Reduction in Time-to-Sleep through EEG Based Brain State Detection and Audio Stimulation

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ABSTRACT

We developed an EEG- and audio-based sleep sensing and enhancing system, called iSleep (interactive Sleep enhancement apparatus). The system adopts a closed-loop approach which optimizes the audio recording selection based on user's sleep status detected through our online EEG computing algorithm. The iSleep prototype comprises two major parts: 1) a sleeping mask integrated with a single channel EEG electrode and amplifier, a pair of stereo earphones and a microcontroller with wireless circuit for control and data streaming; 2) a mobile app to receive EEG signals for online sleep monitoring and audio playback control. In this study we attempt to validate our hypothesis that appropriate audio stimulation in relation to brain state can induce faster onset of sleep and improve the quality of a nap. We conduct experiments on 28 healthy subjects, each undergoing two nap sessions - one with a quiet background and one with our audio-stimulation. We compare the time-to-sleep in both sessions between two groups of subjects, e.g., fast and slow sleep onset groups. The p-value obtained from Wilcoxon Signed Rank Test is $1.22e-04$ for slow onset group, which demonstrates that iSleep can significantly reduce the time-to-sleep for people with difficulty in falling sleep.

I. BACKGROUND

Studies have shown that soothing audio stimulation can help to improve the quality of sleep in nearly all age groups [1]–[4]. A study conducted by Johnson in 2003 [5] suggests that music is beneficial for people with sleep (onset) problems as it can decrease the frustration and dread associated with sleep complaints. Since the application of music intervention does not involve extensive investments in training or tools, it is relatively inexpensive, portable and readily available to the masses [6]. In 2009, de Niet *et al.* [7] conducted a survey about the efficacy of audio as a form of sleep-promoting intervention. The authors performed meta-analysis of data from previous research findings and concluded that music-assisted relaxation had a moderate effect on the sleep quality of patients with sleep complaints. Most studies on music-induced sleep have focused mainly on patients with sleep problems. The assessments of sleep quality have been based mainly on feedback from patients, subjects or care givers. To the best of our knowledge, there is few studies quantify the effectiveness of audio stimulation in terms of promoting sleep onset in the healthy population.

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In recent years, a number of sleep enhancing products or systems have been developed. They can be categorized into three different groups. The first group deals with sleep tracking and provides recommendations for improving sleep. An example of such a product in this group is Sleep Tracker, which was developed by Zeo (Boston, 2003). This application helps to track users' sleep cycles, providing them with information on their sleep patterns, and recommendations on how to improve their sleep quality. The second group provides assistance in waking up users in the appropriate stage of their sleep. Example products are Wakemate (Perfect Third Inc. San Francisco), Lark(Lark Technologies, CA) and Renew Sleepclock (Gear4, Hong Kong). These products track the users' sleep patterns and wake them up gently by using either sounds or vibrations from a wristband when the users are in light sleep stage. The third group consists of sleep induction systems, an example of which is Nightwave (Coherence Resources Inc., Portland). These systems help to induce sleep through the playback of audio, white noise or sounds that match the frequency of the brainwaves to calm the user down and help him fall asleep.

Existing sleep enhancement or regulation system usually rely on an open loop approach. In this research, we developed a novel closed-loop system to help people gain faster and better sleep. The EEG- and audio-based sleep sensing and enhancing system, called iSleep (interactive Sleep enhancement apparatus), collects EEG data to monitor sleep status and consequently provides user the appropriate audio stimulation to shorten the time to sleep onset. We also conduct validation experiments to quantitatively assess the efficacy of the system.

II. METHOD

A. The iSleep Prototype System

Figure 1 shows the architecture of the iSleep prototype we develop. The system comprises of two major parts: iSleep mask to be worn by user and iSleep Mobile App to be installed in a mobile device.

1. Sleep Mask

The prototype of iSleep mask is shown in 2. The single channel EEG unit based on Neurosky's TGAM model is integrated into the sleep mask that can be worn comfortably. The sensing electrode is silver-chloride metal electrode positioned at FP1 while both reference and ground electrodes are attached to the left earlobe using a spring-loaded earclip. Besides EEG hardware, Bluetooth stereo speakers are also embedded into the iSleep mask at appropriate locations as shown in Figure 2. EEG signals are sampled at $512Hz$ and

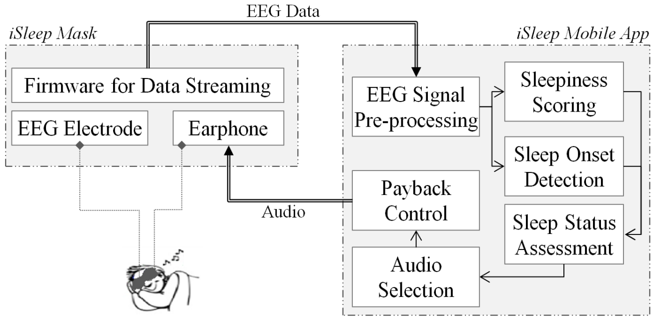

Fig. 1. **Framework of iSleep system**

raw EEG readings with electrode contact status are wirelessly transmitted to the iSleep Mobile App .

2. iSleep Mobile APP

The app is implemented and deployed to an iPhone 5S with iOS7. It communicates with the iSleep mask using bidirectional Bluetooth communication. Raw EEG readings are streamed to the app whereas the selected audio will be streamed back to iSleep mask .

The iSleep Mobile App consists of several modules. The signal pre-processing module removes artifacts from and normalizes the EEG raw data. The resulting data is then sent to the sleepiness scoring module and sleep onset detection module. The sleepiness score and sleep onset detection are then combined to assess the current sleep status.

B. Sleepiness Scoring and Sleep Onset Detection Modules

Quantifying the sleepy states of the person from his brainwave is the key leading to the selection of the most suitable audio for inducing further sleepy states.

We deploy a machine learning algorithm for sleepiness scoring. A frequency optimization method, Common Spectral Pattern (CSP), is adopted to model the brain responses to audio stimulus. The idea is to find the optimal spectral filters to maximize the separation between sleepy and non-sleepy states. A Support Vector Machine (SVM) classifier is trained to discriminate sleepy from non-sleepy status from EEG signals. The output of the classifier is a continuous parameter with range [0,1], which, represents the distance to Wake (0) and Sleep (1). We define this parameter as the sleepiness score. This module was trained and evaluated based on a previous experiment conducted on 43 subjects, each participated in a 20 minutes session where the subject listened to exciting music for 10 minutes followed by sleep-inducing audio sound for another 10 minutes. The details of EEG signal spectral feature extraction, CSP algorithm and classifier modeling can be found in [8].

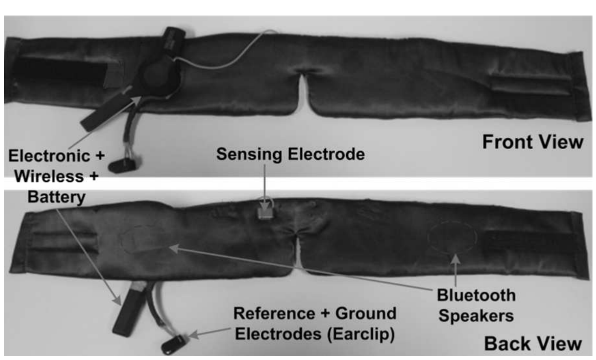

Fig. 2. **iSleep Mask Prototype**

In the sleep onset detection module, an effective rule based engine which detects sleep onset based on trends of spectral power ratio is developed. The parameters for rule based engine are fine-tuned based on a previous experiment of 40 sleep sessions conducted on 20 subjects. During the experiment both headband EEG and PSG data were recorded and sleep onsets were annotated manually by a sleep specialist. The module is able to detect sleep onset highly accurately, as reported in our previous work [9].

C. Closed-loop Sleep Inducing Process

The iSleep system adopts an innovative closed-loop approach for selecting suitable relaxing audio sound adaptively based on the sleep sleepiness score detected from EEG data.

A set of N acoustical features are pre-computed for all audio files in our audio library. The acoustical features, denoted as $\{f_n|_1^N\}$, include root mean square, tempo, brightness, roughness, Mel-frequency cepstral coefficient (MFCC), pitch, inharmonicity, key, chromagram, mode, tonal centroid and Shannon entropy etc. We then define the similarity between any two audio pieces as the Euclidean Distance in the acoustical feature space:

$$S_{ij} = \sqrt{\sum_{n=1}^{N} (f_n^{\{i\}} - f_n^{\{j\}})^2}$$

where S_{ij} denotes the similarity between audio pieces M_i and M_j, $i, j \in \{1, ..., L\}$ from the audio library which contains L audio records.

A set of parameters based on sleepiness score are calculated for a rule-based engine for audio playback controlling:

- $Mass$ - moving average of sleepiness score
- $GMass$ - gradient of $Mass$
- $SMass$ - sum of $Mass$ over a period of time T

We also defined two parameters for audio controlling:

- T_{GMass} threshold set for GMass
- T_{SMass} - threshold set for SMass

The sleep inducing process starts with the application of the iSleep mask on the subject. Once the setup is ready, the iSleep Mobile App starts to play an random selected audio piece through the headphones. Then our rule-based engine will take over the audio selection and playback control. Algorithm 1 illustrates the psudo-code of rule-based audio selection and feed.

III. Experiment and Result

A. Experiment Setting

We conduct experiment to compare the time-to-sleep between two groups of nap sessions - one with and one

```
Data: EEG, M_i|_{i=1}^{L}
current ← genRandomInt(1, L) ;
playback(M_current) ;
sleepOnset = getOnset(EEG) ;
while sleepOnset == False do
    sleepScore = getSleepScore(EEG) ;
    [Mass, GMass, SMass] =
    processScore(sleepScore) ;
    if SMass < T_SMass and GMass < T_GMass then
        S_list = sort(getSimilarity(current,L)) ;
        current = getIndex(Maximum(S_list)) ;
        playback(fadeoff) ;
        playback(M_current) ;
    else
        continue;
    end
    sleepOnset = getOnset(EEG) ;
end
playback(fadeoff) ;
```

Algorithm 1: Pseudo Code of closed loop music playback control

without audio stimulation. The experiments were conducted in a quiet and isolated sleep lab in Institute for Infocomm Research, Singapore after obtaining the approval from a local Institutional Review Board (National University of Singapore). All subjects had signed the consent form and were informed fully about the nature of the experiment. Each subject conducted two sessions of nap. In order to minimize the deviation of subject sleeping behavior due to different times within a day, the two session for each subject were arranged in the same time slot on two different days (9:30am - 10:30am, 11:00am - 12:00pm, 2:30pm - 3:30pm and 4:00pm - 5:00pm). During each session, the subject was asked to lie down comfortably on an inclined comfortable chair. With the iSleep mask covering his/her eyes, the subject was asked to relax and go to sleep. At the same time, the iSleep Mobile App was activated to start EEG recording. During the first session, audio volume was set to zero and no audio was played. During the second session, adaptive audio was played when EEG recording and analysis was started. Each session lasted 60 minutes.

Subject eligibility was evaluated before the experiment, by answering the question [Do you mind listening to the relaxation music while trying to sleep?] Only those whose answers were [yes] were considered as valid subjects. Furthermore, each subject was also advised to adhere to the following rules, failing which the session would not be conducted:

1) To have at least 6 hours of sleep the night before the experiment.
2) Not to consume any alcoholic or caffeinated drinks (e.g. coffee, tea) on the day of the experiment.

A total of 28 valid subject (16 male and 12 female, age 19 to 52) EEG data was collected for assessing the time of sleep onset and the average sleepiness score during the 1 hour nap.

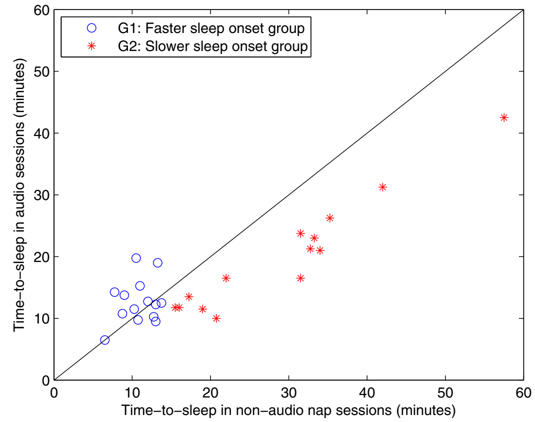

Fig. 4. **Comparing Time-to-Sleep in 2 nap sessions**

B. EEG Signal Processing

Figure 3 illustrates the signal processing of EEG data during an 1 hour nap session. The top plot shows the original EEG signal. The middle plot shows slow wave of the spectral band power ratio extracted from the EEG signal after artifacts removal. The black bar is where the sleep onset detected by our algorithm. The bottom plot shows sleepiness scores detected along overlapping sliding windows with length of 1.5 seconds. The red square marks the time point when the iSleep system detects the audio playing is not sleep-inducing for that subject, and another piece of audio file which is least similar to the current one is selected to play. We observe the sleepiness score's increment with this suitable audio stimulus introduced, following which the sleep onset is detected.

C. Comparison of time to sleep onset

Reported in a research conducted by Bishop *et al.* [10], the distribution of time to sleep onset is 13.4 ± 12.7 minutes for healthy subjects. In our experiment, however, on average it takes longer for subjects to fall in sleep, probably because the experiments are conducted during day hours.

Based on [10], we categorize the subjects into two groups depending on the sleep onset detected in the control session, e.g. non-audio sessions:

- *G1* - fast sleep onset group, $T_{onset} < 13.4$ minutes
- *G2* - slow sleep onset group, $T_{onset} > 13.4$ minutes

where T_{onset} is the time-to-sleep measured in non-audio sessions. Coincidentally, our experiment results a even number of subjects in the two group. Figure 4 shows the time-to-sleep detected for each subject during the audio session and the non-audio session. We observe that the audio stimulation helps shorten the time-to-sleep in all subjects of G2 group.

In Figure 5, the boxplots visualize the distribution of time-to-sleep detected in audio and non-audio sessions of the two groups respectively. For *G1*, no significant difference is observed between the two sessions. However, for *G2*, we observe a significant reduction of time to sleep in audio sessions. We conducted the Wilcoxon Signed Rank Test to

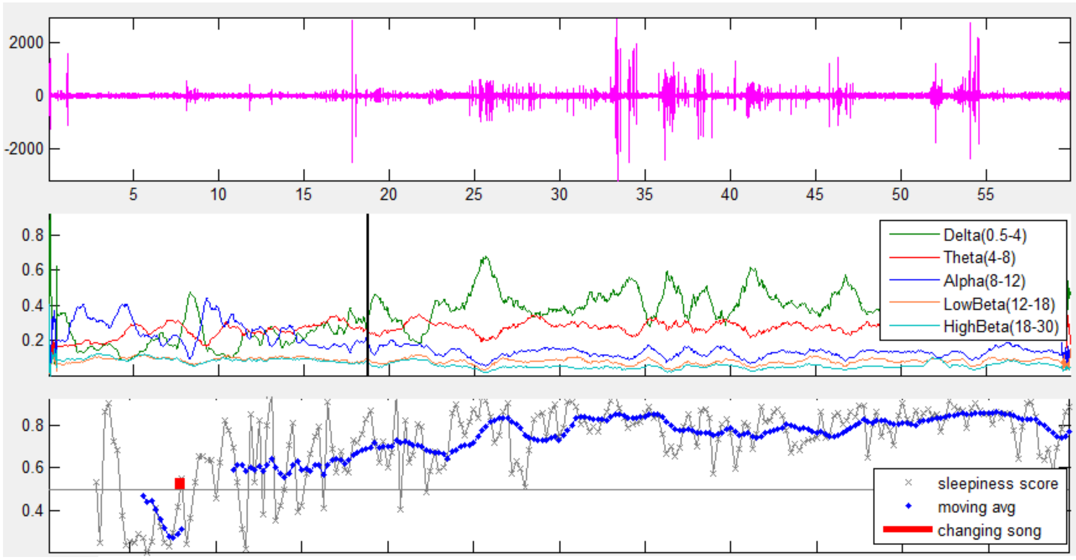

Fig. 3. **iSleep EEG signal and the processing results during an 1 hour nap audio session. Top: original EEG signal. Middle: slow wave of spectral band power ratio, the sleep onset detected is shown as the vertical black bar. Bottom: sleepiness score across the 1 hour nap**

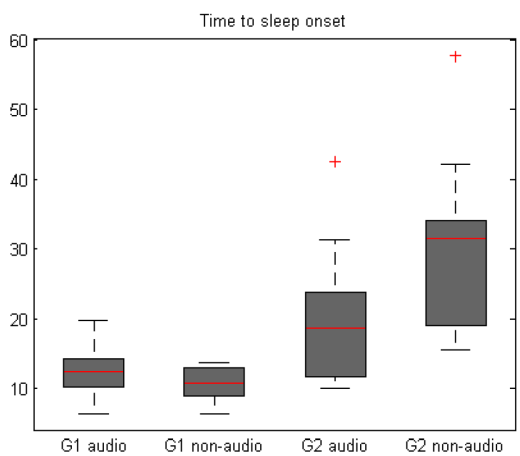

Fig. 5. **Comparison of time to sleep onset between audio and non-audio sessions. G1 - fast sleep onset group; G2 - slow sleep onset group.**

compare the time-to-sleep between the audio and non-audio sessions. For *G1* fast sleep onset group, the test yields a p-value of 0.142, indicating no significant difference found. For *G2* slow sleep onset group, the test yields a p-value of $1.22e-04$, which implies statistical significant shorter time to sleep onset in audio sessions. Such result suggests that the iSleep prototype can help those people with difficulty in falling asleep effectively.

IV. Discussion

Audio is one of the most commonly-used self-help strategies to promote sleep. As introduced in the section I, a number of sleep enhancing products or systems have been developed in recent years. The iSleep system differentiates itself from the rest by adaptively provide the appropriate audio stimulation to user, based on live analysis of his brain wave pattern. Such a 2-way feedback process allows the system taking active measures in facilitating sleep. By conducting quantitative study, we demonstrate that the innovative closed-loop sleep sensing and enhancing system, iSleep, can effectively improve nap quality in terms of reduction of time-to-sleep for the subjects who take longer to fall sleep.

The research on EEG-based audio stimulation optimization for sleep is still preliminary, and the results are not completely conclusive. Our future work will extend the experiment duration to whole night sleep, and further validate the efficacy of iSleep in extended periods of sleep in the night.

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