Which Neural Signals are Optimal for Brain-Computer Interface Control?

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Abstract. We compared the encoding and decoding performance of several intracortical neural signals—single units, multi-units, and band-limited local field potential (LFP) power—within an eye movement brain-computer interface (BCI) paradigm. We find that broadband high-frequency LFPs exhibit the best performance, and may be an easily obtainable, high-performance signal for BCI applications.

Keywords: single units, local field potentials, intracortical, decoding, monkey, saccade

1. Introduction

There has been considerable controversy over which neural signals are best for controlling a brain-computer interface (BCI). While single-unit spikes have long been considered the "gold standard" in the field, some recent studies have suggested unsorted multi-unit activity [Stark and Abeles, 2007] or local field potentials (LFPs) [Mehring et al., 2003] provide more accurate decoding, while others maintain the superiority of single units [Bansal et al., 2012]. We compare these signals' information content and decoding accuracy for saccade direction, using intracortical recordings from a non-human primate performing a delayed saccade task (see related abstract from our group describing an eye-movement BCI system). Both measures suggest the optimal signal is broadband high-frequency LFP power, which likely reflects neuronal spiking near the recording electrode.

2. Material and Methods

We analyzed signals from three 32-channel Utah arrays implanted into the frontal eye field (FEF), supplementary eye field (SEF), and dorsolateral prefrontal cortex (PFC) of a macaque monkey. Spiking and LFP signals were simultaneously recorded from all 96 electrodes while the monkey performed a delayed saccade task. On each task trial, one of six spatial locations was briefly cued. The monkey held this location in working memory over a 750 ms delay period, and then executed a saccadic eye movement to the remembered location. Here we focus our analysis on neural activity during the delay period, which likely reflects motor intentional signals that are most relevant for BCI control. Multi-units were obtained by high-pass filtering the raw data at 250 Hz, and counting all waveforms crossing a channel-specific manual threshold. Single-units were sorted out of the set of suprathreshold waveforms online using multiple time-amplitude windows. LFP signals were obtained by initially filtering the raw continuous data from 0.3–500 Hz, then extracting band-limited power by additional band-pass filtering and computing the magnitude of the Hilbert transform. Standard definitions of LFP bands were used: delta (1–4 Hz), theta (4–8), alpha (8–12), beta (12–30), gamma (30–80), and high-frequency (80–500). Neural information content was quantified by the percent of channels showing significantly different activity across saccade direction in a 1-way ANOVA. A cross-validated linear discriminant was used for decoding analyses; this was found to provide as good or better prediction as other popular decoding methods.

3. Results

Across eight daily sessions, we found significant neural information ($p < 0.01$, ANOVA) about intended saccade direction in an average of $12 \pm 0.6\%$ (across-session mean $\pm$ SEM) of recorded single units, $15 \pm 0.9\%$ of multi-units, and $31 \pm 2.4\%$ of high-frequency LFPs. Significant information was found less frequently in the LFP beta (25%) and gamma (20%) bands, and rarely within other bands. More detailed spectral analyses confirmed these results, showing a peak of saccade information in the beta band (~15–30 Hz), and a strong broadband increase of information at frequencies above ~80 Hz. These results suggest that LFPs, especially in the high-frequency band, may provide particularly information-rich signals for an eye-movement-based BCI.

We then compared the accuracy of these signals for decoding saccade direction (cross-validated percent correct). Again, high-frequency LFPs greatly outperformed (74 ± 1.8%; across-session mean ± SEM) both multi-units (46 ± 1.1%; $p = 8{\times}10^{-10}$, t-test) and single units (47 ± 0.9%; $p = 1{\times}10^{-9}$, t-test). Decoding accuracy for all other LFP bands was significantly lower. More detailed analysis of the high-frequency LFP band revealed that decoding performance exhibited a broad optimum at low-cutoff frequencies of ~60–150 Hz and high-cutoff frequencies above ~350 Hz. These results suggest that a broad, high-frequency LFP band provides the best decoding of eye movement signals.

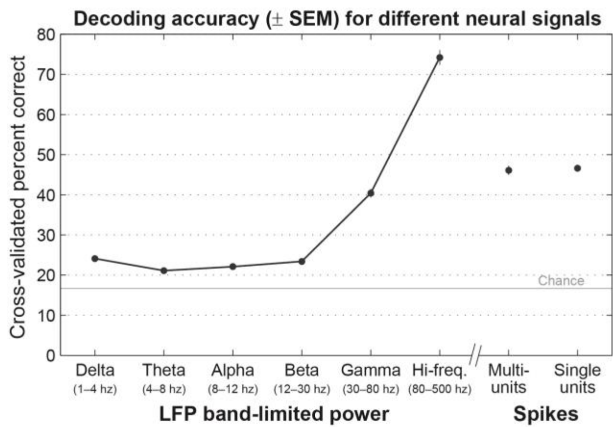

Figure 1. *Decoder performance (percent correct for cross-validated prediction) for several types of neural signals: band-limited LFP power for several frequency bands, unsorted multi-units, and isolated single units. High-frequency LFP power (80–500 Hz) greatly outperforms any other examined signal.*

One remaining question is what underlying neural source these high-frequency LFP signals reflect. We observed moderately strong correlations between high-frequency LFP power and multi-unit spike count within each electrode, and found that a classifier using both types of signals resulted in no performance improvement over high-frequency LFPs alone. These results suggest that high-frequency LFPs may largely reflect local spiking activity (cf. [Ray and Maunsell, 2011]), possibly integrated over a larger volume than traditional spiking signals. This possibility is supported by the fact that the improvement of LFP power over spiking signals is much larger in SEF and FEF—where functional organization for saccade direction might render such integration beneficial—than in PFC, which lacks strong functional organization for saccades.

Finally, preliminary results indicate that higher-order spectral features might also provide useful BCI signals. We found that both the magnitude and phase of delay-period cross-electrode LFP coherence, for all pairs of studied areas, carried information about intended saccade direction. Within individual electrodes, the strength of cross-frequency coupling between high-frequency power and beta/gamma-band LFP phase also reflected the intended saccade. Ongoing efforts aim to incorporate these spectral features into our decoding model.

4. Discussion

We compared several candidate neural signals, and found optimal decoding of intended eye movements from high-frequency LFP power. As alluded to in the Results section, this band most likely reflects integrated spiking signals from the neuronal population near the recording electrode, thus containing more sub-threshold information that is lost in the spike detection process. In contrast to traditional spiking signals, high-frequency LFPs are very easy to obtain, requiring data sampling no higher than ~1 kHz, no computationally expensive spike extraction/sorting algorithms, and no manual intervention. Thus, our results suggest high-frequency LFP power may be an inexpensive, fast, and very information-rich signal for BCI applications.

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