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The Influence of Music with the Binaural Beat Effect on Heart Rate during Daytime Sleep in Humans

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Objective. To test the hypothesis that music with a binaural beat (BB) effect can increase activation of the parasympathetic compartment of the autonomic nervous system (PANS) as daytime sleep gets deeper. **Materials and methods.** Comparison parameters were the power of the high-frequency components of the spectrum of variability of subjects' heart rate computed in sequentia l 2-min periods during 20-min naps. Parameters were compared on going to sleep on the background of music with the BB effect (stimulus) and going to sleep in the quiet (control). **Results and conclusions.** Statistical comparison demonstrated a higher level of activation of the PANS on going to sleep on the background of the stimulus as compared with the control. This is consistent with conclusions in other reports on the positive influence of sound stimuli with the BB effect on the PANS.

Keywords: binaural beat, falling asleep, insomnia, heart rate variability.

Beating is an objective physical phenomenon arising on superimposition of two oscillatory processes at close frequencies. In psychoacoustics, "binaural" and "monaural," or acoustic, beating are distinguished. Acoustic low-frequency beating is most easily heard if two electrical signals of constant but slightly different frequencies (for example 248 and 252 Hz) are superimposed and delivered to a sound transducer (loudspeaker) – the result is that we hear periodic rises and falls (pulsation) in the loudness of the sound at the difference frequency, in this case 4 Hz. These signals can also be delivered simultaneously to two loudspeakers positioned close together, which causes the same beat to be heard. In this situation, summation of the signals does not affect the end result, as it reaches the ear in the same form – oscillations in the intermediate carrier medium, i.e., air. There is another version of superimposing these signals – directly within the listener's brain. This is achieved by delivering the same signals, at 248 and 252 Hz, separately – one to the right ear and the other to the left (for example, using stereo headphones). This situation also produces the sensation of beating at same frequency, 4 Hz, though it is now of a different nature and is linked with the physiological mechanisms of spatial sound source localization. This beating is termed binaural beat (BB). This differs from monaural beat (MB) in lacking an intermediate physical carrier in the form of air or some other medium. BB was first discovered by the German researcher Dove [1] and was later described by Thompson [2].

It should be noted that the word combinations "BB in sound" or "sound with BB" are not entirely correct, first because we are referring to two sounds rather than one and, second, we cannot say that this phenomenon is objective: a person perceives BB not via the auditory sensory system but within the CNS. In addition, the degree of susceptibility to BB depends on the level of attention the listener pays to it [3], though some people, for example, those with Parkinson's disease, are entirely unable to perceive it [4]. This explains the interest in this phenomenon, which blurs the boundaries between the "objective" and "subjective."

The most obvious difference between BB and MB is that BB is audible only in the case of low production

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("carrier") frequencies. They are best perceived with carrier frequencies around 440 Hz; increases in frequency lead to reductions in the discriminability of the beat. The range 200–900 Hz is optimum for perception. Data from recent studies show that people can clearly distinguish BB with carrier frequencies all the way up to 1400 Hz, the level of discriminability decreasing linearly with increases in the carrier from 700 to 1400 Hz [5]. As regards the frequencies of the BB itself, these are heard over the range 2–35 Hz [6]. At smaller frequency differences between channels, only the change in the location of the sound source (the stereopanorama) is perceived, while at greater frequency differences each ear hears its own separate tone.

Another distinguishing feature of BB is their low amplitude. For example, standard acoustic beat obtained by superimposition of two sounds of identical loudness can have loudness ranging from 0 to four times the loudness of each of the sounds. BB are perceived only as weak modulation of the loudness of a single sound. Assessment of the depth of this modulation gives a result of about 3 dB, or about one tenth the loudness of whispering [4].

The attractiveness of this effect for improving sleep comes from the fact that a person can perceive its action at very low loudness, at the edge of the threshold of perception [4], i.e., this stimulus creates little interference with the process of relaxing. Despite the fact that a series of studies demonstrating improvements in the characteristics of sleep in humans under the influence of sound stimuli based on BB has now been reported, the actions of BB on sleep have received insufficient study. This applies particularly to objective studies based on analysis of electrophysiological parameters, for example the electroencephalogram (EEG) or electrocardiogram (ECG). There is a small number of reports satisfying these requirements [7–10].

On the one hand, studies have been reported demonstrating the effectiveness of music for the treatment of insomnia. This method has become popular in recent years as it lacks side effects [11–13]. Questionnaires indicate [14] that 25% of people use music as a means to facilitate going to sleep. The influence of music on the process of sleep has been addressed in scientific reviews [13, 15–18]. It is therefore logical to suggest that the combination of music and correctly selected BB should also improve sleep, as demonstrated in [10]. This report described analysis of the effectiveness of a sound stimulus using sleep consolidation as a parameter determining the probability of finding the subject in the state of slow-wave sleep. However, heart rate variability (HRV) provides another potential parameter. Furthermore, in cases in which full sleep monitoring is impossible, analysis of HRV provides a simple assessment of a person's functional state.

The high-frequency component of HRV (HF) corresponds to activity in the parasympathetic compartment of the autonomic nervous system (PANS), while the role of the low-frequency (LF) component thus far remains unclear [19–21]. It may reflect both sympathetic and parasympathetic activity. The relative contributions of these compartments are described by the ratio of the corresponding HRV power levels (the so-called autonomic balance index, ABI = $= P_{LF}/P_{HF}$) and by normalized spectral power levels:

$$HF_{n.u.} = P_{HF}/(P_{LF} + P_{HF}) \text{ and } LF_{n.u.} = P_{LF}/(P_{LF} + P_{HF}) \text{ [22].}$$

Thus, the LF and HF components of the HRV spectrum can be used as a quantitative measure of sympathetic and parasympathetic responses to a given stimulus. In any case, this approach is appropriate for analysis of PANS activity, as the HF component of HRV is determined exclusively by this [23].

It is interesting that while ANS activity during nocturnal sleep is less well studied [24], its profile in daytime sleep remains insufficiently investigated. Furthermore, the transient stability of the spectral components of HRV during daytime sleep is poorly studied, which limits the reliability of the data from occasional studies. Nonetheless, it has been shown that the process of slow-wave sleep (both daytime and nocturnal) in the human ANS is dominated by parasympathetic activation. Quantitatively, this is apparent as an increase in the power of the HF component of the HRV spectrum [25, 26]. The same is seen in the process of resting after physical exercise [27, 28].

The aim of the present work was to test the hypothesis that music based on BB at frequencies in the θ and δ EEG ranges can increase activation of the PANS as the depth of daytime sleep increases. Moreover, a similar quality has been observed in the EEG θ range using monotonous BB-based sound stimuli based on recovery from dosed physical exercise [29].

Materials and Methods. ***Subjects.*** The experimental group consisted of 22 medical students (12 male, age 18–22 years, mean age 19.8 ± 0.8 years). Each participant signed informed consent to take part in the experiment. The subject had to take part in two experiments; in one, the subject went to sleep with music, while in the other the subject went to sleep without music (control). The order of the experiments was balanced over the cohort; a randomly selected 13 of the 22 subjects performed the control situation first. Experiments with each participant were performed in the daytime, from 13:00 to 16:00, with intervals between the two experiments of 1–15 days. Of the 22 subjects, data from 20 were used for the comparative analysis. Data from the other two subjects were unsuitable for analysis because of the large number of artifacts on ECG traces.

Apparatus and experimental procedure. The sound stimulus was an electronic musical composition of duration 20 min 16 sec, giving BB of 4 and 2 Hz. Of this play duration, the first 19 min was "programmed" for going to sleep and the remainder for gradual awakening. The stimulus was presented using Bose QC-25 full-size stereo headphones (sensitivity 97 dB, impedance 32 Ω, with active noise reduction switched off). Loudness was selected individually such that the music could be heard well but without interfering with going to sleep, i.e., 55–57 dB sound pressure level.

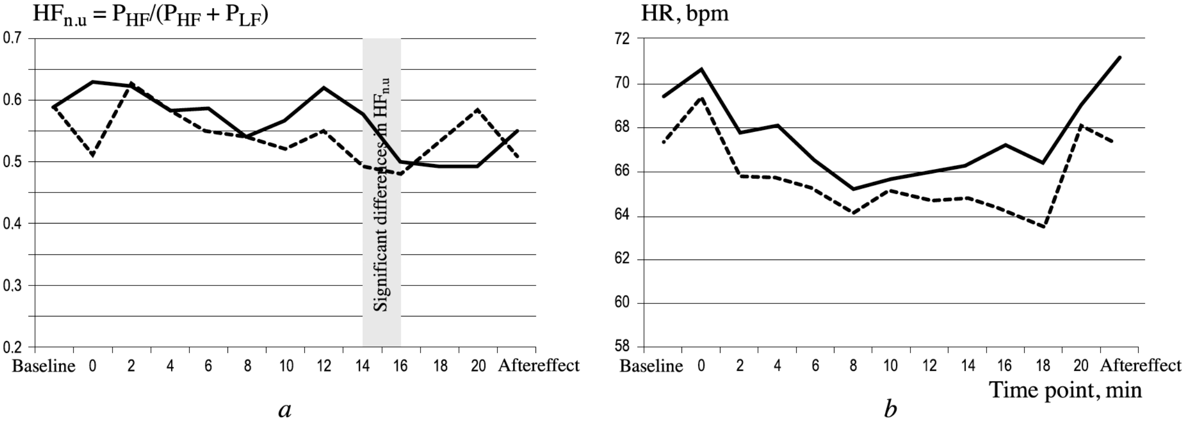

Fig. 1. Changes in cohort median values for parameters during the experiment. *a*) Changes in cohort median values of the high-frequency component of the HRV spectrum (HF$_{\text{n.u.}}$, ordinate) during the experiment. The bar shows the 2-min epoch in which significant differences in HF$_{\text{n.u.}}$ in stimulation and control conditions were seen (Wilcoxon test, $p = 0.021$); signs test, $p = 0.0037$); *b*) changes in cohort median HR (ordinate) during the experiment. No statistically significant differences in subjects' HR were seen in stimulation and control conditions. ——) Stimulus; - - -) Control.

Subjects were placed in a sound- and lightproof location at a stable temperature of 24°C. Polysomnogram (PSG) recordings were made during the experiment at a sampling frequency of 500 Hz; recordings consisted of 16 EEG channels connected by the monopolar 10–20 scheme, along with one ECG channel and one electrooculogram (EOG) channel, using a Neuropolygraph 24 wireless programmable system (Neurotech, Taganrog).

After positioning the electrodes, the subject was placed on a couch and was in the horizontal position for the first 15 min to stabilize HR. Checks were made that the subject did not go to sleep during this period. Subjects were then told to close their eyes and baseline recording of the PSG was run for 3 min. The music was then started and, after 21 min, when the music ended, the subject was woken (if he/she had fallen asleep) and a further 3-min PSG recording was made with the eyes closed. In control experiments, the experimental scheme was the same except that the stimulus was not presented, only a start marker being made on the trace.

Data processing. HRV was analyzed by transferring the ECG signal from the overall PSG to a separate file, which was then loaded into processing package Kubios HRV 2.1 [30], from which sequences of R–R intervals (henceforth the signal) were extracted and analyzed. The software was used for preliminary detrending of the signal using a smoothing parameter $\lambda = 500$ (with an estimated filter cutoff frequency of fc = 0.035 Hz). This procedure removed slow trends, including nonlinear, which would otherwise lead to distortion of the signal. The ECG was then assessed visually for artifacts, and these were first corrected manually and then by interpolation using the Kubios HRV algorithm set to the "medium" level [30]. The boundaries of the HRV frequency ranges were set as follows: HF 0.15–0.6 Hz, LF 0.04–0.15 Hz. The frequency ranges were calculated using a fast Fourier transform (FFT), based on the Welsh periodogram method [30] with a window width of 256 sec and 50% overlap. The interpolation frequency had a standard value of 4 Hz.

After detrending and artifact correction, the signal was divided into 13 2-min intervals, providing adequate duration for analysis of HRV frequency ranges as described in [23]: 1) baseline; 2) epoch 1; 3) epoch 2; ...; 12) epoch 11; 13) aftereffect. Analysis of parasympathetic activity in Kubios HRV 2.1 in the 13 intervals calculated the normalized spectral density of HRV power in the high-frequency range HF$_{\text{n.u.}}$. ABI was not analyzed in this study because of its identical relationship with HF$_{\text{n.u.}}$, such that it is redundant: $\mathrm{HF}_{\text{n.u.}} = 1/(1 + \mathrm{ABI})$.

Statistical data analysis. In view of the significant deviation in the data distribution from the normal, data were described using median values rather than means. Comparison were made using two paired nonparametric tests: the signs test and the Wilcoxon test. The significance level was taken as $p < 0.05$.

Results. We present below the results of testing the suggestion formulated in the review part of this report, that music based on BB in the θ and δ EEG frequency ranges would help enhance activation of the PANS as daytime sleep became deeper. The hypothesis that such music would affect the subjects' heart rate (HR) was also tested.

For each of the 13 2-min epochs (including baseline and aftereffects), the null hypothesis was that there would be no significant difference in HF$_{\text{n.u.}}$ between the control and experimental cohorts in the epoch under study. The null hypothesis for HR was formulated in the same way.

Significant differences in HF$_{\text{n.u.}}$ were found in epoch 9, i.e., from the 14th minute to the 16th, with $p < 0.05$, Wilcoxon linked pairs test. At other epochs, including baseline and aftereffect, differences were not significant (see Fig. 1, *a*). HR was also compared for the 13 epochs. There were no significant differences between the stimulus and control conditions here in any of the epochs (see Fig. 1, *b*).

Discussion. Thus, the null hypothesis regarding HF$_{\text{n.u.}}$ was rejected for one comparison epoch out of 13, which is evidence for significant differences in PANS activation in this epoch due to presentation of the BB-based musical stimulus. It should be noted that no unambiguous trend to increased PANS activity reflected in the parameter $HF_{n.u.}$ was seen during the experiment in either the stimulus or control conditions (see Fig. 1, *a*). However, such a trend is expected on the basis of the demonstrated increase in PANS activity as sleep became deeper [25]. Its absence appears to be associated with the presence of transient awakenings by the subjects, significantly greater in controls than in stimulation conditions, which produced significantly higher levels of sleep consolidation in the latter situation [10]. As regards PANS activity, its value ($HF_{n.u.}$) during the greater part of the experiment was higher in stimulation conditions than control conditions; significant differences were seen closer to the end of the experiment, from the 14th minute to the 16th (see Fig. 1, *a*). The absence of significant differences in $HF_{n.u.}$ In the first 2-min comparison epoch was consistent, as it is evidence of the absence of any differences in subjects' heart rate parameters before the experiment started.

The question of changes in HR as an effect of BB (see Fig. 1, *b*) remains controversial. No significant differences were seen in the present study between the experimental and control series. Differences were also not seen in [29, 31]. On the other hand, significant changes in HR in response to music with the BB θ effect were seen in [32].

The cause of these contradictions may be in the different experimental protocols, including differences in stimulus duration, different sets of beats and carrier frequencies, and different levels of subjects' attention to stimuli [3], as well as strong differences in individual reactions to the stimulus [33]. In addition, confidence in results is in some cases decreased because of lack of control of the experimental conditions and incomplete descriptions of the experimental protocol, as well as the lack of data on parameters of the EEG and other autonomic functions (ECG, respiration, oximetry, etc.)

Conclusions. Thus, the present study shows that analysis of HRV can be used to assess consolidation of daytime sleep in people; the method used is a test of autonomic nervous system activity. The results obtained here are consistent with data [10] on the positive effects of music with the BB effect on the consolidation of daytime sleep and with the conclusions of [29] that θ-range BB influences activation of the PANS during the process of relaxation after physical exercise.

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The authors declare no conflicts of interests.

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