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Toward a minimally invasive brain–computer interface using a single subdural channel: A visual speller study

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ABSTRACT

Electrocorticography (ECoG) has attracted increasing interest for implementing advanced brain–computer interfaces (BCIs) in the past decade. However, real-life application of ECoG BCI demands mitigation of its invasive nature by minimizing both the size of the involved brain regions and the number of implanted electrodes. In this study, we employed a recently proposed BCI paradigm that utilizes the attentional modulation of visual motion response. With ECoG data collected from five epilepsy patients, power increase of the high gamma (60–140 Hz) frequency range was found to be associated with the overtly attended moving visual stimuli in the parietal-temporal-occipital junction and the occipital cortex. Event-related potentials (ERPs) were elicited as well but with broader cortical distribution. We achieved significantly higher BCI classification accuracy by employing both high gamma and ERP responses from a single ECoG electrode than by using ERP responses only ($84.22 \pm 5.54\%$ vs. $75.48 \pm 4.18\%$, $p<0.005$, paired t-test, 3-trial averaging, binary results of attended vs. unattended). More importantly, the high gamma responses were located within brain regions specialized in visual motion processing as mapped by fMRI, suggesting the spatial location for electrode implantation can be determined prior to surgery using non-invasive imaging. Our findings demonstrate the feasibility of implementing a minimally invasive ECoG BCI.

Introduction

The past decade has seen promising development in brain–computer interfaces (BCIs) aiming to help severely motor disabled patients to interact with the external world by directly interpreting brain activity. While the majority of BCIs rely on brain activity recorded with non-invasive electroencephalograph (EEG) technology (Daly and Wolpaw, 2008; Lebedev and Nicolelis, 2006), interest has increasingly been drawn toward the use of invasive electrocorticographic (ECoG) signals for BCI applications (Lebedev and Nicolelis, 2006; Leuthardt et al., 2004; Schalk and Leuthardt, 2011).

Compared to EEG, ECoG has two major advantages for implementing advanced BCIs. First, the spatial resolution of ECoG is much higher than that of EEG. ECoG records signals originating from brain tissues directly beneath the electrode surface (surface area of 1–10 mm^2) with little influence from adjacent tissues (Bullock et al., 1995; Nunez and Srinivasan, 2006), whereas EEG's spatial resolution is at a multi-centimeter scale due to volume conduction of currents through tissues of the head. Such a fine spatial resolution makes ECoG ideal for imaging the cortical dynamics of sensory and cognitive functions that originate from relatively small brain regions (Liu et al., 2009; Mesgarani and Chang, 2012; Vinjamuri et al., 2011). Second, low voltage, high frequency brain activity that is barely detectable in scalp EEG is readily observed in invasive ECoG recordings (Leuthardt et al., 2004). In the past few years, ECoG BCIs have achieved promising results using brain signals extracted from the motor cortex (Kubanek et al., 2009; Miller et al., 2010; Vinjamuri et al., 2011), language-related brain regions (Leuthardt et al., 2011; Pei et al., 2011a), as well as auditory and visual cortex (Brunner et al., 2010; Wilson et al., 2006).

When using ECoG or other invasive recording techniques, it is preferable to minimize the cortical area used for acquiring sufficient neural information for BCI applications. To date, ECoG BCI studies have been carried out with epilepsy patients who underwent open skull surgery and implantation of large electrode arrays for clinical purposes. However, surgery of this type is both unnecessary and risky for the potential BCI users (i.e. patients with amyotrophic lateral sclerosis). Instead, electrodes for BCI purposes can be inserted through a burr hole into the brain, thus implementing a 'minimally invasive' BCI, given that sufficient information can be extracted within a limited cortical area.

The recently developed visual motion BCI paradigm using motion onset visual evoked potentials (mVEPs) may serve as a candidate for building minimally invasive BCIs (Guo et al., 2008; Jin et al., 2012). The mVEP speller utilizes the modulation effect of mVEPs by overt attention

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(i.e., eye gaze) for a spelling application: the attended visual motion stimuli elicit a more negative peak around 200 ms post-stimulus (N200) over parietal-occipital areas than the unattended stimuli, and BCI user intent is classified based on this difference. BCI based on mVEP can be considered an extension of the widely studied P300 BCI (Donchin et al., 2000; Farwell and Donchin, 1988), which utilizes an attention-related positive event-related potential (ERP) peak around 300 ms (P300) over the parietal cortex elicited by the attended visual flash stimuli. Based on invasiveness, mVEP BCI is a better candidate than P300 BCIs, as visual motion processing (reflected by mVEPs in EEG) is believed to be highly focused in a brain region known as the human middle temporal (MT) complex (DeYoe et al., 1996; Huk et al., 2002; Zeki et al., 1991). Compared with other types of BCIs for motor and speech decoding (Kubanek et al., 2009; Leuthardt et al., 2004, 2011), relatively less information is needed for the operation of the mVEP type. By taking advantage of the visual speller design (Farwell and Donchin, 1988; Hong et al., 2009), a 36-choice spelling application can be realized on the basis of a series of binary decisions on whether the stimulus presented at certain time point is attended or not. Moreover, mVEP BCI may further benefit from ECoG recordings with broader frequency band response. Specifically, BCI classification may be facilitated by including the high gamma responses as a new feature, since visual motion processing is reflected in both low frequency mVEP responses (Matsumoto et al., 2004) and high frequency (50–120 Hz) power increase (Rauschecker et al., 2011). In the ECoG-based visual motion BCI, we predicted that stronger high gamma response would be elicited by the attended visual motion stimuli than unattended stimuli.

In this study, aiming for a minimally invasive BCI system, we explored the possibility of implementing an ECoG-based visual motion BCI using only one subdural channel. Five epilepsy patients with ECoG electrodes placed over the parietal-temporal-occipital regions were recruited. To achieve minimal invasiveness, one 'optimal' electrode per patient was selected according to ECoG responses ideal for BCI control. After the selection of the optimal electrode, ECoG signals in both the low frequency range (i.e., the traditional mVEP) and high gamma range were extracted as features for classification. Prior to the electrode implantation surgery, fMRI scans were made for two patients to localize brain regions specialized for visual motion processing. We compared the spatial locations of the optimal electrodes for BCI classification with the functional regions pre-operatively mapped with fMRI to evaluate whether fMRI can guide electrode implantation for BCI purposes. Our results demonstrate that a minimally invasive visual motion BCI can be implemented using non-invasive fMRI measurements to determine the electrode locations pre-operatively.

Materials and methods

Participants

Participants were five patients (see Table 1 for additional information) with intractable epilepsy. Intracranial ECoG electrode grids were temporarily placed in their brain to localize seizure foci prior to surgical resection. The patients all had normal or corrected-to-normal vision. Written informed consent was obtained from each patient before participation. This study was approved by the Institutional Review Board at both Tsinghua University and the affiliated Yuquan Hospital.

Each patient had an 8-, 16- or 32-electrode grid (4 mm electrode diameter and 1 cm inter-electrode center-to-center distance) placed over the right or left parietal-temporal-occipital region. Grid placement and duration of ECoG monitoring were determined entirely based on the clinical requirements.

Table 1
Clinical profiles of the subjects.

Subject	Age	Sex	Seizure type	Electrode placement	Seizure focus
A	12	M	CP	Right PL, OL	Right posterior OL
B	24	M	SP and SGTC	Right TL, PL	Right PL
C	18	F	CP	Left TL, PL, OL	Left PL
D	18	M	SP	Left PL, OL	Left posterior OL
E	14	M	CP and SGTC	Right PL, OL & Left OL	Right anterior OL

Abbreviations: M, male; F, female; SGTC, secondarily generalized tonic-clonic; CP, complex partial seizure; SP, simple partial seizure; TL, temporal lobe; PL, parietal lobe; OL, occipital lobe.

Stimuli and procedure

Visual motion stimuli were displayed on a 17-in. LCD monitor (DELL FP1708, USA) with 60 Hz refresh rate and 1280×1024 pixel resolution. The viewing distance was 50 cm. The visual speller interface is a 6 by 6 matrix of virtual buttons, as shown in Fig. 1a. In each virtual button, a vertical bar with a height of 1.73° visual angle appeared (motion-onset) at the right border of a vacant rectangle and moved leftward at the velocity of 2.00°/s before it disappeared (motion offset), forming a brief motion stimulus. The entire process of onset, motion and offset took 150 ms. The stimulus onset asynchrony (SOA) between two motion stimuli was 200 ms. As shown in Fig. 1b, the motion stimuli in the virtual buttons occurred in a random order by row/column. The overall luminance level of the stimulation screen was 40 CD m^{-2} from the patients' viewing distance. The contrasts of the motion stimuli were well above the perceptual threshold and presentation of the motion stimuli did not significantly change the luminance level.

Patients participated in two offline experiment sessions. Each session consisted of six blocks, in which the patients were instructed to overtly attend to one of the virtual buttons as target. The patients were required to mentally count the number of times the moving bar appeared in the attended button without moving their mouth. During one block, the six column stimuli and the six row stimuli were presented in a random order and were repeatedly presented for 10 or 15 times. The repetition number was decided prior to the experiment, depending on the patients' physical state and willingness. In both sessions, the six virtual buttons on the diagonal of the speller matrix from top-left to bottom-right were sequentially used as the attentional target. A trial was defined as the EEG recording epoch relative to the stimulation of a single row or column stimulus (see *Analysis of ERP and high gamma responses* for details on trial definition), with trials of attended stimuli as target trials and trials of unattended stimuli as non-target trials. As previous studies showed that no substantial difference in the elicited brain responses were found for the column and row trials (Hong et al., 2009), we did not differentiate these trials in this study. Therefore, a total number of 240/ 360 target trials and 1200/ 1800 non-target trials were acquired during the whole experiment, for repetition number of 10/ 15 per block. Presentation of the stimuli was controlled with MATLAB (the Mathworks, Natick, USA) using Psychophysics Toolbox 3.0 extension (Brainard, 1997).

Data collection

In all experiments, ECoG data were recorded from implanted electrodes using a 96-channel g.USBamp amplifier/digitizer system (g.tec, Graz, Austria). The amplifier sampled the signal at 1200 Hz using a high-pass filter with a 0.1 Hz cutoff frequency and a notch filter at 50 Hz to remove power line noise. Four electrodes that were placed on the external surface of the skull with the contacts of the electrodes facing away from the skull were used as ground and reference (two as ground and another two as reference, for redundancy).

All MRI data were acquired on a Philips Achieva 3.0T TX scanner before implantation. The fMRI scan was performed covering the whole brain, using gradient-recalled Echo Planar Imaging (EPI) with following parameters: matrix size: 128×128, voxel size: 1.8×1.8×3 mm^3, TR: 3 s, TE: 30 ms, 47 slices. T1-weighted structural MRI images were acquired with an MPRAGE sequence. Imaging parameters were as follows: matrix size: 256×256, voxel size: 0.9×0.9×1 mm^3, 180 slices.