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Decoding hand gestures from primary somatosensory cortex using high-density ECoG

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ABSTRACT

Electrocorticography (ECoG) based Brain-Computer Interfaces (BCIs) have been proposed as a way to restore and replace motor function or communication in severely paralyzed people. To date, most motor-based BCIs have either focused on the sensorimotor cortex as a whole or on the primary motor cortex (M1) as a source of signals for this purpose. Still, target areas for BCI are not confined to M1, and more brain regions may provide suitable BCI control signals. A logical candidate is the primary somatosensory cortex (S1), which not only shares similar somatotopic organization to M1, but also has been suggested to have a role beyond sensory feedback during movement execution. Here, we investigated whether four complex hand gestures, taken from the American sign language alphabet, can be decoded exclusively from S1 using both spatial and temporal information. For decoding, we used the signal recorded from a small patch of cortex with subdural high-density (HD) grids in five patients with intractable epilepsy. Notably, we introduce a new method of trial alignment based on the increase of the electrophysiological response, which virtually eliminates the confounding effects of systematic and non-systematic temporal differences within and between gestures execution. Results show that S1 classification scores are high (76%), similar to those obtained from M1 (74%) and sensorimotor cortex as a whole (85%), and significantly above chance level (25%). We conclude that S1 offers characteristic spatiotemporal neuronal activation patterns that are discriminative between gestures, and that it is possible to decode gestures with high accuracy from a very small patch of cortex using subdurally implanted HD grids. The feasibility of decoding hand gestures using HD-ECoG grids encourages further investigation of implantable BCI systems for direct interaction between the brain and external devices with multiple degrees of freedom.

1. Introduction

The research of Brain-Computer Interface (BCI) systems for restoring and replacing motor function or communication in severely paralyzed people has increased significantly in the last decades (Daly and Wolpaw, 2008; Miller and Hatsopoulos, 2012). To date, most BCI studies have focused on the sensorimotor cortex (Brodmann areas, BA, 1–4) (Yuan and He, 2014), which is known to have a direct relationship with movement execution, attempt and imagery (Hochberg et al., 2006; Leuthardt et al., 2004; Miller et al., 2009b, 2010; Pistohl et al., 2008). The sensorimotor cortex can be divided into the primary motor cortex (M1, BA4) and the primary somatosensory cortex (S1, BA1-3). Both areas are somatotopically organized (Penfield and Boldrey, 1937) and provide rich spatial detail that could be exploited for BCIs with multiple degrees-of-freedom. In particular, a distinct portion of M1 denoted the "hand knob" has been proven to directly control hand movements (Yousry et al., 1997) and there is strong evidence from micro-array and needle recordings from both non-human primate (Georgopoulos et al., 1986) and human (Hochberg et al., 2006) studies that this region allows decoding of arm and hand motor movements.

Even though M1 has been the main target for motor-related BCI control studies, S1 would be a logical alternative candidate due to its somatotopic organization. On the one hand, S1 is known to be related to afferent signal processing in humans, mostly present during touch, proprioception and pain perception (Martuzzi et al., 2014; Stringer et al., 2014). On the other hand, there is evidence for a role of sensory information during movement execution and attempted movement (Cramer et al., 2005; Kikkert et al., 2016). Recent predictive and

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feedback models for voluntary control, for example, suggest that there may be driving connections from S1 to M1 (Adams et al., 2012; Scott, 2012), providing good reason to believe that S1 would encode similar topographical activation patterns as M1 during movement execution and attempted movement tasks, and thus be a potential target for future BCIs.

Several studies in humans have shown successful decoding of hand related tasks from the sensorimotor cortex (M1 and S1 combined) using subdurally implanted electrodes (electrocorticography, ECoG) (Chestek et al., 2013; Kubánek et al., 2009; Miller et al., 2009b; Pistohl et al., 2011; Schalk et al., 2007), but so far, only one study (Chestek et al., 2013) has indicated that S1 alone may provide informative signals for BCI purposes. In these studies, standard clinical grids were used, which cover a relatively large area of cortex with spatial resolution of one electrode (or small clusters of microelectrodes) per cm^2. Notably, we have previously shown that motor representations of the different fingers are located within an area of about 1 cm^2 (Siero et al., 2014), meaning that standard clinical grids fail to capitalize on the spatial detail of this cortical feature. Additionally, decoding from large regions of cortex that extend widely beyond the topographical representation associated with the movement of interest (e.g., "hand knob" for hand movements), makes it unclear what cortical functions are involved in decoding.

In the present study, we specifically address the question whether hand movements can be decoded from the S1 hand region alone. We investigate whether four complex hand gestures, previously shown by our group to be spatially decodable from the sensorimotor cortex as a whole (Bleichner et al., 2014), can be decoded exclusively from S1 using both spatial *and* temporal information. Additionally, in order to investigate whether the S1 discriminative neuronal information is decoupled from sensory feedback, we analyzed the spatiotemporal response prior to movement onset. To prevent spatial undersampling, we used grids with a high-density of electrodes (9/cm^2). We focus on the high-frequency broadband or gamma-band power change of the ECoG signal (70–125 Hz) (Crone et al., 1998; Miller et al., 2009a, b), which has been shown to have a time-locked response to motor execution, is commonly spatially specific (Buzsáki and Wang, 2012; Hermes et al., 2012; Siero et al., 2014), and allows for optimal decoding of hand gestures (Bleichner et al., 2014). In short, in the current study, we compare the classification scores based on spatio-temporal gamma-band features between high-density-ECoG electrodes localized over S1, M1 and both M1 and S1 (sensorimotor cortex). Additionally, we introduce a new method for trial re-alignment that minimizes confounding effects caused by the temporal differences in the electrophysiological response to the task.

2. Materials and methods

2.1. Subjects

Subjects of the study were five patients (mean age 31, range 19–45; see Table 1) with intractable epilepsy who were implanted with subdural ECoG grids to localize the seizure focus. This study was approved by the Medical Ethical Committee of the Utrecht University Medical Center. All patients signed informed consent according to the Declaration of Helsinki (2008).

Both standard clinical ECoG and high-density ECoG grids were implanted. Standard ECoG grids had an inter-electrode distance center-to-center of 1 cm and 2.3 mm exposed surface diameter (AdTech, Racine, USA). High-density grids had either 32 or 64 channels, with 1.3 mm exposed surface diameter and an inter-electrode distance of 3 mm center to center (AdTech, Racine, USA). The 32-channel grid covered an area of 2.5 cm^2 (4×8 electrode layout), whereas the 64-channel grid covered an area of 5.2 cm^2 (8×8 electrode layout).

The current study focuses only on the high-density grids that covered (parts of) the sensorimotor cortex (see Table 1 for details), including the hand knob region. Some electrodes were excluded from the analysis due to technical problems (e.g., a broken lead, causing flat or unstable signals) or high power-line noise level. Notably, for none of the patients, the epileptic focus overlapped with the hand knob region. For each subject, the electrodes (Table 1) were localized using co-registration between a high resolution post-implantation Computerized Tomography (CT) scan (Philips Tomoscan SR7000, Best, the Netherlands) and a pre-operative T1-weighed anatomical scan on a 3T Magnetic Resonance system (Philips 3T Achieva, Best, the Netherlands) with algorithms published in (Hermes et al., 2010) and displayed on a cortex surface rendering (Fig. 1). By visual inspection, the projected electrodes anterior to central sulcus were labeled as M1 electrodes, whereas the ones posterior to central sulcus were labeled S1 electrodes. Electrodes over the central sulcus were labeled according to the closest gyrus.

2.2. Task

The task (Fig. 2), as described in (Bleichner et al., 2014), involved the execution of four different hand gestures (G1, G2, G3 and G4), which were taken from the American Sign Language finger spelling alphabet ('D', 'F', 'V' and 'Y', respectively). The participants were asked to copy the gesture presented on the screen using the hand contralateral to grid implantation and hold it for 6 s. The trials were interleaved with a rest condition (6 s), where the subject was asked to place their hand in a relaxed open hand position. Each run consisted

Table 1
Patient characteristics and high-density grid information.

Patient no.	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Age	29	42	19	19	45
Gender	Male	Male	Female	Male	Female
Handedness	Right	Right	Right	Right	Left
Implanted hemisphere	Left	Left	Left	Left	Right
Epileptic resected area	Posterior high parietal	Temporal lobe (including amygdala and hippocampus)	Posterior medial frontal gyrus until pre-central gyrus	Anterior temporal lobe (including amygdala and hippocampus)	Frontal-para-sagittal
High-density grid location	Hand knob (post-central)	Hand knob (pre-central and superior post-central	Hand knob (pre- and post-central)	Hand knob (superior pre-central)	Hand knob (primarily post-central)
Total number of included electrodes	29/32	24/32	32/32	31/32	59/64
Number of electrodes over M1	–	15	16	31	11
Number of electrodes over S1	29	9	16	–	48