ORIGINAL ARTICLE

Differentiation of cognitive-specific states of attention: EEG when verbal memorizing and when recalling

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Abstract

BACKGROUND: Significant widespread differences in hemodynamics and electrodynamics between states of rest with open and closed eyes (default mode brain states) probably are consequences of involuntary shifts between interoceptive and exteroceptive modes of attention. These results make grounds for searches of similar correlates in active mental states. Results of such an attempt applied to states of verbal memorization and recollection using quantitative state-related EEG are presented.

METHODS: Electroencephalograms were recorded in 88 subjects in a resting state with the eyes opened (state EO), during memorization (state M) of verbal bilingual semantic pairs (Latin and Russian), presented on a screen, and during recollection (state R) of the learned information Statistical comparison of the EEG spectral power (local synchronization) and coherence (spatial synchronization) in the frequency bands theta, alpha1, apha2, beta1, beta2 and gamma showed that induction of the states M and R led to multiple significant changes in the EEG absolute power and coherence as compared to the state EO and as compared between active states R and M.

RESULTS: The results demonstrate that mnestic states of memorization and recollection are catered with rather different brain functional states reflected in system reorganizations of brain electrodynamics on the levels of local and spatial synchronizations both.

CONCLUSION: The observed differences can be related to changes of the exteroceptive–introceptive attention balance.

Introduction

In light of the ideas on the existence of different forms of attention maintaining different kinds of activity, including the state of rest (a default mode of brain function – (Raichle *et al* 2001; Raichle & Snyder 2007)) , the problem of a physiologically justified hierarchical taxonomy of forms of attention, based not only on behavioral characters, but also on specific brain correlates and corresponding brain mechanisms, is important, but far from being explored fair enough.

In particular, exteroceptive and introceptive aspects of attention only quite recently were proposed as a base for such taxonomy (Chun *et al* 2012), though suggestions that certain features of the dynamics of physiological parameters are caused by, e.g., transition to the dominance of memory retrieval in mental activity have some history (Ray & Cole 1985; Aftanas & Golocheikine 2001; Cooper *et al* 2003, 2006). It was also shown by the methods of tomographic evaluation of local hemodynamics (Marx *et al* 2003, 2004) and quantitative electroencephalography (Danko 2006; Boytsova

& Danko 2010) that significant differences in hemodynamics and, especially, electrodynamics between the states of quiet wakefulness with the eyes closed and open are widely distributed over the brain cortex. These differences testify to fundamental changes in brain operation modes for minimal behavioral differences and are most likely to be consequences of an involuntary anticipatory transition to the mode of processing predominantly external information from the mode of processing predominantly internal information. These findings were obtained in studies where subjects were at rest. The present study continued the line to assess EEG effects of directional changes in information flow and, correspondingly, in characteristics of mental attention, in states of definite mental activities.

Methods

The study was performed with 88 students of the Modern Academy for the Humanities aged 17–20 years (39 men and 49 women). The subjects were informed about the purposes, methods, and protocol of the experiments and signed an informed consent to participation in the study.

The EEG was recorded in the following states: rest with the eyes open (state REO), memorizing (learning by heart – state M) of bilingual verbal semantic pairs (Latin and Russian), and recalling (check – state R) of the learned information.

Three series of seven pairs of nouns were presented for learning on a monitor screen, the exposure of each pair being 5 s. One and a half minutes after the end of each presentation, the memorization was checked by presentation of the Latin terms from pairs of the previous series. Each term was exposed for 2 s. After the appearance of the permission signal (a question mark) on the screen, subjects had to give an oral response. If subjects could not recall the Latin equivalent, they pronounced an agreed upon, previously specified word.

For EEG recording, 19 active electrodes in accordance with the complete international 10–20 system were used with linked earlobe reference electrodes (monopolar derivations). In order to exclude fragments with artifacts from subsequent processing, the recordings were analyzed and edited. All these procedures, as well as the calculation of quantitative EEG parameters, were performed using the WinEEG software package (v. 2.79, NPF Mitsar, St. Petersburg).

The mean estimates of the EEG absolute power for each lead and EEG coherence for each pair of leads were calculated for each subject in a specific state. The estimations were made for the spectral components averaged in the bands θ (4–7 Hz), α 1 (7–10 Hz), α 2 (10–13 Hz), β1 (13–18 Hz), β2 (18–30 Hz),and γ (30–40 Hz). Arrays of the obtained estimations for EEG absolute power were normalized using the Y= logX transform and for EEG coherence using Y= log (X2/(1 – X2)).

Statistical analysis of the obtained arrays was aimed at revealing significant differences between the calculated EEG parameters in the compared states of the subjects. The repeated measures analysis of variance method was used. The significance of differences between the mean values corresponding to the examined states was estimated according to the within-subjects design. For the analysis of the EEG power spectrum parameters, D×S×Z plans were used, where D is the factor of frequency band, S is the factor of state, and Z is the factor of area (leads). Due to the great number of variables, we used the designs S×Z to analyze the EEG coherence parameters. These designs were applied in each frequency band individually. Here, Z was a topographic factor with specific pairs of leads as gradations of the factor.

The Greenhouse–Geisser adjustment was used for determining the significance of the main effects and interactions. The topography of significant differences was determined by means of post hoc comparisons using Fisher LSD test. The null hypothesis (the absence of significant differences between the arithmetic means) was rejected if the probability of error was equal to or lower than 0.05.

In addition to the EEG, the electrocardiogram was recorded (the right-/left-hand leads) in 32 of the subjects in order to monitor the HR. After the performance of each series, these subjects were also asked to subjectively estimate the difficulty of the task on a ten-point scale, where a score of 1 corresponded to "no difficulty" and a score of 10, to "extremely difficult, almost impossible." The significance of differences in subjective scores of difficulty between the states of memorization and retrieval and the significance of differences in the mean HR between all three states were determined by Student *t*-test for dependent samples.

To assess the reproducibility of the EEG dynamics, the pooled group of subjects was randomly divided into two subgroups of equal size (44 subjects).

Results

The mean HR in subjects in the state of rest was 76 bpm, whereas, in the states of memorization and retrieval of information, it was somewhat higher (81 and 79 bpm, respectively). According to the test used, only the difference in HR between the states of rest and memorization was significant.

The difference in subjective task difficulty turned out to be nonsignificant (the mean scores of task difficulty were 6.3 for memorization and 6.6 for retrieval). The mean percentage of correct responses in the control task was 58%.

The effects of all factors under study and of the D×S×Z interaction on the EEG power were highly significant even in the subgroups, i.e., after a decrease in the size of each sample to 44 subjects.

As can be seen in Figure 1, the main features of changes in EEG powers in comparisons between all three states (M, R, and REO) are reproducible in both groups. These features are: a vast topographic representation of significant EEG power differentials in frequency bands θ, β2 and γ for the contrasts R –REO and R–M and in the α2 band for the contrasts R–REO and M–REO; coincidence of the signs of EEG power changes in the θ, β2, and γ bands for all contrasts; the predominance of increases of the power in the M and R states relative to REO , in frequency bands θ, β2 and γ, more pronounced in the M state; the predominance of decreases of the power in the M and R states relative to REO , in a frequency band α2; and differences in the signs of changes in the EEG power in the α1 band, i.e. mostly increases upon the transitions REO→R and mostly decreases upon the transitions REO→M.

The global character of EEG power effects is supported with numbers in Table 1 where the number of areas with statistically significant differences between the states in EEG powers for the whole group (N=88) are shown.

Comparative analysis of the results obtained for the two subgroups (Figure 2) between each other points to the reproducibility of the main results for coherence dynamics as well. The main features reproduced in the subgroups are: the multiplicity of significant differences in the analyzed contrasts and frequency bands; a predominantly decreasing coherence in the M–R and M–REO contrasts; in the R–REO contrast predominantly increasing coherences in frequency bands γ and β2 and more noticeable increases of EEG coherence as compared to the M–REO contrast in other frequency bands.

Number of statistically significant differences between the states in EEG coherences (corresponding number of lead pairs) for the whole group (N=88) are shown in Table 2.

Discussion

First of all the results demonstrate that such cognitive specific active states as memorizing (M) and recall (R) are notable for their multiple EEG power and coherence differences. The differences are highly significant, reproducible in groups and widespread over the cortex to an extent that they can be treated as systemic ones. Similar multiple significant differences in the EEG power and coherence were found between the states of

Tab. 1. The number of areas with statistically significant differences in EEG power between the states (Fisher test) in different frequency bands for .

States compared	Frequency bands					
	Gamma	Beta2	Beta1	Alpha2	Alpha1	Theta
M–R			+1	+2	+2	+2
	−19	−17	−12	−13	−17	−17
M–REO	+19	+9	+10		+4	+14
				−19	−10	
R–REO	+19	+19	+12		+19	+19
				−18		

Note: Abbreviations are explained in the text.

Tab. 2. The number of statistically significant differences in EEG coherence between the states.

States compared	Frequency bands					
	Gamma	Beta2	Beta1	Alpha2	Alpha1	Theta
M–R		+1	+8	+9	+5	+10
	−146	−127	−80	−51	−88	−80
M–REO	+47	+26	+15	+2	+11	+18
	−63	−62	−50	−81	−101	−65
R–REO	+134	+95	+49	+9	+23	+77
	−1	−23	−28	−67	−26	−29

Note: maximum possible number of lead pairs for 19 leads is 171.

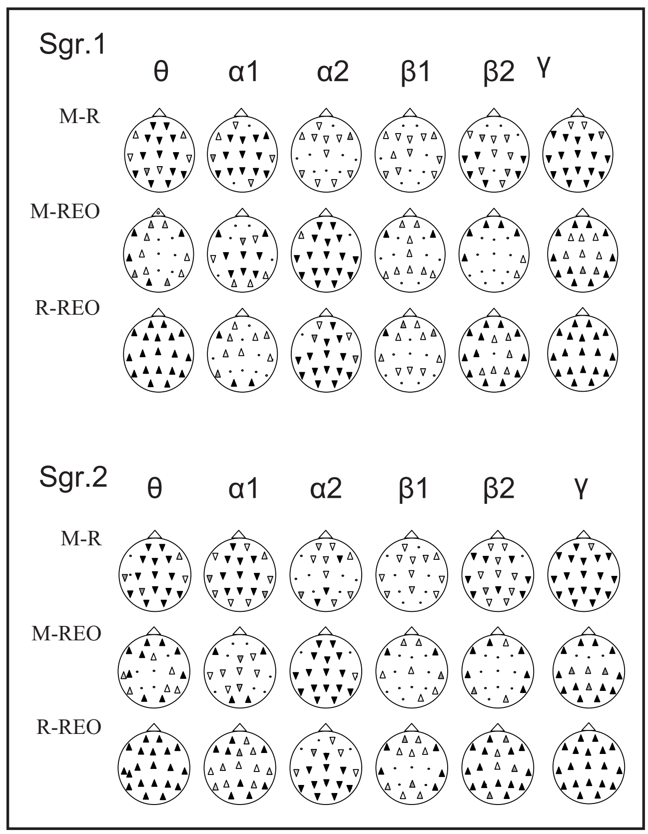

Fig. 1. Significant differences in the local EEG power in frequency bands θ, α1, α2, β1, β2, and γ between states: memorization of Latin–Russian pairs/recalling of translation of Latin words (M–R), memorization of Latin–Russian pairs/rest with the eyes open (M–REO) (the latter is taken as the baseline), recalling of translation of Latin words/baseline (R–REO). The data were obtained from subgroups Sgr.1 and Sgr.2, 44 subjects each. Upward and downward arrows at sites of derivations point, correspondingly, to higher and lower values of power in the first of the compared states. The density of arrow shading corresponds to the significance of differences.

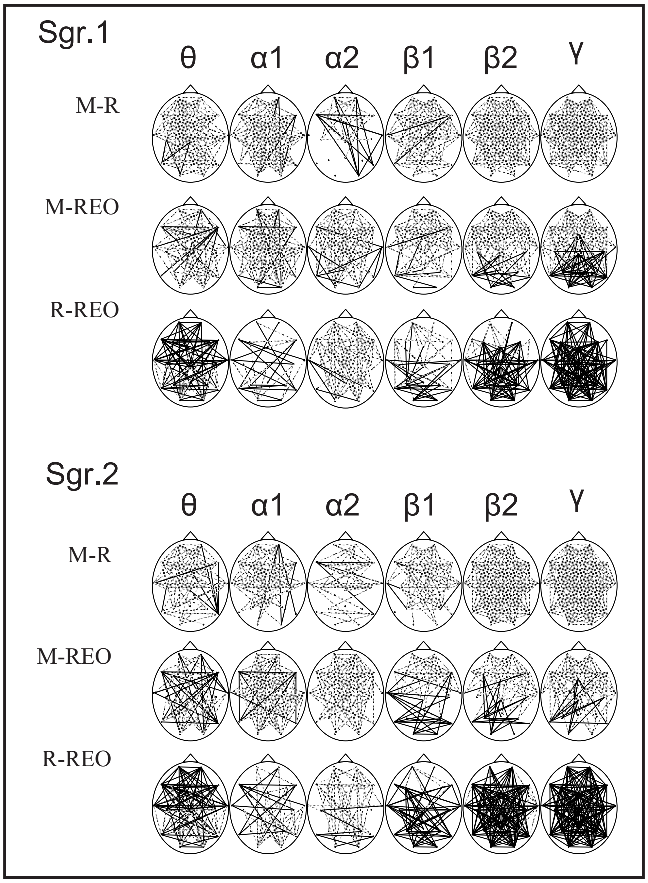

Fig. 2. Differences in EEG coherence for the same contrasts and subgroups as in Fig. 1. A solid line connecting the corresponding lead pairs indicates a higher coherence in the first of the contrasted states; a dotted line, a lower value.

rest with the eyes closed and rest with the eyes open (Danko 2006) and now between the states of definite mental activities.

What physiological mechanisms could underlie the observed well-pronounced, reproducible, multicomponent, widely spread differences in EEG power and coherence between the states under consideration, especially between states M and R?

In the chapter on attention of a popular textbook on psychophysiology (Danilova 2004) the relationships between the physiological mechanisms of attention and the mechanisms of functional states, as well as the operation of the brain modulatory system, was considered on the basis of concepts of local and phasic activations that determine the attention selectivity and specifics of mental operations. Widespread (generalized) tonic brain activations were associated exclusively with levels of wakefulness (levels of arousal) which mandatory included changes in vegetative nervous system. Such generalized reaction of activation was regarded as an increase in excitability, lability, and reactivity of the corresponding neural structures being reflected in alpha rhythm blockade (desynchronization) and/or enhancement of the EEG high frequency oscillations.

But we have a number of reasons to abandon arousal here as a main factor in our experimental situation: no significant differences in heart rates in the comparison M–R; no differences in subjective evaluations for task difficulties; no correspondence with arousal effects in signs of effects in low and high frequences for M–R comparisons; no coincidence in signs of coherence effects if compared with data in sleep-wake cycle (Cantero *et al* , 1999, 2004).

Thus, it seems more probable that the generalized changes in the EEG parameters are caused mainly by cognitive factors. The observed results can be treated in terms of the concept of "specificity of nonspecific activation" (Anokhin 1968), introducing the notion of "cognitive-specific functional states." Otherwise, in more preferable way, an attempt can be made to find a link with the mechanisms of integrative mental attention as a manifestation of intersystem relations in current activity, providing steady preparedness for performance of this kind of activity (Bezdenezhnykh 2003). The observed characteristics of the processes confirm distant assumption (Bechtereva 1978) based on summarizing the experience of pioneering neurophysiological research in human mental activity: "… the changes in EEG in the process of mental activity reflect not so much the active state of individual cerebral structures as the general changes that are likely to optimize the conditions for the corresponding activity."

The multiplicity of the observed effects in the integrative states of mental attention correspond, to a certain degree, to the data on the anatomic representation of the preparatory, orienting, and controlling components of attention in different areas of the cortex and subcortex (Posner & Petersen 1990). This makes it rather probable for subcortical structures to play an important role in the formation of mental attention states and EEG. These structures include the thalamus, midbrain, and limbic structures, which are considered to be modulating brain systems (Danilova 2004; Danilova & Krylova 2005). This assumption is also supported by the well-known data on the anatomic (to the extent of the accessible spatial resolution) and neurotransmitter closeness of the brain systems responsible for the regulation of states in the sleep/wakefulness terms and states of tonic nonspecific attention (general alertness, vigilance, sustained attention) (see, e.g., the reviews Robbins 1997; Robbins *et al* 1998; Coull 1998; Oken *et al* , 2006), as well as the data on the role of thalamocortical interactions in activations, such as arousal, and selective attention to external stimuli (Newman 1997; Steriade 2000; Saalmann & Kastner 2011).

Arguments were given that the observed effects of transitions between the states of quiet wakefulness with the eyes closed and open (Danko 2006; Boytsova and Danko 2010) can be explained partly by transitions from domination of introceptive attention to readiness for exteroceptive attention and vice versa. A more detailed comparison of significant differences in the M–R contrast (Figures 1 and 2) and in the contrast between rest with the eyes open and rest with the eyes closed (Danko 2006) show that these contrasts share multiple decreases in EEG power and coherence throughout the cortex surface. In the M–R contrast, these decreases are the most distinct in the frequency bands γ, β2, and α1. These commonality of EEG features may be interpreted as a reflection of different balances of the exteroceptive and introceptive directions of attention in the M and R states, i.e., the higher prevalence of the exteroceptive direction in the M state and interoceptive one in the R state. Note that, in this situation, we can speak only about the balance between the prevalences of these directions, and by no means about their mutual exclusion. It should be noted that we do not consider the factor of attention direction to be unique. Even in the relatively simple case of transition between the rest states, superposition of at least two components of the EEG dynamics may be suggested (Danko 2006; Boytsova and Danko 2010).

The observed multiplicity of significant differences in the EEG power and coherence upon changes in the type of mental activity shows that the specific features of mental attention states can manifest themselves with system-forming integrated indicators of interactions between neuronal ensembles, i.e., local and spatial synchronization of EEGs in totality of frequency bands. This is apparently in line with a number of current concepts on how the brain functions, including those on the role and characteristics of the functional brain system activity in facilitating mental activity (Alexandrov 1999; Alexandrov & Jarvilehto 1993; Anokhin 1978; Sudakov 1984; *et al*); the spatially distributed and temporally parallel information processing by the brain (Bressler 1995; John *et al* 1997; Mesulam 1990, 1998; Varela *et al* 2001; *et al*); and the role of neuron activity synchronization in the regulation of the conditions for a specific activity (top-down effects) (Basar *et al* 2001; Bressler & Tognoli 2006; Buzsaki & Draguhn 2004; Engel *et al* 2001; Hummel & Gerloff 2006; Womelsdorf & Fries 2007).

Conclusions

1. Mnestic states of memorization and recollection are catered with rather different brain functional states reflected in system reorganizations of brain electrodynamics on the levels of local and spatial synchronizations both.
2. The observed statistically significant differences in EEG averaged power and coherence, when contrasting memorization, recollection and rest with the eyes open, demonstrate multiplicity and intergroup reproducibility, being observed in all the studied frequency bands and over most of the cortex surface.
3. Comparing the differences in the EEG parameters allows us to assume that changes of the exteroceptive–introceptive attention balance play notable role in specifics of attention providing either memorization or recollection. Activation of the exteroceptive component of attention is characterized, to a first approximation, by decreasing EEG power and coherence over all cortex areas; activation of the interoceptive component by increasing the power and coherence. This effect is the most distinct in the frequency bands β2 and γ and least distinct in the α2 band.

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