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Direct effects of audio-visual stimulation on EEG

*M. Teplan**, *A. Krakovská*, *S. Štolc*

Institute of Measurement Science, Slovak Academy of Sciences, Dúbravská cesta 9, Bratislava 842 19, Slovak Republic

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ABSTRACT

In the course of 2 months, 25 repetitions of a 20 min audio-visual stimulation (AVS) program with stimulations at 17, 9, 4, and 2 Hz were applied to 6 volunteers. EEG data were recorded from 6 scalp locations prior, during and after AVS. In order to identify direct and transient changes in EEG under influence of AVS, total power, relative frequency band powers and magnitude-squared coherences were estimated. Intense brain wave entrainment as a direct reaction to AVS was significant through increase of spectral powers and coherences around the stimulating frequency bands in the occipital areas, spreading also to the central and frontal regions. However, these excitations were 'short-lived'. On the other hand some signs of interhemispheric cooperation (coherences in the narrow bands around 2, 4, and 17 Hz at parieto-occipital areas) remained increased during the investigated 3 min after AVS. As going through further AVS sessions the driving response progressively enhanced for 2 and 4 Hz stimulation in centro-parietal locations. Progress was also found in the left and right hemisphere synchronization examined by coherences. In perspective, the results contribute to deeper comprehension of photic stimulation approaches as a technique of guided entrainment of the brain waves or intermediate increase of hemispheres' synchronization.

1. Introduction

Audio-visual stimulation is a way of external influence of the brain by rhythmic light and sound stimuli. A rapid change in a sensory stimulus initiates a transient evoked potential. If this stimulus occurs repetitively at a rate high enough to prevent the evoked potentials (EPs) from returning to a baseline state, the elicited response is developed in a form of steady-state evoked potential [1]. A distinctive feature of the visual steady-state evoked potential (SSVEP) is that it comprises sinusoidal components at stimulus frequency and its harmonics. Mechanisms governing neuronal activity are sensitive enough to be entrained by repetitive low amplitude EPs. Under entrainment of the brain waves this kind of resonant effect is understood. AVS primarily activates brain centers for visual and sound processing. The topography of the low-frequency SSVEP is generally characterized by amplitude maximum in the occipito-parietal region.

Throughout history, several studies have been devoted to the effects of external stimulation on the cortical EEG, predominantly in photic driving response [2–5]. An interest in using visual and auditory rhythmic stimulation as a means of inducing relaxation or hypnosis raised in the middle of the last century [6]. More recently, devices using light and sound at specified frequencies have been used to 'drive' the EEG toward certain frequencies. In the last decades audio-visual stimulation has been reported as an effective method for relieving dental anxiety [6], to induce hypnagogic states [7], helping to relieve tension and migraine headaches [8,9], for therapeutic effect on premenstrual syndrome [10], to improve behavioral and cognitive functions of learning disabled boys [11], to alleviate the cognitive dysfunctions in connection with closed head injury [12], and damages from aneurysms and strokes [13].

* *Corresponding author*. Tel.: +421 2 59104536; fax: +421 2 54775943.
E-mail address: michal.teplan@savba.sk (M. Teplan).

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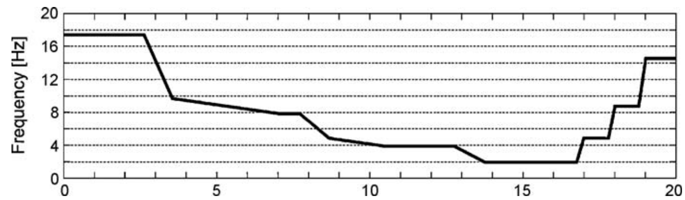

Fig. 1 – Scheme of frequency profile of the 20-min AVS program. The program stimulated the brain from 17 Hz down to 2 Hz and back to 15 Hz.

Comprehensive review of the AVS effects [14] suggests that AVS is an effective therapeutic tool.

Driving response has been found by Lazarev in majority (70–100%) of children and adolescents [15]; according to the criterion of peak amplitudes 20% larger than the neighbouring frequencies. They have observed response varying with frequency, being the strongest in alpha and theta range. Salansky et al. studied entrainment due to visual stimulation in the range of 1–20 Hz with frequency increment of 0.4 Hz [16]. They found resonance activation only for 20% of stimulation frequency values. Several studies have suggested that photic driving response has a more diffuse distribution on cortical EEG, not only in the occipital regions [7,17].

The findings concerning the rhythmic brain activity are often inconsistent. Transient enhanced response in the alpha range shortly after photic driving was reported by Sakamoto et al. [18]. On the other hand, Brauchli et al. [19] have concluded that audio-visual stimulation with varying frequency and intensity of stimuli have affected mood and autonomic arousal, but not electrocortical variables. Timmermann et al. [17] came also to the conclusion that AVS in the alpha range have no significant effect on the corresponding alpha activity of the cortex. Kawaguchi et al. [20] reported that one-half of their subjects did not produce driving response within the alpha band while being exposed to stroboscopic flashes ranging from 5 to 16 Hz. In the case of another visual stimulation experiment only low-baseline alpha participants showed photic driving response within the alpha band [21].

The main purpose of this study is to investigate the AVS effects on EEG on immediate and short-term basis. In particular, the aim is (1) to quantify direct impact of AVS on different cortex regions and (2) to find out whether the response of the cortex to the stimulation evolves throughout the training process of 25 sessions. In addition, we evaluated (3) transient effects lasting few minutes after the end of the stimulation.

2. Materials and methods

Six right-handed healthy subjects (2 females and 4 males) volunteered for 25 audio-visual trainings. Participants ranged in age from 24 to 39 years, with a mean of 25.5 years, S.D. 5.1 years. They did not have any neurological deficit and were not taking any drugs known to affect the EEG. The participants gave their written informed consent prior to their inclusion in the experiment.

2.1. *Parameters of audio-visual stimulation*

Overall training of each subject from the test group consisted of 25 AVS program sessions, each of 20-min length. Each person attended only one session per working day. Due to weekends or other exceptional events, separation between stimulations could be prolonged to several days. Subjects were lying in a darkened, electrically shielded room during the session. AVS was provided by commercially available Voyager XL light and sound synthesizer (Theta Technologies). The device consisted of headphones and glasses with red light-emitting diodes connected to a portable unit providing various AVS programs. From about 50 programs offered by the producer of the device we chose one that introduces wider range of stimulating frequencies. The AVS program stimulated brain at the following frequencies (Fig. 1): 17 Hz during the first 3 min followed by fast decrease to 10 Hz and slower decrease to 8 Hz during min 4–8, then fast decrease to 5 Hz during min 8–9, slower decrease to 4 Hz during min 9–10, steady 4 Hz during next 3 min followed by decrease to 2 Hz during min 13, steady 2 Hz during min 14–17, and then stepwise return through 5 Hz, 9 Hz to 15 Hz at min 17–20. Visual stimulation was provided by rectangular red light diode pulses with a number of switches determining the stimulation frequency. Sound beats were produced from three sine wave pulses. One wave was fixed to stable frequency at 280 Hz. Then, a recquired number of beats per second was controlled by distancies of two other frequencies from 280 Hz. For example for 17 Hz: 263, 280, and 297 Hz, while for 2 Hz: 278, 280, and 282 Hz.

2.2. *EEG recording*

As we were interested in changes evoked by AVS, data from 3-min period prior to each AVS training were firstly recorded. Subjects were instructed to keep their eyes closed and relax both physically and mentally. The lying position during the EEG measurements was comfortable enough to avoid unwanted activities and to diminish the occurrence of artifacts caused by feeble motion. After the initial EEG recording, headphones and glasses were placed over the electrode cap and the participants were instructed to stay released and to follow the AVS. Subjects were provided with AVS for 20 min, with simultaneous EEG recording. After the stimulation, a post-session EEG during relaxed wakefulness with closed eyes was recorded for another 3 min.

Unipolar EEG montage comprised eight channels with electrodes placed on F3, F4, C3, C4, P3, P4, O1, O2 locations according to the International 10–20 system. The reference electrode was located at Cz and the ground electrode at Fpz point. A standard cap system (Electro Cap Inc.) with Ag–AgCl electrodes was employed. In order to prevent signal distortions, impedances at each contact electrode-scalp were kept below 5 kΩ, and balanced within 1 kΩ of each other.

EEG amplification unit was characterized by the following parameters: Number of channels: 8, amplifying gain: 402, sampling frequency: 500 Hz, A/D converter resolution: 16 bits, input resolution: 0.46 μV, noise: max 4.1 μV pp. (0.07–234 Hz), low pass filter: 234 Hz (−3 dB), high pass filter: 0.07 Hz (−3 dB).

The total of 3600 electroencephalograms (25 pre-AVS, AVS, and post-AVS 8-channel recordings from 6 subjects) were analyzed first by on line visual control of the ongoing EEG and later by off-line analysis. From the 8-channel recording between active electrodes and the reference electrode six difference signals F3C3, F4C4, C3P3, C4P4, P3O1, and P4O2 were derived by off-line transformation in order to avoid undesirable effects of common reference electrode. Sequences contaminated by either subject-related or technical artefacts and obvious sleep occurrences were excluded. A digital high pass FIR filter with cut-off at 0.75 Hz and with width of 3000 data points and Blackman window was utilized.

2.3. *Computed EEG measures*

To uncover changes in the obtained EEG data, we computed the following characteristics: total power, relative frequency band powers, and magnitude-squared coherences. The volunteer's subjective perception of the training process was also monitored.

To study the effects of 20-min stimulation program, we concentrated on separate time windows with stable stimulation near 17, 4, and 2 Hz, and a time window with decreasing stimulation covering part of the alpha range (Fig. 1). Narrow frequency windows designated as 17 Hz (specifically 17.3–17.43 Hz), 4 Hz (3.81–3.94 Hz), and 2 Hz (1.87–2.0 Hz) were considered. A broader frequency window 8.5–9.5 Hz was chosen for testing the degree of entrainment within the alpha range (marked as 9 Hz), due to the fact that the stimulation in this range was not fixed to stable frequency in the chosen program. Power spectrum was utilized by Fast Fourier algorithm. Variation of power spectral density was diminished by summation of 10 consecutive points in periodograms. Frequency resolution was 0.06 Hz. Relative powers and coherences for the narrow frequency bands at 17, 4, and 2 Hz were counted from 3 components localized symmetrically within these bands. Total power was computed for 0.5–45 Hz band.

Extend of the brain wave entrainment was researched through comparison to non-stimulation conditions represented by the period prior to stimulation. From the 3-min resting intervals total power, relative band powers and band coherences of the examined frequency bands were computed, resulting in the reference values for each subject and session. Entrainment of the brain waves during the stimulation by concrete frequency was then evaluated as a difference of relative power between stimulation and prestimulation period. Thus values of the entrainment intensity reflect shift in the contribution of power in the respective frequency band during the stimulation process.

2.4. *Statistical analysis*

For quantification of direct and transient effects nonparametric Wilcoxon matched-paired test was chosen. In the case of direct effects group of single data obtained during the AVS were compared with prestimulation data. For transient effects differences between two groups consisted of 25 values obtained as inter-person averages for the particular training sessions were quantified.

For quantification of trends in the entrainment, evolution of examined measures during the whole experiment period of 25 AVS sessions were tested for linear trends. In order to evaluate group-average trends, linear regression model was applied. Its significance was tested by an ANOVA *F*-test. The significance criterion was $p \leq 0.05$, testing for H_0: slope $b = 0$ against H_1: $b \neq 0$. For significant trends, distribution of residuals from regression model was checked by Shapiro–Wilk test for normality.

3. Results

3.1. *Direct effects: brain-wave entrainment*

Direct reaction to AVS was well developed in majority of the stimulation sessions. First of all, total EEG power during stimulation increased in parieto-occipital areas, with the highest increases of 1.2-times (medians) during 4 and 2 Hz stimulation in the right hemisphere (Table 1). In these two cases the rise was realized from initial median value 23 (quartiles 14.6 and 36.7) and 22 (13.5 and 35.4), respectively. In fronto-central locations total power decrease by 20–27% was observed. For some subjects the power occasionally increased up to 4.8-times, with the rise being not always connected to gain in the stimulation band only: In some cases the stimulation induced high amplitude alpha waves responsible for the overall power increase.

Concerning particular cortex locations and stimulation frequencies, boxplots of the entrainment intensity from all artefact-free data (across persons and sessions) are displayed in Figs. 2–5. As the obtained entrainment intensity distributions were not symmetrical, medians were used as representative values for presented evaluations.

Relative powers in the narrow bands around 17 Hz, 9 Hz, 4 Hz, and 2 Hz increased expressively in all cortex locations. This fact was confirmed by Wilcoxon paired test with *p*-values not exceeding 10^{-6} for all of the cases but 2 Hz in F4C4 ($p < 10^{-4}$) and 9 Hz in F3C3 and F4C4 with *p* slightly bellow 0.05. Prior to stimulation, the average reference relative powers (through all persons and all cortex locations) were 0.18% (S.D. = 0.11%) for 17 Hz, 6.52% (5.49%) μV^2 for 9 Hz, 0.54% (0.38%) for 4 Hz, and 1.49% (0.88%) for 2 Hz ranges.

Boxplots (Figs. 2–5) show that variability of cortex reaction was considerable, with the extreme values mainly in the occipital regions. Average power spectra for the 4 different stimulation frequencies just from parieto-occipital cortex location P4O2 are presented in Figs. 6–9. Entrainment of the brain waves as a specific brain response followed the stimulation profile presented in Fig. 1. However, the cortex reaction

Table 1 – Ratio of total power (0.5–45 Hz) during stimulation to total power prior to stimulation for different stimulation frequencies. Medians from all subjects and sessions with quartiles in the brackets.

	17 Hz	9 Hz	4 Hz	2 Hz
F3C3	0.79 (0.64, 1.03)	0.75 (0.58, 1.00)	0.77 (0.57, 0.98)	0.73 (0.53, 1.02)
F4C4	0.80 (0.65, 1.00)	0.75 (0.57, 0.96)	0.77 (0.61, 0.95)	0.79 (0.58, 1.14)
C3P3	0.91 (0.75, 1.24)	0.75 (0.63, 1.10)	0.84 (0.62, 1.15)	0.76 (0.49, 1.08)
C4P4	0.95 (0.81, 1.22)	0.74 (0.61, 1.02)	0.83 (0.64, 1.15)	0.87 (0.56, 1.23)
P3O1	1.05 (0.89, 1.31)	0.97 (0.68, 1.34)	1.16 (0.80, 1,70)	1.04 (0.68, 1.65)
P4O2	1.03 (0.85, 1.27)	1.02 (0.81, 1.33)	1.20 (0.84, 1.79)	1.20 (0.78, 1.67)

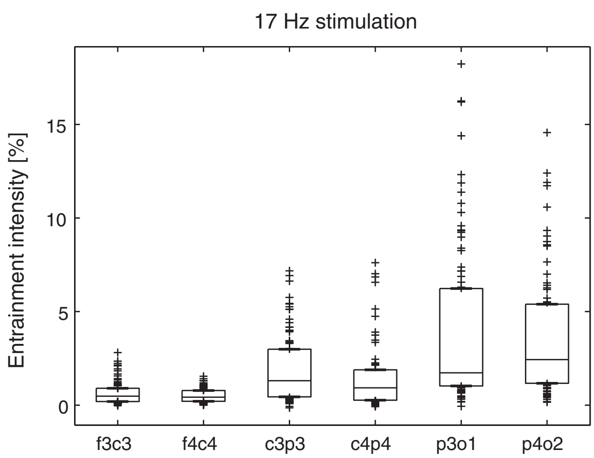

Fig. 2 – Boxplots for 17 Hz narrow frequency band (17.3–17.43 Hz). Differences of relative power between stimulation and prestimulation period. The boxes have lines at the lower quartile, median, and upper quartile. Wilcoxon paired test of stimulation and prestimulation data: All *p*-values <10^{-11}.

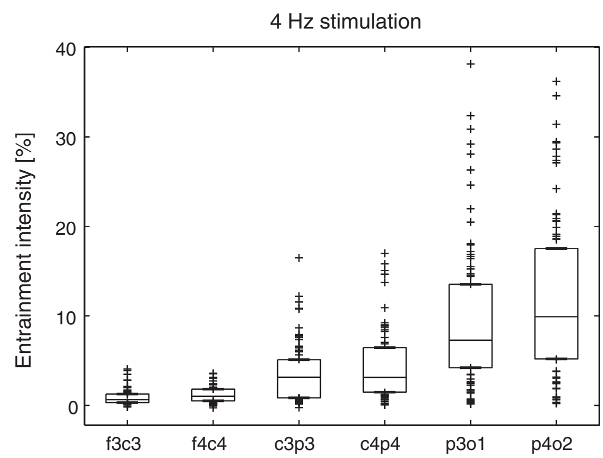

Fig. 4 – Boxplots for 4 Hz narrow frequency band (3.81–3.94 Hz). Differences of relative power between stimulation and prestimulation period. Wilcoxon paired test of stimulation and prestimulation data: All $p < 10^{-11}$.

comprised also several harmonic frequencies (Figs. 8 and 9) mainly due to the rectangular visual input caused by sharp switches of LED diodes. Preservation of spontaneous alpha activity was also often notable in individual spectra.

The strongest entrainment can be expected in the occipital areas as the dipole sources directly associated with visual inputs are localized just there. Moreover, it is apparent that from the backward regions the specific rhythms spread as far as to frontal areas of the cortex. Without focusing on the mechanism of spreading (generally synaptic or volume conductance), entrainment's attenuation is notable. In the case

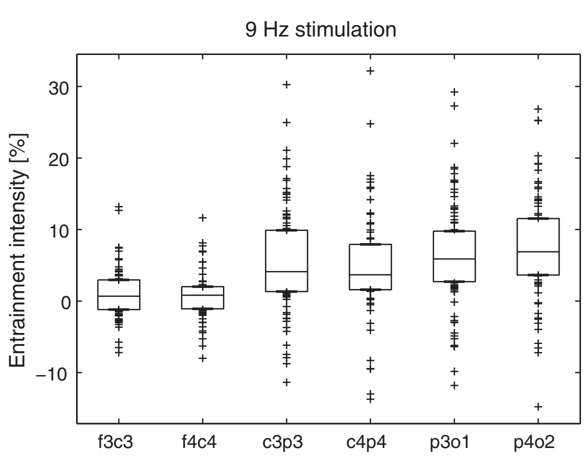

Fig. 3 – Boxplots for 9 Hz frequency band (8.5–9.5 Hz). Differences of relative power between stimulation and prestimulation period. Wilcoxon paired test of stimulation and prestimulation data: For F3C3 and F4C4 $p < 0.05$, all other $p < 10^{-6}$.

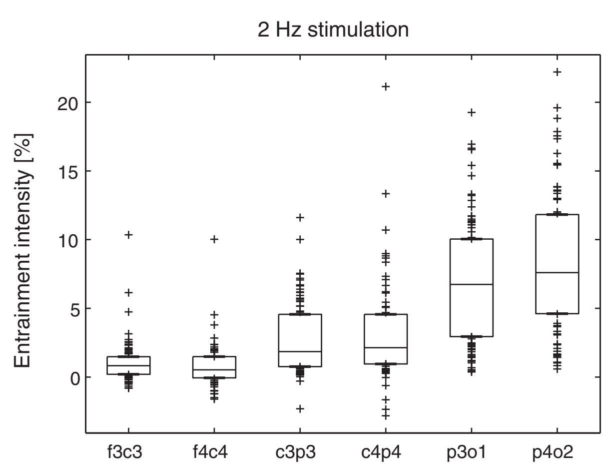

Fig. 5 – Boxplots for 2 Hz narrow frequency band (1.87–2.0 Hz). Differences of relative power between stimulation and prestimulation period. Wilcoxon paired test of stimulation and prestimulation data: For F4C4 $p < 10^{-4}$ and for all other $p < 10^{-9}$.

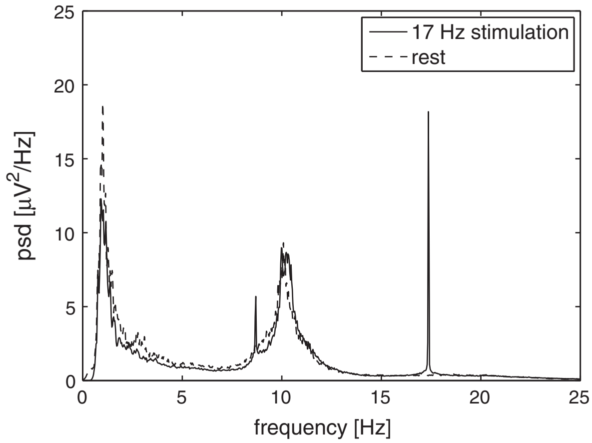

Fig. 6 – Average power spectral density from P4O2 location during stimulation near 17 Hz and during rest.

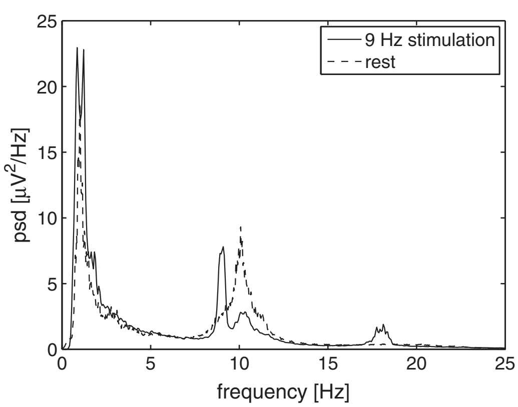

Fig. 7 – Average power spectral density from P4O2 location during decreasing stimulation from 9.5 to 8.5 Hz and during rest.

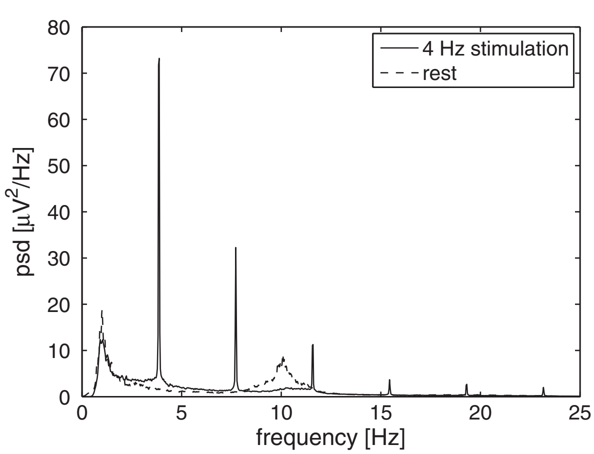

Fig. 8 – Average power spectral density from P4O2 location during stimulation near 4 Hz and during rest.

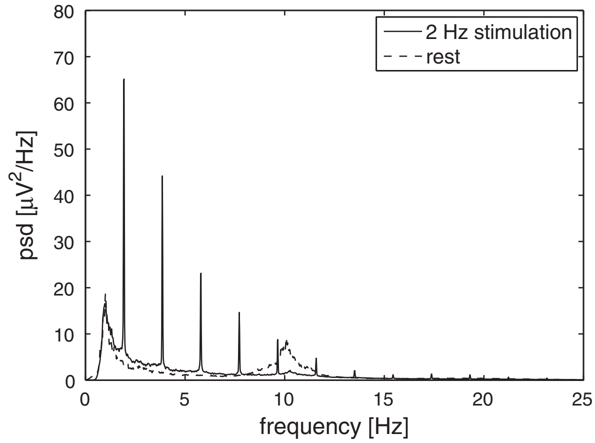

Fig. 9 – Average power spectral density from P4O2 location during stimulation near 2 Hz and during rest.

of 17 Hz stimulation the frontal reaction was 5-times lower in comparison with backward regions and for 4 and 2 Hz the frontal entrainment was even 10-times lower.

The highest median increase of relative band power, by 10%, was realized in the right parieto-occipital location during 4 Hz stimulation (Fig. 4). In some cases of 4 Hz stimulation, cortex at parieto-occipital locations was able to utilize stimulation extremely effectively: More than one third of the whole power from 0.5 to 45 Hz band was located in the narrow band of 0.13 Hz width around 4 Hz. During prestimulation period it was only about 1%.

Entrainment in the alpha range was characterized with relative power increase by 0.7% in frontal regions to rise by 6.9% in occipital regions. However, comparison of the alpha entrainment intensity to the other stimulation bands was limited as the stimulating frequency range was wider and the flickering was gradually decreasing from 9.5 Hz to 8.5 Hz.

Concerning coherences, the results were the following. During AVS coherences in all stimulation bands significantly increased (by Wilcoxon $p < 0.006$) in all three cortex regions (the rise was nonsignificant only for 9 Hz stimulation at FC location). As both left and right visual stimulation was identical with respect to frequency and phase, the findings seem to be expectable. Coherence increase was weaker further apart from the visual cortex location (Table 2). The 17 Hz flashes evoked the strongest reaction: the rise of average coherence from 0.29 to the value of 0.81 in parieto-occipital areas.

3.2. *Trends in entrainment*

The finding of the strong entrainment ability of the cortex gives rise to another question: Does the repetitive use of AVS

Table 2 – Coherence average values during the stimulation in 4 frequency bands. Reference values from prestimulation period are provided in parentheses.

	17 Hz	9 Hz	4 Hz	2 Hz
FC	0.45 (0.20)	0.36 (0.34)	0.51 (0.39)	0.52 (0.45)
CP	0.62 (0.23)	0.59 (0.37)	0.67 (0.23)	0.54 (0.30)
PO	0.81 (0.29)	0.73 (0.42)	0.86 (0.41)	0.78 (0.37)

Table 3 – Schematic depicting of rising (↗) trends in the entrainment level during long-term AVS training. Significance of the trends: *p*-values <10^{-4}.

	17 Hz	9 Hz	4 Hz	2 Hz
F3C3	–	–	–	–
F4C4	–	–	–	–
C3P3	–	–	↗	↗
C4P4	–	–	–	↗
P3O1	–	–	–	–
P4O2	–	–	–	–

further increase the entrainment scale? To find the answer, evolution of the band powers during the whole experiment period of 25 AVS sessions were tested for trends.

In the cases of higher frequency stimulations (17 and 9 Hz) no increase in entrainment ability was found. Significant increases of entrainment within 25 experimental days were only observed during 4 Hz stimulation in the left central region ($p < 10^{-4}$), and during 2 Hz stimulation in the left and right central cortex locations ($p < 10^{-5}$ and $p < 10^{-4}$, Table 3). We checked trends of individual subjects as well, to see whether they had trends in the same direction as group-average trend. The strongest trend appeared in C3P3 location at 2 Hz stimulation (Fig. 10). In this case relative power in the narrow band around 2 Hz, which took about 1% of the whole power during the first stimulation session, increased to approximately 4% at the end of the training. If formulated from the perspective of multiplication of the relative power: while during the first session the stimulation doubled the power around 2 Hz, during the 25th session the increase was almost sevenfold in average.

The overall spectral power displayed certain trend as well. With a growing number of completed trainings, the total power gradually increased in frontal cortex regions during stimulation with slower frequencies (2 and 4 Hz). The most distinctive trend was found for 4 Hz stimulation in the right fronto-central location, where the total power decreased 0.8

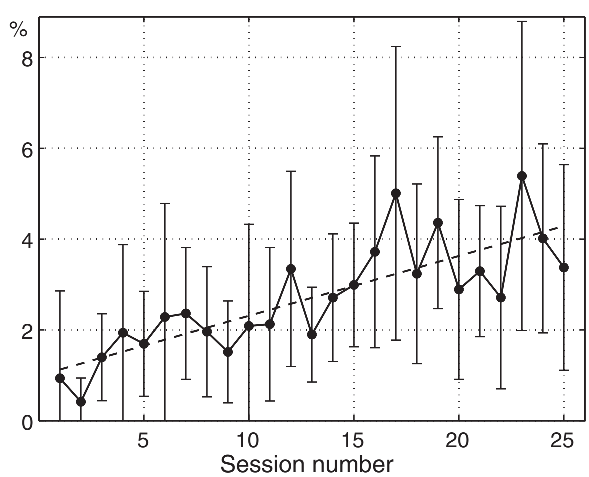

Fig. 10 – Evolution of the entrainment intensity (relative power differences between stimulation and prestimulation period) in the narrow frequency band (0.13 Hz) around 2 Hz in C3P3 location during 2 Hz stimulation (average from 25 training sessions of 6 subjects; standard deviation depicted by bars).

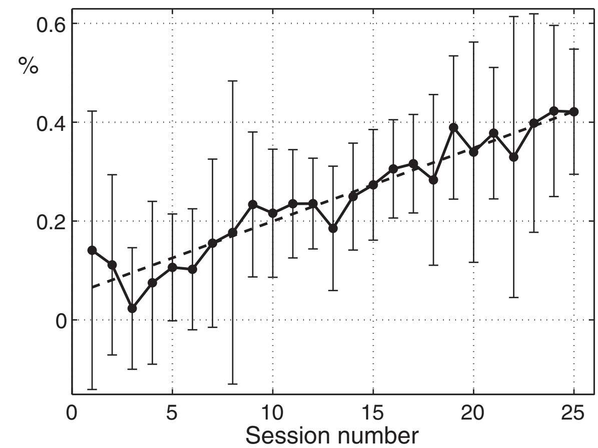

Fig. 11 – Coherence differences between stimulation and prestimulation period in the narrow frequency band around 2 Hz in FC location during 2 Hz stimulation (average progress from 25 training sessions of 6 subjects; standard deviation depicted by bars).

times during the first stimulation (compared to prestimulation 3 min) and rose mediumly 1.7 times during the last of the 25 training sessions.

As concerns hemisphere synchronization during the stimulation, AVS training turned out to be effective as well: 2, 4, and 9 Hz coherences increased in PO, and 2 and 4 Hz coherences increased also in CP and FC cortex areas. The strongest trend was realized for 2 Hz coherence between F3C3 and F4C4: from the average rise of coherence by about 0.1 during the first session up to the rise by 0.4 during the 25th session ($p < 10^{-12}$, Fig. 11).

3.3. *Transient effects*

For the purpose of exploring transient effects of the stimulation, 3 min EEGs recorded right after AVS were compared to those recorded before AVS. Let us begin with the findings about transient effects on the narrow bands around the stimulating frequencies. In spite of the fact that during the stimulation EEG signal overcame drastic changes, these alterations seem to be 'short-lived': Few minutes after AVS no consistent pattern of persistent excited powers was found. On the contrary, a few decreases (compared to the state before the stimulation) may indicate certain opposite reaction of the cortex. For example power losses in the right centro-parietal region for 2 Hz (from 0.8% before AVS to 0.5% after AVS, $p < 0.003$) were observed.

Performances of the wider spectral bands were also investigated. The strongest changes occurred in high frequency domain of 12–45 Hz. Absolute power from this band expressively decreased after AVS in comparison with period prior to the stimulation, in spite of the fact that the total power was not distinctively different.

As regards interhemispheric coherences of the narrow stimulating bands, some consistent changes over posterior areas were observed. In the parieto-occipital area increased intermespheric synchronization persisted 3 min followed after the end of the stimulation session in all narrow bands around 2, 4, and 17 Hz, while for broader alpha range around 9 Hz it was diminished ($p \in \langle 0.0008, 0.02 \rangle$). Partial maintenance of pronounced lower frequency synchronization between left and right hemisphere was also validated from the perspective of wider band coherences: Persistent increase was revealed for coherence in 2–6 Hz band in centro-parietal and parieto-occipital areas, furthered by higher 0.5–2 Hz and 6–8 Hz coherences only in centro-parietal areas. In the case of the alpha range (8–12 Hz) again we did not observe synchrony endurance after the stimulation.

4. Discussion

In this paper effects of a commercially available light and sound synthesizer were examined. The flashing light stimulus was found to impose strong immediate changes of the cortical EEG. On the other hand the auditory stimulation seems to play less expressive role in the AVS driving effects.

As AVS consists of two components of stimulation, we tested contribution of audio stimulation and visual stimulation separately. Sources of auditory evoked potentials (EPs) are located in temporal cortex and in auditory brainstem structures. We checked out direct reaction to audio stimulation on other than temporal locations. Concerning power increase, there was no apparent influence on FC, CP, or PO areas within stimulating frequency range. However, Will and Berg [22] found enhanced synchronization with stimulation by slow audio beats in delta and theta ranges in Cz area.

Earlier studies of audio-visual stimulation were often directed toward investigating alpha activity mainly in the occipital regions [4,5]. However, several recent experimental studies have suggested that AVS has a more diffuse effect on the brain activity [7,17]. It is important to develop a more thorough understanding of rhythmic stimulation, particularly photic stimulation, on the cortical EEG.

As described above, the reaction to AVS spread from the visual cortex to the other brain locations. This seems to be in accordance with [23], where signs of visual EP spreading, but none of audio EP spreading were found. To ensure that the obtained entrainment signal was of physiological nature i.e., not caused by electrical appliances of AVS system, we realized control measurements with active optical stimulation but with paper shield to blank out the glasses, in order to preclude the sight from the stimulation.

The strongest entrainment was attained for occipital regions and for the stimulation at 4 Hz, when the power in the narrow stimulating frequency band rose mediumly 18 times and in some single cases even about 80 times. Shift in coherence followed similar scenario during the stimulation: also being the strongest in the occipital areas. For example, during 4 Hz stimulation the coherence rose to the value of 0.86 from 0.41 prior to the stimulation.

According to Fedotchev et al. [24], an increasing rate of continual change of the stimulation frequency has attenuating impact on the resonance reaction, tested for velocity conditions of 0.05 and 0.2 Hz/s. In our case the rate of decrease in the alpha range was probably too slow (approximately 0.01 Hz/s) to play significant role in comparison to fixed frequency stimulation. More influential may be a fact, that in the normal state the alpha waves are usually dominant part of EEG, with different locations of alpha peaks for different subjects. Stimulation by the subject's intrinsic alpha frequencies led to power enhancement. Strong driving response at the frequency closest to the alpha peak of the resting EEG was also observed in [15]. However, when the stimulation alpha range and the subject's reference alpha band did not overlap, the baseline alpha peak was partly put down at the expense of stimulus frequencies (evident in Fig. 7).

Most of the drastic EEG changes during the stimulations seem to be 'short-lived'. No persistent excited powers few minutes after the stimulation compared to the state before the stimulation were found. Actually several decreases were observed. On the other hand, coherences for lower frequencies persisted at increased level from the central to occipital areas. However, as our previous study showed, no sign of enhanced hemispheres cooperation held over the training day [25]. In experiment by Frederick [26] even short-term endurance of the coherence enhancement was disputed.

A natural question to ask is whether repetitions of the stimulation training may have any impact on entrainment ability of the brain. As the results showed the influence was limited – progress occurred only for 2 and 4 Hz stimulation in the central cortex location.

Regarding subjective experiences, quite often participants reported various pleasant and colorful visions during certain stages of the stimulation session. Sometimes personal reminiscences surfaced. In one case AVS evoked discomfort feelings, so that the subject considered to withdraw from the experiment.

Nevertheless, the strong immediate EEG changes induced by photic stimulation deserve closer attention and further research. For example, electroencephalography can be used as an effective platform for the brain–computer interfaces. Our study shows how cortex reacts to certain stimulating frequencies and how to evaluate effectively this information. Concentrating on the flashing lights of different frequencies, followed by recording of the entrained EEG rhythms can then be used to control cursor movement in one or two dimensions or for other computer actions.

Photic stimulation techniques can also be seen as a promising nonpharmacological treatment strategy especially in disorders where guided entrainment of the brain waves or intermediate increase of synchronization of hemispheres is desired. However, let us recall our previous study indicating that, on a long term basis, use of AVS may suppress the cooperation between the hemispheres [25]. Obviously, extensive and very cautious large-scale controlled studies should be performed before any therapeutic application.

Conflict of interest

None declared.

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