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Individual trial-to-trial variability of different components of neuromagnetic signals associated with self-paced finger movements

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HIGHLIGHTS

- Brain magnetic signal associated with voluntary movement displays robust waveshape.
- The waveshape is decomposed into components on the basis of their temporal behavior.
- Three main components behave individually in each voluntary movement event.
- In spite of high variability of the components the movement is executed perfectly.
- The contribution of each component to the movement control can be studied in detail.

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ABSTRACT

We measured magnetic cortical responses to self-paced finger movements. Wide frequency band measurements revealed sharp elements of the response wave-shape, and allowed analysis of individual trials. The signal time course was decomposed into three components in the time window from 600 ms before to 600 ms after the movement. Each component had its own wave-shape and highly individual behavior. Two components displayed large trial-to-trial amplitude variations, whereas the amplitude of the third, high-frequency component remained stable. The frequency spectrum of the high-frequency component decayed exponentially, which indicates deterministic dynamics for the processes generating this magnetic signal. In spite of the large variations in the movement-related cortical signals, the movement itself, as measured by accelerometer attached to the finger tip, remained stable from trial to trial. The magnetic measurements are well-suited to reveal fine details of the process of movement initiation.

1. Introduction

The variability of single-trial responses of the brain is extensively debated, but with no generally accepted explanation [1–6]. Responses related to external stimulation are affected by the variability in the subject's attention or in the gain in the ascending pathways from the sensory organs to the cortex. In the present study, we measured cortical magnetic signals associated with self-initiated brisk finger movements; thereby minimizing instabilities associated with external stimulation. The outcome of the cortical activity, i.e., the finger movement, is nearly identical in each trial, whereas the recorded signals vary substantially. These large variations are a major challenge in the construction of brain-computer interfaces, which convert brain signals into commands for machines (prosthesis, for example) [7]. Brain signals in different frequency bands and spatial locations can be considered as indicators of the subject's intention to make a certain movement. There are examples of successful implementation of brain-controlled mechanical devices, where considerable training effort is needed to achieve a reliable performance [8]. In these cases the human brain of the subject selects appropriate brain signals in order to the control the device. It would be of great interest to identify movement-related patterns of brain signals that could be used for device control without training.

Self-paced movements are preceded by a non-oscillatory EEG signal called the Bereitschaftspotential and its magnetic counterpart, the readiness magnetic field [9]. The time courses of EEG and MEG signals reveal contributions of multiple sources [10–13]. The magnetic signals typically have an M-type wave-shape with two prominent peaks, whereas the EEG signal often lacks the central depression [9,14]. This difference is due to the spatial and

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directional selectivity of the sensors: magnetic sensors mainly pick up activity from the cortical fissures and are virtually insensitive to the activity on the outer cortical surface, which contributes the most to the EEG signal. The fact that MEG ignores activity of many sources in the brain facilitates the detailed analysis of the detected magnetic signals [15,16]. In the present study, we examine the behavior of multiple components contributing to the magnetic responses related to self-paced finger movements.

2. Method

Eight young volunteers (4 males and 4 females, age 21–30 years, mean 27, all right-handed) took part in the study. None of the participants had known neurological or psychiatric disorders. The study was approved by the local ethics committee of the Moscow University of Psychology and Education and was conducted following the ethical principles regarding human experimentation (Helsinki Declaration). The subjects were instructed to make right index finger extension at their own will, to keep the finger briefly in the up-position, and then to move it back to original position. Both hands were resting on a table, the right one on a soft cushion resembling computer mouse. This series of events took about three seconds; natural scatter in the trial duration was about 15%. Each subject made more than 140 finger movements. Magnetic brain responses were recorded using a helmet-shaped whole head magnetometer (Elekta Neuromag MEG system, 306 channels) in the Moscow University of Psychology and Education. During the measurement the participants were sitting in a magnetically shielded room. The movement was monitored by a 3D accelerometer fixed to the tip of the finger. The instant of maximum acceleration could be clearly distinguished in each trial (see Fig. 1A) and was used as a reference point for averaging. The magnetic signals were filtered at 0.03–330 Hz and recorded at the sampling rate of 1000 Hz. To avoid distortion of the wave-shapes, no additional filtering was applied to the data. For all sensors, 1200-ms epochs centered at the maximum acceleration point for each trial were extracted and subsequently analyzed using custom-made MATLAB scripts.

3. Results 1: Three components of the response

Fig. 1B shows magnetic recordings from 6 sensors (depicting data from one of the two planar gradiometers at each location) for the right index finger movement. The maximum signals were seen over the expected location of the primary motor cortex. Signals in the maximum-amplitude channel for two other subjects are included for comparison (Fig. 1A). The response curves display sharp deflections, which suggest prominent changes in the behavior of the pools of cortical neurons contributing to the signal. In these wide frequency band data, changes in the local curvature of the wave-shape are evident, with clearly discernible curved and straight lines. We often observed peaks of triangular shape in the magnetic records. A triangular shape could be readily identified in the signal time course for all subjects. Sometimes the waveform was slightly distorted or had a split tip as shown in Fig. 1A for the Subject 3. For one of our subjects the maximum response was observed much lower than for the other subjects (sensor 55—two sensors below number 16 in Fig. 1). The sharp details in the responses indicate a high degree of time locking between cortical events and the fast acceleration phase of the finger movement in our experimental setup. The latency jitter of the response to externally presented stimulus is often observed in EEG experiments and is a subject of extensive analyses [17]; this jitter smears the recorded wave-shapes and complicates the decomposition of the signals. In contrast, the quality of our data from self-paced finger movements allowed the extraction of the triangular contribution,

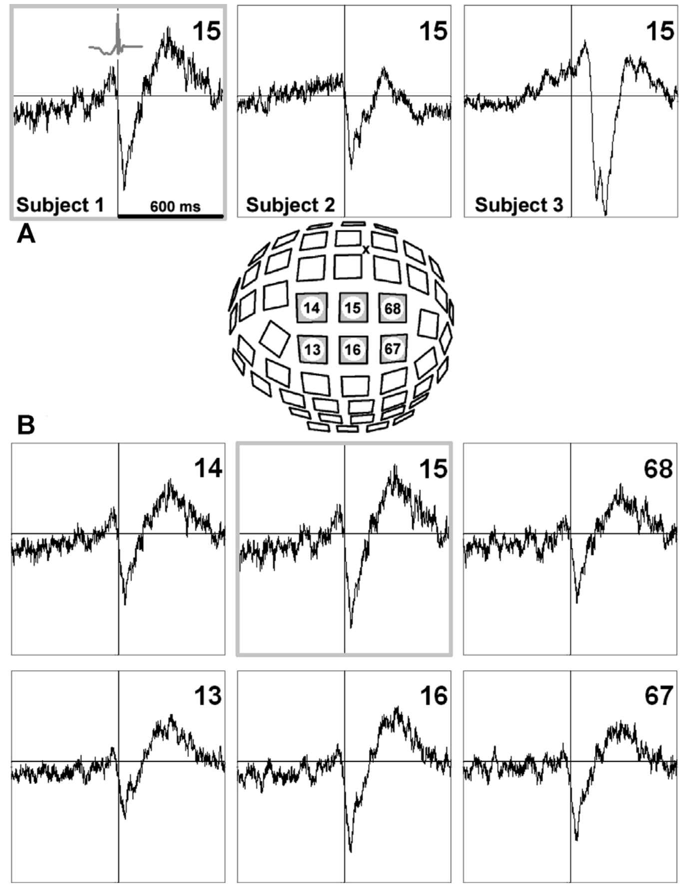

Fig. 1. Magnetic responses to right index finger movement. (A) Signals on the sensor 15 for three subjects. Average of 141 trials for the Subject 1, 165 trials for the Subject 2 and 250 trials for the Subject 3. Gray curve shows the accelerometer signal used as a reference time point for averaging. Sensor positions are shown on the helmet, viewed from the left side. The cross indicates vertex, nose points to the left. Frequency band up to 330 Hz. Full amplitude scale 12 ft/cm. (B) Average signals for the Subject 1 in 6 adjacent planar gradiometers covering left side of the head.

labelled “Comp2” in Fig. 2A. This deep-V-shaped response likely reflects proprioceptive afference to the cortex. The remaining signal after removal of the triangular contribution was quite regular and could be approximated with the smooth curve shown as “Comp1” in Fig. 2A (for this particular subject, an inverse hyperbolic cosine, which declines exponentially on both sides of the maximum). The residual was a noise-like high-frequency signal shown at the center in Fig. 2A. The three signal components contain different frequencies and are not orthogonal (in the mathematical sense) to each other. The main distinguishing factor is their time course. Note that these overlapping components are superimposed in the time domain, in contrast to a series of subsequent response peaks, which are commonly referred to as components in the analysis of EEG and MEG signal wave-shapes.

4. Results 2: Variability of the components

The high quality of the recorded signals made single-trial analysis possible. For the signal time course of each trial, the best fitting linear combination of the components Comp1 and Comp2, obtained from the averaged data, were determined (Fig. 2B). The amplitudes of the two components varied substantially across trials and their changes correlated only weakly. The high variability of the magnetic response signal is consistent with previous reports [2]; here we analyze it in fine detail. The accelerometer traces showed some variations in the dynamics of the finger movement; however, we