Journal of Neuroscience Methods 203 (2012) 311–314

Contents lists available at SciVerse ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

Clinical Neuroscience
Short communication

Signals from intraventricular depth electrodes can control a brain–computer interface

Jerry J. Shih[a], Dean J. Krusienski[b,*]

[a] Department of Neurology, Mayo Clinic, Jacksonville, FL 32224, USA
[b] Electrical & Computer Engineering Department, Old Dominion University, 231 Kaufman Hall, Norfolk, VA 23529, USA

ARTICLE INFO

Article history:
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

ABSTRACT

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 have 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.

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 SDEs 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

* Corresponding author. Tel.: +1 757 683 3752; fax: +1 757 683 3220.
E-mail addresses: shih.jerry@mayo.edu (J.J. Shih), deankrusienski@ieee.org (D.J. Krusienski).

0165-0270/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jneumeth.2011.10.012

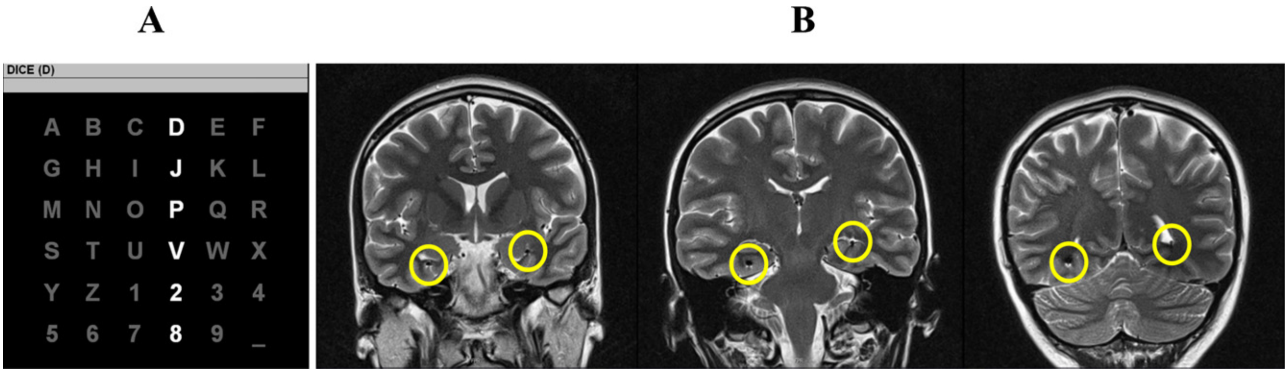

Fig. 1. (A) The 6 × 6 matrix used in the current study. A row or column flashes for 100 ms every 175 ms. The letter in parentheses at the top of the window is the current target character "D." A P300 should be elicited when the fourth column or first row is flashed. After 15 flash sequences, the collected brain responses are processed, classified, and online feedback is provided directly below the character to be copied. The process is then repeated for the subsequent target characters. (B) Post-implant brain MRI. T2-weighted coronal sections through anterior, middle and posterior temporal lobe (from left to right) demonstrating the intraventricular location of stereotactic depth electrode in the left temporal lobe and the intraparenchymal location of the stereotactic depth electrode in the right temporal lobe (encircled in yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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 neuronavigational 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 electrodes 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

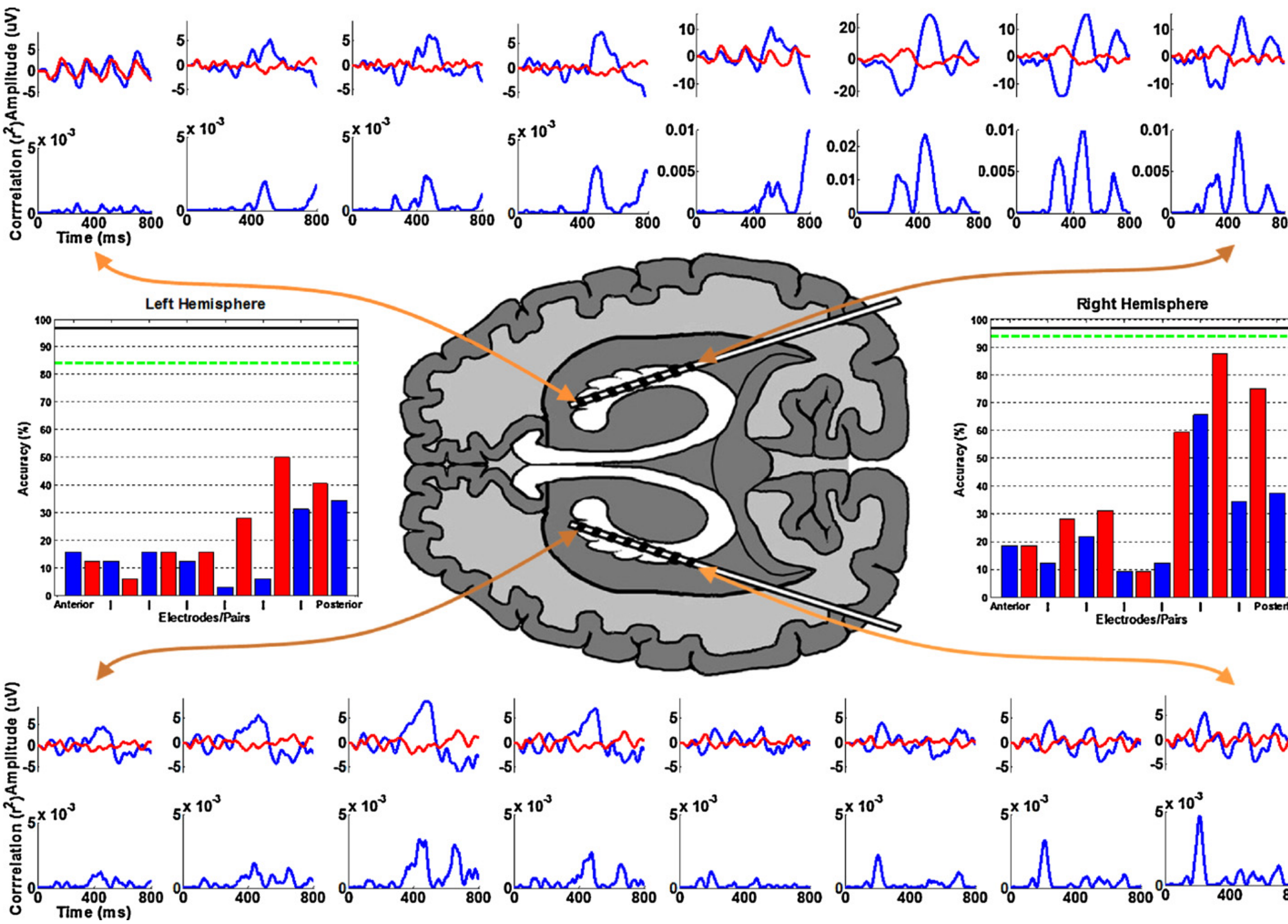

Fig. 2. The ERPs and the respective r^2 correlations with the task are plotted in the periphery, ordered corresponding to the provided axial viewpoint representing the approximate relative electrode positions (note that for the purposes of the illustration the left hemisphere electrodes are not shown in the ventricle). These waveforms represent the average responses to the target (blue) and non-target (red) stimuli, with 0 ms indicating the stimulus onset. Note that the four most posterior responses in the right hemisphere are plotted on different scales for emphasis. 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%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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

Akhtari M, Bryant HC, Mamelak AN, Heller L, Shih JJ, Mandelkern M, et al. Conductivities of three-layer human skull. Brain Topogr 2000;13(1):29–42.

Behrens E, Schramm J, Zentner J, Konig R. Surgical and neurological complications in a series of 708 epilepsy surgery procedures. Neurosurgery 1997;41(1):1–9, discussion 9–10.

Blakely T, Miller KJ, Zanos SP, Rao RP, Ojemann JG. Robust, long-term control of an electrocorticographic brain–computer interface with fixed parameters. Neurosurg Focus 2009;27(1):E13.

Burneo JG, Steven DA, McLachlan RS, Parrent AG. Morbidity associated with the use of intracranial electrodes for epilepsy surgery. Can J Neurol Sci 2006;33(2):223–7.

Clarke JM, Halgren E, Chauvel P. Intracranial ERPs in humans during a lateralized visual oddball task. II. Temporal, parietal, and frontal recordings. Clin Neurophysiol 1999;110(7):1226–44.

Farwell LA, Donchin E. Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. Electroencephalogr Clin Neurophysiol 1988;70(6):510–23.

Felton EA, Wilson JA, Williams JC, Garell PC. Electrocorticographically controlled brain–computer interfaces using motor and sensory imagery in patients with temporary subdural electrode implants. Report of four cases. J Neurosurg 2007;106(3):495–500.

Halgren E, Baudena P, Clarke JM, Heit G, Marinkovic K, Devaux B, et al. Intracerebral potentials to rare target and distractor auditory and visual stimuli. II. Medial, lateral and posterior temporal lobe. Electroencephalogr Clin Neurophysiol 1995;94(4):229–50.

Hochberg LR, Serruya MD, Friehs GM, Mukand JA, Saleh M, Caplan AH, et al. Neuronal ensemble control of prosthetic devices by a human with tetraplegia. Nature 2006;442(7099):164–71.

Krusienski DJ, Sellers EW, McFarland DJ, Vaughan TM, Wolpaw JR. Toward enhanced P300 speller performance. J Neurosci Methods 2008;167(1):15–21.

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

Krusienski DJ, Shih JJ. Control of a visual keyboard using an electrocorticographic brain–computer interface. Neurorehabil Neural Repair 2011b;25(4):323–31.

Lee JH, Hwang YS, Shin JJ, Kim TH, Shin HS, Park SK. Surgical complications of epilepsy surgery procedures: experience of 179 procedures in a single institute. J Korean Neurosurg Soc 2008;44(4):234–9.

Lenhardt A, Kaper M, Ritter HJ. An adaptive P300-based online brain–computer interface. IEEE Trans Neural Syst Rehabil Eng 2008;16(2):121–30.

Leuthardt EC, Gaona C, Sharma M, Szrama N, Roland J, Freudenberg Z, et al. Using the electrocorticographic speech network to control a brain–computer interface in humans. J Neural Eng 2011;8(3):036004.

Leuthardt EC, Schalk G, Wolpaw JR, Ojemann JG, Moran DW. A brain–computer interface using electrocorticographic signals in humans. J Neural Eng 2004;1(2):63–71.

Ludowig E, Bien CG, Elger CE, Rosburg T. Two P300 generators in the hippocampal formation. Hippocampus 2010;20(1):186–95.

McFarland DJ, Sarnacki WA, Vaughan TM, Wolpaw JR. Brain–computer interface (BCI) operation: signal and noise during early training sessions. Clin Neurophysiol 2005;116(1):56–62.

Nijboer F, Sellers EW, Mellinger J, Jordan MA, Matuz T, Furdea A, et al. A P300-based brain–computer interface for people with amyotrophic lateral sclerosis. Clin Neurophysiol 2008;119(8):1909–16.

Santhanam G, Ryu SI, Yu BM, Afshar A, Shenoy KV. A high-performance brain–computer interface. Nature 2006;442(7099):195–8.

Schalk G, McFarland DJ, Hinterberger T, Birbaumer N, Wolpaw JR. BCI2000: a general-purpose brain–computer interface (BCI) system. IEEE Trans Biomed Eng 2004;51(6):1034–43.

Schalk G, Miller KJ, Anderson NR, Wilson JA, Smyth MD, Ojemann JG, et al. Two-dimensional movement control using electrocorticographic signals in humans. J Neural Eng 2008;5(1):75–84.

Sellers EW, Vaughan TM, Wolpaw JR. A brain–computer interface for long-term independent home use. Amyotroph Lateral Scler 2010;11(5):449–55.

Serby H, Yom-Tov E, Inbar GF. An improved P300-based brain–computer interface. IEEE Trans Neural Syst Rehabil Eng 2005;13(1):89–98.

Song JK, Abou-Khalil B, Konrad PE. Intraventricular monitoring for temporal lobe epilepsy: report on technique and initial results in eight patients. J Neurol Neurosurg Psychiatry 2003;74(5):561–5.

Vansteensel MJ, Hermes D, Aarnoutse EJ, Bleichner MG, Schalk G, van Rijen PC, et al. Brain–computer interfacing based on cognitive control. Annals of neurology 2010;67(6):809–16.

Vaughan TM, McFarland DJ, Schalk G, Sarnacki WA, Krusienski DJ, Sellers EW, et al. The Wadsworth BCI Research and Development Program: at home with BCI. IEEE Trans Neural Syst Rehabil Eng 2006;14(2):229–33.

Wilson JA, Schalk G, Walton LM, Williams JC. Using an EEG-based brain–computer interface for virtual cursor movement with BCI2000. J Vis Exp 2009(29).

Winslow BD, Christensen MB, Yang WK, Solzbacher F, Tresco PA. A comparison of the tissue response to chronically implanted Parylene-C-coated and uncoated planar silicon microelectrode arrays in rat cortex. Biomaterials 2010;31(35):9163–72.

Wolpaw JR, Birbaumer N, McFarland DJ, Pfurtscheller G, Vaughan TM. Brain–computer interfaces for communication and control. Clin Neurophysiol 2002;113(6):767–91.

Wong CH, Birkett J, Byth K, Dexter M, Somerville E, Gill D, et al. Risk factors for complications during intracranial electrode recording in presurgical evaluation of drug resistant partial epilepsy. Acta Neurochir (Wien) 2009;151(1):37–50.