Measures of EEG in the context of long-term audio-visual stimulation

M. Teplan, A. Krakovská, S. Štolc

Institute of Measurement Science, Slovak Academy of Sciences,
Dúbravská cesta 9, 841 01 Bratislava, Slovakia
Email: michal.teplan@savba.sk

Abstract. *In order to identify direct, transient, as well as long-term changes in human cortex under influence of repetitive training with audio-visual stimulation (AVS) various linear and nonlinear measures were estimated. In the course of 2 months, 25 repetitions of a 20 min AVS program with stimulation frequencies in the range 2-18 Hz were applied to 6 healthy volunteers. EEG data were recorded from 6 head locations during relaxed wakefulness prior, during and after AVS. Evolution of examined measures during the whole experiment period was analyzed with respect to the significance of their linear regression. Dynamics of direct reaction to AVS was well developed in 4Hz-entrainment with increase of driving response to this particular power band. Transient effects displayed significant decreases in beta and gamma bands across head locations, and increase of theta-1 and alpha-1 coherence in central cortex regions. Long-term AVS significantly increased power in lower frequency bands (4-10Hz) in frontal and central cortex locations. Inter-hemispheric coherence in alpha-1 band displayed significant increase between frontal parts in contrast to the decrease of both linear correlation and mutual information. Correlation dimension significantly decreased in some locations while entropy displayed an ascending trend.*

Keywords: Electroencephalography (EEG); Audio-visual stimulation (AVS); Spectral power; Nonlinear measures

1. Introduction

Audio-visual stimulation (AVS) is a simple method for external influence on the brain. The source of rhythmic stimulation such as light and sound synthesizers delivers the AVS signal to the brain through peripheral nerves. Headphones and glasses with light-emitting diodes are usually utilized.

During AVS adaptation of dominant EEG frequency to external stimuli may be observed [1]. This kind of resonant phenomena is known as entrainment of the brain waves.

Audio-visual stimulation has been reported to influence sleep and learning disorders, neurological disorders, addictions, tension, anxiety, premenstrual syndrome, migraine headaches, etc.. AVS has become popular mainly for assumed induction of relaxing effects and altered states of consciousness. The main purpose of this study was to investigate the effects of AVS on the EEG on the long-term basis. Up to now, most of the EEG research on AVS has focused on direct and short-term effects of AVS (during and shortly after the stimulation). Moreover, we have utilized both linear and nonlinear approaches for EEG analysis of the AVS effects. In contrast to the linear description (as e.g., frequency analysis), it is natural to expect that the neuronal dynamics may behave in a non-linear manner. The growing need for a better understanding of brain dynamics and the recent emergence of a physics of non-linear systems have stimulated the development of more advanced data analysis techniques, often referred to as non-linear methods. Complexity measures related to the concept of entropy rates estimation were reported by Rosipal [2] to be useful for determining depth of anaesthesia. Results by Kobayashi et al. [3] showed successful discrimination of sleep stages by measure of correlation dimension.

2. Subject and Methods

Subjects and EEG recording

Six right-handed healthy subjects (2 females and 4 males) volunteered for the AVS training. Overall training of each subject from the test

group consisted of 25 AVS program sessions, each of 20-minute length. AVS was provided by commercially available light and sound synthesizer. We chose a program described as suitable for AVS beginners to make acquaintance with different "mind states" according to their frequency profile performed. The program stimulated the brain at following frequencies: 18 Hz during first 3 minutes, then 18-10-8 Hz at min. 4-8, 8-5 Hz at min. 8-9, 5-4 Hz at min. 9-12, 4-2 Hz at min. 13, 2 Hz at min. 14-17, 5,9, and 15 Hz at min. 18-19 [Fig.1]. EEG data from 3-minute period before, 20-minute during and 3-minute period after each AVS session were recorded. Monopolar EEG montage comprised eight channels with electrodes placed on F3, F4, C3, C4, P3, P4, O1, and O2 locations according the International 10-20 system. The reference electrode was located at Cz and the ground electrode at Fpz point.
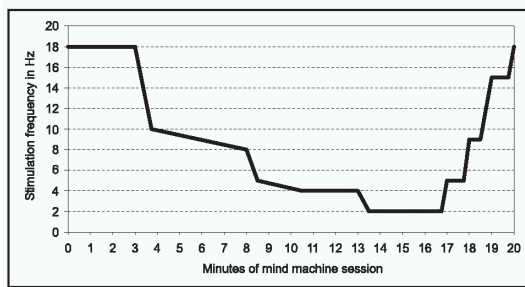

Fig.1. Frequency profile of 20-minute AVS program. The program stimulated the brain from 18 Hz down 2 Hz and back to 15 Hz.

Measures

To uncover objective changes from obtained EEG data, we computed the following characteristics: (1) Spectral measures: total power, frequency band powers, spectral edge frequency, and spectral entropy; (2) nonlinear complexity measures: histogram based entropy, and correlation dimension; and (3) interdependency measures: linear correlation coefficient, mutual information, and coherence. Volunteer's subjective perception of the training process was also monitored.
Frequency spectrum was divided into 9 bands: delta-1 (0.5-2 Hz), delta-2 (2-4 Hz), theta-1 (4-6 Hz), theta-2 (6-8 Hz), alpha-1 (8-10 Hz), alpha-2 (10-12 Hz), beta-1 (12-16 Hz), beta-2 (16-30 Hz), and gamma (30-45 Hz).

Our aim was to uncover statistically significant trends in examined measures. Evolutions of test group averages during the course of the AVS training were calculated for each individual measure. Linear regression model was derived, and its significance was tested by an ANOVA F-test with a treshold at $p=0.05$.

3. Results

Direct AVS effects

During time period within stimulation at 18, 10-8, 4, and 2 Hz relative powers of bands ling around entraining frequency were computed [Tab.1]. The most significant increases were observed during 4 Hz stimulation in central and occipital locations [Fig.2] which may correspond to strong theta responsiveness found in [4].

location / band	F3 C3	F4 C4	C3 P3	C4 P4	P3 O1	P4 O2
2Hz	-	-	8	-	-	-
4Hz	-	-	8	8	8	8
10Hz	-	-	-	9	-	9
18Hz	-	-	8	-	-	-

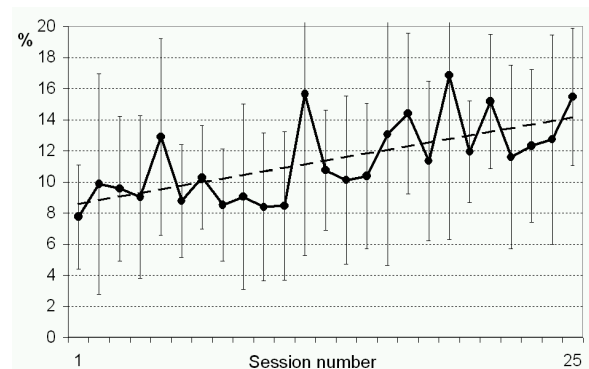Tab.1. Schematic depicting of rising and decreasing trends during AVS at specific frequency.

Fig.2. Evolution of relative power in C4P4 in frequency band 3.6-4.8 Hz during stimulation at 4Hz (standard deviation depicted by bars).

Transient AVS effects

We examined differences in individual measures in respect to prestimulation and post stimulation period by means of Wilcoxon matched-paired test. The strongest and topologically widest changes occured in beta-1

and beta-2 power bands in central and occipital cortex regions. From interdependencies evaluated between left and right hemispheres coherence in theta-1 and alpha-1 bands increased in central locations.

Long-term AVS effects

Significant increase of power in theta-1, theta-2, and alpha-1 band was observed in frontal and central regions. While theta-1 and theta-2 displayed significant increase in F3C3, C3P3, and C4P4 locations, alpha-1 showed increase in all four locations F3C3, F4C4, C3P3, C4P4 (Fig.3). According to Basar [5] theta and alpha rhythms might reflect fundamentally different functional operations.

A concept of 'selectively distributed theta system' was proposed by him, covering structures located in different brain areas able to produce theta activity spontanously or as a reaction on external or internal stimulus. Theta might deal with integrative cognition and association functions and in frontal cortex also with response-controlling function: Increased theta power implies decreased reaction of the cortex to sensory stimulation [5].

Total power (0.5-45Hz) increased significantly in central region. We detected left-right asymmetry of total power distribution in central cortex locations as well. During the training weeks the dominant activity of dipole sources in frequency interval 6-10 Hz moved from the left side to the right side of the cortex.
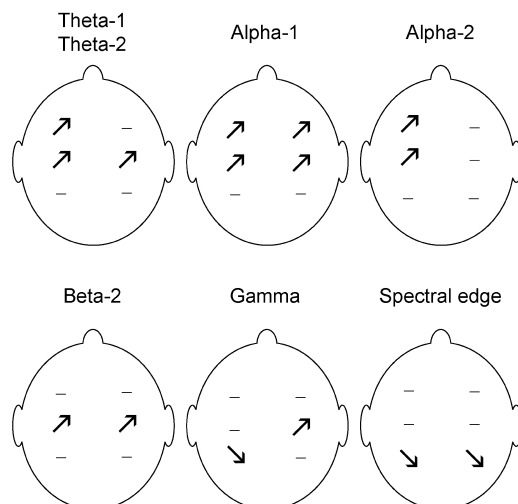

Fig.3. Illustration of significant trends in spectral measures across cortex regions.

Spectral entropy as a linear complexity measure significantly increased in C3P3 channel during the training period. Increase in histogram-based entropy estimators was obtained in F3C3 location.

Complexity of the system is often estimated by correlation dimension (CD)[6]. The CD may indicate chaos or identify low-dimensional determinism and estimate the minimum number of variables that must be considered in the description of the dynamics. Topographically wider changes occurred in the CD that decreased in all six channels, significantly in three of them: F3C3, F4C4, and C4P4.

Both linear correlation coefficient and mutual information significantly decreased in parieto-occipital parts. The concept of mutual information was firstly established in the field of communications theory, later it was adopted to EEG analysis for evaluating certain nonlinear correlation between two time series. In fact, mutual information measures the amount of information shared between two time series [7]. Mutual information appeared to be almost two times more sensitive in relative change from initial values than linear correlation (28% vs. 16% decrease).

Coherence analysis revealed significantly increased coherence in the alpha-1 band in frontal regions, while theta-1 and theta-2 coherences displayed opposite trends in this region.

While general well-being before each day relaxation period displayed no significant trend, subjective measure which evaluated general release accomplished during relaxation interval prior to stimulation (both rated on 7-point bipolar scale) showed significantly increasing trend towards better performance.

4. Discussion and conclusions

We detected several significant changes characterizing direct, transient and long-term effects on EEG during regular use of AVS.

The extend of entrainment is dependant on baseline (prestimulation) EEG. In addition to Rosenfeld et al. [8], who found that low prestimulation alpha power implies higher alpha entrainment, we found that increasing theta-1 and theta-2 coincided, at least in central cortex region, with rising entrainment by 4 Hz signal.

Our results show that regular training with AVS does induce long-term changes in cortex functioning, such as those commonly reported to be features specific to relaxation or altered states of consciousness [9].

As a contribution to linear characteristics, we found significant trends in the behaviour of some non-linear measures. Nonlinear complexity measures might represent new possible indicators of dynamical changes of resting EEG, or these changes might be indexed better by a combination of linear and non-linear EEG variables [10].

We can not exclude a possibility that certain contribution to long-term relaxation effects could come from repetitive relaxation training itself, regardless the use of AVS. Subjects might adapt gradually to experimental conditions and develop some progress reflected in trends of studied measures.

Despite our findings about the measurable influence of AVS, we are very skeptical regarding the declarations found in various manuals of popular AVS machines claiming that after some training (minimally 30 repetitions) one may learn to distinguish among beta, alpha, theta and delta "states" and even to induce these states voluntarily when desired.

The present study was conducted to fill a gap in the knowledge of brain functioning during long-term AVS training. Gathered evidence in a form of trends of certain linear and nonlinear measures indicates that AVS training may serve as useful tool for evoking long-term changes in resting EEG and in the improvement of relaxation abilities.

However, further research is needed to support extensive clinical applications of AVS technology. For future studies we suggest investigation of long-term AVS with simultaneous recording of other relevant physiological parameters (e.g. electrodermal resistance, respiratory rate) for determination purposes, and post measurements after longer time-period from completion of long-term AVS experiment.

References

[1] Walter V.J. and Walter W. G.: The central effects of rhythmic sensory stimulation. Electroenceph. Clin. Neurophysiol., 1949, 1:57-86.

[2] Rosipal R.: Kernel-Based Regression and Objective Nonlinear Measures to Assess Brain Functioning. PhD thesis. University of Paisley, Scotland, 2001.

[3] Kobayashi T. et al.: Correlation Dimension of human sleep electroencephalogram. *Psychiatry and Clinical Neuroscience,* 2000, 54.

[4] Lazarev V.V. et al.: Photic driving in the electroencephalogram of children and adolescents: harmonic structure and relation to the resting state. *Brazilian Journal of Medical and Biological Research*, 2001, 34: 1573-1584

[5] Basar E. et al.: The selectively distributed theta system: functions. *Int. J. Psychophysiol.*, 2001, 39: 197-212.

[6] Galka A.: Topics in Nonlinear Time Series Analysis. With Implications for EEG Analysis, World Scientific, 2000.

[7] Abarbanel H. et al.: Analysis of Observed Chaotic Data. Springer-Verlag New York, 1996.

[8] Rosenfeld J. P. et al.: The effects of alpha (10 Hz) and Beta (22 Hz) "entrainment" stimulation on the alpha and beta EEG bands. Applied Psychophysiol. & Biofeedback, 1997: 3-20.

[9] Morse, D.R.: Brain Wave Synchronizers: A Review of Their Stress Reduction Effects and Clinical Studies Assessed by Questionnaire, Galvanic Skin Resistance, Pulse Rate, Saliva, and Electroencephalograph., *Stress Medicine*, 1993, 9:111-126.

[10] Teplan M. et al.: EEG responses to long-term audio-visual stimulation. Submitted to *International Journal of Psychophysiology.*