Steady State Visual Evoked Potentials in the Delta Range (0.5-5 Hz)

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Abstract. The usually 'accepted' limits of Steady State Visual Evoked Potentials are in the 3-60 Hz range. Recent studies reported SSVEP activities below 3 Hz, which remains a matter of debate. We recorded EEG responses to stimuli from 0.5 to 13 Hz. We first confirm the possibility to elicit SSVEP below 3 Hz. Afterwards, for the first time, we show that SSVEP recorded in the δ (0.5-5 Hz) range seem to describe several subsystems, with peaks near 1, 2.5 and 5 Hz (close to subharmonics of 10 Hz). Finally, we report surprising results in the lower frequency ranges, with responses for almost all harmonics (*e.g.* 15 peak responses between 0.5 and 14.5 Hz for stimuli at 1 hz).

1 Introduction

Sensory evoked potentials are electrical potentials, recorded from the nervous system of human or animal, while stimulating sense organs. EEG evoked potentials (EP), as distinct from spontaneous potentials (background EEG), can be interpreted as the reorganization of the spontaneous brain oscillations in response to the stimulus [2, 1]. Contrary to event-related potentials, these potentials are time-locked to the stimulus. Therefore they can be enhanced using averaging techniques on several trials [4]. It is well-known that following the presentation of a transient visual stimuli, an EEG response in the visual areas can be recorded. However, flash VEP and pattern VEP (reversal or offset/onset) are the most completely studied and described types of VEP (see [3] for review).

Such visual stimuli usually induce transient responses of the visual system. However, using long stimulus trains, a stable VEP is produced, which can be displayed using averaging techniques. These EEG waves are termed as "steady-state" visual evoked potentials (SSVEP) of the human visual system [5], and can also be observed with other electrophysiological technique (local field potentials, magnetoencephalography). Steady-state potentials are to be distinguished from transient potentials, because their constituent discrete frequency components remain closely constant in amplitude and phase over a long time period [6].

The usually 'accepted' limits of SSVEP are in the 3-60 Hz range. What happens below and above these frequencies is not well-documented. Recent studies reported SSVEP activities below 3 Hz (1-100 Hz EEG in [9], 0-20 Hz MEG in [10]). Nevertheless, many recent publications still convey the notion that SSVEP can only be recorded above 3 or 4 Hz (*e.g.* above 6 Hz in [11]). The present study seeks to demonstrate the SSVEP phenomena in the low frequency range (δ = 0.5-5 Hz), using EEG responses recorded during continuous flash VEP stimulation.

2 Methods

2.1 EEG Data - SSVEP in the δ Range

Five subjects without history of epileptic seizure or related troubles (males, age $\simeq 30 \pm 1.6$[1]) gave their informed consent for this experiment. Flickering light can trigger photosensitive epilepsy. Before recording the EEG session, subjects received detailed information about photosensitive epilepsy. After EEG was set-up, subjects were first exposed to flickering light and tested for any pre-symptoms of epilepsy[2] (no subject were rejected).

EEG was recorded in a dark room with a G-Tec system cap, with a sampling rate of 512 Hz, notch filtering at 50 Hz, and online bandpass filter at 0.01 and 100 Hz. We compared SSVEP every 0.5 hz until 5 Hz with those recorded at 7, 10 and 13 Hz, frequencies which have been thoroughly studied in the literature. Hence, SSVEP were recorded with the stimulus frequencies $\nu_i \in \mathbf{V} = [0.5, 1, 1.5, 2, 2, 2.5, 3, 3.5, 4, 4.5, 5, 7, 10, 13]$ Hz. For each frequency, we recorded first a baseline period of 20 sec (rest with eyes opened). Next we alternated 20 times a 10 second period of stimulation[3] with 5 second period of rest. Stimulation was performed with a flash VEP, obtained by blinking white square of 5 cm side (*i.e.* 128×128 pixels) at the center of a computer screen. Fixation task was performed with a non blinking gaussian noise of the same dimension. EEG was recorded with 20 channels placed according to the 10-20 international system, together with vertical and horizontal electrooculogram. Epochs with too strong artifacts were rejected[4]. Stimuli were recorded simultaneously in an additional channel (using a G-tec g.TRIGbox). The distance to the screen was controlled for all subject to be $\simeq$ 1 m, in a dark room.We averaged the EEG at electrode Oz[5] over all trials and all subjects (totaling 80-100 trials for each stimulus frequency, as some trials were rejected when noise was too high).

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[1] $\pm$ indicates standard-error

[2] During a first trial session pre-symptoms of epilepsy were observed (= from simple headache to EEG sharp waves) - any such symptoms would have lead to rejection of the subject

[3] long duration is needed for low frequency stimulation, for instance at 0.5 Hz it takes 1 second to stimulate one cycle only

[4] and especially one subject fell asleep in the middle of one session

[5] Oz = Occipital area channel, where the source of SSVEP is usually detected in scalp EEG. Occipital channels are located above the visual cortex.

2.2 Fourier Power Analysis

The Fourier power $\mathbf{\Phi}$ was computed using the Welch method (4 sec. Hanning windows with 50% overlap, whole 10 sec stimulation period) in bins of $s = 0.1$ Hz for 0.1 to 15 Hz. The signal-to-noise ratio of SSVEP $\mathbf{SNR}(f_p)$ was then computed using the ratio of Fourier power at a given frequency f_p to its n-adjacent frequencies power:

$$\mathbf{SNR}(f_p) = \frac{n.\mathbf{\Phi}(f_p)}{\sum_{k=s}^{s.n/2} \mathbf{\Phi}(f_p + k) - \sum_{k=s}^{s.n/2} \mathbf{\Phi}(f_p - k)} \quad (1)$$

with n pair. This SNR measure have been used successfully to enhance SSVEP peaks [12]. We used $n = 6$, so that the frequencies $f_p \pm 0.4$ Hz were taken into account. In other words, for each stimulus frequency $\nu_i \in \mathbf{V}$, with $\mathbf{V} = [0.5, 1, ..., 4.5, 5, 7, 10, 13]$ we obtained a Fourier SNR vector $\mathbf{SNR_i}(f_p)$ with $f_p \in [0.5 - 14.6]$ Hz. Fourier power and SNR were computed for each trials, and averaged afterwards. Computations were done with Matlab (The MathWorks, Inc.). Results presented here come from the Oz[5] electrode; scalp propagation will be presented in an extended version of this paper (due to limit of space).

3 Results

3.1 Is there anything below 5 Hz?

For each $\nu_i \in \mathbf{V}$, we reported on a curve the average Fourier power value $\overline{\mathbf{\Phi_{i,s,t}}}(\nu_i)$ (grand average during stimulation at frequency ν_i, for all trials t and all subjects s, at the frequency ν_i). We compared these Fourier powers against the average Fourier power during the baseline period $\overline{\mathbf{\Phi_{s,t}}}$ (average for all subjects, over all frequencies in [0.5–5] Hz). As can be seen on Fig.1, for all stimulation frequencies, we observed an increased Fourier power as compared to the baseline. The stimulation induced changes in EEG power for all frequencies below 5 Hz.

3.2 Periodic but not sinusoidal

One would expect SSVEP to look like a sinusoidal curve. This is however incorrect: SSVEP are know to have strong amplitude at the stimulus frequency, but also at its harmonics. The Fig.2 shows the SSVEP averages with the stimulus frequency $\nu_i = 1$, 2.5, 5 and 10 Hz (similar results are observed for all frequencies). The curves are periodic and nearly sinusoidal (blue curves), but they seem more complex for lower frequencies (see e.g. the curve at $\nu_i = 1$ Hz on Fig.2 *vs.* the curve at $\nu_i = 10$ Hz). This could be explained by two possibilities: either the several harmonics of 1 Hz are superimposed; or what we recorded is not SSVEP, but a succession of transient VEP.

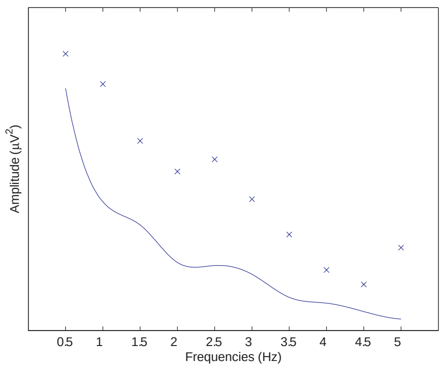

Fig. 1. Average Fourier power. Crosses: average Fourier power $\overline{\mathbf{\Phi}}_{\mathbf{i,s,t}}(\nu_i)$ during continuous flash VEP stimulation for each $\nu_i \in \mathbf{V}$, depending on the frequency of the stimulation. Lower curve: average power $\overline{\mathbf{\Phi}}_{\mathbf{s,t}}$ during rest with eyes opened.

3.3 SSVEP or transient VEP?

The best solution to check for the presence of SSVEP against transient VEP is to use Fourier representation. It is because SSVEP are stable (not transient), that their frequency components remain nearly constant, leading to a significant change of Fourier power at their peak frequency. Furthermore, SSVEP should display changes at harmonics of the stimulus frequency. We averaged the Fourier SNR computed for all subjects and all trials (80-100 trials per frequency, as explained above). The Fig.3 shows the result $\overline{SNR_{i,s,t}}$ of the Fourier SNR computation for all frequencies during stimulation at frequency ν_i (grand average for all trials t and all subjects s). All stimuli induced a peak at the stimulus frequency and harmonics. The results obtained in the low ($\nu_i = 0.5 - 3$ Hz) δ range prove that SSVEP were elicited. Harmonic responses surprisingly did not disappear in higher frequency ranges, for instance the $\nu_i = 1$ Hz SSVEP has 15 peaks from 0.5 to 14.6 Hz, including the 0.5 subharmonic. In most cases however the subharmonics were weaker (they were clearly observed only for the $\nu_i = 1$, 2 and 13 Hz SSVEP).

3.4 SSVEP δ subsystems

For each ν_i, we reported on a curve the average Fourier SNR value $\overline{SNR_{i,s,t}}$(grand average at the frequency ν_i - *i.e.* the arrows on Fig.3). This shows the evolution of SSVEP amplitude depending on frequency. The curve (Fig.4) shows four peaks: at $\nu_i \simeq 1$, $\nu_i \simeq 2.5$, $\nu_i = 5$, and $\nu_i = 10$ Hz. All activities below 5 Hz have a lower SNR, which could explain why they often get unnoticed in the literature.

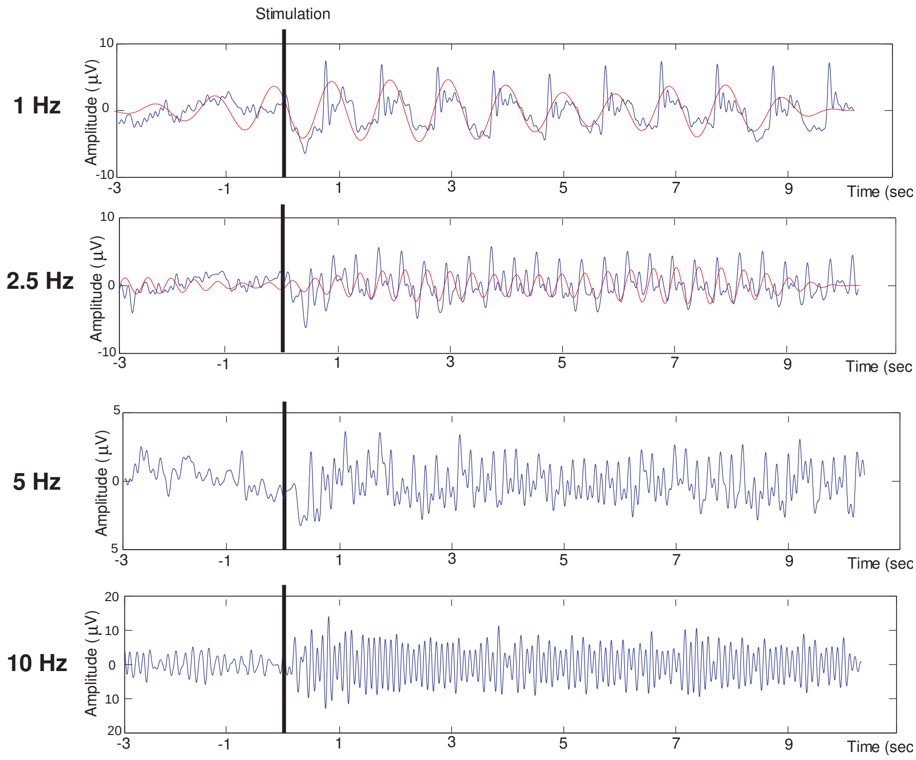

Fig. 2. Averaged SSVEP for the stimulus frequency $\nu_i = 1$, 2.5, 5 and 10 Hz. The curves are periodic, but not sinusoidal. For more convenience, a superimposed red curve representing the curve filtered around the SSVEP frequency ± 0.25 Hz is also displayed for the 1 Hz and 2.5 Hz SSVEP (representing the SSVEP without its harmonics).

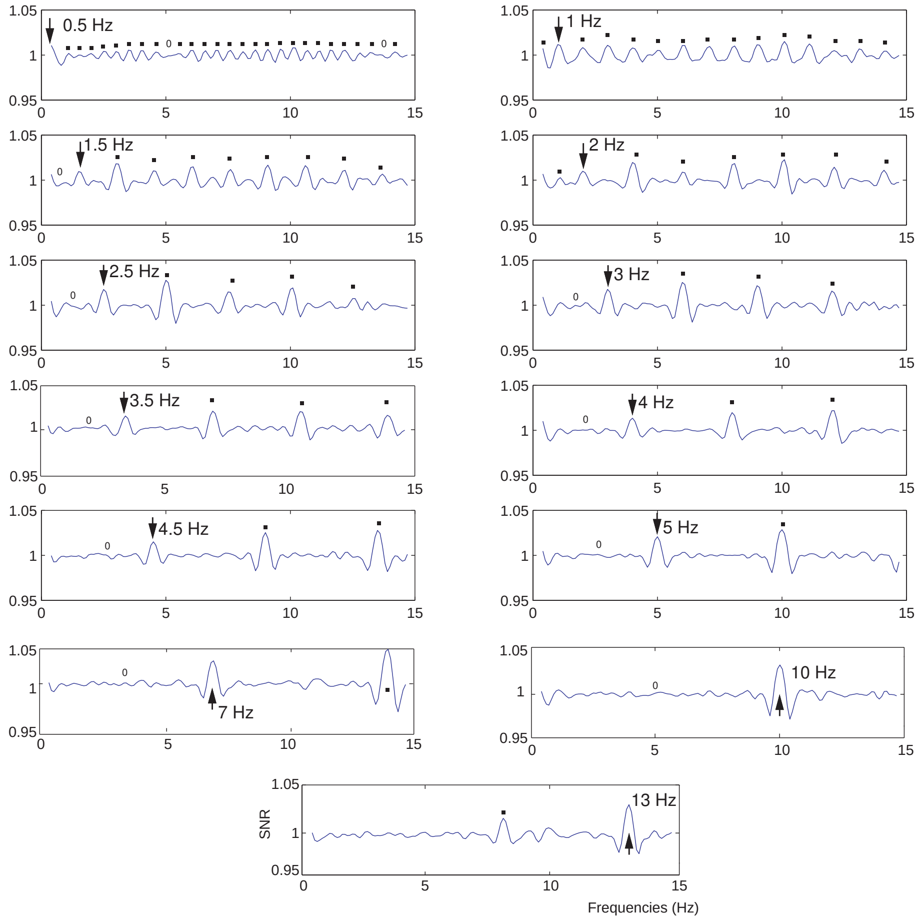

Fig. 3. Averaged Fourier SNR $\overline{SNR_{i,s,t}}$ for each frequencies. Responses are visible at the stimuli frequency, but also at their harmonics. Arrows represents the expected SSVEP frequency, dots the harmonics or subharmonics found, and zeros expected harmonics or subharmonics that were not observed reliably. The evoked activity below $\nu_i = 3$ Hz match the definition of SSVEP: they have nearly constant frequency components at the stimuli harmonics.

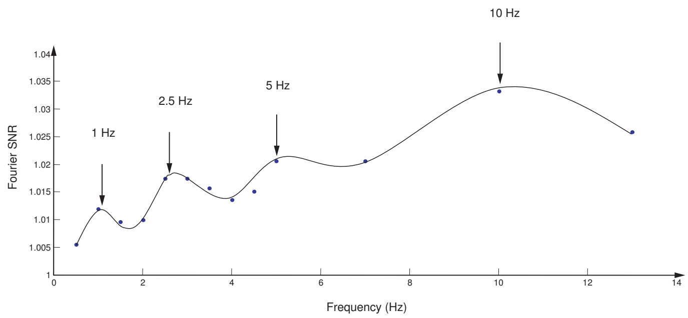

Fig. 4. SSVEP δ range subsystems. The dots represents the average Fourier SNR values $\overline{SNR_{i,s,t}}$ for each stimulus frequency ν_i, over each trial t and each subject s. The well-known peak of power at $\nu_i = 10$ Hz is observed, together with peaks at $\nu_i \simeq 1$, $\nu_i \simeq 2.5$, and $\nu_i = 5$ Hz.

4 Discussion and Conclusion

We have shown that stimulation in frequency range as low as 0.5 Hz elicit periodic nearly sinusoidal evoked potentials (see Fig.2). Contrary to SSVEP in higher frequencies (> 5 Hz), the δ range SSVEP are less sinusoidal. However, in all frequencies, the same phenomenon was observed: an increase of amplitude at the SSVEP frequency during stimulation (see Fig.1), with peaks for all harmonics of the SSVEP frequency (see Fig.3). The distortions observed in lower frequencies are hence attributed to the contribution of their several harmonicsand to the poor signal-to-noise ratio of signals in very low frequencies.

Despite years of investigation, SSVEP remains a complex mechanism, which is not yet completely understood. It is usually decomposed in three different subsystems, which can be considered as three functional flicker components [7, 6, 8]:

1. A primary component dominating in high frequency (gamma 25-60 Hz range).
2. A secondary component dominating in the 15-25 Hz range.
3. A rhythmic after-discharge dominating in low frequency (5-15 Hz range).

SSVEP recorded in the δ ($\nu_i \in [0.5 - 5]$ Hz) range seem to describe several subsystems, with peaks near $\nu_i = 1$, 2.5 and 5 Hz. To the best of our knowledge, these new components were never described. These peaks are, interestingly, close to the 10 Hz subharmonics: 1.25, 2.5 and 5 Hz (we did not unfortunately record SSVEP at 1.25 Hz). This fits with the theory developed in [9]: SSVEP induced by a flickering light without pattern have been shown to elicit better responses for harmonics of 10 Hz (10, 20, 40 and even 80 Hz). Our study thus confirms the importance of the 10 Hz rhythm in SSVEP. We could expect to find other peaks at lower frequencies (*e.g.* 0.75 Hz or 0.375 Hz), but the limited precision of recording devices, and the presence of artifacts in the δ range, would make it very difficult to measure them.

Finally, a crucial question remains: what effect could we expect from stimulations in low frequency ranges? What could be the outcome for the brain of the surprising EEG changes observed (*e.g.* every 0.5 Hz for SSVEP at $\nu_i = 0.5$ Hz, see Fig.3)? One of our subject for instance consistently fell asleep after a few trials during flickering stimulation below 2 Hz. The effects (especially cognitive effects) for very low frequencies (below 3 Hz) are certainly worth some complementary investigations.

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