DESIGNING AUDITORY STIMULUS FOR SLEEP ENHANCEMENT

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ABSTRACT

Recently, two research groups have reported that the depth and/or duration of Slow Wave Sleep (SWS) sleep can be increased by playing short sounds with approximately 1 second intervals during or prior to SWS sleep. These researchers have used sounds with neutral or negative valence: sinusoidal 1-kHz tones or 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 and/or duration of SWS sleep taking into account both the need of fast rise times and pleasantness. Here we report results of a listening test in which we compared the pleasantness of 10 natural, short instrument sounds with fast rise times. The results will be used as the basis for choosing the optimal sounds for the sleep studies.

1. INTRODUCTION

There is some very 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 sleep 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.

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, 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 information about sounds does not remain only in 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. [7] 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 of EEG during deep sleep stages [8].

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, we propose that they may be a candidate for being responsible for the effects of repetitive sound stimulation in enhancing delta activity in the EEG.

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 [9].

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 patients to fall asleep optimally, and to stay asleep, we believe that the sounds must be subjectively very pleasant and played with low volume.

Our goal was to choose sounds that are optimal in evoking strong responses in the basal ganglia (short, loud, fast rise time, large frequency content) and optimal in helping the subjects fall asleep or stay asleep (soft and pleasant).

2. SLEEP ENHANCEMENT

2.1. Methods

In order to accomplish the partially contradictory goals of evoking strong responses and helping to stay asleep, we chose a set of 9 percussion sounds from Logic Pro version 9.1.8 sound sample library. All sounds were cut to the duration of 500 ms with a fall time of 100 ms. One of the sound examples Orchestral percussions, was also filtered with a low-pass filter with a cut-off frequency at 1500 Hz to study the spectral effects. The sound was included in the listening test both in its original form and separately in the filtered form. Thus, the listening test included 10 sound samples.

We recruited 18 participants aged 28-58 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.

2.2. Auditory stimulus design constraints

We aimed at selecting a set of 10 sounds to be compared in the listening test. As a prerequisite for a sound to be chosen, we decided that the rise time of the sound must be 10 ms or shorter. This decision is based on the nature of variation that rise times have on sound-elicited brain responses like the event-related potentials [10]. We decided to use a collection of percussion-like instruments to maximize the pleasantness and to achieve short rise times.

3. SELECTING THE AUDITORY STIMULISET

We selected an African percussion instrument kalimba, three classical orchestral instruments, a vibraphone and a marimba from Logic Pro software including high-quality recordings of the instrumental sounds (see Table 1). The kalimba was used with two ground notes, C0 and C1, and the vibraphone and marimba were used with two ground notes C1 and C2. These levels were chosen to achieve maximal pleasantness. In addition, one of the classical orchestral percussion sounds was presented with and without a 1.5-kHz low-pass filter. Thus, a total of 10 sounds were chosen for the listening test. These 10 sounds were cut to the duration of 500 ms with a 100-ms fall-time. The original, completely natural rise times ranged from 2 to 20 ms.

4. TEST PROTOCOL

The participants were instructed to rate the pleasantness of the sounds with a scale from -5 to 5. They were instructed to picture themselves in a dark room, attempting to sleep, and having selected this sound material on the background. The participants were listening to the sounds either with high-quality loudspeakers or headphones in a typical, quiet office room. They adjusted the loudness level according to their preference. The sounds were played in series of one sound played five times presented at the rate of 0.9 Hz, that is, with a 600-ms silence between the 500-ms sounds. This presentation rate is similar to what will be used in the forthcoming experiments. The participants were instructed to play the series of 5 sounds as many times as they wished, and thereafter give their rating of pleasantness. The participants were instructed to ignore the possible, minor loudness differences between the sounds.

5. RESULTS

The results show quite systematic variations between the chosen instrument sounds as seen in Figure 1 and especially the four groups of instruments that were used as seen in Figure 2. Especially the Marimbas and the Vibraphones were found to be more pleasant while the Kalimbas and the Classical orchestral percussion instruments were found to be less pleasant as seen in Table 2.

Stimulus	Description
Kalimba 1 (K1)	African percussion instrument, Ground Note C0
Kalimba 2 (K2)	African percussion instrument, Ground Note C1
Orchestral 1 (O1)	Combination of orchestral percussion instrument
Orchestral 2 (O2)	Combination of orchestral percussion instrument
Orchestral 3 (O3)	Combination of orchestral percussion instrument
Orchestral 4 (O4)	Combination of orchestral percussion instrument
Vibraphone 1 (V1)	Vibraphone, Ground Note C1
Vibraphone 2 (V2)	Vibraphone, Ground Note C2
Marimba 1 (M1)	Marimba, Ground Note C1
Marimba 2 (M2)	Marimba, Ground Note C2

Table 1: Stimuli

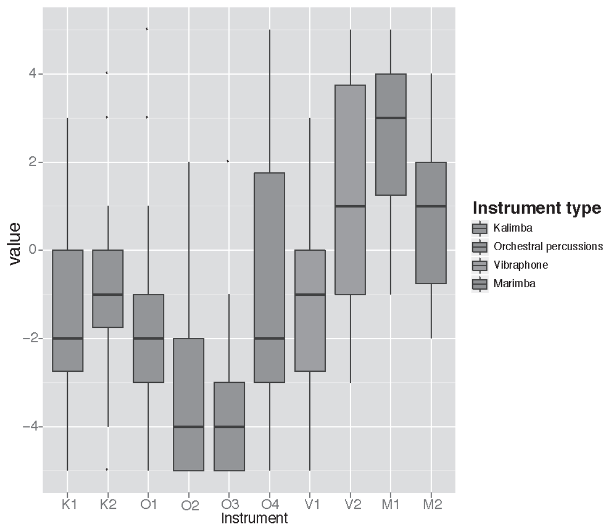

Figure 1: Boxplot of ratings for all stimuli. See Table 1 for stimulus abbreviations.

ANOVA shows significant differences between the instrument types i.e. instrument categories differ significantly from each other ($p < 0.01$). The order from least pleasant to the most pleasant is as follows: Classical orchestral percussion, Kalimbas, Vibraphones, and Marimbas. The differences between pleasantness of the sounds from the instrument groups were quite systematic on the group level, while some individuals were found to differ from the group in their ratings.

The effect of the low pass filter was not very strong. The filtered sound (O3 in Figure 1) was rated slightly less pleasant than the original sound (O2 in Figure 1).

A pairwise comparison between all pairs of instrument types was made by using the Tukey test (see Table 3) and the Kruskal-Wallis test (see Table 4). These comparisons show that several of the pleasantness ratings of the instrument categories differ from each other. For example, the ratings of Marimba instrument sounds are higher than those of Kalimba and Orchestral Percussions, and also the ratings of Vibraphone instrument sounds are higher than those of Orchestral Percussions.

Stimulus	Median	Group median
Kalimba 1	-2	-1
Kalimba 2	-1	
Orchestral 1	-2	-3
Orchestral 2	-4	
Orchestral 3	-4	
Orchestral 4	-2	
Vibraphone 1	-1	0
Vibraphone 2	1	
Marimba 1	3	2
Marimba 2	1	

Table 2: Stimulus medians and instrument group medians

	difference	lower	upper	adjusted p
Orch-Kal	-1.36	-2.62	-0.10	0.03
Vibr-Kal	1.00	-0.46	2.46	0.29
Mar-Kal	2.72	1.26	4.18	0.00
Vibr-Orch	2.36	1.10	3.62	0.00
Mar-Orch	4.08	2.82	5.35	0.00
Mar-Vibr	1.72	0.26	3.18	0.01

Table 3: Difference in Instrument groups using Tukey's ŒHonest Significant Difference method. The intervals base on the Studentized range statistics in multiple comparisons of ANOVA results.

	observed difference	critical value	statistically different
Kal-Orch	27.85	28.06	FALSE
Kal-Vibr	17.60	32.40	FALSE
Kal-Mar	48.67	32.40	TRUE
Orch-Vibr	45.45	28.06	TRUE
Orch-Mar	76.52	28.06	TRUE
Vibr-Mar	31.07	32.40	FALSE

Table 4: Multiple comparison test after Kruskal-Wallis. p.value: 0.05. Those pairs of groups which have observed differences higher than a critical value are considered statistically different at the given probability (p level).

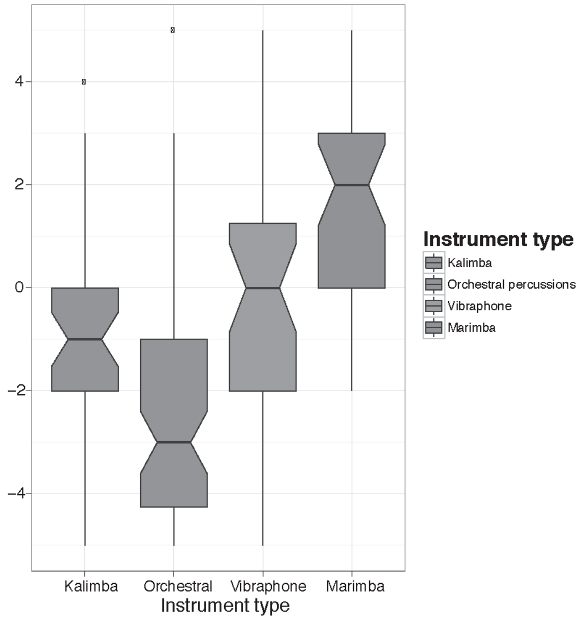

Figure 2: Boxplot of ratings for instrument groups.The notches in the box are a graphic confidence interval about the median of the sample. A side-by-side comparison of two notched box plots is the graphical equivalent of a t-test.

6. DISCUSSION

Pleasantness rating of a sound is based on an individual, subjective experience. Thus one can expect that the variations between individuals are large. There are some key aspects, however, that determine pleasant sounds. Typically, sounds with low frequency content are rated as pleasant [11], but not always [12]. Typically, pleasant sounds feature slow temporal modulations rather than prominent, rough-sounding modulations [13]. It is beneficial if the sounds used for the attempt to increase the depth and/or duration of SWS sleep are pleasant. This is especially true if the person wakes up at night with the sounds on. For this reason, it is good if the person has chosen the sound him/herself and finds them pleasant. Many of the sounds in this listening test were found to be pleasant, so they make a good candidate to be used as sounds during or prior to SWS sleep. In the forthcoming reports, the effects of these sounds presented during sleep will be reported.

Sleep affects sound processing in many ways. It has been shown that number of sleep spindles predicts sleep stability during sound stimulations [14] and similarly phase of slow oscillations determines the subcortical and cortical activation of sounds [15]. Recently sound stimulus linked to the phase slow oscillations has been linked into memory enhancement [3].

Our goal was to choose sounds that are optimal in evoking strong responses in the basal ganglia (short, fast rise time), but also pleasant.

7. ACKNOWLEDGMENT

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