Development of an Intracortical Eye Movement-Based Brain-Computer Interface

S. L. Brincat[1*], A. F. Salazar-Gómez[2*], N. Jia[2], M. Panko[2], E. K. Miller[1], F. H. Guenther[2]
[1]Massachusetts Institute of Technology, Cambridge, MA, USA; [2]Boston University, Boston, MA, USA
**denotes equal contribution*

Correspondence: S.L. Brincat, MIT, 77 Massachusetts Ave. 46-6241, Cambridge, MA 023139 USA. E-mail: sbrincat@mit.edu

Abstract. We present an eye-movement-based brain-computer interface (BCI) developed in a non-human primate that decodes intended saccadic eye movements from intracortical signals. We propose that this BCI system could be used to restore simple communication to patients with locked-in syndrome.

Keywords: locked-in syndrome, eye movements, intracortical, monkey

1. Introduction

Brainstem stroke, traumatic brain injury, or neurodegenerative disorders like amyotrophic lateral sclerosis can result in locked-in syndrome, characterized by near-total paralysis despite relatively intact cognitive function. These patients could benefit immensely from a simple, easy-to-use brain-computer interface (BCI) to restore some communication with the outside world. We employ a non-human primate model to test the feasibility of using intracortical eye movement signals to control a BCI, with the aim of eventual application to human locked-in patients. Intracortical recordings can provide much more information-rich signals than the EEG signals used in most previous BCIs developed for this patient population. The saccadic eye movement system has several potential advantages over the arm movement signals typical used for BCI applications: there is a direct mapping between the effector space and a 2D cursor system, unlike the complex degrees of freedom in arm movements; it is specialized for rapid targeted movements that would be ideal for navigating augmentative and alternative communication software; it has minimal reliance on proprioceptive feedback; and there is a tight link between the eye movement system and top-down attentional control, suggesting these signals may be particularly amenable to volitional control. Our results show that eye movements can successively drive a BCI, opening the door to future clinical applications.

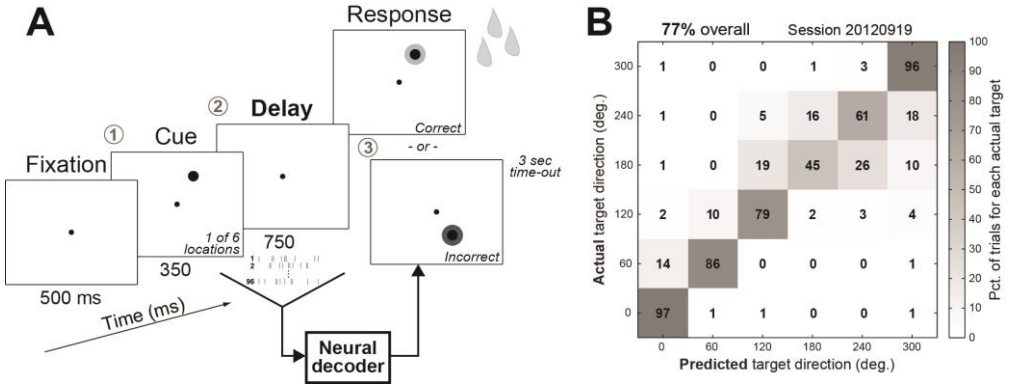

Figure 1. *(A) Brain-controlled delayed saccade task. A spatial cue (1) instructs the saccade location for this trial. Neural activity during the memory delay period (2) is used to decode the intended location, and produce a "virtual saccade" (3) at the end of the trial. (B) Confusion matrix showing decoder performance from an example session. Each matrix cell (heat map and overlaid numbers) represents the percentage of trials for a given instructed saccade location (y-axis) that each location is predicted by the decoder (x-axis).*

2. Material and Methods

We implanted three 32-channel Utah arrays (Blackrock Microsystems) into the left frontal eye field (FEF), supplementary eye field (SEF), and dorsolateral prefrontal cortex (PFC) of a macaque monkey. Spiking and local field potential (LFP) signals were simultaneously recorded from all 96 electrodes while the monkey performed a delayed saccade task (Fig. 1A). On each task trial, one of six spatial locations was briefly cued. The monkey was trained to hold this location in working memory over a 750 ms delay period, and then execute a saccadic eye movement to the remembered location. On some experimental sessions, a brain-controlled version of the task was performed—the intended saccade was decoded from neural activity during the delay period, and a cursor was then moved to the decoder-predicted location, replacing the overt motor response with a "virtual saccade". Positive or negative reinforcement—liquid reward or an increased waiting time for the next trial, respectively—was then delivered conditional on whether the decoded location correctly matched the instructed one (but independent of any possible overt eye movements). These brain-controlled trials were always preceded by a separate block of standard delayed saccade trials (involving overt saccades) that were used to train parameters for a linear discriminant classifier. The classifier was trained on the mean power within a high-frequency LFP band (80–500 Hz) across the entire delay period, for each channel. This signal provided the highest decoding accuracy in extensive offline analyses (see related abstract from our group).

3. Results

We were able to decode intended eye movements with high accuracy (Fig. 1B). Across 11 BCI sessions, saccade locations were correctly predicted on 72% (± 3% SD) of trials on average, significantly higher than chance accuracy (16.7%) for all sessions ($p \approx 0$; binomial test). Accuracy was much higher (88 ± 2%) when considering only saccade locations contralateral to the implanted arrays (ipsilateral locations only: 56 ± 6%; cf. variation across matrix diagonal in Fig. 1B), reflecting a contralateral representational bias in the implanted cortical areas. These results suggest an improved BCI system could be achieved with bilateral implants or laterally biased sampling of target locations. Though all array channels were used for online decoding, we compared the individual contribution of each of the three implanted areas in offline analyses. SEF signals provided significantly better decoding performance (74 ± 2%) than FEF (25 ± 3%; $p = 3\times10^{-21}$, t-test) or PFC (23 ± 2%; $p = 4\times10^{-23}$), suggesting it is a particularly rich source of signals for an eye movement BCI, though this result may reflect the fact that delay period activity, rather than activity during the actual movement was used for decoding. The monkey quickly learned that overt responses were unnecessary in the brain-controlled task, and often went through multiple successful trials without making any eye movements, indicating saccade intention signals are sufficient to control a BCI. Finally, decoder performance has largely been preserved at almost one year post implant, suggesting our BCI system can have the longevity required for long-term clinical applications.

4. Discussion

We have demonstrated that intracortical eye movement signals can be used to control a simple BCI with a high level of performance. Because of the eye movement system's simple kinematics and control, and its close ties to top-down attention, we expect a BCI using these signals to be relatively easy to learn to volitionally control. This is particularly important for patients with locked-in syndrome, a population with variable residual cortical function that has seen little success with previous BCI systems. We plan to integrate this BCI with our recently developed "app"-based Unlock Project BCI framework [Brumberg et al., 2012] aimed at providing communication and other functionality to locked-in patients.

Acknowledgements

This study is supported in part by CELEST, a National Science Foundation Science of Learning Center (NSF OMA-0835976). Thanks to J. Roy, D. Ouellette, N. Hatsopoulos, and M. Salvato for technical assistance.

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