Age-Dependent Changes of the EEG Data: Comparative Study of Correlation Dimension D2, Spectral Analysis, Peak Alpha Frequency and Stability of Rhythms

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Abstract - **The aim of this study was to present new methods to explore the EEG dynamic changes during human development and aging and to assess its advantages. The electroencephalogram (EEG) was recorded from 19 scalp locations from 246 healthy subjects ranging from 3 to 75 years old. All participants were divided in to six groups: preschool childhood, middle childhood, adolescence, early adulthood, middle adulthood, late adulthood. We recorded EEG with closed eyes, open eyes and during fingernails scratching auditory stimulation. The comparative analysis included spectral analysis, peak alpha frequency, correlation dimension D2 and stability of rhythms. We found significant age differences in 6 age groups using the described methods. Moreover, we've found the edge between adolescence and adulthood using narrowband D2 at alpha-rhythm frequencies. Unpleasant auditory stimulation proved to be more sensitive to age differences in comparison with resting states. Our results support previous findings describing aging and developmental EEG changes, but also provide qualitatively new results.**

Keywords: **Aging, development, EEG, correlation dimension D2, peak alpha frequency, stability of rhythms.**

I. INTRODUCTION

The most developmental and aging changes of the EEG are well known. There is a large amount of neurophysiological data about EEG specific features in elderly human subjects and children from newborn up to school-aged. For example, changes in EEG coherence and phase difference were present from approximately 6 months to 4 years of age meeting a significant linear trend to higher coherence in close electrodes and longer phase delays in distant electrodes [1]. Normal pediatric EEG activity is more group-wise variable than adult EEG. Pre-school children EEG usually combines mixed theta and alpha-rhythms, with the latter increasing with age, and finally in elementary school children EEG the alpha rhythm (8-10 Hz) power usually dominates in resting state with closed eyes (further called background) [2], [3]. The aging healthy brain demonstrated reduced amplitude variability, increased irregularity at shorter time-scale, decreased complexity at long scales, and spatial differentiation in activations [4].

Meanwhile, it is still very difficult to differentiate EEG of adult subjects from youth's (form 18 y.o.) till Middle Ages (to 40 y.o). Usually, these two groups are considered to be one group. However, young and middle-aged people have significantly different reaction to brain injuries not only neurophysiologically, but also clinically. The younger the brain is the more is it able to recover from brain injury. So, it's necessary to differentiate them by their EEG prior to the possible injury.

Nonetheless, some studies reveal the difference, for example, investigating sleep disturbance (insomnia). The EEG differences between middle-age and youth can be observed at the moment of waking up and correlate with stress level [5].

Usual spectral analysis shows no difference in frequency power spectrum between these two groups. Thus, in our research we wanted to investigate and validate another method of EEG analysis, which would be sensitive to some entropy, plasticity and other dynamics-dependent values of the EEG in time domain (without averaging over time). There already are the data, demonstrating the entropy of EEG signals presented systematic age-related behavior *[4]*. Thus, to differentiate EEG of different aging groups we suggest to measure these EEG parameters using correlation dimension D2 on wideband EEG and separately on some narrowbands, and also stability of rhythms (see Methods) in the same ways.

Another method which was already approved in patients with traumatic brain injury [6] showed that during emotional stimulation there was different EEG reorganization depending on the severity of trauma. Neuroimaging studies showed that behavioral and brain responses to stimulation differs during development and aging, for example, there are studies proving negative stimuli to induce more pronounced brain response relative

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to positive or neutral stimuli. [7], [8]. In normal aging, the preference for the negative stimuli shifts towards a preference for the positive stimuli compared to both the negative and neutral stimuli [9].I.e. negative stimulation is clinically significant and age-dependent, so, it is employed in this study.

Other research use factor analysis to decompose EEG into isolated inphase signals (factors) showed that the EEG records of older adults yielded significantly more factors than those of younger adults in every task condition. In addition, eigenvalues (weights) for the first factor were significantly larger in younger adults than older adults. These results are interpreted as indicating a greater degree of complexity in the spatial distribution of EEG activity in older adults, possibly reflecting an age-related decrease of coordination of cortical areas [10].

In our study we focused on the negative auditory stimulation (sound of fingernails scratching the blackboard, also called noise) that was chosen as most tempest and unpleasant sound by 189 subjects-respondents [11].

II. METHODS

A. Subjects

A total of 246 subjects ranging in six groups:

Group 1. Preschool and Early Childhood: male - 3-7 y.o.; female – 3-6 y.o.

Group 2. Middle childhood: male - 8-12 y.o.; female – 8-11 y.o.

Group 3. Adolescence: male - 17-21 y.o.; female – 16-20 y.o.

Group 4. Early adulthood: male - 22-35 y.o.; female – 21-35 y.o.

Group 5. Middle adulthood: male - 36-60 y.o.; female – 36-55 y.o.

Group 6. Late adulthood: male - 61-75 y.o.; female – 56-75 y.o.

(see table1 with descriptive statistics)

Table1: Descriptive statistics

groups	gender	amount	mean, years	SD, years
Preschool childhood	m	17	4,4	1,3
	f	18	4,4	1
School childhood	m	21	9,9	1,5
	f	20	9,4	1,2
Adolescence	m	21	19,1	1,4
	f	21	18,3	1,3
Early adulthood	m	22	27,7	3,9
	f	25	27,5	3,8
Middle adulthood	m	24	48,8	7,5
	f	21	45,7	6
Late adulthood	m	18	67,7	4,6
	f	17	66,8	6,1

The inclusion/exclusion criteria were: reported normal development and no history of neurological disorders such as epilepsy, head injuries. All of the subjects hadn't taken medication of any kind at least 24 hours prior to participating in this study. All of the preschool/school-aged children were within the normal range of intelligence as measured by the WISC-R and none of them were classified as learning disabled nor were any of the school-aged children in special education classes.

B. EEG Recording

During the EEG recording the subjects sat in a comfortable position in an armchair in an acoustically and electrically shielded chamber. The participants were instructed to remain calm, with their eyes closed, to avoid falling asleep and to avoid thinking about anything specific.

Brain electrical activity was recorded using a 19-channel EEG recording device, Encephalan, with the recording of polygraphic channels (Poly4, Medikom MTD, Taganrog, Russian Federation).

The amplifier bandpass filter was nominally set to 1.6-30 Hz. Continuous EEG was acquired with AgCl electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, O2) according to the International 10–20 system with a sampling rate of 250 Hz. The electrodes placed on the left and right mastoids served as joint references under unipolar montage. The vertical electro-oculogram (EOG) was measured with AgCl cup electrodes placed 1 cm above and below the left eye, and the horizontal EOG was measured with electrodes placed 1 cm lateral from the outer canthi of both eyes. The electrode impedances were maintained at less than 10 kΩ.

C. Stimuli

We recorded EEG in 3 states: with closed eyes, with open eyes and during auditory stimulation (fingernails scratching the blackboard) with closed eyes. Every state was no less than fifteen minutes long.

D. EEG Analysis

EEG epochs lasting 15 min were analyzed further. The EEG signals were cleaned from eye movements according to the EOG data with the Encephalan software. Small intervals affected by muscle activity were excluded manually using visual inspection. All the following processing was performed using EEGLab [12] plugin for MatLab (Mathwork Inc.).

E. Spectral Analysis

Fast Fourier Transform (FFT) was used to analyze the frequency spectrum and phase differences. The EEG spectrum was estimated throughout 45 (15 for each state) randomized 1 min periods of open-eyes state, 1min background and 1 min period of unpleasant sound. The resulting spectra were integrated over intervals of unit width (2-3 Hz, 3-4 Hz, etc., 19-20 Hz). These values were statistically compared between groups and their correlations (with significance) with age were calculated.

F. Peak alpha frequency (PAF)

PAF was taken as the frequency from range 8-13 Hz with maximal spectrum power. The values were again compared between groups and correlations with age were assessed.

G. Correlation dimension D2

We calculated correlation dimension D2 in different ways:

1) for initial wideband (2-20 Hz) EEG, 2) for 9 narrowband (2-4 Hz, 4-6 Hz, 6-8 Hz, 8-10 Hz, 10-12 Hz, 12-14 Hz, 14-16 Hz, 16-18 Hz, 18-20 Hz) filtered EEG.

We've calculated fractal dimension D2 in the following cases: using the whole frequency range of the examined signal (2-20 Hz) and using 2 Hz-wide frequency ranges (2-4 Hz, 4-6 Hz, …, 18-20 Hz). Filtering was conducted using forward FFT, zeroing some samples and then reverse FFT (rectangular characteristic). D2 was calculated using Higuchi method [13]. It employs the idea that the length of the polyline, constructed on a subset of points of the original curve depends on a stride of the subet in the following way: $D2 = \frac{d\log(L(k))}{d\log(k)}$, where k is the stride and L(k) is the length of the polyline. As long as some different subsets with the same stride exist, the average length on these subsets is taken.

H. Stability of rhythms

To express the dynamics of (de-)synchronizing of different rhythms we've applied the following method. Firstly we've calculated the envelope of the EEG signal, again using the whole frequency range and a set of small narrowband filters. It's easily made using Hilbert transformation [14]. Secondly, having an envelope, we can assess the (in-)stability of its amplitude by calculating its average frequency using FFT, of course, discarding the value accounting for mean value of the envelope. This value is the only result of this processing, being called stability-value later.

We calculated the resulting values in the same way as D2, i.e. for wideband and narrowband filtered EEG.

I. Statistical analysis

A one way and the repeated measures ANOVA with Bonferroni correction for multiple comparison, $p < 0.05$, was completed to determine age effects on EEG metrics. Age-related effects were characterized by analyzing power and other EEG statistics using ANOVA grouping factor. The correlations ($p<0.01$) between age and EEG features were assessed in all groups of subjects (1-6 gr.) and also in groups of healthy adults (3-6 gr.).

J. Ethics Statement

This study was approved by the Ethics Committee of Institute of Higher Nervous System and Neurophysiology of Russian Academy of Science. All subjects provided written informed consent after they had received a complete description of the study.

III. RESULTS

A. Spectral Analyses

children showed significantly higher low-frequencies spectrum power compared to adults. Delta- and theta-rhythm and alpha-rhythm power during noise was significantly higher compared to the background in children. In adults significant differences were found only in theta-rhythm frequencies: during stimulation it was significantly lower compared to the background. The differences was significant in parietal and temporal and occipital areas (P3, P4, Pz, T6, T5, O1, O2) (Table 2).

Table 2: Significant differences between auditory stimulation and background in different groups of subjects (t-test, $p<0.05$) "+" means the higher power spectrum during stimulation, "-" means the opposite relation, grey filling – no significant differences

	Gr.1	Gr.2	Gr.3	Gr.4	Gr.5	Gr.6
2-3 Hz	+	+				
3-4 Hz	+	+				
4-5 Hz	+	+	-	-	-	-
5-6 Hz		+	-	-	-	-
7-8 Hz	+					
8-9 Hz	+	+				
9-10 Hz	+	+				

B. Peak alpha frequency

PAF during background significantly differed in different groups of subject, though there were no significant differences compared to auditory stimulation in any group. The adults were characterized with higher PAF compared to children (one-way ANOVA $F(5, 245)=9{,}22$ $p<10^{-5}$).

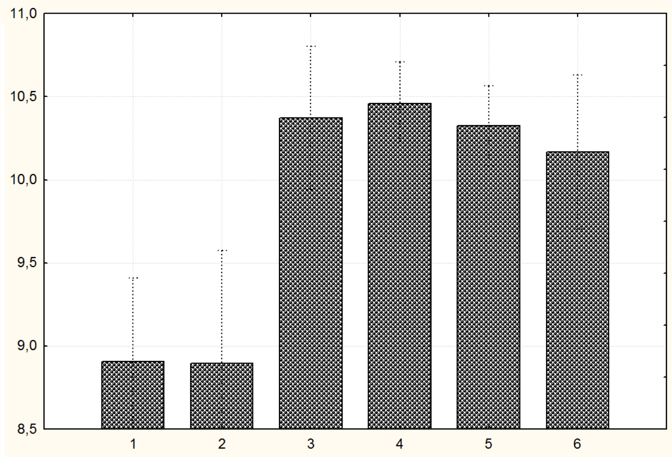

Figure 1: Peak alpha frequency in background in 6 groups of subjects (x-axis: 1 - Preschool childhood; 2 - School childhood; 3 - Adolescence; 4 - Early adulthood; 5 - Middle adulthood; 6 - Late adulthood). y-axis – frequency, Hz.

C. Correlation dimension D2.

Wideband D2 analysis showed significant increase during auditory stimulation compared to resting states (only in children). There were no significant changes of the D2 during stimulation in adults. Narrowband D2 also showed significant age and state differences (Table 3).

The differences between open and closed eyes resting states were found only in alpha-rhythm frequencies (8-12 Hz), D2 was higher in closed eyes state.

Table.3: Correlation dimension D2 differences between auditory stimulation and background (t-test, p<0.05) "+" means higher D2-value during stimulation, "-" means lower D2-value during stimulation, grey filling and absent frequencies – no significant differences

	Gr.1	Gr.2	Gr.3	Gr.4	Gr.5	Gr.6
2-4 Hz				+	+	+
10-12 Hz	-	-	-	+	+	
12-14 Hz	-			+	+	+
16-18 Hz		+		+	+	
18-20 Hz		+		+	+	

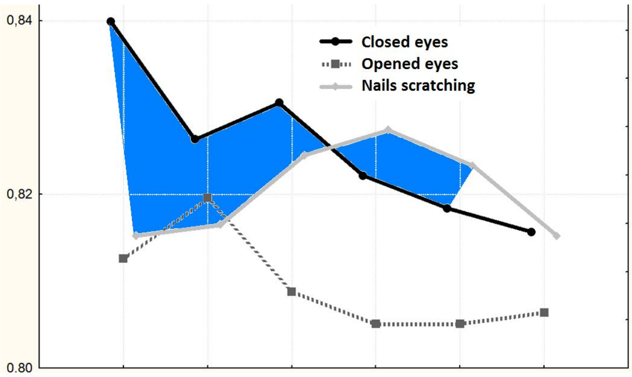

Figure 2: D2-values in alpha-rhythm narrowband (10-12 Hz) for three states (closed eyes, opened eyes, nails scratching sound) in 6 groups of subjects (x-axis: 1 - Preschool childhood; 2 - School childhood; 3 - Adolescence; 4 - Early adulthood; 5 - Middle adulthood; 6 - Late adulthood), y-axis – D2-values

D. Stability of rhythms

In wideband analysis we found significant increase in envelope frequency during auditory stimulation compared to background. The correlation with age was found only for stimulation state in central and frontal electrodes (p<0.05, r = 0.34) (figure 3).

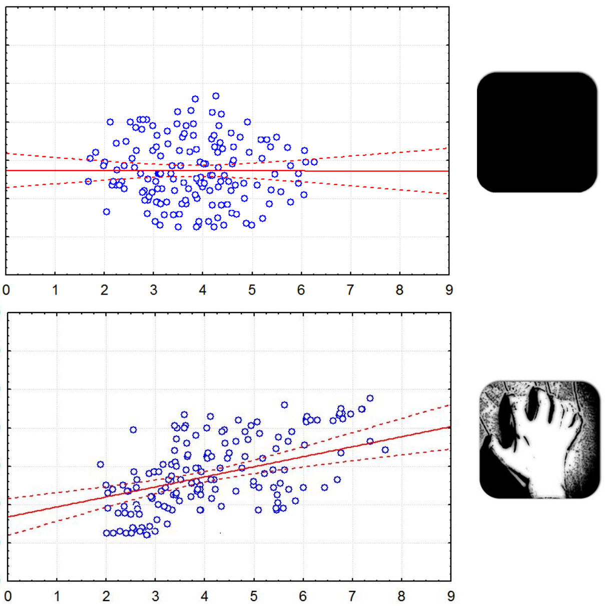

Figure 3: The correlation between stability-value and age

The narrowband analysis showed significant differences between the closed eyes state and auditory stimulation in different groups (Table 3).

Table 3: Stability differences between auditory stimulation and background (t-test, p<0.05) "+" means the higher stability during stimulation, "-" means lower stability, grey filling – no significant differences

	Gr.1	Gr.2	Gr.3	Gr.4	Gr.5	Gr.6
2-4 Hz	+	+	-	-	-	-
4-6 Hz	+	+	-	-	-	-
6-8 Hz	+	+	-	-	-	-
8-10 Hz	+		-	-	-	-
10-12 Hz	+	+	-		-	-
12-14 Hz	+	+	-	-	-	-
16-18 Hz	+	+	-	-	-	-
18-20 Hz	+	+	-	-	-	-

There were also significant differences between stability-values in the narrowband cases. The lowest values were found to correspond to alpha-rhythm frequencies for each state and almost each group (figure 4).

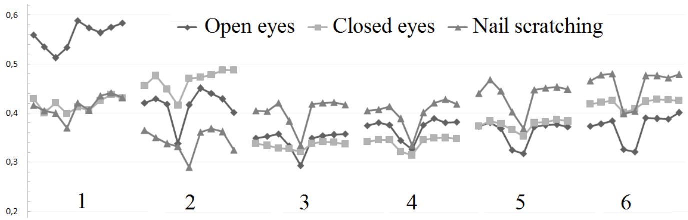

Figure 4: Stability (the y-axis) for three sates (closed eyes, opened eyes, nails scratching sound) in 6 groups of subjects (x-axis: 1 - Preschool childhood; 2 - School childhood; 3 - Adolescence; 4 - Early adulthood; 5 - Middle adulthood; 6 - Late adulthood).

IV. DISCUSSION

Our results support previous findings describing aging and development changes of the EEG well known characteristics such as spectral analysis and PAF. For example, elderly patients showed EEG oscillations 2- to 3-fold smaller in amplitude than younger adults. Qualitatively, EEG appeared to remain similar regardless of age, showing prominent alpha (8-12 Hz) and slow (0.1-1 Hz) oscillations. [15]. PAF was showed to have age and individual differences and moreover was depending on type of cognitive load [16], [17]. PAF was smaller in children and elderly, but also varied among individuals [18], [19].

Our result demonstrated that different groups of adults can be differentiated by the EEG parameters using the proposed analysis. Thus, we found the EEG differences between adolescence and early adulthood groups: group alpha-rhythm narrowband D2 during noise become higher than in background somewhere between age of 18 to 25 years. This alpha-rhythm D2 behaviour shows that youth (group 3) EEG is more similar with that of with children (groups 1, 2) but not with adults (group 4-6).

The findings of EEG and alpha slow with age showed to be related with findings in Alzheimer's disease where increased slowing predominates [20].

Wideband *D2 analysis let us find significant differences* between the background and noise only in children, while narrowband D2 showed significant age- and state-dependent changes on many frequencies (delta-, alpha- and beta-rhythms).

We also found that unpleasant auditory stimulation led to significant changes of stability, *which can be described as positive* correlation with age. Thus, during noise age differences are more pronounced, as it was presumed. This finding let us to differentiate the EEG response to unpleasant emotional stimulation in different age groups of subjects and patients. Using stability analysis we found that aplha-rhythm amplitude is most stable in all groups of subjects except for preschool children, who showed the lowest values for theta-rhythm and less stability in general. Previously we found that patients after TBI demonstrate higher similarity of EEG spectrum power to children than to adults [11] and we suppose, these patients might show low stability, i.e. similar to preschool children. Moreover, different data showed the dysfunction of the apha-rhythm activity in TBI patients which is expressed in more variable alpha-rhythm power and leads to absence of desynchronization behavior [21]

V. CONCLUSION

1. Our results support previous findings describing aging and development EEG changes, obtained using spectral analysis and peak alpha frequency analysis.
2. Alpha-rhythm narrowband D2 showed age-related changes between age of 18 to 25 years, which might be described as higher similarity of youth (group 3) alpha-rhythm D2 behaviour with children, but not with adults.
3. The unpleasant auditory stimulation proved to be more sensitive to age: only during such stimulation a correlation of calculated values with age was found, i.e. positive correlation of the stability-value.

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