Performance and control error related neuronal signals in human ECoG recordings

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Abstract

In this study we investigated error related neuronal signals in a continuous task. Signals were recorded from two human subjects with electrocoticography (ECoG) electrode implants. Results show that there are neuronal signals coding for task performance related errors and for control errors, mostly in high gamma (f>60Hz) frequency range.

1 Introduction

Brain-machine interfaces (BMIs) enable subjects to control external devices like computers, robotic arms or prostheses directly by their brain activity [1,2]. To this end BMIs decode the movement intention of the subject from its neuronal activity and send respective control signals to the external effector. Typically the accuracy of the decoding is not perfect and, occasionally, a decoding error will occur where the effector does not perform the intended movement. After the subject has received feedback about the decoded state brain signals could indicate the occurrence of an error. Such error related neuronal activity could improve a BMI in the following two ways. Firstly, to detect the occurrence of an error and modify the decoded state retroactively. This would be especially useful in the case of two possible decoding states [3]. Secondly, neuronal error signals could be used to adapt the decoder and thereby improve decoding [4]. This is particularly useful as neuronal activity during BMI tasks can be non-stationary and thus, for a static decoder the decoding performance would decrease over time.

From previous studies it is known that error-related neuronal signals can be found in human EEG and fMRI [5]. These studies investigated error-related signals using trial-based paradigms with a binary outcome, correct or false. Therefore, the reported error signals provide the information whether the subject performed the whole trial correctly or not. While these signals can be discriminated very reliably, information that is provided is binary and trial-based, and therefore limited. Therefore it is not clear if during a continuous BMI control task, e.g. continuous cursor control, such error related activity can be detected and if this responses are similar to the trial based error responses. We were also interested if one can differentiate the error releted signals related to different contexts. In the task two kinds of errors were present: one related to the subject's performance, and the second one related to the subject's control.

Here we show that in brain activity measured directly from the surface of the human brain by means of electrocorticographie (ECoG) neuronal correlates of both types of errors can be found and that these signals can be differentiated.

2 Methods

2.1 ECoG experiments

2.1.1 Subjects and recordings

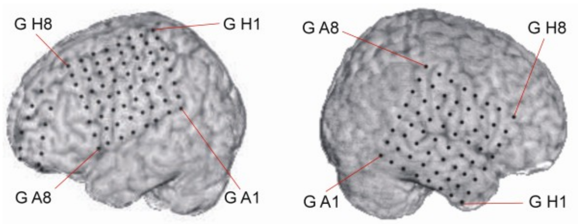

Fig. 1 MRI image of the ECoG electrode implants for subject 1 **(left)** and subject 2 **(right)**.

Two patients suffering from intractable pharmaco-resistant epilepsy were included in the study after having given their informed consent. 8*8 stainless steel electrodes grids were subdurally implanted over the left prefrontal and parietal lobe for patient 1 and right temporal and parts of prefrontal and parietal lobe for patient 2 (see **Fig 1**) for pre-neurosurgical epilepsy diagnosis. The site of electrode implantation was exclusively based on the requirements of the clinical evaluation. The study was approved by the University Clinic's ethics committee.

2.1.2 Task

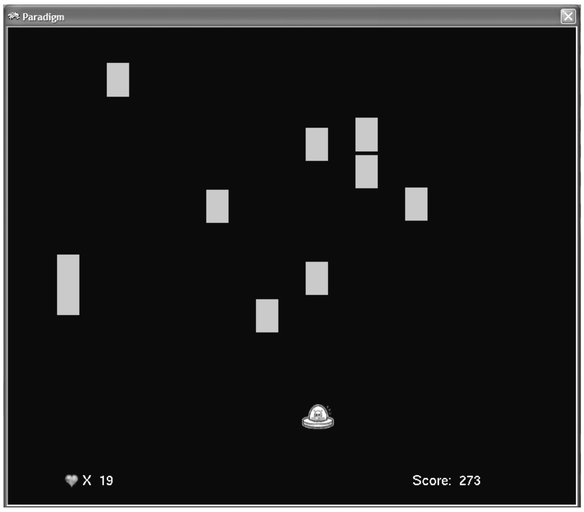

Fig. 2 Subject moved the spaceship in one dimension trying to avoid blocks falling from the top.

The task consisted of two different sessions :(I) In movement sessions subjects played a simple game in which they controlled a spaceship with an analogue joystick in the horizontal dimension (left-right, **Fig. 2**). The task was to evade the blocks dropping from the top of the screen at a constant speed. The game was challenging enough so that subjects from time to time collided with a block (performance error). In addition the spaceship would occasionally move in the opposite direction to the joystick movement (control error). To test for attention after a random time (30 seconds on average) the colour of the spaceship changed from time to time and subjects were asked to report this. As a measure of performance, points were awarded for moving the spaceship. (II) In replay sessions subjects looked at the replay of one of their earlier movement sessions and were also asked to report colour changes. Control errors were noticeable only by both controlling the spaceship and looking at the screen.

2.1.3 Events

Three different events were defined: collision of a spaceship with a block, control error and change of spaceship color. Times of these events were recorded in sync with the neuronal data and a trial was defined as a recording 500ms prior to the event till 2500ms after the event. All the trials that had events within less than 3 seconds from any other events were left out of the analysis.

2.2 Data analysis

2.2.1 Preprocessing

Electrocorticograms (ECoGs) were digitized at either 256 Hz sampling rate using a clinical AC EEG-System (IT-Med, Germany). All signals were re-referenced by using a common-average reference.

2.2.2 Time-frequency analyses

Time-resolved fast Fourier transformations (TRFFT) were applied using a Hamming window. Baseline power was computed from taking the average of the power spectral densities (PSD) calculated on recordings between trials (see 2.1.3). Normalized PSDs were computed by normalizing each frequency bin by the baseline PSD. Frequency band response was defined as mean over frequency bins of the normalized PSD. To show average frequency band responses, the mean over trials was calculated. In addition, the signal to noise ratio (SNR) of the frequency band response was calculated as:

$$SNR(t_i; f_1, f_2) = \frac{\left|\mu_{EVENT}(t_i; f_1, f_2) - \mu_{BASELINE}(f_1, f_2)\right|}{\sigma_{EVENT}(t_i; f_1, f_2) + \sigma_{BASELINE}(f_1, f_2)}$$

Where "t_i" is the time of the middle of the TRFFT window, f_1 and f_2 define the frequency band and μ is the mean and σ is the standard deviation of the frequency band response over trials, either for the event or for the baseline condition.

3 Results

Neuronal responses related to the block collisions were similar for movement and replay sessions and were highly discriminable from the baseline response with SNR going up to 1.15. The majority of the high SNR responses were in the intermediate and high frequency ranges above 25Hz. **Fig. 3** shows an example for a channel G_A3 above parietal cortex.

Responses for the control error were present only for the movement sessions. Again a response was found mainly for the frequencies above 25Hz exhibiting a lower SNR than the performance error with SNR values reaching up to 0.8.

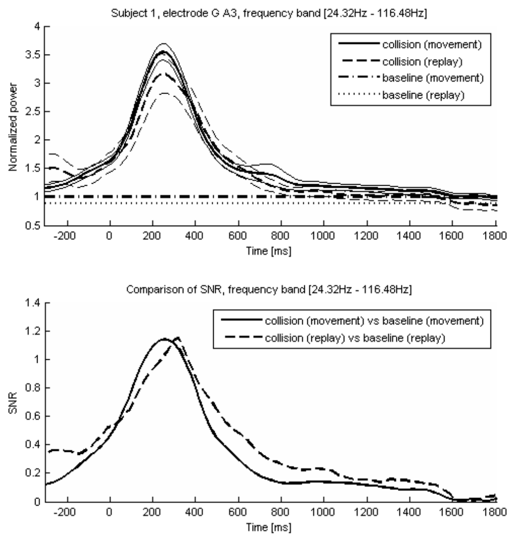

Fig. 3 **(up)** Mean and standard error of the mean of block collision and baseline neuronal signals in movement and replay sessions for subject 1, electrode G_A3. **(down)** SNR for collision vs baseline for movement and replay sessions.

In both subjects electrode locations of control error responses largely overlapped with locations of electrodes showing response with high SNR during a performance error. For both subjects there were electrodes where the control error response was completely missing and electrodes where the responses for these two events were significantly different from the baseline and from one another (**Fig. 4**)

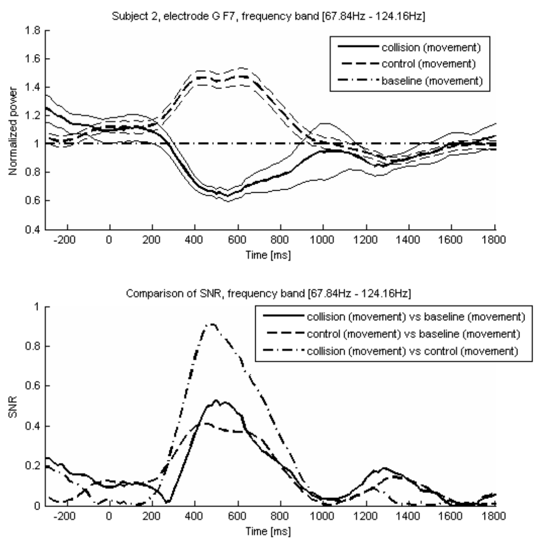

Fig. 4 **(up)** Mean and standard error of the mean of block collision, control error and baseline neuronal signals for subject 2, electrode G_F7. **(down)** SNR for collision vs baseline, collision vs control and control vs baseline for movement and replay sessions.

4 Discussion

Here we investigated the neuronal correlates of error signals in a continuous task. Two different error events were introduced: block collision, which was a performance related error, and an event in which control of the spaceship was altered (control error). Neuronal activity was measured using electrodes implanted directly on the surface of the brain (ECoG). Results suggest that neuronal correlates of these two events can be discriminated from the baseline activity and from one another. To verify this statement detection of these signals from the continuous ECoG recording should be carried out, and this is planned for the future. If successful, such error detection from brain signals could be used to facilitate adaptation of the BMI decoder and thus, improve the performance of BMI applications.

5 Literature

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