COMPARING AUDITORY STIMULI FOR SLEEP ENHANCEMENT: MIMICKING A SLEEPING SITUATION

Miika Leminen, Lauri Ahonen, Matti Gröhn, Minna Huotilainen, Tiina Paunio, Jussi Virkkala

Finnish Institute of Occupational Health
Brain and Work Research Center
Topeliuksenkatu 41 a A, FIN-00250 Helsinki, Finland
`firstname.lastname@ttl.fi`

ABSTRACT

Recently, two research groups have reported that the depth and/or duration of Slow Wave Sleep (SWS) can be increased by playing short sounds with approximately 1 second intervals during or prior to SWS. These studies have used sounds with neutral or negative valence: sinusoidal 1-kHz tones or short pink noise bursts. Since music therapy research shows beneficial effects of pleasant, natural sounds and music, the sounds in the experiments may have been suboptimal. Thus, we aimed at choosing optimal sounds such that they could be used in increasing the depth or duration of SWS taking into account both the need of fast rise times, short duration, and pleasantness. Here we report results of a listening test mimicking a sleeping situation in which the subjects compared how pleasant, relaxing, and image-evoking they found 3 natural, short instrument sounds with fast rise times compared to a short pink noise burst used in the previous experiments. The natural sounds were selected from our previous listening test as the most pleasant ones. The results will be used as the basis for choosing the optimal sounds for the sleep studies.

1. INTRODUCTION

There is some recent evidence that short sounds played during the deep sleep can enhance the power in the delta rhythm band of the electroencephalogram (EEG) [1, 2, 3]. Importantly, research seems to suggest that the stronger delta rhythm observed in the EEG during the stimulation with sound resulted in similar beneficial effects on memory and cognition that are observed with naturally occurring strong delta activity during sleep [3], i.e., the rhythmically presented sounds increased the memory recall. Better and deeper sleep in general is associated with cognitive and emotional benefits.

When a sound starts and reaches the outer, middle, and finally the inner ear, a series of neural events takes place. The information about the sound, its features and properties, is transferred to the different nuclei of the auditory system, giving rise to well-determined synchronous activity of the neurons in each nucleus. The characteristics of the neural activity in the nuclei depend on the sound parameters, especially the rise time, attack properties, amplitude, and the frequency content of the sound. Specifically, sounds with fast rise times and large amplitudes evoke the strongest and most synchronous neural activity. In order for a sound to evoke such clear brain activity at the thalamic and cortical level, it must be loud enough, the rise time must be fast enough (faster than at least 50 ms, preferably on the order of 5-10 ms), the sound should be preceded by a silence or a relatively quiet period of at least 200 ms, and the sound itself should contain a large selection of audible frequencies.

The neural activity evoked by sounds is not restricted to the auditory system, but has further-reaching impacts. Several areas of the brain receive input on sound-related events. For example, studies in brain responses to music have shown that large brain areas are activated by listening to music, including the areas in the somatosensory and motor systems, cerebellum, and large areas of the frontal cortex [4]. In addition, listening to sounds with a repetitive rhythm or beat, the dopaminergic areas of the brain are activated, which in turn alters the physiological status of the individual [5]. Dopamine is one of the main candidates of transferring this effect to the body [6]. It has been proposed that the basal ganglia could be an important gateway to such events, since they receive information about onsets of sounds and are strongly related to the timing of events, movements, etc. Interestingly, basal ganglia may also have a role in the process of shifting towards deep sleep and the generation of rhythmic activity in the delta range during deep sleep stages.

Since the basal ganglia play such a pivotal role both in timing the external and internal events like sound and movement, and possibly in the shift towards deep sleep and delta generation, they may be a candidate for being responsible for the effects of repetitive sound stimulation in enhancing delta activity.

During sleep, the processing of sounds in the brain differs greatly from that occurring during awake state. Several of the typical cortical event-related potentials (ERPs) are missing or appear with a slow latency and smaller or larger amplitude compared to awake state.

Sounds presented during sleep may disturb sleep and may have detrimental effects of memory consolidation during sleep. Sleeping in noisy surroundings may result in poor quality sleep and in the morning, the individual may feel less refreshed by the sleep than after sleeping in quiet conditions. There are, however, examples of positive effects of sound in the situation of falling asleep. In music therapy, for example, soft music may be used to help the patients fall asleep. Masking music or white noise is also sometimes used to help the patients fall asleep when sleeping in noisy conditions with disturbing noise like conversation. In order for the falling asleep to occur optimally and the patients to stay asleep despite the sounds, however, the sounds must be of low amplitude and subjectively very pleasant.

In addition to subjective ratings, there exist several measures of valence in physiology. For example, the activity of facial muscles is repeatedly found to be associated to valence [7]. Also, heart rate and its variability have been associated with valence. These signals provide an alternative means to study valence, and may be regarded as a more objective window to the valence of sounds than subjective ratings. Typically, the subjective ratings and the objective measurements are found to be in a good agreement. In certain conditions, however, the participants are not conscious of their own emotions. This can be achieved by for example presenting an emotional stimulus for a very short time, so that it is only processed unconsciously. Even in those cases, however, the participants show changes in the physiological signals indicating valence, even though the conscious subjective pleasant ratings cannot be used [8].

In our previous listening test [9], we compared the pleasantness of 10 short instrumental sounds with fast rise times. These sounds belonged to four instrument families: Western orchestral percussions, african percussions (kalimba), marimbas, and vibraphones. Those tests, performed in day-light in office surroundings, identified 3 most pleasant instrument sounds. Our goal here was to choose sounds that are optimal in evoking strong responses in the basal ganglia (short, loud, fast rise time, large frequency content), pleasant, evoking positive images, relaxing, and optimal in helping the subjects fall asleep or stay asleep while alone in bed in darkness.

2. LISTENING TEST

2.1. Subjectcs

We recruited 6 participants aged 29-59 years to perform the listening test. All participants had some experience in listening tests: some had previously taken part in a few listening tests, and others had a lot of experience in judging and comparing sounds at a professional level. All participants reported to have normal hearing.

2.2. Auditory stimulus selection and presentation

From our previous experiment [9], we chose those three sounds, all from different sound families, that received the highest pleasantness ratings in the listening test. We compared these three sounds to the pink noise used by Ngo et al in their experiments [2, 3]. Four sounds[1] used in the experiment are described in Table 1.

The hearing level of each participant was first tested for each of the 4 sounds separately. The presentation of each sound took 5 minutes. The sounds were presented with 1-s intervals. During the first 30 seconds, the sound pressure level was increased slowly from 0 dB HL to 20 dB HL. During the next 4 minutes, the sounds were presented at 20 dB HL. During the last 30 seconds, the sound pressure level was decreased slowly from 20 dB HL to 0 dB HL. All four sounds were presented as separate 5-minute trains during which the subject was laying comfortably on a bed in darkness but not sleeping. This presentation method was chosen to be similar to previous studies [1]. After each train of sounds was presented, the subjects put on the lights and sat at a desk answering the questions. The order of the blocks was randomized across the subjects.

[1] All sounds can be downloaded from http://www.brainworklab.fi/projects/sds

2.3. Methods

During the listening, we recorded psychophysiological data by using facial EMG and ECG.We used 2 bipolar EMG recordings for two facial muscles: corrugator supercilii above left eye, traditionally associated with negative valence (fear, anger, sadness) and zygomaticus major at left cheek, traditionally associated with positive valence (happiness), see Figure 1, [7]. The data was recorded via Enobio (Neuroelectrics, Spain) with 500-Hz sampling and offline filtered with 20-Hz highpass filter. The RMS value for each block and muscle was calculated for the whole 4-min block. Then data was normalized within subject by a subject mean over all 4 conditions in order to compare individual subject data in group level. Finally the facial EMG valence scale was built by subtracting the normalized RMS value of corrugator supercilii from zygomaticus major, and by re-scaling the measure to scale between -10 and 10, where positive values indicate positive valence, negative values negative valence and absolute size of a response is comparable between subjects as maximal within subject response is scaled to be the same (10 or -10). ECG was recorded with the same Enobio equipment with one bipolar lead. R-peaks were detected with Remlogic (Embla, Canada) software and analyzed with custom-made Matlab script and the median of R-R interval (RRI) was calculated for each subject and block.

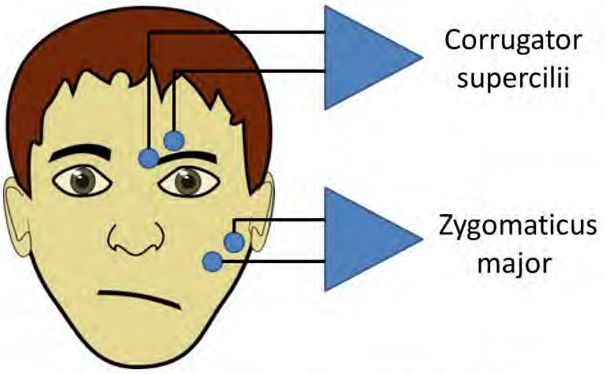

Figure 1: Placing of the facial EMG electrodes.

The participants were asked to evaluate the sound qualities during the stimulation. Our questionnaire included 6 questions for 3 subscales. Each subscale included two questions; one forward and one reversed. Subscales estimated how pleasant, relaxing, and image-evoking the sounds were found to be. Answers were given in scale of 1 to 5.

The differences between means was tested via paired-samples t-test.

3. RESULTS

The results from the behavioral evaluation, by using a combined scale with a sum of all three subscales (see Figure 2), revealed that the pink noise burst was rated significantly more pleasurable than the Kalimba and Vibrafone sound samples. To test the possible differences between marimba and pink noise, we took the three subscales separately (see Figure 3). The separate evaluation revealed a significant difference between the relaxing qualities of the two sounds so that pink noise was rated as more relaxing than marimba.

Stimulus	Description
Kalimba	African percussion instrument, Ground Note C1
Vibraphone	Vibraphone, Ground Note C2
Marimba	Marimba, Ground Note C1
Pink Noise	No Ground Note

Table 1: Description of auditory stimuliset

The results from the facial EMG electrode signals didn't reveal significant difference, which is most probably due to a small sample size and a large inter-individual variance in the signals. Visual inspection (see Figure 4) revealed that the ratings of the 3 instrument sounds and the EMG signals recorded during the presentation of the same sounds showed a high degree of concordance: high pleasantness ratings were associated with positive EMG valences. In contrast, however, the EMG results of the pink noise suggested a clearly negative valence, even though the behavioural ratings were highly positive.

No significant differences were found in the heart rate measurements between RRI medians recorded while the participants were listening to the sounds during the 4-minute intervals (see Figure 5).

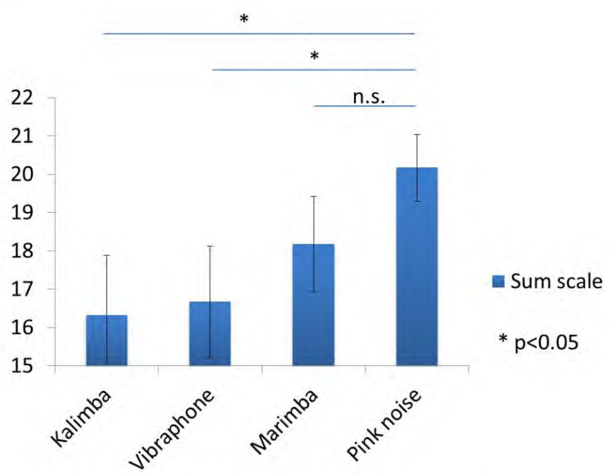

Figure 2: Sum scale (all three subscales summed) of questionnaire for all the sound samples. Significant mean differences ($p<0.05$) are marked in the figure.

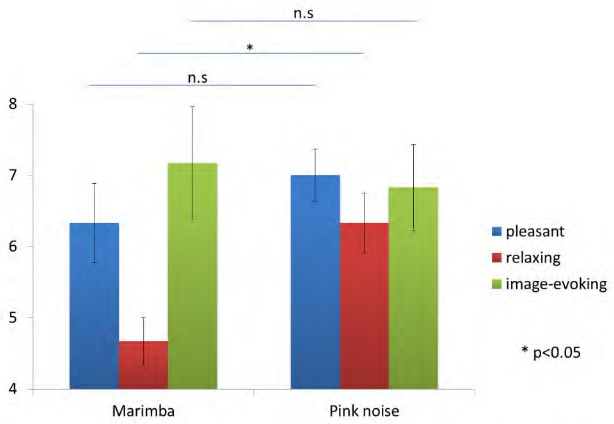

Figure 3: Behavioural subscales for the marimba and pink noise sound samples. Significant mean differences ($p<0.05$) are marked in the figure.

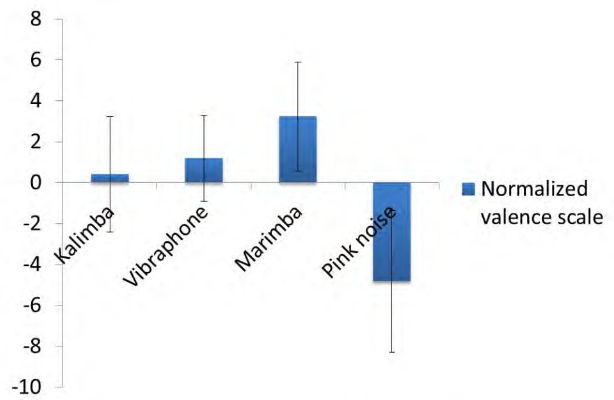

Figure 4: Normalized valence scale of facial EMG data (for details see section Methods) and standard errors for all sound samples. Positive values indicate positive valence and negative values negative valence.

4. DISCUSSION

Pleasantness ratings are highly subjective experiences. External situations like room lighting may also have effects on the experience. We wanted to bring the listening situation as close to the final use of the sounds as possible.

It is important that the sounds used for the attempt to increase the depth and/or duration of slow wave sleep are pleasant. This is especially true if the person wakes up at night with the sounds on. The sounds should evoke positive associations and images in darkness. For this reason, it is good if the person has chosen the sound him/herself and finds them pleasant and familiar. Here, we investigated the pleasantness ratings during a situation which resembled a natural sleeping situation.

Our goal was to choose sounds that are optimal in evoking strong responses in the basal ganglia (short, fast rise time), but also pleasant. In addition, we wanted to compare the sound used by Ngo et al in their successful studies [2, 3]. We expected to find the instrument sounds to be rated more positively than the pink noise. In the subjective ratings, however, the pink noise was found to be most pleasant and relaxing. The subjective ratings of the pink noise were surprisingly high, especially when compared to the instrument sounds.

Interestingly, however, we found that the physiological objective measures recorded from facial muscles revealed a different result than the subjective ratings. Within the category of 3 instrument sounds, the valence ratings from the subjective ratings and the facial muscles were in good agreement, but the results for the pink noise were contradictory. While the pink noise was subjectively rated as the most pleasant and relaxing of all 4 sounds, the phys-

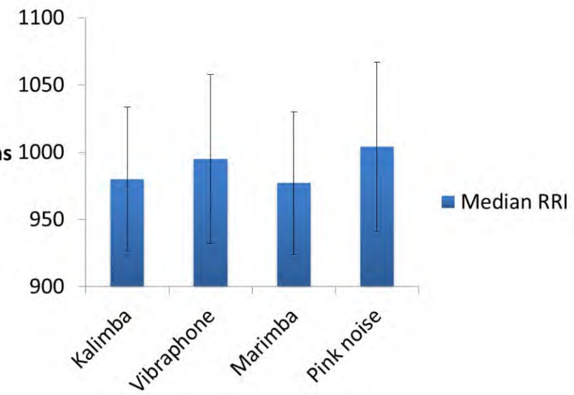

Figure 5: Group mean of median RRI and standard errors in milliseconds for all sound samples recorded during the 4-minute period while listening to the sounds.

iological signals showed strongest negative valence for the pink noise.

The discrepancy between the subjective and objective measurements is an interesting one. The good agreement in the instrument category reveals a typical result in which high pleasantness is correlated to high activity of zygomaticus major and low activity of corrugator supercilii as found in several previous studies [7]. The contradiction across the two categories, i.e., instrument sounds vs. noise burst, may reflect differential processing modes in the categories in either the subjective ratings or in the objective measures.

These findings, especially the contradiction between the subjective ratings and the physiology, are difficult to explain.. Some researchers, however, have found similar disagreements between subjective evaluations of emotions, voluntarily imagined emotions, and facial muscle activity, especially in male participants [10]. In addition, within-participant variance in the agreement may be larger in male participants [10]. To overcome the question of within-participant variance, a larger number of sounds and more repetitions would be needed. In addition, for statistical investigations, more participants would be required.

5. ACKNOWLEDGMENT

This research is funded by Tekes the Finnish Funding Agency for Technology and Innovation. We thank reviewers for their valuable feedback to this article

6. REFERENCES

[1] G. Tononi, B. Riedner, B. Hulse, F. Ferrarelli, and S. Sarasso, "Enhancing sleep slow waves with natural stimuli," *Medica Mundi*, vol. 54, no. 2, pp. 73–79, 2010.

[2] H. Ngo, J. Claussen, J. Born, and M. Mölle, "Induction of slow oscillations by rhythmic acoustic stimulation," *J. Sleep Research*, vol. 22, no. 1, pp. 22–31, 2013.

[3] H. Ngo, T. Martinetz, J. Born, and M. Mölle, "Auditory closed-loop stimulation of the sleep slow oscillation enhances memory," *Neuron*, vol. 78, no. 3, pp. 545–553, 2013.

[4] V. Alluri, P. Toiviainen, I. Jääskeläinen, M. Sams, E. Glerean, and E.Brattico, "Large-scale brain networks emerge from dynamic processing of musical timbre, key and rhythm," *Neuroimage*, vol. 59, pp. 3677–3689, 2012.

[5] A. Blood and R. Zatorre, "Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion," in *Proc. of the National Academy of Sciencs of the United States of the America*, 2001, pp. 11 818–11 823.

[6] V. Salimpoor, M. Benovoy, K. Larcher, A. Dagher, and R. Zatorre, "Anatomically distinct dopamine release during anticipation and experience of peak emotion to music," *Nature Neuroscience*, vol. 14, pp. 257–264, 2011.

[7] I. Mauss and M. Robinson, "Measures of emotion: A review," *Cognition & Emotion*, vol. 23, no. 2, pp. 209–237, 2009.

[8] U. Dimberg, M. Thunberg, and K. Elmehed, "Unconscious facial reactions to emotional facial expressions," *Psychological Science*, vol. 11, no. 1, pp. 86–89, 2000.

[9] L. Ahonen, M. Gröhn, M. Huotilainen, S. Jagadeesan, T. Paunio, and J. Virkkala, "Designing auditory stimulus for sleep enhancement," in *Proc. of the 19th Int. Conf. of Auditory Display (ICAD 2013)*, Lodz, Poland, 2013.

[10] G. Schwartz, S. Brown, and G. Aher, "Facial muscle patterning and subjective experience during affective imagery: Sex differences," *Psychophysiology*, vol. 17, no. 1, pp. 75–82, 1980.