Effects on Sleep by "Cradle Sound" Adjusted to Heartbeat and Respiration

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Abstract

This paper reports a cradle sound system creating and reproducing sounds and music appropriate for human sleep with heartbeat and respiration signals sensed by biological sensors. To get further supporting evidence, we started a study aiming at exploring what sound attributes, such as waveforms, tones, and tempos, are necessary for a sound capable of improving sleep latency. We expected that a cradle sound whose tempo was slightly slower than those of heartbeat and respiration could slow them and could promote natural sleep. Subjects listening to this sound during their sleep showed: (1) Multiple sound types with different tones have an effect to shorten sleep latency. (2) Remarkable effects are observed in subjects with long sleep latency. (3) Sustained synthetic chord used for inducing respiration did not improve sleep latency. (4) There is no correlation between subject's sensibility evaluation to sound and the effect shortening sleep latency.

Introduction

Nearly 20 percent of the Japanese people have some complaints of sleep difficulties (MHLW 2008).

Poor sleep quality may affect cognitive function, impaire efficiency at work, and increase traffic accidents (including public transportation accidents), which may cause potentially-serious social losses.

Pharmacological treatments with hypnotics are used to reduce sleep latency, increase sleep maintenance and improve sleep quality. But in some cases, hypnotics may also decrease muscle tone and decrease balance, which might be associated with falls and bone fructures. Moreover, the lack of sleep in the elderly may increase the risk of illness, such as depression, dementia, and respiratory problems (Sonia 2009).

For sleep environment related to sound, increasing urbanization may increase unwanted sounds and noise coming in day and night. Such noise may have negative effects on sleep. Background noise can increase sleep latency or time to fall asleep from full wakefulness. Even during sleep, unwanted sounds can reduce Non-REM sleep and this decreases sleep efficiency to prevent a good sleep (Alain 2007).

Reversely, silence existing in a draft-free house may causes ear ringing symptoms, and it is difficult to sleep in a too quiet environment. On the other hand, some sounds can help to induce relaxation and create comfortable environment.

What do you think of when hearing "a good sleep"? Is it to be able to sleep easy (fall asleep quickly) whenever you want to? or fall into a deep sleep? or feel refreshed after it? Some people, to make up for the shortage of sleep, may might say "I want to get a full night's sleep" and some, "I want to get rid of my sleepiness as much as possible in even during short lunchtime break". To accomplish their hopes, some of them do exercise, change their rhythm of daily life, or take a sleeping pills.

If hearing a sound can ease your sleep problems and eventually leads to a good sleep, it could be referred to as a fruitful option. We verified whether sounds influence the improvement in sleep quality, referring to such functional sounds as "cradle sound".

The effect of music on heartbeat is well known (Yoshiyuki et al. 2003). Heart and respiration rates are also known to fall when you fall asleep (Harper et al. 1987) (Otsuka et al.1991) (Shimohira et al. 1998).

Looking at sleep based on the above results, if the rates can be decreased by listening to a functional sound during sleep, it could help inducing sleep. Controlling human sleep by using biological rhythms prone to synchronize with the tempo of a sound heard is our basic point of view.

Our previous exploratory studies showed that some types of sounds decrease sleep latency and make sleep cycle stable compared to "No sound (silent)" by having subjects listen to a content with a slightly longer period (five percent each) than those of their heartbeat and/or respiration (Yamaki 2015) (Ishihara 2014). In the studies we mainly used natural wave sounds to synchronize biological rhythms.

The current experiment with more subjects aims to verify (1) whether sound types other than wave sounds have the same effect as well, (2) what kinds of properties they have, and (3) whether individual differences in impression of sounds, not differences in sound, affect the effectiveness.

This paper consists of six sections: Section 2 for Cradle Sound System, Section 3 for Experimental and Analysis Methods, Section 4 for Results, Section 5 for Discussion, and Section 6 for Conclusion

Cradle Sound System

Cradle Sound Operating Principles

Sounds used as cradle sounds consist of (1) heartbeat-based sounds—sounds or music adjusted for personal heartbeat by changing tempos, (2) respiration-based sounds—sounds or music adjusted for personal respiration by changing tempos, and (3) background sounds not adjusted for use.

The sound system stores sound waveforms close to a breathing cycle, such as natural ocean waves, into a memory in advance, and then reads it for playback while making tempos a little bit slower than those of received respiration signals. The system, with a view to adding comfortable feeling, uses 1/f fluctuation to the order of calling sounds, the period of playbacks, and the amplitude of playback. The same as above applies to heartbeat. For background sounds, the system simply plays back recorded natural sounds etc. repeatedly to embellish adjusted sounds.

The sound system thus uses individual's biological information to optimize sounds in real time. Moreover, allowing you to combine natural sounds infinitely enables generating comfortable cradle sounds, which will not make you feel bored even if you listen to it every night. The system expected a cradle sound to induce your heartbeat and respiration to synchronize with it, make you feel calm, and promote natural sleep.

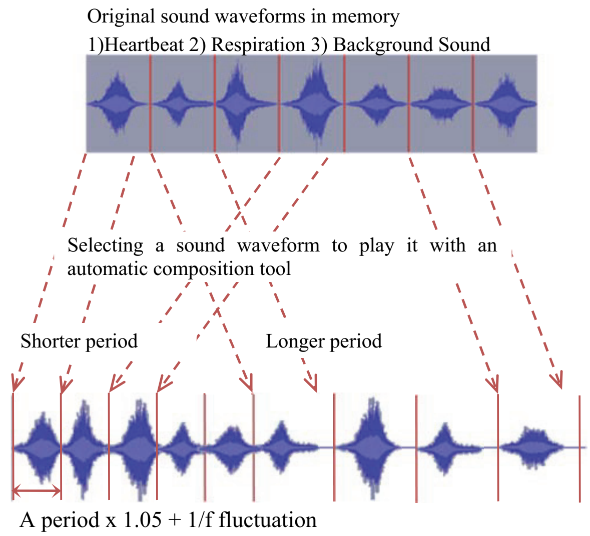

Figure 1

Experimental Apparatuses

Fig. 2 shows experimental apparatuses: (i) Biological Sensors (ii) PC with a sound generator (iii) Speakers.

To get biological information, the system used a sheet-shaped bed sensor *EMFIT* (VTT Technical Research Center of Finland) placed under and in the center of your chest between the bed frame and the mattress. Using non-invasive monitoring without physical restraint allows getting biological information (heartbeat, respiration, body motion) in the same environment as usual. The system recorded subject's biological information from the sensors on a PC at bedtime.

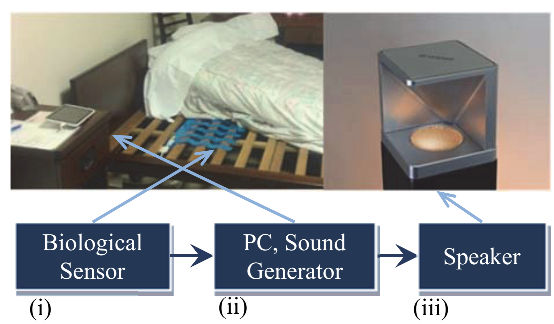

Figure 2

The biological sensors send biological information to a sound source in a Windows tablet PC, and then a dedicated sound generator developed with *Max/MSP* (developed by Cycling '74) creates synthetic sounds and feeds it to a Yamaha *Relit LSX-700* speaker system. This speaker, placed at the foot of the bed, draws on the concept of providing a more natural acoustic space by reflecting sound off a wall and such (Takadama 2015).

Experimental Apparatuses

Fig. 3 shows the features of six types of sound contents used.

	Feature	Respiration-linkage sound	Heartbeat-linkage sound
No.1	No sound	—	—
No.2	Sounds of insects in a forest	Sustained synthetic chord	—
No.3		Synthetic chord fading in/out	—
No.4	Tibetan Singing Bowl	Decay sound of a bell	Small-sized bell
No.5	Japanese percussion instrument beats	—	Japanese percussion
No.6	Wave sound (natural)	Wave sound (natural) fading in/out	Synthetic decay sound

Figure 3

No.1: we applied no sound. A reference to compare the effectiveness between this content and others.

No.2: we applied Sustained sound, whose rate was linked to the participant's respiratory rate (Fig.4).

No.3: we applied Fade-in/out sound whose rate was linked to the participant's respiratory rate only.

No.4: we applied a combination of sounds. *Tibetan Singing Bowl* based sounds linked to respiratory rate. Another is small bell sound linked to heartbeat.

No.5: we applied Japanese percussion sound linked to heartbeat.

No.6: we applied a combination of sounds. Wave sound linked to respiration and heartbeat (used successfully in the last experiment).

In No.2 and No.3 we used the similar sounds. In other conditions, we used different sounds with different impressions.

Experimental and Analysis Methods

Experimental Methods

This experiment was performed from Nov. 2014 to Feb. 2015, Twenty-two participants were recruited in our company (20 men and 2 females from 26 to 51, averaged 43 years of age) selected from healthy employees. We provided explanations about its aims and ways to secure participant's consent with a consent form. After that, we made sure they were all healthy with *Pittsburgh Sleep Quality Index* and hearing tests and then conducted a questionnaire survey on participant's sensibility to tones and sleep habits. The experiment used *RION audiometer type AA-77A* in a soundproof room (Yamaha *AVITECS*) for testing the sense of hearing.

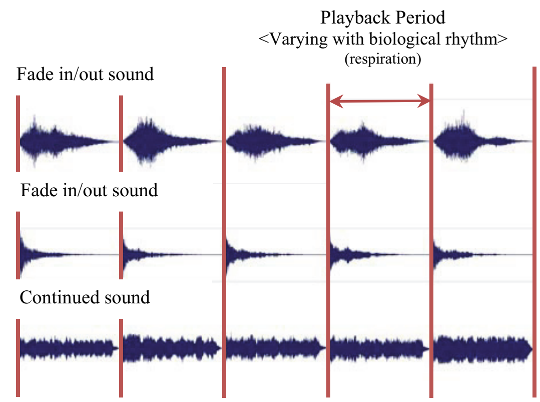

Figure 4

Each experiment was conducted through night, from 22:00 to 06:00, on weekdays in an in-house accommodation. We expected that setting an early bedtime than usual would make it harder to fall asleep.

The room temperature was air-conditioned to about 20 degrees in advance. To prevent unwanted sound from its fan, the conditioner was configured to operate in silent and weak airflow modes. Before each experiment, we conducted a survey on sleep to participants using *OSA sleep inventory MA version* (OSA-MA) (Yamamoto 1999) and performed a blood pressure check with *OMRON HEM-1025*.

Each experiment used one content per night for a randomly selected participant.

The tempo of a cradle sound was set to 1.05 times the biological rhythms of participants s, and its sound pressure, the maximum volume level of SPL = 40dB (A) within the range not to disturb subject's sleep. The volume level was decreased to 33dB (A) one hour after getting asleep to remove effects on sleep quality. This experiment used *RION sound level meter NL-22* for measuring sound pressure. The level of background noise was roughly 30dB (A) or less through each night.

After wake-up, we conducted another survey using the OSA-MA and an additional survey on the impression of sounds.

Analysis Methods

We analyzed differences of effects on sleep latency between No.1 (No sound) and others and how the following collateral conditions relates to sleep latency: questionnaire results after a wakeup, evaluation results of subject's sensibility to sounds, subject's sense of hearing, blood pressure, the number of experiments, atmospheric conditions, room types, and days of the week.

Moreover, we grouped the subjects into two types according to differences in sleep latency with no sound and the sense of hearing to compare effects on sleep latency between subjects in each group and between groups.

Sleep latency is defined as the time from bedtime to sleep onset. For a bedtime, we comprehensively determined it by sight with subject's body motion, and a time when "Play" button on a tool running on the PC is pressed at around the requested bed time (22:00). Sleep onset is defined as the moment when a body motion level is kept lower than 20 for at least 120 seconds.

For the analysis, we adopted a non-parametric test—Wilcoxon signed rank test—using R (programming language) and Microsoft Excel 2013. As for correlations, Pearson's product-moment correlation coefficient (p) is used and if p is less than 0.05, then it is defined as significantly different.

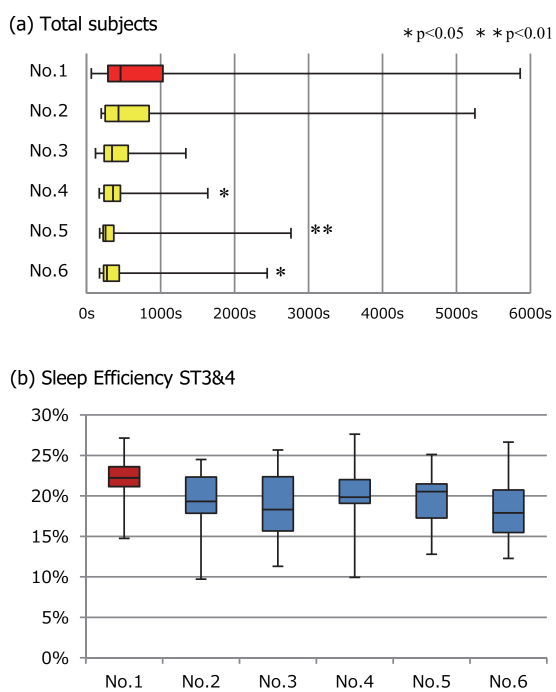

Figure 5

Results

Multiple Contents Shortening Sleep Latency

As shown in Fig.5 (a), this experiment found that four types of sounds with different tones out of five had the tendency to shorten the latency, compared to No.1 (No sound). The figure shows No.4 through No.6 have a statistically noticeable effect on sleep latency.

Fig.5 (b) shows no sounds have effect on sleep efficiency during sleep. Sleep efficiency is defined as a proportion of *ST3&4* (total of stages 3 and 4 in sleep depth) to total sleep time.

Remarkable Effects Found in Subjects With Long Sleep Latency

Focusing on a subject (n=12) who have a long sleep latency over 400 seconds with No.1 (no sound), we found No.3 through No.6 also had a significant effect to shorten their sleep latency, as shown in Fig.6. The results indicate sleeping while listening to a sound helps fall asleep earlier than usual, and this implies that bells, Japanese percussion instruments, and synthetic chords, other than wave sound, could be available for improving sleep latency.

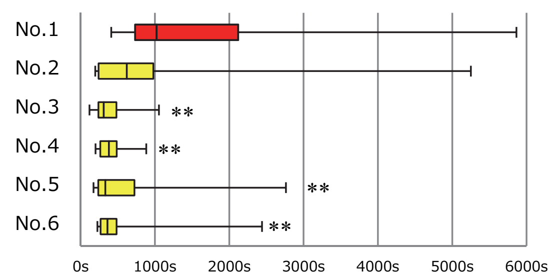

Figure 6

Sustained Sound (No.2) Having no Effect on Sleep Latency

Focusing on *Respiration-based Sound*s (No.2 through No.4 and No.6 in Fig.5 (a)), we found No.2 had no significant effect compared to No.1 but No.3 (Fade-in/out type) had an effect to shorten sleep latency; the two are similar in tone but quite different in effect. Both No.4 (decay type) and No.6 (Fade-in/out type) also have the positive effect. This experiment found that *Fade-in/out* and *Decay* type sounds (No.3, No.4, and No.6) helped shorten sleep latency, but *Sustain* type sound (No.2) did not.

No Correlation Found Between Sensibility to Sounds and Effects

Neither questionnaire results after a wakeup nor survey results of subject's sensibility to sounds could explain the above results. (Fig.7)

Effects of Sense of Hearing

For subject's sense of hearing, this experiment found subjects with a relatively better hearing tended to take a longer time to fall asleep in a silence, but it was statistically insignificant (Fig.8). Assuming the higher sense of hearing in the low- and mid-frequencies the longer the sleep latency in no sound, the following is very interesting; Do subjects bother about a faint noise from inside or outside a room? or Is the room too silent for them to sleep?

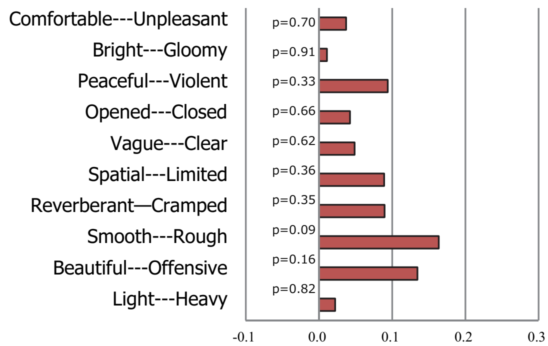

Figure 7

Control Conditions

We anticipated *Circadian Rhythm* would be a control condition as individual's usual bedtime is ignored in this experiment. As shown in Fig.10, we grouped subjects according to whether their usual bedtime is before midnight, based on the questionnaire survey results. Sleep is thought to be less affected by Circadian rhythm in this experiment, as differences between groups are not significant.

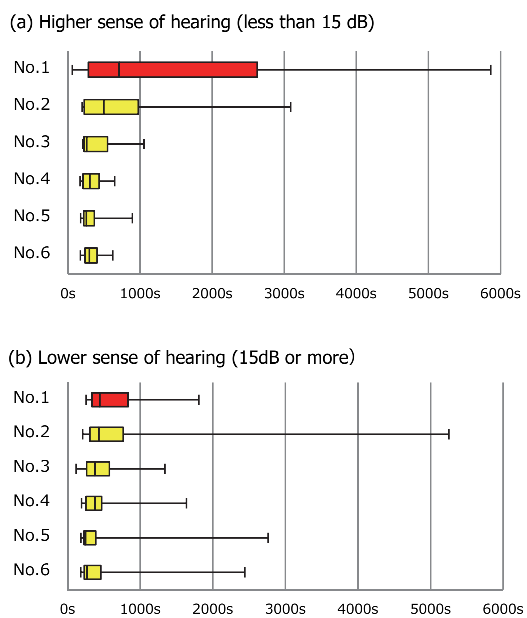

Figure 8

Collateral Conditions

This experiment found factors other than sounds, such as the number of experiments, days of the week, atmospheric conditions, and blood pressure, did not affect the results (Fig.11); that is, the effect shortening sleep latency resulted from the differences in effects of sounds only.

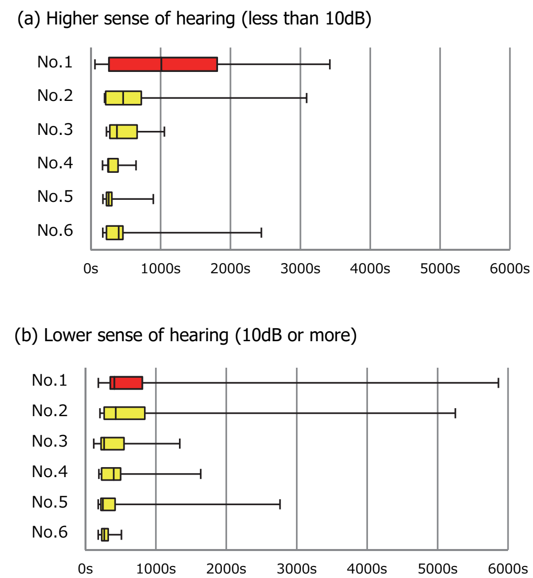

Figure 9

Discussion

A significant discovery this time is that several quite different sounds have an effect of shortening sleep latency. The sounds of No.3–6 consist of different tones and some of them differ in speaker position or with what biological rhythm to synchronize it. The authors expected that we would find some common properties of sounds helping shorten sleep latency if one or two sounds showed a promising effect, but the result is unexpected. In addition, a result showing that subject's sensibility to sounds has no such positive effect is wholly unexpected. This means creating sound to your sound taste is not a promising solution.

Although we have not identified the differences of effects on sleep latency between heartbeat-based and respiration-based sounds, heartbeat-based sounds of No.4 through No.6 show relatively positive effects, and respiration-based sounds, positive effects with Fade-in/out or Decay type sounds, but not with Sustain.

A breathing cycle of about four seconds is long enough for you to perceive changes in sound volume. This continual change may make it easy to catch the tempo of sounds when Fade-in/out or Decay sound is used, but difficult when Sustain is used, because you must perceive changes only at the end of each cycle. The rate of change with time in amplitude may be significantly related, as seen in Fade-in or Fade-out sound.

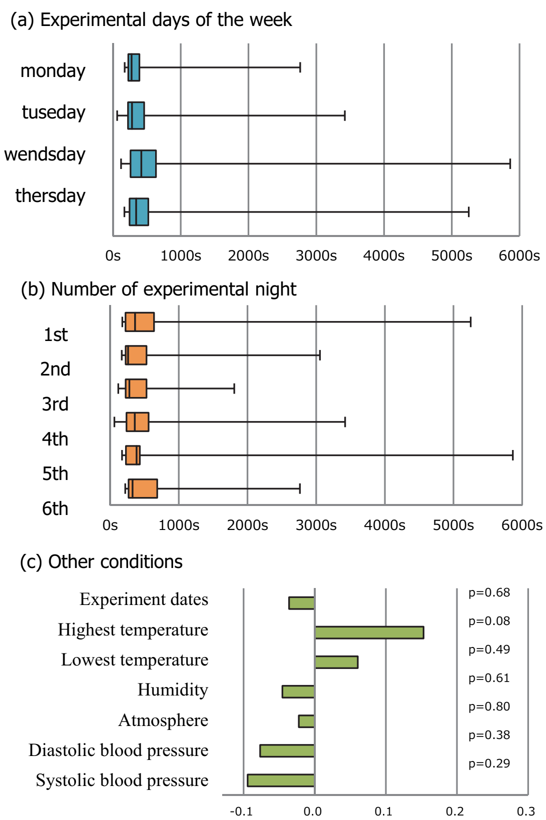

Figure 10

From a viewpoint of the sense of hearing, subjects with higher hearing tend to take a longer time to fall asleep in no sound as stated above. If it is caused by perceiving undesired sounds or unsettling silence, using an appropriate sound could resolve this issue. The results this time seem to be partly due to the effect of masking undesired sounds or distracting yourself from ringing in the ears or being lost in thoughts in a silence, but then there is the fact that No.3 had an effect of shortening sleep latency but No.2 did not. Therefore, shaping a sound waveform to synchronize it with biological rhythm play an important role in shortening sleep latency, having a higher potential to elicit further effects than the masking and distracting effects.

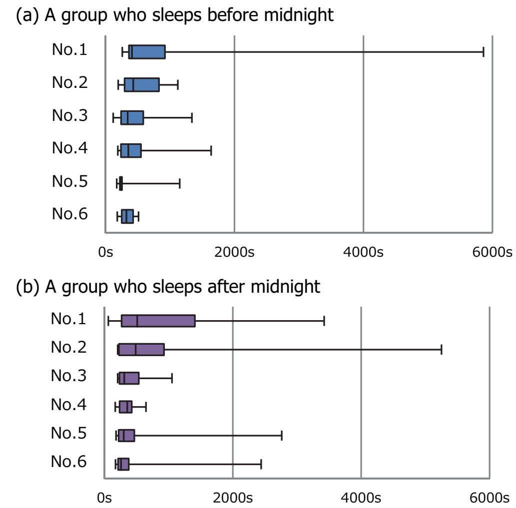

Figure 11

Conclusion

This study revealed multiple types of sounds other than wave sounds also had the positive effect to shorten sleep latency. In addition, since the effect is noticeable among subjects with relatively longer sleep latency, it could be a clue to find a solution for a person who has difficulty falling asleep. However, there are many things we do not know about optimal sound waveforms and conditions.

From now, we will keep on studying the following:

1)Verifying the differences in effects of using respiration-based sounds only or heartbeat-based sounds only or both, and verifying the effects of changing tempo multiplication factors.

2) Revealing the correlation between the sense of hearing and sound volume.

3) Researching optimum cradle sounds with data mining and clustering techniques.

4) Measuring biological rhythm accurately in Sleep Laboratory to verify the effects in a general household.

We would like to analyze the mechanism how the characteristics of a sound relate to shortening sleep latency through further researches. To explore cradle sounds for a good sleep is also one of research questions for getting a deep sleep and waking up feeling good, not only for shortening sleep latency. To meet individual needs for good sleep and many sufferings caused from aging or poor health, we hope to contribute to producing sounds for improving your sleep while keeping on collaborating with external agencies, such as university laboratories and medical institutions.

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