Electrophysiological study of the monkeys' brain rhythms

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***Abstract—* In electrophysiological experiments on humans and animals has been shown that the brain's response to rhythmic stimulation changes not monotonously with a change in the frequency of stimulation. The dependence of the response magnitude on the input frequency is characterized by local maxima, the so-called "resonant frequencies" which neuronal origin is still poorly understood. In the present study we asked a question, whether resonance-like frequencies depend on intrinsic dominant brain rhythms observed in resting-state EEG.**

Four Macaca Mulatta monkeys were stimulated by flickers at 22 different frequencies from 2 to 42 Hz in 2 Hz steps. The magnitude of the response was assessed as the power of sinusoidal oscillations of the steady-state evoked potentials with a frequency corresponding to stimulation. Then the dependences of the response magnitude on the stimulation frequency were compared with the EEG spectra obtained without stimulation.

The results obtained revealed at least two resonant frequencies in the visual system of monkeys, the use of which causes the strongest response to rhythmic stimulation. The first frequency is fairly stable for all animals tested and is in the 6-12 Hz range. It coincides with the internal dominant rhythm of the monkey brain with a frequency of about 10 Hz, observed on the EEG at rest, which is similar to the human's alpha rhythm. The second range of resonance frequencies at 14-17 Hz was observed in three monkeys, while in one animal it was much wider - in the range from 22 to 30 Hz. Analysis of EEG spectra at rest did not reveal frequency peaks that would correlate with the second range of resonance frequencies.

***Index Terms* — brain rhythms, electroencephalogram, flicker stimulation, monkey, resonant frequencies**

I. Introduction

Investigation the neurophysiological basis of human brain functioning is difficult without the use of animal models. The closest animals to humans according to the anatomical and physiological characteristics are monkeys. So, information about electrical processes in the monkeys' brain can be extrapolated to some extent to humans for understanding the principles of human brain functioning. As especial interest is investigation of the brain rhythms as a fundamental feature of neuronal activity in animals and humans. Particularly, we were interested in the phenomenon of 'neuronal entrainment' – temporal synchronization of neural responses to external rhythms. In electrophysiological experiments on humans (Regan, 1989; Herrmann et al., 2001), monkeys (Nakayama and Mackeben, 1982) and cats (Rager and Singer, 1998) has been shown that the brain responsiveness to rhythmic stimulation does not change uniformly with changing stimulation frequencies. The dependence of the response magnitude on the input frequency is characterized by local maxima, the so-called "resonance-like frequencies" which neuronal origin is still poorly understood. In the present study we asked a question, whether resonance-like frequencies depend on intrinsic dominant brain rhythms observed in resting-state EEG?

To our knowledge, there is only one study of correlation between individual dominant brain frequencies and preferred flicker frequency (Birca et al, 2006). No significant correlation was found, probably because few frequencies have been used (only four). Therefore, the aim of our study was careful identification of resonance-like frequencies in the monkeys' brain with the help of wide range of flicker frequencies and comparison the data received with spectral characteristics of EEG recorded in the absence of stimulation.

II. Methods

Four monkeys Macaca Mulatta mean age 9 years took part in the experiment. EEG electrodes were attached to the bone over occipital, parietal, central and frontal lobes, on the central line, left and right hemisphere, similarly to the International 10-20 electrode system for human EEG recording. Photic stimulation was presented through standard LED flash stimulator placed in front of the animal's head at a distance 2 meters. 22 flicker frequencies were used – from 2 to 42 Hz with 2 Hz step (two from four animals were presented 24 frequencies with additional frequency of 44 and 46 Hz). Stimulation began after dark adaptation with initial frequency of 2 Hz which was replaced by the next frequency of 4 Hz, then 6 Hz and so on. Stimulation by each frequency lasted 3 minutes, and in total experiment took around 70 minutes. After automatic artifact rejection from EEG based on amplitude threshold, the steady-state evoked potentials (SSVEP) were averaged for each frequency. The magnitude of the response was estimated as the power of SSVEP's sinusoidal oscillations with frequency corresponding to the stimulation.

During light stimulation, the animals sat on a primate chair in a dark room with limited ability to turn their heads but could move their eyes freely. Since we did not control gaze position and to obtain reliable data, each experiment was repeated more than 10 times on separate days. The results were then averaged to reduce possible fluctuations caused by eye movements. Resting-state EEG was recorded in awake animals for 15-20 minutes in a primate chair placed in a continuously lit room, without any task or stimulation. The recordings were repeated more than 10 times on different days, which gave about 3 hours of continuous EEG. After rejection of amplitude artifacts, the Fourier spectra of the resulting EEG were calculated for each animal.

III. Results

SSVEPs recorded in all four animals from parietal, central and frontal sites showed one local maximum in response to flashes in the frequency range 6-10 Hz, with a tendency to lower frequency at frontal sites. Results obtained from occipital electrodes showed second prominent local maximum in the frequency range 14-30 Hz, depending on the animal. Figure 1 represents electrophysiological data obtained from all four animals at electrodes placed over the center of occipital lobe (an analog to human channel Oz).

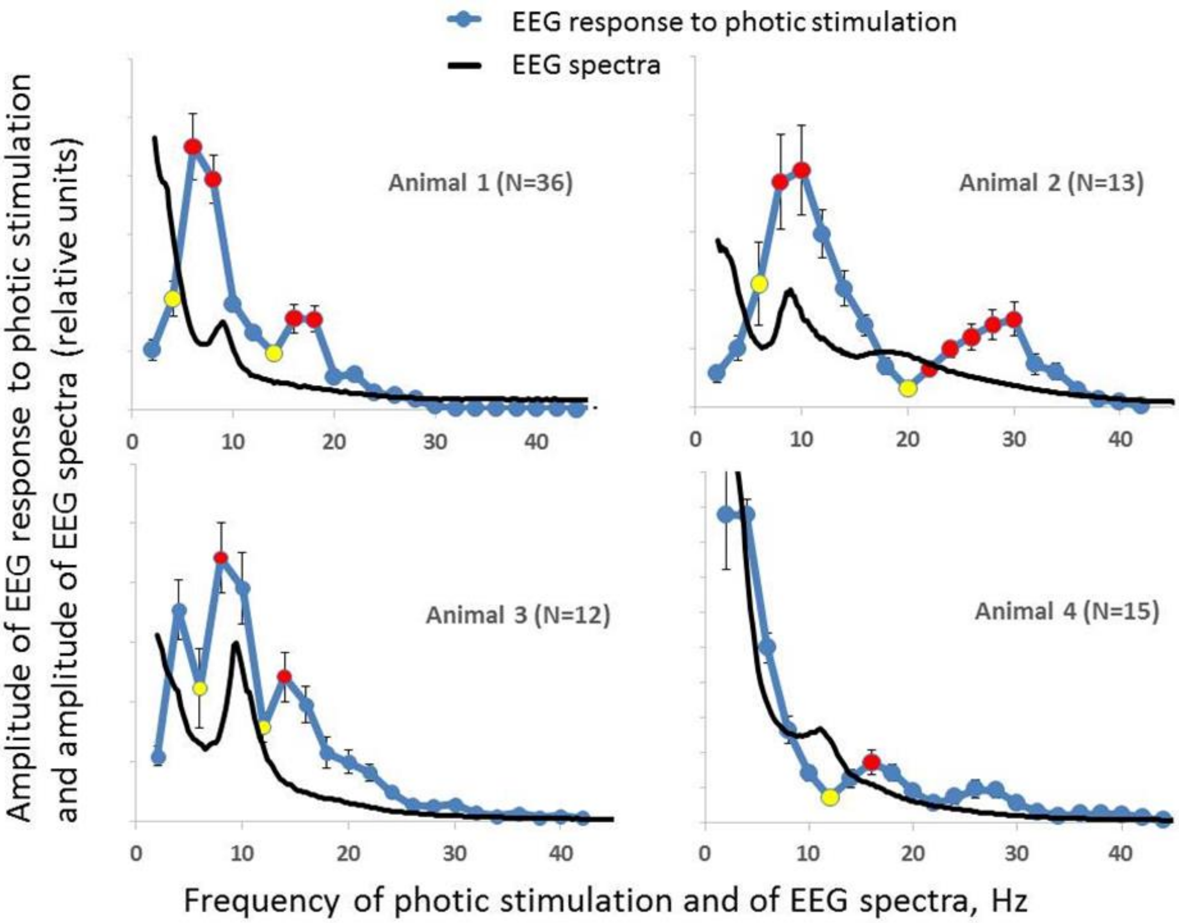

Figure 1. Fourier spectra of EEG recorded at occipital site in rest conditions (black lines) and dependence of the brain response magnitude on frequency of photic stimulation (blue lines with dots). Red dots represent statistically significant local maxima of the response (Comparison with preceding points marked yellow by Paired Wilcoxon Test, P<0.05). N – number of experiments carried out on different days on one animal. Error bars represent Standard Errors.

The power of SSVEPs to photic stimulation and Fourier spectra of resting-state EEG obtained for each animal were superimposed on the same frequency scale. For graphic comparison both values have been converted to relative units. As it is seen from the figure, three from four animals show two significant local maxima at the response-frequency curve (red dots). For animal №1 first maximum was in the frequency range 6-8 Hz, second peak was at flash frequencies 16-18 Hz. Animal №2 showed first maximum at frequencies 8-10 Hz and second maximum at 30 Hz (but frequencies at 22-28 Hz also evoked significantly greater responses comparatively to the preceding frequency 20 Hz). First peak response at animal №3 was at frequency 8 Hz and second peak observed at 14 Hz. Fourth animal showed only one significant peak at frequency 16 Hz. Another peak at frequencies 26-28 Hz did not reach statistical significance (P=0.16). Lower frequency peak at about 10 Hz was absent at electrode Oz, but at adjacent electrodes placed over left and right sides of occipital lobe (channels O1 and O2) we observed also significant maximum in response to flashes at frequencies 10-12 Hz. However at these two electrodes higher frequency peak at 16 Hz was less prominent.

EEG spectra obtained at the same electrodes in resting-state conditions showed one maximum at frequency range 9-11 Hz resembling human alpha-rhythm, because as in humans it is localized at occipital and parietal areas. Note, however, that in humans, the alpha rhythm is usually observed when eyes closed, whereas our monkeys kept their eyes open for most of the time the EEG was recorded. The frequency of this rhythm slightly varied across four animals: №№ 1, 2, 3 showed peak amplitude at frequency about 9 Hz, whereas for animal №4 the peak was at 11 Hz.

IV. Discussion

As follows from the above data and Figure 1, there are at least two resonance frequencies in the visual system of monkeys, the use of which causes the strongest response to rhythmic stimulation. The first frequency is quite stable across all animals tested and is in the range of 6-12 Hz. It coincides with the internal dominant rhythm of the brain, observed on the EEG at rest, which is similar to human alpha-rhythm. Second resonant frequency diapason was observed at 14-17 Hz in three monkeys, whereas for one animal it was much broader, in the range between 22 and 30 Hz. Analysis of EEG spectra at rest did not reveal any frequency peaks which would correlate with the second resonance frequency diapason.

Thus, the dependence of response magnitude of the monkeys' visual system on the flicker frequency is not monotonic but has two local maxima. One of which coincides with the dominant brain rhythm at frequency about 10 Hz. Exploring the neuronal nature of this phenomenon is a matter of future research.