Steady-State Visual Evoked Potentials: Distributed Local Sources and Wave-Like Dynamics Are Sensitive to Flicker Frequency

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Summary: Steady-state visual evoked potentials (SSVEPs) are used in cognitive and clinical studies of brain function because of excellent signal-to-noise ratios and relative immunity to artifacts. SSVEPs also provide a means to characterize preferred frequencies of neocortical dynamic processes. In this study, SSVEPs were recorded with 110 electrodes while subjects viewed random dot patterns flickered between 3 and 30 Hz. Peaks in SSVEP power were observed at delta (3 Hz), lower alpha (7 and 8 Hz), and upper alpha band (12 and 13 Hz) frequencies; the spatial distribution of SSVEP power is also strongly dependent on the input frequency suggesting cortical resonances. We characterized the cortical sources that generate SSVEPs at different input frequencies by applying surface Laplacians and spatial spectral analysis. Laplacian SSVEPs are recorded and are sensitive to small changes (±2 Hz) in the input frequency at occipital and parietal electrodes indicating distinct local sources. At 10 Hz, local source activity occurs in multiple cortical regions; Laplacian SSVEPs are also observed in lateral frontal electrodes. Laplacian SSVEPs are negligible at many frontal electrodes that elicit strong potential SSVEPs at delta, lower alpha, and upper alpha bands. One-dimensional (anterior-posterior) spatial spectra indicate that distinct large-scale source distributions contribute SSVEP power in these frequency bands. In the upper alpha band, spatial spectra indicate the presence of long-wavelength (>15 cm) traveling waves propagating from occipital to prefrontal electrodes. In the delta and lower alpha band, spatial spectra indicate that long-wavelength source distributions over posterior and anterior regions form standing-wave patterns. These results suggest that the SSVEP is generated by both (relatively stationary) localized sources and distributed sources that exhibit characteristics of wave phenomena.

Key words: SSVEP; Laplacian; Source localization; Spatial spectrum; Neocortical dynamics.

Introduction

Functional brain networks that process sensory inputs can be investigated using paradigms that drive populations of cortical neurons with a periodic stimulus. Steady state visual evoked potentials (SSVEP) or magnetic fields (SSVEF) can be easily detected by Fourier analysis of EEG or MEG signals when human subjects are presented with a sinusoidal contrast or luminance modulation of fixed frequency, often superimposed on cognitive task-related images (Regan 1989; Silberstein 1995; Narici et al. 1998; Srinivasan et al. 1999; Silberstein et al. 2003, 2004; Srinivasan 2004). SSVEPs are measured in narrow (usually <0.1 Hz) frequency bands centered on the stimulus frequency. Since typical EEG/MEG artifacts, such as muscle potentials, tend to have broadband spectra, the narrow-band signal-to-noise ratio of the steady-state response can be made arbitrarily large by simply increasing the duration of stimulation. This approach has had immense practical value in segregating stimulus related brain activity from both artifacts and spontaneous brain activity in cognitive and clinical studies.

Early human studies using EEG electrodes positioned over occipital cortex (Sperkerjse et al. 1977; Regan 1977; Tyler et al. 1978; Regan 1989), and local field potentials recorded within monkey visual cortex (Nakayama and Mackeben 1982) demonstrated that steady-state responses recorded over visual cortex depend on the temporal frequency of visual input. The dependence of the magnitude of the steady-state response on the input frequency is characterized by local maxima in the response amplitude at the stimulation frequency in at least three different “resonance” bands. At occipital electrodes, these bands are roughly 7-10 Hz, 15-20 Hz, and 40-50 Hz, which Regan (1989) labeled as the low, middle, and high frequency region of the spectrum. Even at a single electrode site, individual subjects can show multiple response maxima within these bands. Studies of multi-unit activity (MUA) in the cat visual cortex with periodic stimulation have also shown a similar banded structure.
with peaks in the magnitude of the response at multiple stimulus frequencies in the 4-8 Hz, 16-30 Hz, and 30-50 Hz ranges (Rager and Singer 1998). Steady-state responses in these different frequency bands show quite different sensitivities to physical stimulus parameters (color, spatial frequency, modulation depth, etc.) suggesting that flicker can entrain functionally distinct although spatially overlapping cortical networks at the cm scale of EEG (Regan 1989). Because only a very limited number of electrodes over the occipital lobe were used in these studies, only minimal information was obtained about the spatial properties of SSVEPs in these different frequency bands.

The dynamics of steady-state responses to flickering stimuli have been studied with large (> 128) numbers of EEG electrodes and MEG sensors covering the whole scalp in a number of cognitive tasks such as binocular rivalry (Srinivasan et al. 1999; Srinivasan 2004; Srinivasan and Petrovic 2005), selective attention (Chen et al. 2003; Ding et al. 2005), working memory (Silberstein et al. 2001) and other mental tasks (Silberstein et al. 2003, 2004). In these studies, steady state responses to a flickering visual stimulus have been recorded at many scalp locations beyond occipital channels, including channels over parietal, temporal, frontal, and prefrontal regions, with dynamic responses depending on both the type of stimulus and the cognitive task. Both structured (e.g., gratings) and unstructured (full-field luminance flicker) stimuli can elicit widespread synchronous responses. Modulations of the SSVEP can take place at electrodes in different scalp locations depending on the flicker frequency and the cognitive task. Task-related modulations of frontal SSVEPs can be independent of occipital/parietal responses (Srinivasan et al. 1999; Srinivasan 2004; Srinivasan and Petrovic 2005; Silberstein et al. 2001, 2003, 2004).

The magnitude, phase, and spatial distribution of the SSVEP are extremely sensitive functions of the driving frequency, e.g., sensitive to 1-2 Hz changes (Nunez 1995; Srinivasan 2004; Ding et al. 2005). Steady-state responses are recorded over parietal, temporal, and frontal lobes only over limited frequency ranges in comparison to occipital responses (Narici et al. 1998; Srinivasan et al. 1999; Srinivasan 2004; Ding et al. 2005). The strong dependence of responses far from primary visual areas on the flicker frequency does not easily fit a framework in which the SSVEP is generated by only localized occipital sources (Maier et al. 1987; Muller et al. 1997). Any source model of the SSVEP must account for the complex relationships between the flicker frequency and spatial properties of the source distribution apparent in both EEG and MEG recordings. As flicker frequency is varied, different patterns of cortical source location, magnitude, and/or phase appear to be synchronized within a narrow frequency band surrounding each flicker frequency.

In this study, we attempt to characterize the source distribution of the SSVEP by applying several methods of spatial analysis, as opposed to dipole model fitting. First, we apply a surface Laplacian algorithm to improve the spatial resolution of the EEG signals. The surface Laplacian is the second spatial derivative of scalp potential, which provides estimates of the local current flowing radially through the skull into the scalp (Srinivasan et al. 1996; Nunez and Srinivasan 2006). The effect of the surface Laplacian is to emphasize sources (estimated) within 2-3 cm of the electrode that are “localized”, i.e., small, superficial, synchronous dipole layers that are relatively segregated from the surrounding tissue.

The second approach to spatial analysis adopted for this study is to estimate the wavenumber spectrum of the SSVEP. The wavenumber spectrum decomposes spatial signals in an array of electrodes into its spatial frequency components, analogous to the usual power spectrum of EEG time series. Each temporal frequency band has its own (complex valued) spatial signal, obtain by Fourier transform in the time domain. If different temporal frequencies of visual input are driving different source locations, magnitudes, and phases, the wavenumber spectrum can be used to quantify these differences. The wavenumber spectrum provides information about the relative contributions of source activity organized at different spatial scales (spatial frequency or wavelength) to the SSVEP. By representing the spatial signal as a wavenumber spectrum, we can also directly evaluate how volume conduction influences estimates of SSVEP sources. Unlike the complex source dynamics, the severe low-pass spatial filtering of volume conduction is independent of frequency.

In SSVEP experiments, dynamic properties of the source distribution appear to be strongly dependent on the flicker frequency. Our results indicate that flickering visual stimuli engage both local sources, identified by the surface Laplacian algorithm, and non-local sources distributed over large regions of neocortex. Furthermore, local source activity and large-scale (distributed) sources exhibit different preferred flicker frequencies. The large-scale source dynamics have the appearance of traveling and standing waves in the SSVEP.

**Methods**

**Stimuli**

The stimuli consisted of patterns composed of 600 dots (each of size ~ 0.12 degrees) positioned randomly over a region of visual space centered on the fovea, and covering 10 degrees of visual angle. Each random dot was presented for 8 ms (1 refresh of a screen with vertical refresh rate of 120 Hz). The flicker was generated by pre-