Intracranial Hippocampus Brain

Received 29 August 2011
Received in revised form 12 October 2011
Accepted 13 October 2011

Keywords:
Brain–computer interface
Brain ventricle
Hippocampus
Intracranial electrodes
P300 Speller

A R T I C L E   I N F O

Article history:
Received 29 August 2011
Received in revised form 12 October 2011
Accepted 13 October 2011

A B S T R A C T

A brain–computer interface (BCI) is a device that enables severely disabled people to communicate and interact with their environments using their brain waves. Most research investigating BCI in humans has used scalp-recorded electroencephalography (EEG). We have recently demonstrated that signals from intracranial electrocorticography (ECoG) and stereotactic depth electrodes (SDE) in the hippocampus can be used to control a BCI P300 Speller paradigm. We report a case in which stereotactic depth electrodes positioned in the ventricle were able to obtain viable signals for a BCI. Our results demonstrate that event-related potentials from intraventricular electrodes can be used to reliably control the P300 Speller BCI paradigm.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

A brain–computer interface (BCI) is a device that uses brain signals to provide a non-muscular communication channel (Wolpaw et al., 2002), particularly for individuals with severe neuromuscular disabilities. Some of the most promising signals for controlling a BCI are event-related potentials (ERPs) such as the P300. The P300 event-related potential is an evoked response to an external stimulus that has been traditionally observed in scalp-recorded electroencephalography (EEG). The scalp-recorded P300 response has proven to be a reliable signal for controlling a BCI using the P300 Speller paradigm (Farwell and Donchin, 1988). Based on multiple studies in healthy and disabled volunteers (Serby et al., 2005; Vaughan et al., 2006; Krusienski et al., 2008; Lenhardt et al., 2008; Nijboer et al., 2008; Sellers et al., 2010), the P300 Speller has the potential to serve as an effective communication device for persons who have lost or are losing the ability to write and speak.

Intracranial surface grid arrays and depth electrodes are routinely implanted in humans for localizing epileptic seizure foci because they offer superior spatial resolution and the recorded brain signals are not attenuated by dura, bone or skin (Akhtari et al., 2000). Both styles of electrodes record local field potentials, with the surface grid array recordings referred to as the electrocorticogram (ECoG). Whether intracranial electrode recordings ultimately prove to be superior to scalp electrode recordings in controlling a BCI system remains to be seen. We have recently shown that humans can effectively control the P300 Speller using ECoG (Krusienski and Shih, 2011a) and ERPs recorded from stereotactic depth electrodes (SDE) in the hippocampus (Krusienski and Shih, 2011b). Others have also used intracranial electrode recordings to control a computer cursor (Vansteensel et al., 2010; Leuthardt et al., 2011). The location of the recording electrodes and the types of responses obtained are areas of active research. We report a proof of concept case in which ERPs from intraventricular electrodes were used to control the P300 Speller BCI paradigm.

2. Materials and methods

The subject is a 34-year-old female with medically intractable epilepsy who underwent a clinical evaluation for epilepsy surgery with temporary placement of bilateral hippocampal depth electrodes to localize her seizure focus prior to surgical resection. The plan was to insert SDE into both hippocampal bodies to record and determine the epileptic focus. The patient also consented to participate in an ongoing BCI study approved by the Institutional Review Board of both Mayo Clinic and the University of North Florida.

2.1. Electrode locations and data acquisition

Electrode placements and duration of intracranial monitoring were based solely on the requirements of the clinical evaluation, without any consideration of the BCI study. Two eight-contact stereotactic depth electrodes with 5 mm spacing between
contacts were inserted in a longitudinal fashion along the plane of the hippocampus through an occipital burr hole and guided intra-operatively by an MRI neuravigational system. After electrode implantation, the subject was admitted to the epilepsy monitoring unit to record her typical seizures. EEG data in the epilepsy monitoring unit demonstrated a significant asymmetry in signal amplitude and power between the left and right stereotactic electrodes in the range of 30–50%. This amplitude discrepancy was also observed during the BCI sessions as shown by the averaged responses provided in Fig. 2. An MRI of the brain was then performed and showed the contacts of the left stereotactic depth electrode to lie in the atrium and inferior horn of the left lateral ventricle. The distal contacts lie in contact with the ventricular surface of the left hippocampal formation (Fig. 1B). This confirmed the unanticipated finding that left depth recording contacts were not positioned in brain tissue, but in the ventricular space.

The subject performed BCI testing 24 h after electrode implantation. Testing was performed when the subject was clinically judged to be at cognitive baseline and free of physical discomfort that would affect attention and concentration. Testing was performed at least 6 h after a clinical seizure. Stimuli were presented and the data were recorded using the general-purpose BCI system BCI2000 (Schalk et al., 2004). All electrodes were referenced to a scalp vertex electrode, amplified, band pass filtered (0.5–500 Hz), digitized at 1200 Hz using a 16-channel Guger Technologies g.USBamp, and stored. The signals for the BCI experiments were acquired concurrent with the clinical monitoring via a 32-channel electrode splitter box.

2.2 Task, procedure, and design

The experimental protocol was based on the protocol used in an EEG-based P300 Speller study (Krusienski et al., 2008). The subject sat in a hospital bed about 75 cm from a video monitor and viewed the matrix display. The task was to focus attention on a specified letter of the matrix and silently count the number of times the target character flashed, until a new character was specified for selection. All data were collected in the copy speller mode: words were presented on the top left of the video monitor and the character currently specified for selection was listed in parentheses at the end of the letter string as shown in Fig. 1A. Each session consisted of 8 experimental runs of the P300 Speller paradigm; each run was composed of a word or series of characters chosen by the investigator. The first four runs (16 characters) were used to train a linear classifier using stepwise linear discriminant analysis (SWLDA) and online feedback of the selected character was provided to the subject for all subsequent runs (Krusienski and Shih, 2011a). Two sessions were conducted on consecutive days. Each session consisted of 32 character epochs and lasted approximately 1 h.

2.3 Offline response classification and visualization

Classifiers were generated using the following combinations of electrodes: all 16, 8 right hemisphere, 8 left hemisphere, each adjacent bipolar pair along each strip, and each individually using a common reference. For each channel used in the analysis, 700-ms segments of data beginning 50–ms after each flash were extracted. The data segments were lowpass filtered and decimated to 20 Hz and concatenated by channel for each flash, creating a single feature vector corresponding to each stimulus. The features from the first session were used to generate a linear classifier using linear discriminant analysis. The performance of the classifier for selecting the attended character was tested on the data from the subsequent session.

The ERPs from all electrodes and their $r^2$ correlations (i.e., the proportion of the variance of the instantaneous signal amplitude accounted for by the stimulus type, i.e., target or non-target) with the task are presented in Fig. 2. The waveforms were generated using the average of all training data used for classification. The averaged waveforms were smoothed for visualization using a 0–30 Hz lowpass filter.

3. Results

The results of the offline analysis are provided in Fig. 2. The classification accuracy after 15 flash sequences for subsets of electrodes in the left and right hemispheres is provided in the bar graphs. The blue bars indicate the accuracy using individual common referenced electrodes ordered from anterior to posterior. The intermediate red bars indicate the accuracy using adjacent electrode pairs ordered in the same fashion. The green dashed line indicates the accuracy using all 8 electrodes within a given hemisphere (left: 84.4%, right: 93.8%), and the solid black line indicates the accuracy using all 16 electrodes (96.9%), which also represents the accuracy achieved during the online experiments. Chance accuracy for the task is 2.8%.

4. Discussion

Multiple investigators have used BCI-based methods with scalp EEG and ECoG in humans to control movements through a prosthetic device (Hochberg et al., 2006) or make cursors move on
a computer monitor (Leuthardt et al., 2004; Schalk et al., 2004; McFarland et al., 2005; Santhanam et al., 2006; Felton et al., 2007; Schalk et al., 2008; Blakely et al., 2009; Wilson et al., 2009). Our previous study shows that electrical recordings from human cortex can be translated by P300-based BCI systems to produce accurate and reliable language output at least equal to and possibly superior to recordings obtained from scalp EEG (Krusienski and Shih, 2011b). We have subsequently shown that stereotactic depth electrodes placed in the temporal lobes can record signals to control a BCI-based language communication system (Krusienski and Shih, 2011a). These findings open a new avenue for research on improving communication devices for patients with ALS, spinal cord injuries, stroke, and severe inflammatory polyradiculopathies. As the risks associated with implantation of chronic intracranial electrodes continue to decrease with advances in electrode design and surgical techniques, an intracranial electrode-based P300 Speller may become a viable option for severely disabled individuals with no reliable means of communication.

The present case demonstrates as proof of concept that recording electrodes in the lateral ventricle adjacent to hippocampus can be used to control a brain–computer interface. Since the classifiers were trained and tested using data from successive days, the favorable classification performance indicates that the ERPs are consistent across multiple days. Although maximum classification accuracy (96.9%) was achieved using all electrodes, the 84.4% accuracy achieved by the electrodes within the ventricle is sufficient for effective communication. Additionally, the examination of adjacent electrode pairs indicates that it may be possible to achieve comparable performance by using only a few strategically positioned electrodes. It remains to be shown whether the signals from left or right hippocampal formation are superior for this application, or if this is subject-dependent. An additional patient performing the identical task also produced superior signals from the right hippocampal formation (Krusienski and Shih, 2011b), but it is not clear whether this is circumstantial, pervasive, or due to the disease. In the case that such a hemispherical bias exists, it is possible that electrodes positioned in the right ventricle may have produced superior performance.

The ability to utilize an SDE-based P300 Speller for communication improves the risk/benefit ratio for chronic intracranial implantation compared to ECoG with grid electrodes. SDE are often implanted through occipital burr holes with stereotactic guidance.
In contrast, a craniotomy procedure is most commonly used to place grid or strip electrodes. Postoperative steroids to reduce brain swelling is used after grid/strip implantation, but not after SDE inserted through the occipital approach (personal communication, Robert Wharen, MD, Chief of Neurosurgery, Mayo Clinic Florida). Surgical case series (Behrens et al., 1997; Burneo et al., 2006; Lee et al., 2008; Wong et al., 2009) suggest epilepsy patients undergoing SDE as opposed to subdural grids/extended strips have less morbidity. Intraventricular depth electrodes potentially may have even less long-term morbidity as they reside in the ventricles and are less likely to provoke the foreign body reactions (Winslow et al., 2010) seen with electrodes residing within brain tissue.

P300 ERPs can be recorded from SDE in the human hippocampus (Halgren et al., 1995; Clarke et al., 1999). Ludowig et al. (2010) studied the topography of the medial temporal P300 and found the highest signal amplitude in the anterior subiculum and posterior hippocampal body. All of these previous studies have obtained the P300 from intraparenchymal depth electrodes. However, previous work in epilepsy patients has shown that hippocampal electrical activity can be recorded from electrodes positioned in the inferior horn of the lateral ventricles adjacent to the hippocampal body (Song et al., 2003). Our findings are consistent with these results. We were able to use the intraventricular electrodes to record seizure activity onset and acquire the necessary clinical data to proceed to successful resection of the epileptic focus. Although the amplitude of signals recorded from the intraventricular electrodes is lower than that seen with intraparenchymal recordings, our data demonstrate that these signals can still be accurately classified for BCI purposes. Further studies will be needed to compare the overall feasibility of intraventricular electrodes compared to scalp EEG, ECoG, or hippocampal depth electrodes in controlling a P300 Speller.

Acknowledgments

This work was funded in part by the National Science Foundation (1064912) and the National Institutes of Health (NIBIB/NINDS EB00856).

References

Krusienski DJ, Shih JJ. Control of a brain–computer interface using stereostactic depth electrodes in and adjacent to the hippocampus. J Neural Eng 2011;8(2):025006.