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Decoding Performance for Hand Movements: EEG vs. MEG

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Abstract— **A direct comparison of the decoding performance of EEG and MEG in respect of hand movements is provided in this study. We recorded simultaneously EEG and MEG signals of the human contralateral motor cortex during center-out movements (four targets) and decoded directions by regularized linear discriminant analysis. Similar maximum decoding power (DP) was found for EEG (54%) and MEG (57%) ∼450ms after movement onset, using EEG+MEG the DP remained at 57%. No significant (p>0.05) difference for the maximum DP between the three signals was found. EEG and MEG provided significant (p<0.05) DP ∼0ms and ∼–100ms relative to movement onset. In conclusion, EEG and MEG yield approximately the same maximal DP in this paradigm with the MEG allowing for a slightly and significantly (p<0.05) earlier decoding than the EEG.**

I. INTRODUCTION

Voluntary movements are controlled by several areas of the brain, including primary and premotor cortex. It has been well established that the spiking activity of single neurons in primary motor cortex correlates with various parameters of the movement, including movement direction [1]. Recent studies have shown that also neuronal population signals, as intracortical local field potentials and epicortical field potentials, are directionally tuned and can be used to decode movement direction on a single-trial basis [2], [3], [4], [5]. However, it is less clear whether non-invasive recording techniques like electroencephalography (EEG) and magnetoencephalography (MEG) can be used in this respect and to which amount the direction information contained in EEG and MEG differs. There is an enormous amount of literature on the application of EEG in the field of brain-machine interfaces, showing that it can be used for the control of external devices [6]. However, much less is known about how the decoding accuracy of EEG compares to that of MEG. In our study, we compare simultaneously recorded EEG and MEG with regard to both maximum of and time course of decoding performance during hand movements in different directions.

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II. METHODS AND MATERIALS

A. Recording of Brain Activity

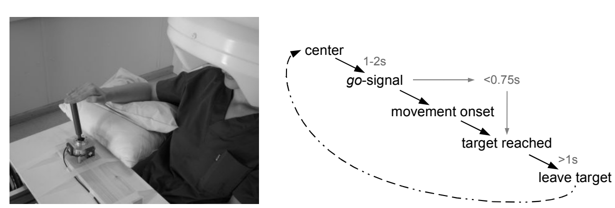
1) MEG System: The magnetic brain activity was measured using a 151-channel whole-head MEG system (VSM MedTech Ltd., Canada) consisting of first-order axial gradiometer with 5cm baseline and approximately 2.5cm intersensor spacing. The system is installed in a electromagnetically shielded room (Vakuumschmelze Hanau, Germany); the noise level is $10fT/\sqrt{Hz}$.

2) EEG System: The electrical brain activity was measured using an AC-coupled EEG system (VSM MedTech Ltd., Canada). Reference electrode was Cz, 20 recording electrodes were positioned medial above contralateral motor cortex with approximately 2.5cm spacing, and one electrode was positioned at each ear. Ground was attached to the neck.

Electrical and magnetical brain activity was recorded simultaneously (embedded in a single recording system) with a sampling rate of 625Hz and an analog low-pass filter with a cut-off frequency of 208Hz.

B. Experimental Setup

Nine right-handed subjects participated voluntarily in this study, which was approved by the local Institutional Review Board. Subjects were instructed to move a joystick from a center position towards one out of four targets (center-out paradigm) using right hand and wrist only. In each trial, the target was chosen by the subject. Subject's elbow rested on a pillow to prevent upper arm and shoulder movements (Fig. 1a); the head was stabilized by small pillows. Deflection of joystick was 4.5cm (19.5°). Targets were arranged in the form of a square with corners pointing left, right, up, and down relative to the subjects frame of reference. The frictionless joystick without return springs was designed to slightly route subject's movements, i.e. only these four targets were reachable. Visual trigger signals were presented on a screen approximately 65cm in front of the subject. These signals were used exclusively to start a trial or to



(a) (b)

Fig. 1. (a) Experimental setup. (b) Sequence of one trial along with time constraints.

indicate possible errors. In addition, a red cross was presented continuously for fixation. The experiment contained three blocks, each block contained several trials, and each trial consisted of the sequence depicted in Fig. 1b. Within the shown time constraints, the sequence was self-paced. Each trial started with joystick in center position and was initiated by presenting a gray circle on the screen. After a variable delay between 1 and 2s, the disappearance of the circle indicated the *go*-signal. A dark gray circle was displayed if time constraints (Fig. 1b) were violated; such trials were invalid and not used, the subject had to center the joystick again. In order to obtain approximately the same number of trials per target, the subject was told which directions were underrepresented after each of the first two blocks. Furthermore, electrooculogram (EOG) was recorded and head movement was monitored.

C. Data Analysis

1) Preprocessing: Data were high-pass filtered (0.5Hz, Butterworth, 3rd-order, zero phase shift) to remove offset and trend. We then redefined a trial as the time window ranging from 1000ms before to 750ms (see Fig. 1b) after movement onset (MO). MO is defined as the time point when the joystick leaves the center position, i.e. the subjects starts to move the joystick. Eye movements were detected in the EOG by threshold detection; all trials containing eye artifacts were discarded. After this preprocessing, on average 68 trials per target and subject (minimum: 52, 53, 54, and 55 for left, right, up, and down, respectively) were used for further data analysis.

A group of 20 contiguous MEG sensors covering the medial contralateral motor cortex, i.e. approximately the same area as the EEG electrodes covered, was defined in order to base analyses on the same brain activity and number of sensors in both EEG and MEG.

2) Decoding: EEG and MEG activity was decoded on a single-trial basis by regularized linear discriminant analysis (RLDA) [7]. The fraction of correctly decoded trials in percent - termed decoding power (DP) - was used as a measure of decoding accuracy. For each subject, a robust estimation of the DP was calculated by averaging the decoding performances obtained by a 10-fold repetition of the following procedure: The order of trials was permutated and the decoding performance was determined in a 10-fold cross-validation, where the set of trials used for training the RLDA and the set of trials used for decoding were mutually exclusive.

Signals in time domain were used as inputs to the RLDA-classification. In this study, EEG and MEG activity of each trial was 3Hz low-pass filtered (Butterworth, 3th-order, zero phase shift) and resampled with 12Hz. Based on these data, a D-dimensional vector was constructed using all D data points of a certain sensor within a certain time window. The tested time windows were centered at different time points within the trial. Here, the windows were shifted continuously in steps of 50ms in order to obtain a temporal evolution of decoding performance. Selecting S sensors, the D-dimensional vectors were concatenated yielding an $S \cdot D$-dimensional vector. These $S \cdot D$-dimensional vectors were constructed for each trial and, finally, used as inputs to the RLDA-classification.

3) Test of Significance: The statistical significance of the decoding power was assessed by testing the DP values against a binomial distribution. Student's paired T-test was used to assess the statistical significance of the differences in time when DP for EEG or MEG reached significance level.

III. RESULTS

In previous studies [2], [3], we have shown that the low-frequency component of intracortical and epicortical field potentials is informative with regard to movement direction. In this study, we therefore investigated the low-frequency component of the recorded EEG and MEG signals. We determined the DP of the low-pass filtered EEG and MEG for cut-off frequencies between 2 and 12Hz and found the highest DP for the 3Hz cut-off frequency. The following results were obtained using this filter setting.

Decoding EEG and MEG in sliding windows results in the time resolved DP (averaged across all subjects) provided in Fig. 2. The signal, which is decoded, was low-pass filtered only until the corresponding end of the decoding window. By this, we ensured that exclusively data before the current time point was decoded. Significant ($p<0.05$) DP could be gained approximately 0ms, -100ms, and -100ms relative to movement onset for EEG, MEG, and EEG+MEG activity, respectively. This time point was significantly earlier for MEG versus EEG ($p<0.05$) and significantly earlier for EEG+MEG versus EEG ($p<0.05$ if all 20 EEG + 20 MEG sensors (not shown) and $p<0.10$ if 10 EEG + 10 MEG sensors were used). DP increased monotonously with time and reached a maximum for all signal types around 450ms after movement onset: EEG 54%, MEG 57%, and

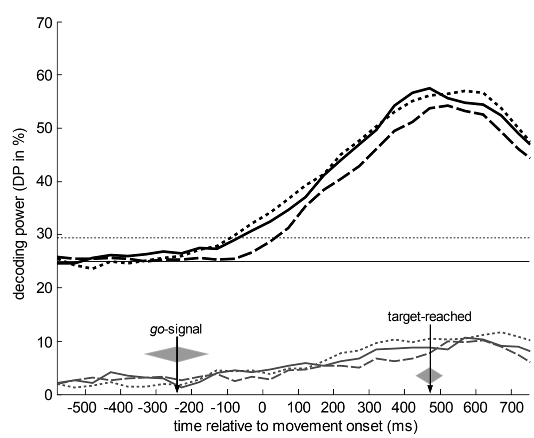
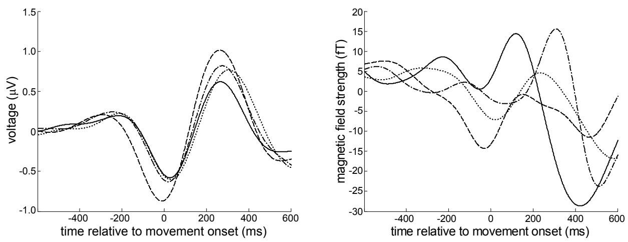


Fig. 2. Time resolved decoding power for EEG (black dashed), MEG (black dotted), and EEG+MEG (black solid), standard deviation for each signal type in gray, respectively. Graphs show DP of epochs of 250ms length immediately before the time indicated on the abscissa; temporal resolution is 50ms. The average time point of the *go*-signal and target-reached is indicated, gray diamonds reflect standard deviation. Horizontal lines: chance level (25%) and significance level (29.4%, $p<0.05$).

TABLE I

DECODING POWER (TIME RELATIVE TO MOVEMENT ONSET)

	EEG	MEG	EEG+MEG
sign. DP at approx.	0ms	-100ms	-100ms
max DP approx.	54%	57%	57%



(a) (b)

Fig. 3. Target dependent signal modulation exemplified for an EEG (a, C3) and MEG (b, MLC21) sensor. Signals were 3Hz low-pass filtered and averaged across all subjects and trials. Curves are assigned to movement direction as follows: solid - down, dashed - up, dash dotted - left, and dotted - right.

EEG+MEG 57%. None of these differences were significant (p>0.05). After this maximum, DP monotonously decreased for all three signal types.

Decoding of EEG+MEG activity was performed with half of the original EEG and MEG sensors in order to obtain the same total number (20) of sensors as for decoding of EEG and MEG. However, using all EEG and MEG sensors together, i.e. 40 sensors, increased maximal decoding performance only slightly (60%, not shown). Results are summarized in Table 1.

For comparison, the 3Hz low-pass filtered brain activity measured by one EEG or MEG sensor is exemplified in Fig. 3a and 3b, respectively. The curves (averaged across all subjects and trials) for the four targets show differences that might be utilizable for the classificator.

IV. DISCUSSION

We showed almost identical maximum decoding performance for EEG and MEG, whereas MEG provided significant direction information earlier than EEG and before movement onset. The combination of both signal types (EEG+MEG) did not yield higher decoding performance.

Both recording techniques, EEG and MEG, provided relatively high decoding power, which is, however, smaller than the DP of intracranial electrocorticography (ECoG) signals recorded during a four target center-out arm reaching paradigm (approximately 80%, [8]). It should be noted that in the ECoG study subjects performed whole arm movements instead of moving only the hand as in the experiments described here. Due to the relatively large hand area in human primary motor cortex, the movement paradigm used here might be advantageous with regard to decoding and, thus, the DP difference between ECoG and EEG/MEG might be even larger if compared in an identical task.

V. CONCLUSION

EEG and MEG can provide similar decoding performance if center-out paradigms are applied and motor cortex activity is analyzed. Either signal type in combination with a center-out task represent an appropriate approach for brain-machine interfaces.

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