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Spectral Components of the P300 Speller Response in Electrocorticography

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***Abstract*—Recent studies have demonstrated that the P300 Speller can be used to reliably control a brain-computer interface via scalp-recorded electroencephalography (EEG) and intracranial electrocorticography (ECoG). However, the exact reasons why some disabled individuals are unable to successfully use the P300 Speller remain unknown. The superior bandwidth and spatial resolution of ECoG compared to EEG may provide more insight into the nature of the responses evoked by the P300 Speller. This study examines the spatio-temporal progression of the P300 Speller response in ECoG for six conventional frequency bands.**

I. Introduction

A Brain-Computer Interface (BCI) is a device that uses brain signals to provide a non-muscular communication channel [34], particularly for individuals with severe neuromuscular disabilities. One of the most investigated paradigms for controlling a BCI is the P300 Speller [10]. Based on multiple scalp-recorded electroencephalogram (EEG) studies in healthy volunteers [13][15][18][25], and initial results in persons with physical disabilities [24][28][33], 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.

More recently, studies have shown that both intracranial electrocorticography (ECoG) and depth electrodes can be used to reliably control the P300 Speller, with performance comparable to EEG [6][16][17]. ECoG has been shown to have superior signal-to-noise ratio, immunity to artifacts such as EMG, and spatial and spectral characteristics compared to EEG [5][11][26]. It is believed that a thorough characterization of the P300 Speller response properties in ECoG will also lead to improved scalp-EEG P300 performance.

Several ECoG studies have attempted to characterize various event-related potentials [14][21][22][30], and a few recent studies have explored the responses to the P300 Speller [6][16][17]. Because the traditional control signal for the P300 Speller is an event-related potential (ERP), the majority of prior analyses have focused on low frequency features in the time domain. Bernat *et al.* (2007) [3] performed a time-frequency decomposition of P300 activity and showed predictable time courses in the delta, theta, and alpha bands. With the increased spatial resolution and spectral bandwidth afforded by ECoG, and the recent association of gamma band features with a wide variety of cortical processes [7][23][32], an examination of the spectral characteristics of the P300 Speller response using ECoG is justified. This paper provides a preliminary spatio-temporal analysis of the P300 Speller responses in the conventional delta, theta, alpha, beta, low-gamma, and high-gamma bands.

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II. Methodology

A. Subjects

Six subjects with medically intractable epilepsy who underwent Phase 2 evaluation for epilepsy surgery with temporary placement of intracranial grid or strip electrode arrays to localize seizure foci prior to surgical resection were tested for the ability to control a visual keyboard using ECoG signals. All six subjects were presented at Mayo Clinic Florida's multidisciplinary Surgical Epilepsy Conference where the consensus clinical recommendation was for the subject to undergo invasive monitoring primarily to localize the epileptogenic zone, and also to map out language and sensorimotor cortex if appropriate. The study was approved by the Institutional Review Boards of Mayo Clinic, University of North Florida, and Old Dominion University. All subjects gave their informed consent.

B. Electrode Locations and Clinical Recordings

Electrode (AD-Tech Medical Instrument Corporation, WI, USA) placements and duration of ECoG monitoring were based solely on the requirements of the clinical evaluation, without any consideration of this study. All electrode placements were guided intra-operatively by Stealth MRI neuronavigational system (Medtronics, Inc., MN, USA). Each subject had post-operative anterior–posterior and lateral radiographs to verify electrode locations. After electrode implantation, all subjects were admitted to an ICU room with epilepsy monitoring capability. Clinical ECoG data were gathered with a 64-channel clinical video-EEG acquisition system (Natus Medical, Inc.; CA, USA). Electrode locations are detailed in Table 1, with the superposition of approximate electrode locations of all subjects illustrated in Figure 1.

C. BCI Data Acquisition

All subjects performed BCI testing between 24-48 hours after electrode implantation. Testing was performed only 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 six hours after a clinical seizure. Stimuli were presented and the ECoG data were recorded using the general-purpose BCI system BCI2000 [27]. All electrodes were referenced to a scalp vertex electrode, amplified, band pass filtered (0.5–500 Hz), digitized at 1200 Hz using 16-channel g.USB amplifiers (Guger Technologies, Graz, Austria), and stored. A laptop with a 2.66 GHz Intel Core 2 Duo CPU, 3.5 GB of RAM, and Windows XP was used to execute BCI2000. The signals for the BCI experiments were acquired concurrent with the clinical monitoring via a 32-channel electrode splitter box (AD-Tech Medical Instrument Corporation, WI, USA).

Sub	Age /Sex	Electrode Locations	# BCI Elect
A	41/M	36-contact grid left temporal-occipital 1 x 4 left temporal strip	16
B	29/M	Four 1x6 strips covering left frontal and lateral temporal 2 left hippocampal single depths	26
C	20/F	24-contact grid left parietal	24
D	27/M	36-contact grid left frontal-parietal 2 left hippocampal single depths	32
E	60/M	16-contact grid left temporal-parietal 1 x 4 superior temporal gyrus strip 1 x 6 inferior temporal gyrus strip 1x6 inferior frontal strip 2 left hippocampal single depths	32
F	38/F	20-contact grid left temporal neocortex 1 x 4 left inferior frontal 1 x 6 left medial and basal temporal	30

Table I. The demographics, electrode locations, and number of electrodes used for the BCI experiments for each subject.

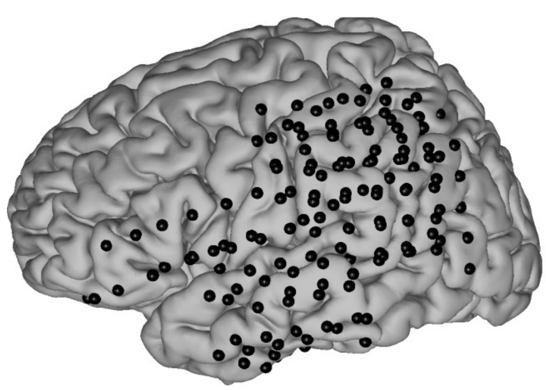

Fig. 1. The superposition of approximate ECoG electrode locations for all six subjects.

D. *Task, Procedure, & Design*

The experimental protocol was based on the protocol used in an EEG-based P300 Speller study [15]. Each 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 was 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 Figure 2. Each session consisted of 8-11 experimental runs of the P300 Speller paradigm; each run was composed of a word or series of characters chosen by the investigator. This set of characters spanned the set of characters contained in the matrix and was consistent for each subject and session. Each session consisted of between 32-39 character epochs. A single session lasted approximately one hour. One to three sessions were collected for each subject, depending on the subject's physical state and willingness to continue.

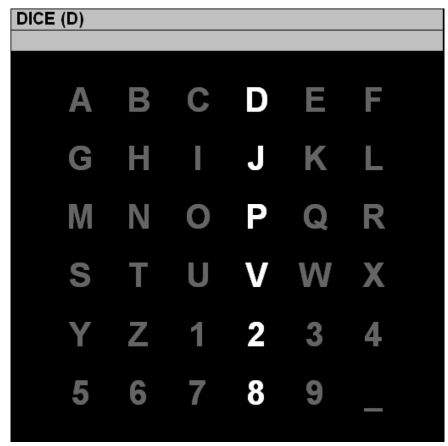

Fig. 2: The 6x6 matrix used in the current study. A row or column intensifies for 100 ms every 175 ms. The letter in parentheses at the top of the window is the current target letter "D." A P300 should be elicited when the fourth column or first row is intensified. After the intensification sequence for a character epoch, the result is classified and online feedback is provided directly below the character to be copied.

E. *Data Analysis*

The first uncorrupted session from each subject was used for the analysis. The band-power was determined for six frequency bands: delta (0-3 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (13-30 Hz), low-gamma (31-70 Hz), and high-gamma (71-200 Hz). The band-power was computed by forward and reverse filtering each channel with a precise FIR filter to produce zero-phase distortion. The resulting channel values were then squared and smoothed using the same zero-phase approach to extract the band-power envelope.

For each channel, 800 ms segments of data following each flash were extracted for the analysis. Each segment was divided into non-overlapping 100 ms partitions and the average band-power for each of the six frequency bands was computed for each partition. The average band-power was then correlated with the binary target labels (i.e., target or non-target flash) and the resultant p-values were computed, where the p-value corresponds to the hypothesis that the correlation between the band-power and the task is zero. The p-values were transformed using –log(p-value) to make the

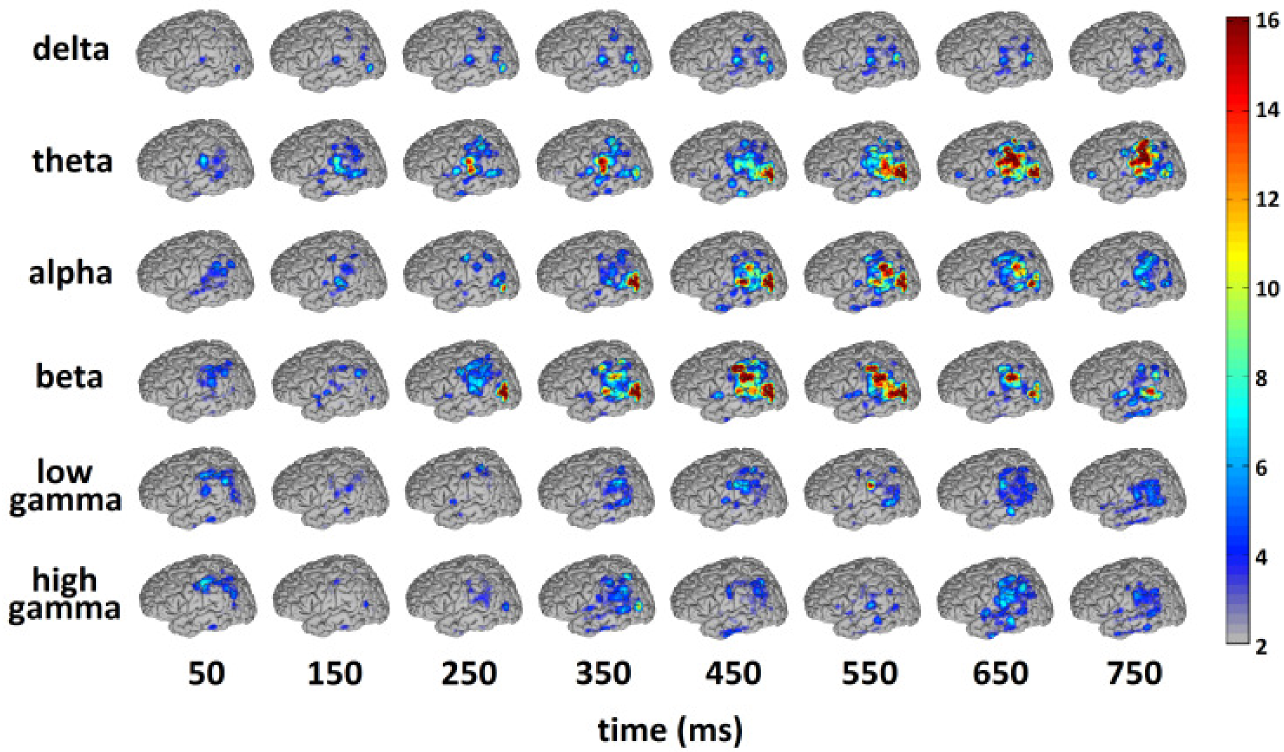

Fig. 3. The transformed p-value topographies for each of the six frequency bands over the 100 ms increments (centered on the values provided on the x-axis). The corresponding color-scale begins fading at a significance level of p = 0.05, which corresponds to approximately a value of 3 on the color-scale. Thus, all colored regions can be considered statistically significant at a level of p = 0.05 or better.

values more amenable for plotting. To visualize the spatial distribution of transformed p-values, each electrode from all subjects was projected onto the 3D template brain model and rendered as a color-coded topographical map using a custom Matlab program that used a Gaussian fading function that decayed to zero at the inter-electrode distance.

III. Results

Figure 3 illustrates the transformed p-value topographies for each of the six frequency bands over the 100 ms increments (centered on the values provided on the x-axis). The corresponding color-scale begins fading at a significance level of $p = 0.05$, which corresponds to approximately a value of 3 on the color-scale. Thus, all colored regions on the plots can be considered statistically significant at a level of $p = 0.05$ or better.

IV. Discussion

This work represents a first attempt to analyze and interpret the P300 Speller response in ECoG in terms of the conventional neural frequency bands. The electrode coverage is primarily over the temporal and parietal lobes, with the significant activations for all bands occurring almost exclusively over the parietal lobe. This parietal activation is consistent with the characteristic location of the significant low-frequency amplitude deflections of the P300 [4], although the present analysis indicates that there is also significant activity in other frequency bands. The prefrontal region is not well sampled in our grid arrays and thus cannot correlate with past research indicating prefrontal P300 activation.

The P300 Speller is a variation of the classical oddball paradigm [9], which requires both an attentional and memory component. In addition to the low-frequency P300 amplitude deflections, delta and theta frequency activities have been related to oddball target responses [1][2]. Along these lines, one possible interpretation is that the strong oscillatory theta and alpha activity in prefrontal and parietal regions is associated with working memory as suggested in Grimault *et al*. (2009) [12]. In addition, the alpha activations in the parieto-occipital region have been associated with working memory load [31]. Alpha reductions measure increased cognitive processing during the oddball task [35]. Sustained oscillatory activity in the beta band frequency over the parieto-occipital region was seen in n-back memory tasks with the highest memory load [8].

Because the P300 Speller was configured as written language task, where letters are selected sequentially to form words, it is conceivable that portions of language cortex such as Wernicke's area and the angular gyrus [29] are also contributing to the activations. While subjects are instructed to silently count the number of times the target letter flashes to maintain attention, some subjects have reported mentally repeating the target letter after each flash, which would further augment language cortex activations.

In summary, the P300 Speller requires a wide range of neuronal activation likely including attentional, memory, language, and cognitive processing. Our results demonstrate the wide range of frequency activation in the parieto-occipital region. Future work will include increasing the temporal resolution and segment length of the analysis to investigate the intermediate and later temporal activations observed in particular frequency bands. As an alternative to band-power, a Fast-Fourier Transform with spectral normalization will be performed to account for the potential 1/frequency ECoG power spectrum bias when averaging over wide frequency bands. In addition, for a subset of the subjects, the ECoG activations will be compared to scalp-recorded EEG activations collected using the same task.

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