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Association of an individual's ability to overcome desire to fall asleep with a higher anterior-posterior gradient in electroencephalographic indexes of sleep pressure

Arcady A. Putilov *, Olga G. Donskaya

Research Institute for Molecular Biology and Biophysics, Siberian Branch of the Russian Academy of Medical Sciences, 2, Timakova Street, Novosibirsk 630117, Russia

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ABSTRACT

Individual differences in ability to overcome desire to fall asleep cannot be accurately predicted from subjective and objective measurements of sleepiness level. Previously, we showed that an exponential buildup of sleep pressure during prolonged wakefulness can be accurately traced with electroencephalographic (EEG) indexes, such as Spectral Sleep Pressure Component (SSPC) score and score on the 2nd principal component (2PC) of the EEG spectrum. The anterior-posterior gradients in SSPC and 2PC scores were calculated as the differences between frontal and occipital scores and examined as possible correlates of individual's ability to overcome desire of falling asleep. Fifteen young and 15 older adults participated in two identically designed sleep deprivation experiments. After, at least, 12 hours of wakefulness, resting EEG recordings were obtained from frontal and occipital derivations with 2-h intervals during 26–50 hours. Due to irresistible desire to sleep, 11 young and 5 older adults completed <25 required EEG recordings. SSPC and 2PC scores were computed and, by subtracting occipital scores from frontal scores, the anterior-posterior gradients in SSPC and 2PC scores were calculated on one-min intervals of 5-min eyes closed EEG records. The analysis of these anterior-posterior gradients revealed their age-related difference and association with the number of completed EEG recording sessions (13–25). This association remained significant after accounting for age, alertness-sleepiness level, minute of eyes closed recording, and day of experiment. It seems that the anterior-posterior gradients in the EEG indexes of sleep pressure are the objective correlates of individual's ability to overcome desire to fall asleep.

1. Introduction

Solid evidence has been provided for existence of substantial differences between individuals in vulnerability to sleep loss, and it has been shown that such differences are often characterized by within-individual stability and robustness (Van Dongen et al., 2005). It has been also stressed that the study of individual variation in vulnerability to sleep loss has important implications for the safety critical occupations and procedures and for the symptomology and treatment of sleep disorders (King et al., 2009).

It has been also reliably demonstrated that there exists a substantial age-associated difference in vulnerability to sleep loss with older people showing a better than younger people tolerance to sleep deprivation (Duffy et al., 2009; Dijk et al., 2010; Silva et al., 2010; Landolt et al., 2012).

Individuals seem poor in predicting their ability to keep waking for a long time in condition of sleep loss. In particular, subjective sleepiness fails to predict the falling asleep event (Kaplan et al., 2007; Herrmann et al., 2010). Moreover, it is unlikely that even objective measurements of sleepiness can provide a good gauge to the falling asleep event. For example, some participants of our sleep deprivation studies showed dramatic deterioration of their subjectively and objectively measured alertness-sleepiness level but, despite this, they kept waking until the very end of the experiment. In contrast, such deterioration was less pronounced in other participants but some of them terminated their further participation in the experiment due to irresistible desire to sleep (Putilov, 2016; Putilov and Donskaya, 2016). In sum, subjective and objective measurements of sleepiness cannot accurately predict individual differences in ability to overcome desire of falling asleep.

Therefore, in the present report we tested whether individual differences in sleep-enforcing effect of prolonged wakefulness can be related to variation in a novel index of EEG brain activity. The following earlier published reports on the waking EEG indicators of vigilance state prompted the calculation of this index. The prolonged wakefulness and transition from wakefulness to sleep are characterized by changes in the anterior-posterior gradients of spectral EEG powers (De Gennaro et al., 2001; Marzano et al., 2013) as well as in principal component structure of the EEG signal (De Gennaro et al., 2001; Putilov, 2010). In the course of prolonged wakefulness, an increasing trend of

* Corresponding author at: 11, Nipkowstr., 12489 Berlin, Germany.
E-mail address: putilov@ngs.ru (A.A. Putilov).

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spectral power in the theta band in eyes open condition reflects a buildup of sleep pressure (Cajochen et al., 1995; Finelli et al., 2000; Aeschbach et al., 1997, 2001). This power tends to increase more in an anterior EEG derivation than in a posterior derivation, primarily in caffeine-sensitive individuals (Rétey et al., 2006). Landolt et al. (2012) showed that an anterior-posterior gradient in theta power calculated as a difference between powers in anterior and posterior derivations reflects individual differences in responses to prolonged wakefulness and caffeine. Therefore, we examined an anterior-posterior gradient in spectral EEG indexes of sleep pressure as a possible predictor of individual's tolerance to sleep-enforcing effect of sleep deprivation.

Two such indexes named "Spectral Sleep Pressure Component (SSPC) score" and "score on the 2nd Principal Component (2PC) of the EEG spectrum" where proposed in our earlier studies (e.g., Putilov, 2016) for measurement of buildup of sleep pressure in waking individuals. It was shown that a pure exponential rise is exhibited during prolonged wakefulness by difference in SSPC or 2PC scores calculated for the 1st and 3rd min of 5-min eyes closed relaxation (Putilov, 2016). It was also shown that the time courses of SSPC and 2PC scores correlate with the time course of alertness-sleepiness level. The time courses of sleepiness and the buildup of sleep pressure were more accurately described by using SSPC and 2PC scores than with such traditional indicator of this pressure as theta power. Moreover, this power measured in eyes open condition even weaker correlated with sleepiness than power in eyes closed condition (Putilov, 2016). The latter result agrees with some other reports (e.g., Leproult et al., 2003; Marzano et al., 2007) on comparison of spectral EEG powers in eyes open and closed conditions as objective indicators of sleepiness.

Although alertness-sleepiness level was closely associated with SSPC and 2PC scores (Putilov, 2016; Putilov and Donskaya, 2016; Putilov et al., 2017), the ability of a participant of our sleep deprivation experiment to stay awake till the very end of the experiment did not correlate with such scores. In the present paper we, being encouraged by Rétey et al. (2006) and Landolt et al. (2012) reports, decided to examine for the first time whether this ability correlates with an anterior-posterior gradient calculated as a difference between frontal and occipital SSPC or 2PC scores. Positive results of such examination can allow the conclusion that the anterior-posterior gradient in sleep pressure is an objective correlate of individual's sleep resistance, and, if replicated, these results can have implications for the safety critical occupations and procedures, such as driving.

The following hypotheses were tested. The anterior-posterior gradients in two sleep pressure indexes (SSPC or 2PC) were different in study participants characterized by A) younger and older ages and B) lower and higher tolerance to sleep-enforcing effects of sleep deprivation. It was additionally expected that C) these were the same-directional differences in the anterior-posterior gradients.

2. Methods

Participants of two identically designed sleep deprivation studies were 15 young and 15 older adults. The ages of young adults (8 females) ranged between 19 and 26 years with mean $\pm$ SD (Standard Deviation) of 22.9 $\pm$ 2.7 years. The ages of older adults (10 females) varied from 45 to 66 years with mean $\pm$ SD of 53.1 $\pm$ 7.2 years old. The sleep deprivation experiments were performed in accordance with the ethical standards laid down in the Declaration of Helsinki, and their protocols were approved by the Ethics Committee of the Research Institute for Molecular Biology and Biophysics. Informed written consent was obtained from each participant studied as paid volunteer.

Participants were recruited either from the staff of the medical research institutes or from surrounding community. They denied current health problems, a history of psychiatric or sleep disorders, and shift work or trans-meridian flights during the preceding month. For a week prior to the experiment, participants were asked to keep their regular sleep-wake schedule, and they were additionally asked to report history of their sleep for each of these days.

Participants arrived in the research unit on Friday, between 18:00 and 18:30 h, to leave it on Sunday after 19:30 h. The experimental procedure started with the brief instructions. Participants were asked to complete, if they can, 25 sessions of resting EEG recordings during the next 50 h. The first recording session started at 19:00 h, and the following 25 sessions were separated by 2-h intervals. Each EEG recording was made in the eyes open and eyes closed conditions (for the first two and the following 5 min, respectively). The study participants were under continuous supervision by the members of the research team to ensure that they always remained awake between the EEG recordings.

Participants were informed that they would receive a bonus that depends upon the duration of maintaining wakefulness in the experiment. For instance, their payment will increase on 100% in the time interval between the 16th and 25th recording sessions. Nevertheless, approximately a half of participants terminated their further participation in the experiment after 13–23 recordings due to irresistible desire to fall asleep (see Results).

Participants were also engaged in various performance measurements and questionnaire assessments scheduled between EEG recordings. When they were not participating in the research procedures, participants were allowed to read, write, play board and computer games, surf the Internet, watch TV, and listen to music. They were informed that they can consume light snacks and drinks (with exception of alcohol and caffeinated beverages) throughout the experiment at self-chosen times, and, moreover, they can freely move between several rooms of the research unit. Smoking was not permitted, and participants were also asked to avoid any medications and heavy meals, vigorous physical activity, and exposure to light >500 lx.

Both before and after each EEG recording session participants were asked to self-rate their subjective state. Their alertness-sleepiness was self-scored with the 9-step Karolinska Sleepiness Scale or KSS (Åkerstedt and Gillberg, 1990).

Frontal and occipital electrodes were used for all resting EEG recordings with one of the active electrodes placed in the middle from the top of the head to forehead (Fz–A2) and another placed midway between O1 and O2 (Oz-A2) of the International 10–20 system of electrode placement. Ten20 conductive paste was used for fixing the electrodes (Nicolet Biomedical, Madison, WI, USA). The electrodes were removed after each EEG measurement. The exact positions of active electrodes were preliminary inked by permanent marker.

The EEG signals were recorded via a 16-channel electroencephalograph (Neuron-Spectrum-2, Neurosoft, Ivanovo, Russia). Impedance of electrode/skin conductance was kept <5 kΩ for each electrode. The EEG signals were conditioned by the high-pass, low-pass and notch filters (0.5 Hz, 35 Hz, and 50 Hz, respectively), sampled and stored on a hard disc with a frequency of 200 Hz.

Each EEG record was visually inspected on 2-s epochs for removing epochs containing artifacts from further analysis. The FFTW (Fastest Fourier Transform in the West) package was applied to compute power spectra for the artifact-free epochs (Frigo and Johnson, 2005; see also www.fftw.org). Rectangular window taper was used on 1-s epochs without overlap for calculating absolute spectral power densities (μV2) for each single-Hz frequency bandwidth (i.e., 0.50–1.49 Hz, 1.50–2.49 Hz, 2.50–3.49 Hz, etc.). These values were averaged within each one-min interval of eyes closed *sec*tion. The minimal number of averaged one-sec spectra was 40.

All further calculations were performed using the SPSS statistical software package (IBM, Armonk, NY, USA, version 22.0). The single-Hz power densities in the frequency range from 1 Hz to 16 Hz were ln-transformed prior to calculation of sleep pressure scores for each of two (frontal and occipital) derivations. To obtain a score on the 2nd principal component (2PC), the 16 ln-transformed single-Hz power densities were weighted and summed:

$$\mathrm{Score} = \Sigma\, w_i * p_i, \tag{1}$$