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A validation study for a consumer-grade auditory-visual stimulation device

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Abstract: Self-care and improving one's well-being has been growing rapidly in recent years for manifold reasons (e.g. higher workload, corona pandemic). Consumer-grade non-invasive stimulation devices are therefore on the rise to counteract the occurrence of mood disorders and burn-out symptoms. Here, we aim at investigating the impact of dynamically varying auditory-visual stimulation patterns on neural entrainment patterns and resonance phenomena.
Twenty-two healthy volunteers (11 female, 25.4±5.1 years, one dropout, seven in control group) participated in the study. EEG data (64 channel; equidistant layout) were acquired pre- and during stimulation for each volunteer. Visual and auditory stimuli were presented via a headset (ATUM, NeuroBright; https://www.neurobright.co.uk/). Presentation patterns (frequency, intensity, spatial distribution) varied within a presentation session but were kept constant across all volunteers. Stimulus intensity was adjusted to individual comfort levels.
Individual alpha peak frequencies (iAPF) were calculated via the power spectral density with 50% overlapping 10s epochs from pre-stimulation segments. For both, the study and the control group, a time-frequency representation was calculated for the pre- and during-stimulation segments. From this, power values were determined for different frequency-bands (iAPF, stimulation frequencies and second harmonics of the latter). Statistical analyses focused on contrasting the power values between pre- and during stimulation.
Mean iAPF values were 10.25±0.99Hz for the study and 10.63±1.21Hz for the control group respectively. Both, power values at the stimulation frequencies and their second harmonics differed significantly between pre- and during stimulation (p_{stim}=0.001; p_{harm}=0.001) in the study group. No such difference was found for the control group (p_{stim}=0.352; p_{harm}=0.237). Further, neither the study nor the control group showed significant iAPF power differences (p_{study}=0.035; $p_{control}$=0.352; alpha*=0.008).
Our results suggest that lightweight, portable auditory-visual presentation devices represent an effective tool for generating entrainment and resonance effects at home. Further analyses will focus on the investigation of individual differences driving such modulatory effects.

Keywords: Photic stimulation, self care, mood disorders, alpha rhythm

1 Introduction

In current times, the importance of self-care is growing tremendously and the search for support for relaxation and mood enhancement at home increases rapidly [3].

Furthermore, a growing body of research has provided evidence, suggesting that rhythmic, auditory-visual stimulation can be linked to alterations in self-reported mental health [1]. Consequently, there has been an increased effort to provide noninvasive stimulation devices for home use (e.g. mindalive inc., Edmonton, Canada; ACTG, Minneapolis, USA).

Such non-invasive stimulation devices use a broad variety of stimulation patterns and multisensory stimulus presentation combinations. They aim to trigger entrainment and resonance effects to affect and alter brain states and/or neural oscillation patterns, and ultimately to improve mood states or memory performance [12].

Prior studies have shown, the impact of rhythmic stimulation patterns upon neural oscillations [6–8, 10, 11]. Specifically, these neural oscillations entrain to the center frequency of the presentation pattern [9, 13]. Additionally, such entrainment effects are also observed within the spectra of the harmonics of the stimulation frequency [7], i.e. the resonance effect. Ultimately, such presentation protocols affect neuronal communication across the cortex [4, 5]. Furthermore, studies have also investigated the interaction between the stimulation frequency and the individual alpha peak frequency (iAPF) [10, 11].

Here, we provided repeated exposure to dynamically varying and ethologically valid stimulus patterns. Consequently, we aim at investigating the impact of these stimulus patterns upon neural oscillations (i.e., entrainment and resonance effects).

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2 Methods

2.1 Study design

A total of 22 healthy volunteers participated in the study, seven of which comprised the control group. Participants within the study group (7 female, mean age: 24.7±3.7 years, 11 right and 4 left-handed, one drop out) received auditory and visual stimulation via a headset. Seven volunteers (control group, 4 female, mean age: 26.9±6.8 years, 6 right and 1 left-handed), received auditory-only stimulation.

Auditory-visual stimuli (auditory-only for the control group) were presented via a consumer-grade device (ATUM, NeuroBright; https://www.neurobright.co.uk/) with spatially distributed LEDs over a period of approx. 16 minutes. The stimulation session was subdivisible into constant frequency sections (fix parts) and ramps (linear rise or fall from one fix part to another). Stimulation frequencies ranged from 8 to 23 Hz, section lengths varied between 12 and 40 seconds, ramps had a duration of 3, 5, or 6 seconds. The order of the stimulation frequencies was chosen with the purpose of relaxation and recovery and is therefore not purely ascending or descending. Within one session, the same auditory and visual stimulation sequences were presented in 3 consecutive loops.

EEG recordings were performed pre- and during stimulation. We applied a 64 channel EEG cap (waveguard^{TM} original CA-212.s1, ANT Neuro b.v., Hengelo, Netherlands) with sintered AgCl pin electrodes. Electrodes were placed according to an equidistant layout. The reference electrode was integrated into the electrode array at a central position (5Z). An external droplead was used for the ground electrode at the left earlobe. Recordings were performed at a sampling rate of 8 kHz using the associated eego64 software (ANT Neuro b.v., Hengelo, Netherlands). For further processing, the recorded data were exported in raw (unprocessed) conditions.

2.2 EEG signal processing

The EEG data analysis part was essentially comprised of four main steps. All steps were performed in MATLAB (The MathWorks, Natick, MA, United States, Version R2021a) using customized algorithms and for both groups, study and control respectively. Except for the band power computation, all subsequent processing steps were performed on a channel subset of thirteen occipital channels (7Z, 8Z, 9Z, 8L/R, 9L/R, 10L/R, 4LD/RD, 5LC/RC).

First, a bandpass filter (Butterworth, 4th order, cut-off: 0.01 and 70 Hz) was applied to all segments. Bad channels were removed and spherical spline interpolated (EEGLAB, [2]) after visual inspection.

Second, with the pre-stimulation segment (resting state, eyes closed) the individual peak alpha frequencies (iAPF) were calculated. Therefore, signals were subdivided into ten second windows with 50% overlap. Power spectral density (PSD) was calculated using the fast Fourier transformation (FFT). Additionally, data were filtered using a Savitzky-Golay filter for smoothing the PSD and thus to solve the potential issue of multiple alpha peaks.

In the third step, the during-stimulation segment got divided into one-second epochs. For each epoch, a PSD (again using FFT) was calculated. A mean across all fixed frequency epochs and ramp epochs was built to determine the power distribution over the cortex in the alpha band (8 - 12 Hz) respectively.

Subsequently, in a fourth step, a time-frequency analysis was performed. First, the pre-stimulation segment was divided into three 40 second epochs. Second, the during-stimulation segment was subdivided as follows. Events for each fix stimulation were extracted containing the preceding and following ramp, as well as the ten s before and after the respective ramp (see figure 2 for an example). Spectrogram calculation was performed using the *pspectrum* function from MATLAB (for each channel from the channel subset and segment, freq. limits: 1-49 Hz).

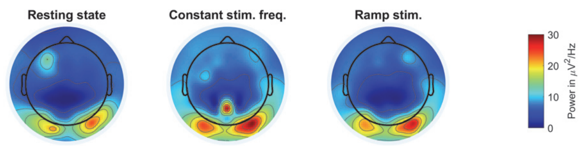

Fig. 1: Grand average alpha band power topographies across resting state (left), all constant frequency sections (middle) and all ramps (right).

2.3 Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp). To asses the impact of auditory-visual stimulation with varying stimulation patterns over a given time, the power differences between during-stimulation and pre-stimulation were compared at each stimulation frequency, the second harmonic of the stimulation frequency, and the iAPF. A Shapiro-Wilk test rejected in six out of twelve cases the hypothesis of a normal distribution.

Thus, the Wilcoxon test for paired samples was used for testing significance between groups. The significance level ($\alpha = 0.05$) was Bonferroni corrected. Subsequently, the corrected significance level was $\alpha^* = 0.008$. Violin plots (see figure 3) of the differences between the corresponding groups enabled a visual inspection of the differences.

3 Results

Peak alpha frequencies were determined for each volunteer individually. The mean iAPF for the study group is 10.25±0.99 Hz and 10.63±1.21 Hz for the control group.

The alpha band power topography is visualized in figure 1. Both, the constant sequences and the ramp sequences show increased power over the occipital cortex compared to the resting state power. The constant sequences show slightly stronger power values than the ramp sections. In figure 2 the grand average across all volunteers from the study group for one segment is shown. Here an exemplar course during a multisensory stimulation (auditory and visual) is shown. Stimulation frequencies were constant for the first 10 seconds (19 Hz), between 15 and 55 seconds (9 Hz), and for the last 10 seconds (14 Hz). Between these sections of constant stimuli, there were linear up- and down-ramps, respectively.

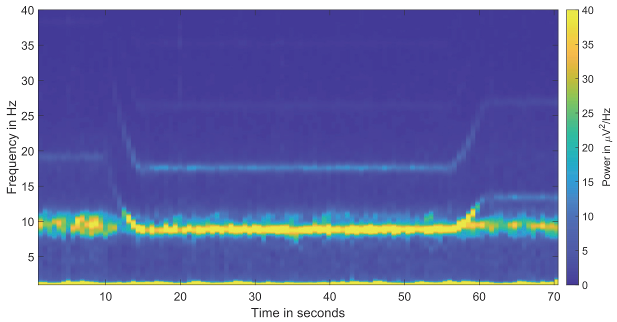

Fig. 2: Grand average spectrogram of the study group for the segment 19 - 9 - 14 Hz.

Over the entire time course, a band with increased power, approximately between 8 and 11 Hz, can be observed. Besides reactions to the auditory-visual stimulation this band shows typical intrinsic alpha activity. During the different stimulation sections, a power enhancement at the respective frequencies and harmonics can be observed. In the shown example, the strongest effect can be seen at 9 Hz stimulation. The power increase is narrowly banded around the stimulation frequency and the more distributed alpha activity is less visible.

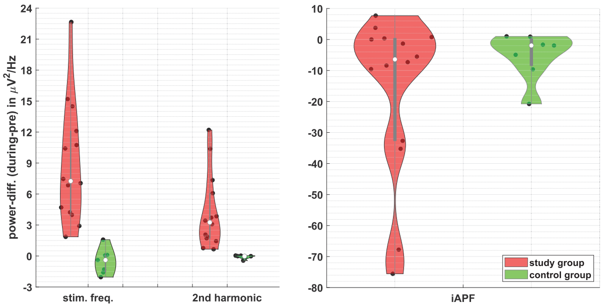

Fig. 3: Power difference between during and pre stimulation session. Grand average across all volunteers and sections. Red: study group, green: control group, points correspond to individuals. Left: stimulation frequency and harmonic, right: iAPF comparison.

Within the study group, a direct comparison of the power at different frequencies was performed. For each section the comparison was computed at the stimulation frequency itself, its second harmonic, and the individually determined peak alpha frequencies.

In the study group, the Wilcoxon test for paired samples showed significant differences between pre- and during stimulation for both, the stimulation frequency (p=0.001) and the second harmonic (p=0.001). In terms of the iAPF (p=0.035) no significant difference between during and pre-stimulation could be observed after the Bonferroni correction ($\alpha^* = 0.008$).

In contrast, none of the pre- and during stimulation segments within the control group differed significantly ($p_{stim.freq.}=0.352$, $p_{harmonic}=0.237$, $p_{iAPF}=0.352$).

Statistical results are illustrated with violin plots (see figure 3) of the differences between during and pre-measurements for the three investigated cases. For both, the stimulation frequency and the second harmonic an extended violin plot above zero can be seen. There is a change (power enhancement) from pre- to during stimulation. The green violins around zero demonstrate that these effects cannot be observed with auditory-only stimulation. The right sub-figure shows a distribution with a tendency to negative difference values. This indicates a power decrease from pre- to during stimulation. The considerable variance of the iAPF in the study group indicates individual effects, but there is no significant group effect between pre- and during stimulation, neither in the study nor in the control group.

4 Discussion

Our study aimed to investigate the effects of dynamically and ethologically valid auditory-visual stimulation compared to auditory-only stimulation. Therefore, auditory-visual stimulation with varying visual stimulation frequencies was applied over a period of 16 minutes. A control group received auditory-only stimulation over the same period of time. Power values from time-frequency representations were therefore compared at specific time points and frequency values pre- and during the measurement.

The observed peaks in the power and second harmonic at the visual stimulation frequency during our auditory-visual stimulation are in line with earlier studies [7, 10, 11]. These effects were not visible for the auditory-only stimuli. Our study used fixed frequencies unlike some previous studies where the stimulation frequencies were adjusted to the iAPF [6, 10, 11]. These studies reported the strongest power response at the iAPF. Visual inspections of our time-frequency representations suggest that frequencies close to the individual alpha peak influence brain rhythms differently compared to stimulation frequencies outside this range.

For all our stimulation frequencies a non-significant change in power at iAPF was observed. However, we observed a considerable variability in the iAPF results (see figure 3) which can be interpreted in the context of individual response differences. Such considerable individual response differences were also reported in [10]. Consequently, the band power changes will be analyzed on a single trial level for each volunteer in a subsequent step [8]. To this end, we will also analyze the ramps and sections with constant frequencies separately.

The results of the current study suggest that the new, consumer-grade auditory-visual stimulation device can entrain brain waves and lead to resonance effects.

Author Statement

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