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Pink noise: Effect on complexity synchronization of brain activity and sleep consolidation

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ABSTRACT

In this study, we hypothesized that steady pink noise is able to change the complexity of brain activities into a characteristic level and it might have significant effect on improving sleep stability.

First, we carried out the brain synchronization test in which electroencephalogram (EEG) signals of 6 subjects were recorded. The whole experiment procedure was divided into 5 blocks in the alternative feeding process of 10-min quiet and 10-min noise. After the complexity analysis of fractal dimension, we found that the complexity of the EEG signals decreased with the introduction of the pink noise exposure, showing the brain waves tended to synchronize with the pink noise induction to reach a low level.

For the sleep quality experiment, 40 subjects were recruited the group of nocturnal sleep experiment and 10 participants were chosen for nap test. Each subjects slept for two consecutive experimental periods, of which one is pink noise exposed and the other is quiet. For both nocturnal sleep and nap tests, the results in the noise exposure group showed significant enhancement in the percentage of stable sleep time compared to the control group based on the analysis of electrocardiography (ECG) signal with cardiopulmonary coupling approach.

This study demonstrates that steady pink noise has significant effect on reducing brain wave complexity and inducing more stable sleep time to improve sleep quality of individuals.

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1. Introduction

As known to all, brain activity has some specialized brain waves appearing with different frequencies at different states. For example, the delta wave, with a relatively low frequency and high oscillation amplitude, characterizes the slow wave sleep stage in non-rapid eye movement period when people sleep (Vincenzo and Stuart, 2010). Many researches tried to induce the brain wave with external stimuli, such as light and sound. In these studies, it has been proved that a simple single structured source is insufficient to change brain waves, according to the falsification of 'binaural auditory' (Stevens, 2003; Wahbeh, 2007) which was once announced to have ability to induce theta waves of brain (Foster, 1990). However, brain activities are complex and chaotic, so it might be possible for a noise source with complex structures to synchronize the brain waves so as to induce people into a specialized sleepy state.

In nature world exists three basic kinds of noise, that is, white noise, pink noise ($1/f$ noise) and brown noise. Pink noise, which randomly distributes in low frequency band with the spectral density $S(f)$ proportional to $1/f^{\gamma}$ with the exponent γ being 1 (Halley and Kunin, 1999), is thought to exist in a profusion of fields such as heart-rate fluctuation of human beings (Leon, 2001), quasar emissions (Dutta and Horn, 1981), human cognition (Weissman, 1988), DNA base sequence structure (Voss, 1992), river discharge (Mandelbrot and Wallis, 1968), and cellular automata (Christensen et al., 1968), etc. This universality of pink noise suggests that it is a general demonstration of complex systems instead of a consequence of special physical interactions (Meijer et al., 1981).

Considering the marvelous phenomenon of pink noise, we hypothesized that it has the ability to change the complexity of brain activity and synchronize it into a characteristic state. Based on this hypothesis, we carried out a test of recording electroencephalogram (EEG) signals from 6 subjects in afternoon nap. The fractal dimensions of EEG signals were analyzed as the parameter of complexity.

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The decreasing trend of brain wave was displayed in the EEG test, a further study came out to examine whether the pink noise could help sleep of individuals based on the conclusion of Zhang et al. (2009) study that brain complexity is lower and lower accompanied with the depth and consolidation of person's sleep.

Meanwhile, some recent studies showed related evidence. For example, in 2010, light music, an example belonging to pink noise, is proved beneficial for elder people to improve their sleep quality as a long term effect (Chan et al., 2010).

Moreover, in a previous study (Suzuki et al., 1991), the steady pink noise with intensity of 35 dB, 40 dB, 50 dB and 60 dB was used to stimulate 4 subjects during sleep and they believed that pink noise could improve the sleep quality of subjects according to the evaluation using the traditional standard of sleep stage classification, known as R & K standard (Rechtschaffen and Kales, 1968). However, it is clear that this conclusion was based on significant increase of light sleep period (especially stage 2) accompanied with declined duration of rapid eye movement.

To classify the sleep states according to a newly developed approach called cardiopulmonary coupling (CPC) (Thomas et al., 2005) in this sleep study, electrocardiogram(ECG) signals were collected from 40 subjects during nocturnal sleep and 10 people during nap, in different sleep environments of quietness as control and steady pink noise exposure as stimulation. Since the whole sleep time of each individual could be little different from the others, the sleep quality is quantified by the percentages of stable sleep time in whole sleep with comparisons between the noise exposure group and the control group.

2. Methods

2.1. Participants

A total of 40 volunteers were recruited by advertisement. All were required in good health, especially with normal hearing, and free from serious illness or use of medications.

Table 1 showed the demographic information of subjects in the three experiments. The mean age of 6 subjects in the brain activity synchronization experiment was 22.4(S.D. $\pm$ 2.5) ranging from 22–25 years, of whom 3 males and 3 females were included.

For the sleep quality test, all the 40 people were involved in the test group of nocturnal sleep, which had a mean age 23.4 (S.D. $\pm$ 2.9) years with a range from 21 to 30 years, including 22 males and 18 females. On the other hand, ten people were chosen randomly for the nap test with the mean age 23.7 (S.D. $\pm$ 1.1) with a range from 22 to 26 years, including 6 males and 4 females.

Volunteers were also prevented from exercising in the experimental duration because a previous study demonstrated that exercise could affect sleep (Sasazawa et al., 1997).

2.2. Experimental design

In the afternoon nap of brain synchronization test, all the 6 subjects were in an alternative feeding process of 10-minute quietness and 10-minute pink noise exposure, and the whole recording procedure continued for 50 min, showed in Fig. 1. Then, the whole experimenting process was divided into 5 blocks and in the pink noise exposed blocks the sound level was controlled between 20 dB and 40 dB selected by the comfort of the individual subject.

As displayed in Fig. 2, in the sleep quality experiment for the nocturnal experiment group, each subject slept at two consecutive nights in a sleep laboratory. To prevent the 'first night' effect which could impair the results of our experiment, we randomized the order of quiet night and noise-accompanied night in different subjects. In the quiet night, subjects slept in a quiet environment while in the noise-accompanied night, they fell asleep accompanied with exposure to a steady pink noise, which lasted a whole night, at the same level as in the brain synchronization test. The mean sleep length was 7.5 h, regarded as reasonable length of normal sleep. Moreover, every subject could choose the most suitable time as they are accustomed to sleep.

In the meantime, each subject in the nap test group took naps in two successive afternoons, with the similar procedure of nocturnal experiment that the order was randomized. The difference was that in the noise-accompanied afternoon the steady pink noise was followed by ten-minute quietness as a sound period after the subject lay down on the bed. This test was different from the brain synchronization test for it used the steady continuous pink noise instead of the intermittent noise block stimuli. Additionally, the mean sleep length was 1 h.

2.3. Signal acquisition and evaluation

In the brain synchronization experiment, we recorded EEG signals of the whole testing procedure and fractal dimension analysis was utilized to each block, and then we could observe the whole variable trend of brain wave complexity in addition to the complexity level of each block.

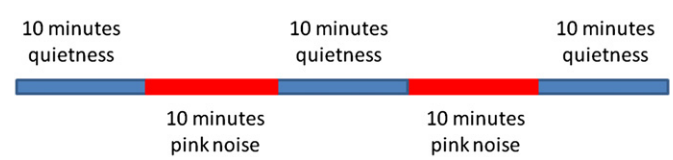

Fig. 1. The experimental design for brain synchronization test.

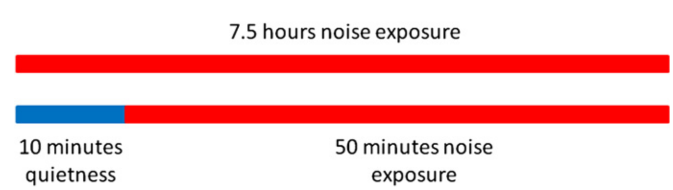

Fig. 2. The experimental design for nocturnal experiment and nap test under noise exposure.

Table 1
Summary of demographic information of subjects.

Test type	Age (Mean $\pm$ S.D.)	Gender		Weight (Mean $\pm$ S.D.)	Education background
		Male	Female		
B.S	22.4 $\pm$ 2.5	3	3	76.2 $\pm$ 2.4	Bachelor
N.S	23.4 $\pm$ 2.9	22	18	74.8 $\pm$ 3.2	Bachelor
NAP	23.7 $\pm$ 1.1	6	4	75.3 $\pm$ 1.9	Bachelor

B.S: brain synchronization experiment; N.S: nocturnal sleep test; NAP: nap test.

In the sleep quality test, a questionnaire was carried out for each individual in the nocturnal sleep group right after sleep to assess his/her feeling about the influence of pink noise on sleep quality. The assessment was generally divided into three levels, namely good, ordinary and bad.

To quantify the noise effect, ECG signals were recorded from every subject through the whole average 7.5-hour sleep by utilizing a small Holter of CPC, which used only a single-lead electrode with diameter of 53 mm on the chest and had much less disturbance than polysomnogram (PSG) machine to sleep, which could help to acquire the results more close to reality.

These recorded single-lead electrocardiographic signals were analyzed through cardiopulmonary coupling method. This approach combines the amplitude fluctuations of QRS wave that are associated with the mechanical effects of ECG-derived respiration signal with heart rate variability changes that are related to neuroautonomic tone modulation mathematically (Thomas et al., 2009). The resultant sleep spectrogram of this method is a map of coupled sleep oscillations, displaying spontaneously transitioning periods of very low frequency coupling (wake or REM sleep), low frequency coupling (“unstable” sleep) and high frequency coupling (“stable” sleep) (Ibrahim et al., 2010). The approach has advantage that it could avoid subjective mistakes made by operators with traditional R & K evaluation and has less disturbance to sleeper than PSG.

Thus, the periods of stable sleep (high frequency coupling regimes) were collected to compare with the whole sleep time for quantitative evaluation of the effect of noise sound on sleep consolidating.

2.4. Statistical analysis

The adjacent blocks in the 50-minute naps was compared by utilizing student’s paired t-test and rank-sum test to evaluate the differences associated with pink noise and quiet state.

Meanwhile, analyses that whether there was significant difference in the percentages of stable sleep time between the noise exposure and control group, were carried out by using paired Student’s t-test or rank-sum test when Student’s t-test was inapplicable due to the existence of heterogeneity of variance.

3. Results

For the brain synchronization experiment, according to the results of fractal dimension analysis for each block as shown in Fig. 3, it demonstrates clearly that each block with pink noise exposure is significantly different from the adjacent blocks with quietness, which implies that the complexity of brain activities tend to be synchronized by the pink noise. Moreover, considering that a significant level decrease of the fractal dimension with the introduction of pink noise and the fractal dimension has a trend to increase like block 3 when pink noise stops, it could be confirmed the pink noise may trigger brain wave into a lower complexity.

In the sleep quality test, the subjective assessment of 40 subjects to the nocturnal sleep exposed to pink noise, as shown in Fig. 4, indicates that 30 persons feel that pink noise has a good effect on sleep while 8 people think no significant improvement in their sleep. Additionally, there are also two subjects feeling bad on sleep.

Fig. 5(a) and (b) display typical CPC spectrums of one subject in this study under quiet and noise exposure conditions. It is very clear that in the noise exposure environment, the number and durations of high frequency coupling sections increase compare to the quiet environment and more continuous high frequency periods are shown, which mean the time of stable sleep for this person has grown and his sleep quality is improved.

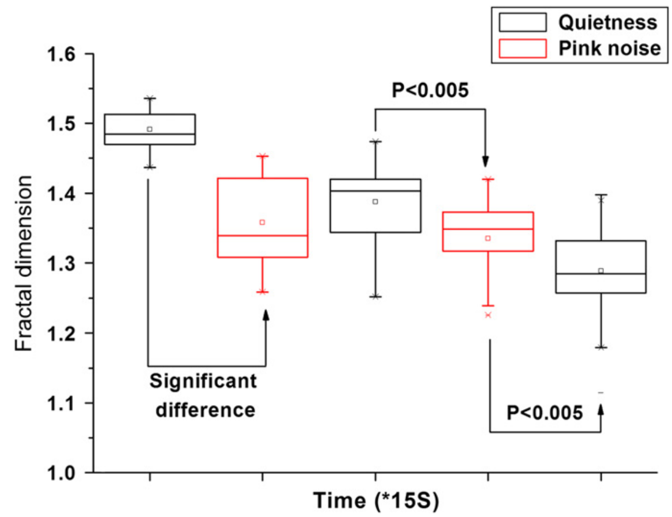

Fig. 3. The comparisons in different blocks which show the pink noise could trigger the brain wave into a lower level of complexity.

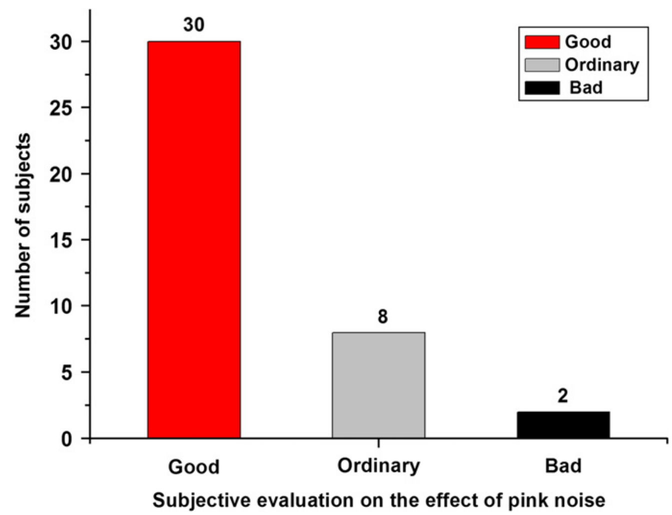

Fig. 4. The assessment of subjects’ feeling about the influence of pink noise on sleep quality. Three levels are divided to describe the feeling: good, ordinary and bad.

Table 2 presents the data of 40 pairs in nocturnal sleep and 10 pairs in nap, respectively, showing the percentages of stable sleep time (SS%), unstable sleep time (USS%) and the time ratio in REM stage and wake states (R & W%) calculated by the CPC method. The results indicate that for nocturnal sleep the noise exposure group reaches a mean of 58% (±13%) stable sleep time while the control group has only 47% (±14%),with 23% higher in percentages. For the nap tests, 64% (±19%) stable sleep time appears in the noise group, much higher than that of 44% (±12%) in the control group, with 45% higher values. Meanwhile, the percentages of both the unstable sleep time and the REM stage & wake time are much reduced in the noise group, which also helps in the improvement of sleep quality accompanied by the increase of stable sleep time.

The results of paired t-test of those data show significant differences in the percentages of stable sleep time between the noise exposure group and the control group, for both of nocturnal

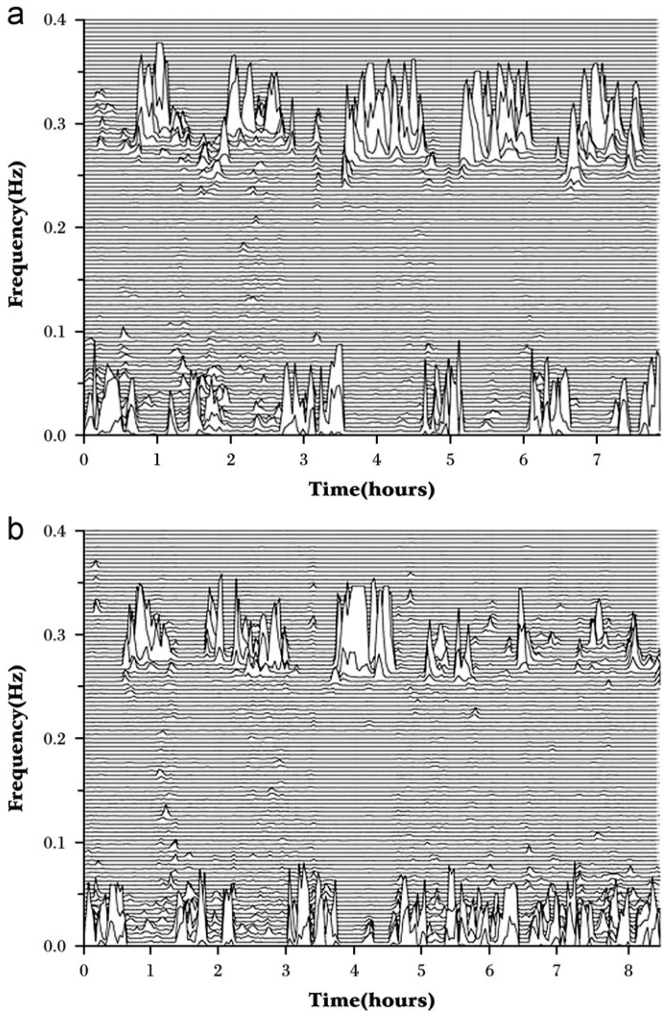

Fig. 5. (a) The typical CPC spectrum of a subject in the quiet sleep and (b) typical CPC spectrum of a subject in the noise exposure sleep.

Table 2
Mean values and standard derivation of percentage in different sleep states.

	Nocturnal sleep		Nap	
	Noise group	Control group	Noise group	Control group
SS%	58 ± 13	47 ± 14	64 ± 19	44 ± 12
USS%	22 ± 10	26 ± 12	18 ± 15	23 ± 14
R & W%	17 ± 6	22 ± 6	16 ± 12	29 ± 10

SS%: percentage of stable sleep time; USS%: percentage of unstable sleep time; R & W%: time ratio in REM stage and wake states.

sleep (P=.0001) and nap experiment (P=.003), as shown in Figs. 6 and 7, respectively.

4. Discussion

In the brain synchronization study, it has demonstrated that the pink noise could synchronize brain wave and induce brain activity into a specialized state, that is, in a lower complexity level. It is expected to understand the reason why the steady pink noise could decrease brain wave complexity and induces the sleepers more stable sleep time with less sleep fragmentation and wake periods.

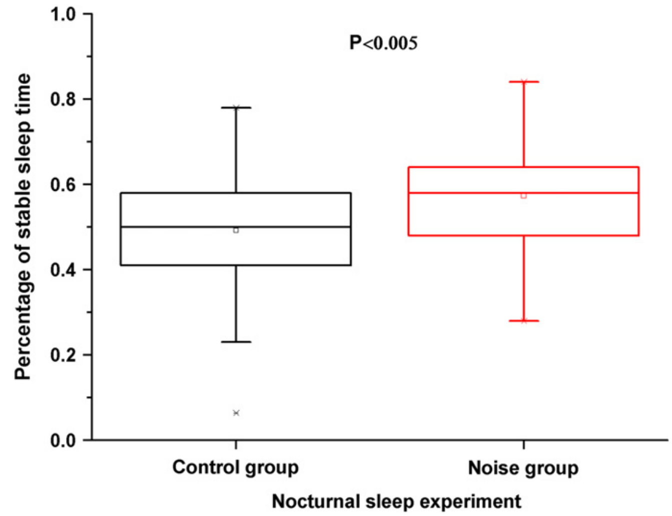

Fig. 6. The comparison between control group and noise group in the test of nocturnal sleep.

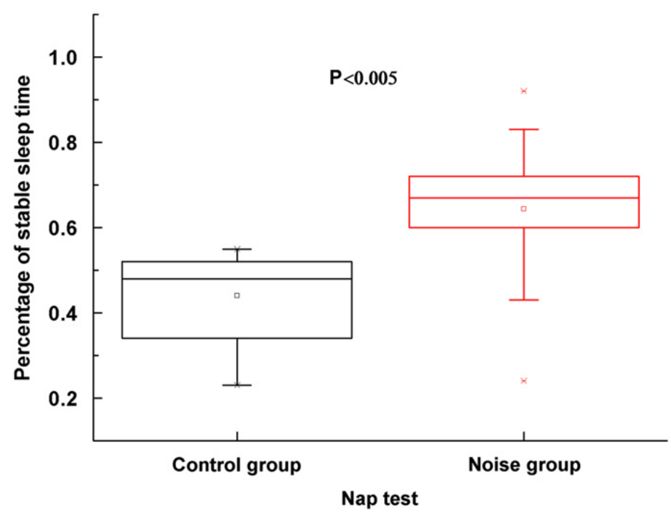

Fig. 7. The comparison between control group and noise group in the test of nap.

According to a recent report (Vincenzo and Stuart, 2010), neuroscientists believe that the slow waves in NREM sleep could be considered as the result of intricate interactions of three cardinal oscillators: a salient cortical oscillator based on synapses and two inherent thalamic oscillators. Considering that those three oscillators could be stimulated simultaneously by specific auditory input, it may mean that the neurons in thalamus might be synchronized with pink noise in a low oscillating frequency band, which is somewhat like stochastic resonance phenomenon, so that slow rhythm could dominate the brain waves to make people have low-level complexity and a more solid sleep when they exposed to pink noise.

Meanwhile, according to the above results of sleep quality experiment with CPC approach, it is found that the ratio of stable sleep time is significantly improved with the introduction of pink noise. Noise is a prominent phenomenon of the environment surrounding us humans (Stansfeld and Matheson, 2003). Many prior studies focus on the impact of environmental noise on human sleep quality and most of the studies show that the noise from transportation (Carter, 1996), aircraft (Basner et al., 2006) and railway train (Vernet, 1979) damage residents' sleep seriously. However, these kinds of noise could be generally regarded as 'intermittent and changeable' white noise, from which the 'continuous and steady' pink noise we used in this study is completely different. In fact, we call it 'noise' is due to the complexity of itself and it is really a kind of pure sound like rainfall existing in the natural world as described in prior, which may have the ability to synchronize the brain activities based on the probable mechanism of stochastic resonance. Additionally, it should be noticed that the sound level is chosen by subjects themselves rather than a specific given value in the traditional studies. This is because everyone has his own comfortable level of auditory and in this study we aim to improve individual's sleep quality with pink noise. It is more reasonable to use a suitable volume to avoid the disturbance of excessive sound exposure to our results.

In this sleep quality test we use a technique call cardiopulmonary coupling (CPC). This method is designed to assess sleep stability using a non-invasive and cost-efficient measure derived from the ECG recording. Generally, deep sleep with fewer interruptions is believed to be associated with more "stable" sleep. However, there has been no prior study showing a solid correlation between the CPC-derived sleep index and traditional sleep stages such as REM, light and deep sleep stages, while the CPC-derived sleep index is well correlated with the CAP and Non-CAP sleep classification interestingly (Thomas et al., 2005). Further studies are necessary to build the mechanistic link between traditional seep stages and sleep stability based on the CPC method.

Also, it should be noted that in the sleep quality test we focus on evaluating the proportion of stable sleep time to whole sleep time in this study, while the length of sleep latency is also a noteworthy parameter for assessing sleep quality since many beings have obstacle to fall asleep. According to the subjective descriptions in our study, over 80% participants thought they fall asleep very soon when exposed to pink noise, although there is no specific data recorded, which could be involved in the further study.

In summary, we present a potential way of physical stimulating method to synchronize the brain complexity into a characterized state, that is, steady pink noise exposure. Based on this phenomenon, we find that it could consolidate sleep at a comfort sound level, which may be a new sleep improving method with much less side effect compared to some traditional therapies, such as hypnotic sleeping pill.

Ethics

We obtained verbal informed consent from all the subjects. As we considered, all the methods involved in this study have achieved clinical acceptance, including pink noise like rain falling and ECG Holter, so there is almost no harm to participants themselves. Under this consideration, we present the whole procedure to subjects in detail and obtained their verbal consent.

Disclosure statement

This was not an industry sponsored study. Pink noise used in this study is generated by the authors themselves. Dr. Jue Zhang, Prof. Jing Fang and Jing Ma are the advisors of this study. Junhong Zhou, Dongdong Liu and Xin Li are the post-graduate students in Peking University who conceived and designed the experiments.

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