Design of electrode layout for motor imagery based brain–computer interface

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A simple electroencephalogram (EEG) electrode layout is proposed to implement a motor imagery based brain–computer interface (BCI). The design was derived from investigation of EEG synchronisation in the motor cortex. A significant improvement in BCI performance was obtained in the new system.

Introduction: A motor imagery based brain–computer interface (BCI) translates a subject's motor intention into a command signal through real-time detection of motor imagery states, e.g. imagination of left and right hand movement. During motor imagery, electroencephalogram (EEG) signals accompany power changes in movement related μ (8–12 Hz) and β (18–26 Hz) rhythms, representing a power increase or decrease named event-related desynchronisation and sychronisation (ERD/ERS) in specific motor cortex areas [1]. The first motor imagery based BCI was developed by Pfurtscheller *et al.* [2] and was based upon the detection of EEG power changes caused by ERD/ERS of μ and β rhythms during imagination of left and right movements. Another motor imagery based approach was to train users to regulate the amplitude of μ and β rhythms to realise 2-D control of cursor movement [3].

Functional neuroimaging studies indicated that motor imagery also activates the supplementary motor cortex area (SMA) [4]. However, existing algorithms for classifying motor imagery states only focus on the ERD/ERS over the primary sensory-motor cortex. How to explore the value of the SMA for motor imagery classification is a challenge because SMA may be activated under all motor imagery states, i.e. no obvious power difference exists. In recent years, measurement of brain synchrony with EEG signals has been applied for exploring the dynamics of brain networks [5]. In our previous study, we investigated the phase synchronisation of μ rhythms between the SMA and the primary motor cortex (M1) and observed a contralateral increased synchronisation similar to the ERD distribution [6]. This phenomenon makes it possible to utilise the signal over the SMA to enhance the significance of power difference between M1 areas, through considering SMA as the reference.

Here we propose a novel electrode layout inspired by the synchronisation between the SMA and M1. The layout of two bipolar leads, i.e. C3-FCz and C4-FCz, is demonstrated to be optimal for recognising motor imagery states, which thus can satisfy the necessity of a practical BCI.

Experiment: Fig. 1 shows the paradigm of online BCI control with visual feedback. The 'left hand' and 'right hand' movement imagination were designated to control vertical cursor movement. The subject sat comfortably in an armchair, opposite a computer screen displaying visual feedback. The duration of each trial was 8 seconds. During the first 2 seconds, while the screen was blank, the subject was in the 'relax' state. Immediately after these first 2 seconds, a visual cue (arrow) was presented on the screen, indicating the imagery task to be performed. The arrows pointing upwards and downwards indicated the imagination of the left hand and the right hand movement, respectively. After 3 seconds, a cursor started to move at constant speed from the left side to the right side of the screen. The vertical position of the cursor was determined by the power difference of μ rhythm between left and right hemisphere (C3 and C4 electrodes). After 8 seconds a true or false mark appeared to indicate the final result of the trial and the subject was asked to relax and wait for the next task. 32 EEG channels with earlobe reference were recorded with scalp electrodes according to the 10–20 international systems of electrode placement, including M1 (C3 and C4) and SMA (FCz) [7]. The signal was digitised at 256 Hz and filtered through a subject specific μ rhythm passband for further analysis.

Phase synchrony: Given $S_x(t)$ and $S_y(t)$ as the signals over electrodes x and y, and $\phi_x(t)$ and $\phi_y(t)$ their corresponding instantaneous phases, the instantaneous phase difference between $S_x(t)$ and $S_y(t)$ is defined as $\Delta\phi(t)$. $\Delta\phi(t)$ is a constant when $S_x(t)$ and $S_y(t)$ are perfectly synchronised. In scalp EEG signals with low signal-to-noise ratio, the true synchrony is always buried in a considerable background noise, therefore a statistical criterion has to be provided to quantify the degree of phase-locking [5]. A single-trial phase locking value is defined for each individual trial as

$$\mathrm{PLV} = |\langle e^{j\Delta\phi(t)}\rangle_t| \tag{1}$$

where $\langle \cdot \rangle_t$ is the operator of averaging over time. In the case of completely synchronised signals, $\Delta\phi(t)$ is a constant and PLV is equal to 1. If the signals are unsynchronised, then $\Delta\phi(t)$ follows a uniform distribution and PLV approaches to 0.

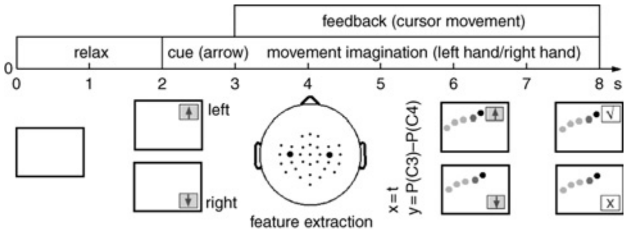

Fig. 1 *Online paradigm of classifying motor imagination of left and right hand movements*

$x = t$ The horizontal cursor position is the time point in the current trial
$y = P(C3)$-$P(C4)$ The vertical cursor position is the accumulated power difference between C3 and C4

Since SMA and M1 areas are considered primary cortical regions involved in the task of motor imagery, we investigated EEG synchrony between these regions (i.e. three electrode pairs of FCz-C3, FCz-C4, C3-C4). Fig. 2 displays the statistical PLV obtained through averaging over all trials in each class. It presents a contralateral dominance during hand movement imagery, e.g. PLV of C3-FCz has a higher value during right hand imagery than left hand. In contrast to C3-FCz and C4-FCz, PLV shows a low synchrony level between C3 and C4 and there exists no significant difference between left and right hand imagery. This observation is consistent with that reported in [8]. Moreover, the synchronisation between FCz and C3/C4 is with a small phase shift (0.008 ± 0.250 rad).

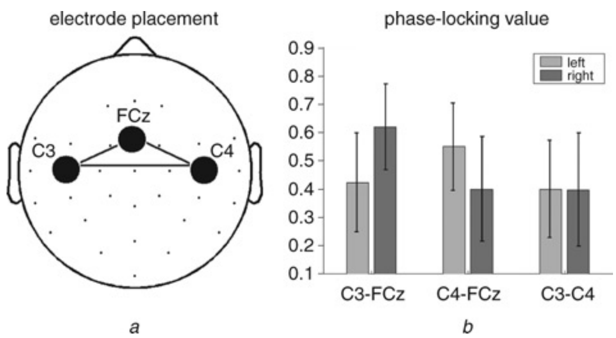

Fig. 2 *Placement of electrode pairs and corresponding statistical PLVs for one subject*

a Placement of three electrodes (C3, C4, and FCz) in system
b Statistical PLVs of three electrode pairs (C3-FCz, C4-FCz, C3-C4)

Electrode layout: Since the SMA can be considered zero-phase synchronised with the ERD region, the power difference between M1 areas can be more significant if using FCz as the reference electrode. As shown in Fig. 3, during left hand imagination the subtraction of zero-phase synchronised $S_{FCz}(t)$ from $S_{C4}(t)$ results in a much lower power, whereas the power of $S_{C3}(t)$ changes slightly after the subtraction ($S_{C3}(t)$, $S_{C4}(t)$, and $S_{FCz}(t)$ are ear-referenced EEG signals on C3/C4, and FCz, between which the power difference is not very significant). This idea can be summarised as the following inequality

$$\begin{aligned}\langle|S_{C4}(t) - S_{FCz}(t)|^2\rangle_t &< \langle|S_{C4}(t)|^2\rangle_t < \langle|S_{C3}(t)|^2\rangle_t \\ &\simeq \langle|S_{C3}(t) - S_{FCz}(t)|^2\rangle_t\end{aligned} \tag{2}$$

where $\langle \cdot \rangle$ is the operator of averaging over the left hand imagination period, and the power difference between $S_{C4}(t)$ and $S_{C3}(t)$ is due to ERD.

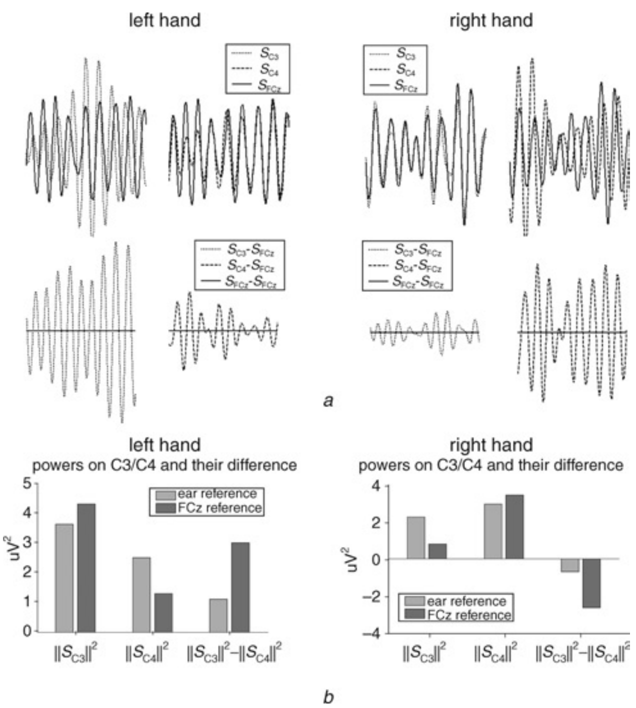

Fig. 3 *Examples of using FCz reference to enhance power difference between C3 and C4 during imagination of left and right hand movement*

a EEG waveforms on C3/C4 and FCz with ear and FCz reference
b EEG powers on C3/C4 and their difference

Results: Table 1 lists power based classification results and the r^2 (i.e. the proportion of the variance of the feature accounted for by label information [9]) of power difference between C3 and C4 on four subjects corresponding to ear reference, common average reference (CAR), and FCz reference. The CAR approach is a highpass spatial filter suited to extracting the localised μ rhythm [9]. Compared with ear reference, the r^2 values are significantly increased when using FCz reference, while the mean accuracy of FCz reference is increased from 83.28 to 88.83%, which is similar to 88.42% of CAR reference using total 32 channels.

Table 1: Classification accuracy ± std on four subjects with ear reference, CAR reference, and FCz reference through 10 × 10 cross-validation (r^2 of the power difference between C3 and C4)

Subjects	Ear	CAR	FCz
ZYJ	91.50 ± 1.05% (0.66)	99.76 ± 0.13% (0.80)	97.28 ± 0.53% (0.74)
ZD	82.87 ± 1.02% (0.46)	86.02 ± 0.96% (0.56)	91.60 ± 0.64% (0.64)
FL	87.87 ± 1.25% (0.60)	91.07 ± 1.03% (0.68)	90.48 ± 0.76% (0.64)
PF	70.89 ± 1.19% (0.24)	76.85 ± 0.82% (0.33)	75.97 ± 1.03% (0.33)
Mean	83.28%	88.42%	88.83%

Conclusion and discussion: SMA has long been recognised to play an important role in the planning of movement, but its value in motor imagery based BCI application has rarely been explored. In our study of brain synchronisation, the SMA activity contains additional motor imagery related information, which can be used to enhance BCI performance. In the power based feature extraction, FCz reference was designated to augment the power difference between the synchronised and unsynchronised M1 sides, although its power was almost the same during both hand imagery states.

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