Comparison of Steady-State Visual and Somatosensory Evoked Potentials for Brain-Computer Interface Control

Dante J. Smith, Lenny A. Varghese, Cara E. Stepp, and Frank H. Guenther

Abstract— **Many proposed EEG-based brain-computer interfaces (BCIs) make use of visual stimuli to elicit steady-state visual evoked potentials (SSVEP), the frequency of which can be mapped to a computer input. However, such a control scheme can be ineffective if a user has no motor control over their eyes and cannot direct their gaze towards a flashing stimulus to generate such a signal. Tactile-based methods, such as somatosensory steady-state evoked potentials (SSSEP), are a potentially attractive alternative in these scenarios. Here, we compare the neural signals elicited by SSSEP to those elicited by SSVEP in naïve BCI users towards evaluating the feasibility of SSSEP-based control of an EEG BCI.**

I. Introduction

Locked-in Syndrome (LIS) is a neurological condition characterized by quadriplegia (loss of limb motion) and anarthria (loss of speech), with consciousness and typically sensory perception preserved [1]–[3]. Insult to the ventral pons such as trauma, hemorrhage, or an infarction as well as progression of Amyotrophic Lateral Sclerosis (ALS) can lead to this condition [4]. LIS also places a large physical and psychological burden on family members due to the near total absence of the ability to communicate with the individual [1]. In some instances, vertical gaze or eyelid movement is preserved [1], [2], [4], allowing for blink-based or gaze-based communications. However, there are many cases in which individuals do not retain this function [1]. When eye or blink motions are not retained, alternative methods of communication must be considered.

Brain-computer interfaces (BCI) convert recorded brain activity into commands for computers or other devices. Electroencephalography (EEG) is a relatively inexpensive, non-invasive method for recording brain activity, making it an attractive option for use in BCI. A variety of EEG signal types have been used for control of BCIs, including the P300 [5], sensory-motor rhythms (SMR) [6], steady-state visually evoked potentials (SSVEP) [7]–[11], and steady-state somatosensory evoked potentials (SSSEP)[12], [13]. SSVEP has shown promise in the lab as a method of controlling BCIs. In this control scheme, a flashing light evokes a response in visual cortex at the same frequency as the flashing frequency [14]. SSVEP and related methods (e.g., M-sequences [9]) have been shown to provide very robust signals and high fidelity across a variety of flash frequencies. When multiple flashing stimuli are present, each stimulus patch can be flashed at a different frequency, and attention to a single patch will enhance the amplitude of the SSVEP at the frequency for that stimulus. Decoding the EEG recording reveals which patch the participant attended to, and this result can be associated with a specific computer command.

SSVEPs are most easily decoded from short EEG segments when individuals can direct their gaze to a specific stimulus patch. In the absence of control over eye movements, it is difficult to maintain fixation or attention to any one given stimulus. Enhancement of SSVEPs via purely "covert" attention (i.e., attention without a gaze shift) to a stimulus patch has been shown to be feasible [11], but efficacy of control is poor [15]. SSSEP represents an alternative that is similar in concept. Vibrotactile stimulation, usually in the form of a vibration or tapping on the epidermis, creates an evoked potential in somatosensory cortex [7],[8]. Somatosensory evoked potentials have the same characteristics as visually evoked potentials in that they are time-locked with the onset of stimulus presentation and have the same frequency as the stimulus. The vibrotactile stimulus is usually applied to the hands or feet, and lateralization of the stimulus translates to a contralateral bias of the evoked potential, which makes decoding the response somewhat easier. The vibrotactile stimulus (referred to as tactile stimulus hereafter) usually takes the form of a high frequency carrier (e.g., 200Hz), modulated by a low frequency envelope (e.g., 17-35Hz) [12], [13], [16]. The high frequency content is used to activate somatosensory receptors in the epidermis [17]–[20], and the low frequency content is used to activate the somatosensory cortex [12], [13], [16]. These stimuli can be attended to by a participant to modulate the frequency content of the EEG signal in a way that might facilitate decoding of a BCI similar to what can be achieved using SSVEPs. Critically, this can be done without necessitating an associated movement, making it ideal for individuals with LIS.

BCI performance using SSSEP has not been characterized relative to BCI performance using SSVEP. As a first step in performing such an evaluation, we sought to compare the signal-to-noise ratio (SNR) of SSSEP and SSVEP in BCI-naïve and neurologically normal participants.

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II. METHODS

A. Participants

Six participants (four female) aged 21 to 24 years participated in this experiment. All participants were naïve to SSVEP and SSSEP stimulation and had normal or corrected-to-normal vision (by self-report). Participants performed the experiment in a sound-treated room and sat in a comfortable chair approximately one foot away from a computer monitor.

B. Stimulation

The presentation apparatus consisted of PC and monitor (Dell 2009wt) for stimulation presentation, as well as a headphone amplifier (Schiit Magni), and a set of C-2 "tactors" (Engineering Acoustics, Inc.).

On each experimental trial, either a visual stimulus or a tactile stimulus was presented to participants. The visual stimulus consisted of a 14 × 14, pattern-reversing black and white checkerboard (with individual checks subtending approximately 1.8°) presented on a black background (Figure 1). This stimulus was generated in Matlab (Mathworks, Natick, MA) and presented to participants on an LCD computer monitor with a refresh rate of 60 Hz using Psychtoolbox[21]. The image of the checkered square alternated polarity (white to black, black to white) at a constant frequency (12 or 15 Hz) depending on the run.

For the tactile stimulus, tactor vibrations were generated via a square wave (23 or 25 Hz) with 50% duty cycle modulating a 200 Hz cosine carrier (Figure 1). The particular square wave frequencies have previously been shown to generate strong, detectable modulations in EEG signals [12], [13]. A tactor was taped to each of the participant's thumbs, and each had the same modulating frequency. The driving signal was generated in Matlab, sent for D/A conversion via the internal sound card (Realtek), and finally amplified using the headphone amplifier.

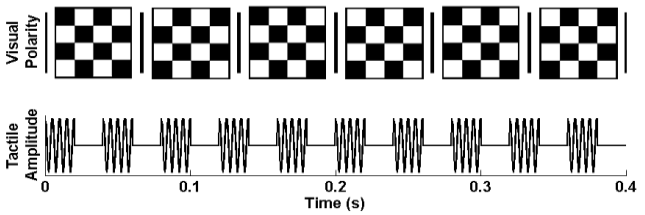

Figure 1: Top: An example 4× 4 15Hz visual stimulus (frame rate = 60Hz). Bottom: A 25Hz tactile stimulus (sampling frequency of 44100Hz). Both are shown in a 0.4s time window.

Figure 2: The Schiit Magni headphone amplifier receives input from a computer's audio card. It provides stereo out which is split between two RCA connectors. Each C-2 tactor (shown here in the palm and on thumb) receive an analog audio signal which is converted to a vibration.

C. EEG Recording

EEG data was obtained using Neuroelectrics' Enobio8 sampling at 500 Hz. Seven Ag/AgCl electrodes were positioned at Oz, C3, C1, Cz, C2, C4, and Fz according to the international 10-20 system. An additional electrode was placed on the participant's temple to record eye blinks. Ground and reference electrodes were each placed on the participant's right mastoid with a small separation between the two electrodes.

D. Paradigm Description

Each participant was tested on two different frequencies for each stimulus type: 12 and 15 Hz for the visual stimulus, and 23 and 25 Hz for the tactile stimulus. Informed consent was obtained from all participants in accordance with the Boston University Institutional Review Board. Each trial consisted of four seconds without stimulation, followed by three seconds of stimulus presentation (Figure 3). The four seconds without stimulation consisted of one second of rest, and three seconds of baseline recording. This trial pattern was repeated for 10 trials in each run. Each participant completed 20 runs, which were distributed over five identical blocks. Each block consisted of four runs, alternating between visual and tactile conditions at each frequency.

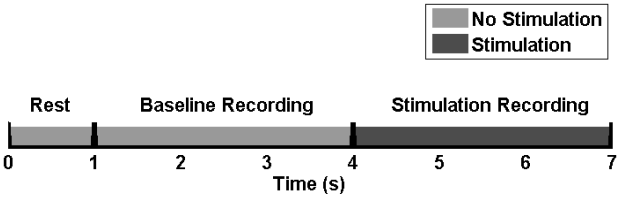

Figure 3: Timeline of an experimental trial. The stimulation recording period consisted of either a visual stimulation or a tactile stimulation.

To promote attention to the task and to minimize the effects of fatigue and boredom, participants completed an oddball-detection task during EEG recordings. Within a given block, the frequency during stimulation was altered for 1.5s for 6-8 trials. For visual trials, the flashing was reduced to 6 Hz and during tactile trials, the vibration was reduced to 10Hz. Participants were asked to identify when they saw or felt the oddball trial and report it audibly. Participants' responses were recorded. Participants were offered a small financial bonus based on their performance in reporting the oddballs (an additional $5-$15). Trials in which oddball stimuli were presented were not included in subsequent analyses.

E. Data Analysis

All data analyses were conducted using Matlab. EEG data was filtered using a 4^{th} order Butterworth low pass filter with a cutoff frequency of 55 Hz. These data were then parsed into trials. For each trial, the three-second stimulation period and the three-second baseline period were separated. The frequency content of each portion of each trial was analyzed by analyzed by applying a Hanning window and computing the FFT magnitudes.

III. Results

In general, frequency analysis revealed peaks at the appropriate locations during stimulation. Figure 4 shows a single participant's response to 12Hz visual stimuli and 23Hz tactile stimuli. Sharp peaks in the |FFT| spectrum coincide with the frequency of stimulation (as well as its first harmonic in the case of the 12 Hz visual stimulus). SSVEP was primarily seen in channels positioned over visual cortex (channel Oz), while SSSEP was more pronounced at more frontal electrode locations (channels C1, Cz, and C2).

Figure 5 shows each participant's SNR for the averaged |FFT|s of each trial condition. There was large inter-participant variability for both visual and tactile trials. However, for a given participant, the SNR values for SSVEP were generally larger than that participant's SSSEP SNR values. Further, all SNR values were larger than 1, suggesting that stimulation increased the associated frequency component in the neural signal.

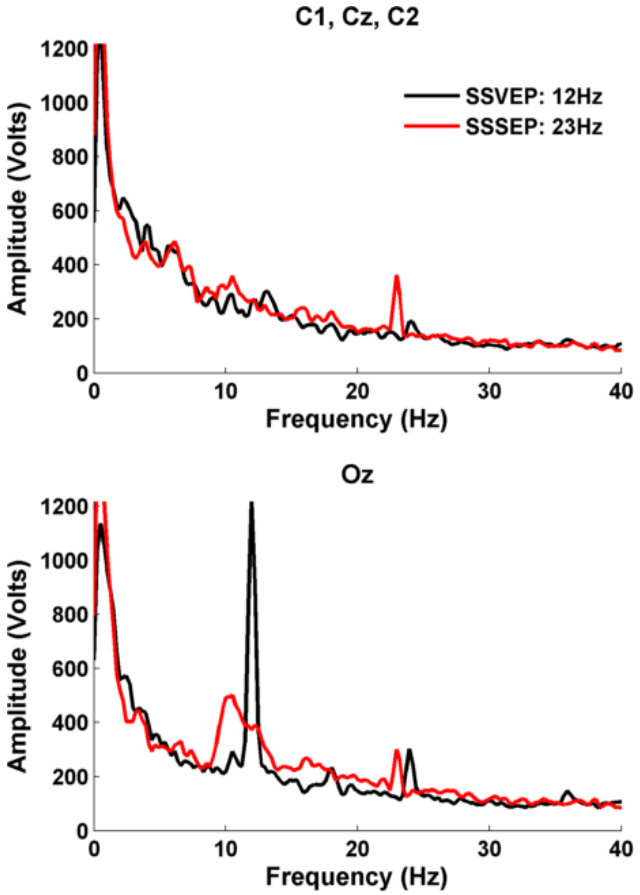

Figure 4: Top: Averaged |FFT|s of channels C1, Cz and C2 (somatosensory cortex) averaged together. Bottom: Averaged |FFT|s from channel Oz (visual cortex). These |FFT| plots show peaks at the frequencies in the spectrum with the most relative power during stimulation. The black solid line is the average |FFT|s for participant 2 (P2) attending to 12Hz visual stimuli. The red solid line is the average |FFT|s of the same participant attending to 23Hz tactile stimuli.

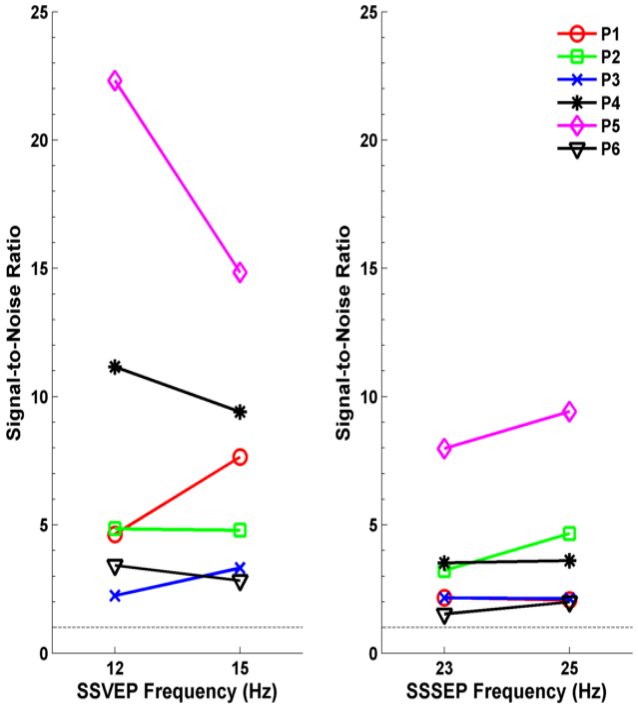

Figure 5: Averaged Signal-to-Noise Ratios for each participant's (P) SSVEP and SSSEP response while attending to different frequencies of stimulation. SNR values for SSVEP are calculated from values at electrode Oz and SNR values for SSSEP are the average of values from electrodes C1, Cz, and C2. The dashed line is the SNR value of 1.

IV. Discussion

We found that in naïve participants, stimulation with pattern-reversing visual patterns or amplitude-modulated vibration stimuli both resulted in an increase in EEG signal strength at the frequency of stimulation relative to the same frequency during periods of no stimulation. We observed this stimulation response to be stronger and more consistently seen when participants attended to SSVEP-generating stimuli. A possible reason for SSVEP responses having higher SNR values than SSSEP is that the visual response has less distance to travel from sensor to cortex than the tactile signal. Degradation of the somatosensory signal could occur in peripheral nerves during transmission through the arm and spinal cord [22]. The visual signal must only travel from the retina through cranial nerve II [23].

Some participants reported that the vibration of the tactors was very soothing, which might have reduced their attentiveness to tactile stimuli, and ultimately, their SSSEP SNR. SSSEP |FFT|s had some instances of a bump or peak between the frequencies of 8-11Hz (alpha band). This can be seen for instance in the lower panel of Figure 4 at 10 Hz. A response within this frequency band over visual cortex is known to be modulated by attentiveness [14]. The other consideration is that this noise is the mu response [24], which is a response to lack of motor activity. Future experiments will create more engaging tactile trials to avoid potential fatigue or boredom.

The frequencies chosen for each stimulus type ultimately did not affect the within-modality SNRs. There are no trends

to suggest that one chosen frequency in a given stimulus modality was better or worse than the other. Previous studies [12], [13] calibrated their stimulation frequencies based on participant-specific resonant frequencies. This was not done for this study in order to test the same frequencies across all participants but merits further examination.

In some participants, evoked potentials appeared in electrodes inconsistent with expectation regarding the cortical location of stimulus processing. This can be seen in the lower panel of Figure 4, where the SSSEP at 23Hz appears in Oz, which is located over visual rather than somatosensory cortex. This effect could make a difference in decoding EEG, but attention to electrode configuration and head size helps to avoid errors that could disrupt BCI control.

One potential confound in the experimental setup was the audible activation of the tactors. The sound generated by the tactor vibration was loud enough to be heard by the participant, even with ear plugs in place. Channel Fz, a channel used in recording auditory evoked potentials (AEPs) shows a surprisingly strong response during tactile trials. However, this observation is not conclusive enough to prove that AEPs were produced during the trial. Future studies will account for this with a short EEG recording in which the tactors are audibly vibrating, but not touching the participant.

Although SSVEPs exhibiting a higher SNR than SSSEPs at the chosen stimulation frequencies, it is unclear at present as to whether this advantage will translate to higher decoding performance when multiple stimulation frequencies are utilized and selective attention to a particular stimulus must be employed to modulate the frequency content of the EEG signals. Follow-up studies will address this matter.

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