BW conditions are the optimal baselines for subject H111.

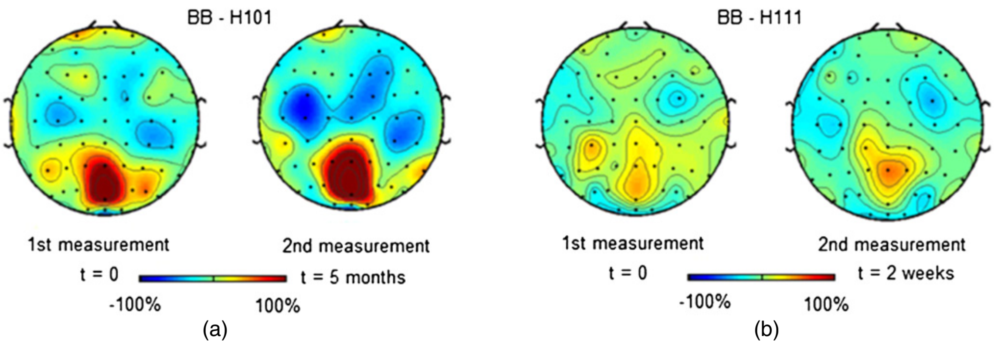

Figure 8. Two examples of topoERDs (subjects H101 and H111, BB baseline movies), showing high similarity between the first and second measurement.

regarding selection of the optimal baseline were found between using the contralateral (C3) and ipsilateral (C4) mu-rhythm. More details are presented in table S2 (supplementary section available at stacks.iop.org/JNE/10/026009/mmedia).

4. Discussion

In this study, we explore the relevance of the choice of baseline on the ERD during motor imagery. Without a stable, and

Table 2. Summary of mu-power ranking among the five baselines in the first and second measurement.

		BB		2B		FL		SH		BW		Time
Subject	Channel	Rank 1st/2nd	Rank changed	Rank 1st/2nd	Rank changed	Rank 1st/2nd	Rank changed	Rank 1st/2nd	Rank changed	Rank 1st/2nd	Rank changed	delayed (month)
H101	C3	2/2	–	1/1	–	4/3	1U	5/5	–	3/4	1D	5.0
H103	C3	4/5	1D	5/4	1U	2/3	1D	3/1	2U	1/2	1D	5.5
H104	C3	2/2	–	4/3	1U	3/1	2U	5/4	1U	1/5	***4D***	6.5
H106	C3	5/4	1U	4/3	1U	2/2	–	3/5	2D	1/1	–	4.0
H107	C3	5/4	1U	4/3	1U	3/2	1U	2/5	***3D***	1/1	–	4.5
H111	C3	5/5	–	4/4	–	1/3	2D	3/2	1U	2/1	1U	0.5

preferably strong, baseline mu-rhythm, the suppression of mu-rhythm during motor imagery cannot be reliably estimated. Our study shows that maximal mu-power is not always found for a 'static baseline' as in some subjects dynamic or quasi-static baselines showed larger mu-powers than static baseline images.

4.1. Mu-power can be maximized depending on the baseline used

In about 67% of the study population particular baselines (not necessary static) showed significantly higher mu-power than others. We did not find a common optimal baseline movie in all subjects, rather each subject showed a different optimal baseline. The preference for particular baselines was found to be reproducible, according to the high spatial similarity between the first and second TopoERDs in subjects who participated twice.

Besides the mu-power difference among five baselines, we found that nearly half of the group 3 subjects did show different mu-power in some particular hand movies. However, this difference was less prominent than that between the five baselines in two aspects: (1) this difference is found in ≈50% of group 3 subjects compared to ≈75% for the five baselines and (2) the absolute mu-power differences between minimum and maximum hand movie mu-power (in ≈70% of group 3 subjects) was about half (or less) of what was found for the five baseline mu-powers (see table S1 columns 6 and 11, available at stacks.iop.org/JNE/10/026009/mmedia). The latter implies that mu-power has a higher variation among the five baseline conditions than among the five hand movies. This high variation among five baselines found in the majority of the study population underlines the stronger effect of baseline on mu-power, and subsequently on ERD than that of hand movie mu-power. This finding implies that it is more difficult to set up the environment to induce maximal baseline mu-power by trying to relax the subjects than to suppress the mu-power by imaging movement.

Group level analysis showed that a significant mu-power difference was only found among five baseline conditions in group 3 while no significant differences were observed among the five hand movies. This confirms the single subject analysis that the difference in ERD was caused by the variation of the baseline rather than that of the hand movie.

As shown in figure 4, two subgroups of mu-suppressive subjects were found and baseline preference subjects represent 50% of the study population (or 75% of group 3 subjects). When a non-optimal baseline is presented to a subject, a clear contralateral ERD will not be observed, as illustrated in figure 7.

All 18 subjects reported mixed responses during the baseline. For instance, many reported that during the BW baseline it was difficult to maintain attention. Some of them started counting the white stripes on the screen. Some of them claimed that it was good to block all movement imagination. During the SH baseline, many subjects reported that it was difficult to block movement imagination. During the FL baseline, most subjects felt most comfortable and most relaxed; sometimes they lost their attention. During the dynamic baselines (BB and 2B), some subjects said that they usually kept their attention to the ball(s). Some claimed that they felt irritation while observing the moving ball(s). It is clear that different visual inputs elicit different responses. In addition, it also shows that even if the same baseline is used, the subject's response is different depending on his or her perspective.

4.2. Mu-ERD found in about 67% of the study population

In 12 subjects (≈67%), a clear contralateral ERD (mu-ERD) was observed. Mu-ERDs could be calculated thanks to high mu-power during baseline. Previous studies reported a percentage of mu-power carrying subjects ranging from 15% to 70% [22–24]. These values were estimated from baseline where subjects were instructed to be relaxed and keep their eyes open. If a single baseline (e.g. 2B, BW or FL baseline) had been used in our study, mu-ERDs would have been found in approximately 40% of the study population. This emphasizes that selection of the optimal baseline enhances the chance of observing mu-ERD.

In the remaining 33%, mu-ERD was not observed (either non-suppressive mu subjects (group1) or mu-absence subjects (group 2). We hypothesize that the subjects in group 1 may show mu-ERD when (1) more meaningful or more complex hand movements are presented or (2) the kinesthetic imaging strategy is pursued [12, 9]. In group 2 subjects, the reason of mu-rhythm absence is unclear; absence was also reported in many other studies [12, 22–24].

4.3. Independence of mu-power from occipital alpha-power during baseline

Two tests were performed to examine possible influence of occipital power on central electrodes (C3 and C4). First, the similar analyses as in tables S1 and S2, available at stacks.iop.org/JNE/10/026009/mmedia, were performed for O1 and O2. The resulting optimal baselines for O1 and O2 were different from those for C3 and C4, respectively. Second, a correlation analysis was performed to compare mu-power or alpha-power for each baseline movie, between electrode pairs: C3–C4, O1–O2, C3–O1 and C4–O2. Strong correlation was found for C3 versus C4 ($r = 0.91$, $P < 0.001$) as expected, while the correlation between the mu-power in C3 and the alpha-power in O1 ($r = 0.25$, $P = 0.056$) was weak. Similarly, strong and weak correlations were found for O1 versus O2 ($r = 0.79$, $P < 0.001$) and for C4 versus O2 ($r = 0.49$, $P < 0.001$).

4.4. Functional interpretation of mu-ERD

There exist two types of mu-band (lower (8–10 Hz) and upper (10–12 Hz)), which result in different reactivity patterns during performing a motor task. While lower mu-ERD is more widespread, upper mu-ERD is more focal [25, 26]. Neuper and Pfurtscheller suggested that the lower and upper mu-ERD lead to different functional interpretations: i.e. the widespread lower mu-ERD indicates all cortical areas involved in a motor task but not necessarily indicates the critical area to support a specific movement as the upper mu-ERD [18]. Thus selection of narrow mu-band depends on desired interpretation; for a general purpose here we used the broad-band mu (8–13 Hz). Specifying an optimal narrow mu-band will not only result in a clearer functional interpretation, it also enhances a chance of observing ERD (since in some subjects only part of the mu-band is suppressed during a motor task).

4.5. Limitations and future improvements of the baseline study

In this study, no EMG was recorded. However, potential muscle activity was monitored by visual inspection. Another limitation of our study is the absence of a systematic criterion for the initial selection of the five baselines used. We used both movies and a static image. Of course, we cannot exclude that there may exist a baseline that is optimal for all subjects, for instance a blank or black screen. However, these two conditions would have resulted in very different luminosities that may have an effect on the ERD. In addition, a black screen may have affected the attention of our subjects who were already sitting in a dim room. The screen with the black background and white stripes was regarded as a compromise between a black screen only and a white screen. A third limitation may seem that no real hand movement was included. In our study, however, we focus on the differential sensitivity of mu-rhythm modulation by various external inputs. Finally, although the duration between baseline (10 s) and hand movie (8 s) was different, the reduction of the baseline length to 8 s did not change the conclusions from this study. The average baseline mu-power reached a stable level after 5 or 6 s (see one example in the supplementary figure S2 available at stacks.iop.org/JNE/10/026009/mmedia).

In closing, our study supports the importance of baselines for ERD outcomes. An ideal baseline should block movement imagination, and induce a relaxed state, while maintaining attention. We show that either static or dynamic baselines can induce or maximize mu-power, with significant inter-individual differences. A common baseline, which maximizes the strength of the mu-rhythm, was not found at group level. However, at the individual level, the mu-rhythm can be induced or maximized by choosing a particular baseline movie. Mu-rhythms recorded during static baselines were not always stronger than those obtained during dynamic baselines. Therefore, we suggest performing a calibration experiment to determine the optimal baseline at the start of any motor imagery experiment.

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