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The Synchronized Enhancement Effect of Rhythmic Visual Stimulation of 40 Hz on Selective Attention*

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Abstract— **Rhythmic visual stimulation (RVS) has been demonstrated to modulate ongoing neuronal oscillations which might be greatly involved in attention processes and thus bring some behavioral consequences. However, there was little knowledge about the effective frequency parameter of RVS which could impact task performance in visuo-spatial selective attention. Thus, here, we addressed this question by investigating the modulating effects of RVSs in different attention-related frequency bands, i.e., alpha (10 Hz) and gamma band (40 Hz). Sixteen participants were recruited to perform a modified visuo-spatial selective attention task. They were required to identify the orientation of target-triangle in visual search arrays while undergoing different RVS backgrounds. By analyzing the acquired behavioral and EEG data, we observed that, compared with control group (no RVS), 40 Hz RVS led to significantly shorter reaction time (RT) while 10 Hz RVS did not bring obvious behavioral consequences. In addition, although both 10 and 40 Hz RVS led to a global enhancement of SSVEP spectrum in the gamma band, 40 Hz RVS led to even larger 40 Hz SSVEP spectrum in prefrontal cortex. Our findings indicate that 40 Hz RVS has an effectively enhancing effect on selective attention and support the crucial role of prefrontal area in selective attention.**

Keywords— rhythmic visual stimulation (RVS); selective attention; EEG spectrum; attention enhancement; gamma oscillations

I. Introduction

Our sensory environment is crowded with complex information which might not be all relevant to immediate purpose. When faced with this visual competition challenge, selective attention supports living organisms to quickly select relevant information and thus improves work efficiency or survival in defending against predators [1, 2]. Along with mounting studies around selective attention, there is growing support that the optimized allocation of attention resources probably profits from brain oscillations in attention-related brain networks. For example, alpha-band (8-12 Hz) oscillations could be considered as a marker of the spatial orientation of visual attention. Since it has been observed that there was enhanced alpha power in visual cortex ipsilateral to the locus of attention and vice versa for contralateral brain regions [3]. Besides, it was found that in parietal-occipital regions, there was asymmetry attentional modulation of gamma-band oscillations (> 30 Hz) which reflected both top-down and bottom-up attentional biases [4]. Electroencephalography (EEG) studies have revealed that patients with neurological disorders like attention deficit hyperactivity disorder (ADHD) might show abnormal patterns of brain oscillations, moreover, this could be strongly related with impaired level of attentional behaviors [5-7].

Owing to the supporting role of brain oscillations in attention function, researchers have been able to investigate feasible approaches to modulate selective attention externally. It is of obvious significance to the development of attention enhancement techniques and even the diagnosis or treatment of attention dysfunction. In recent years, researchers have developed various neural modulation techniques, such as transcranial current stimulation (TES), transcranial magnetic stimulation (TMS) and rhythmic sensory stimuli (RSS). As a main kind of RSS, rhythmic visual stimulation (RVS) could induce cortical neurons to respond at fundamental stimulation frequency and harmonics in the form of steady-state visual-evoked potentials (SSVEPs), which was demonstrated to be an effective tool to investigate the dynamic attentional processes because of its time- and phase-locked characteristics [8]. Such resonance-like phenomenon of endogenous neural oscillations, to some degree, could mediate relevant information processing in selective attention task and further bring behavioral consequences. However, it is worth noting that the modulating effects of RVS might vary with frequency parameter. Therefore, we required participants to perform a covert visuo-spatial selective attention task while taking different RVSs as visual surround. A spatial selective attention task including visual information processing and motor execution was commonly used to investigate the temporal dynamics of attention processes [9]. RVSs with flickering frequencies in the alpha and gamma band were employed in this task due to the prominent relation between selective attention and brain oscillations in these frequency bands [10, 11]. We hypothesized that there might exist one or more frequency parameters of RVSs which could effectively modulate attentional performance. Both behavioral and EEG trait in current task were analyzed to illustrate the potential modulating effects of RVSs on selective attention.

II. Materials and Methods

A. Participants

Sixteen healthy individuals (right-handed, aged 19 to 27 years old, including 7 males) were recruited from Tianjin

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university. All participants had normal or corrected-to-normal vision, and none of them had neurological or psychological disorders. The experimental procedures involving animal models described in this paper was approved by the Institutional Review Board at Tianjin University. All participants were given a written informed consent prior to the experiment and got paid after the experiment for their efforts.

B. Experimental paradigm and procedure

All participants performed a modified visuo-spatial selective attention task with RVS appeared around visual search array. The time course of stimulation sequence was designed as **Figure 1 (a).** Before each session, there would be a cue composed of a word cuing the executive hand (right or left hand) used to perform task and a colored dot (red or green with equal probability) on the concentric fixation cross in the monitor cuing the color of following target. After adequate preparation, participants would end this cuing period by pressing space key of keyboard and start one session. Participants were instructed to concentrate on the fixation cross throughout the experiment. At the beginning of each trial, a concentric square (edge to screen center is 5°) would appear with two small black squares (center to screen center is 3.9°) symmetrically distributed in the third and fourth quadrant of visual field. These two small boxes were used to indicate target location and the remaining area was used to display RVS background in the form of square wave. RVSs in alpha (10 Hz) and gamma (40 Hz) band and a control condition that the concentric square remained white were utilized in current study. These three different visual backgrounds would appear randomly in different trials. The flickering period would sustain for 2900 to 3200 ms. Within the last 800 ms, visual search array consisting of a distractor and a target-triangle would appear simultaneously in the center of two black box. The two triangles had opposite orientations (upward and downward) and different colors (red and green). Participants were required to covertly allocate attention to the locus of triangle with cuing color, and judge its orientation with upward and downward-pointing arrow of keyboard as quickly as possible, by using the index and middle fingers of executive hand. In different trials, target-triangle would be upward or downward with equal probability, meanwhile, appear in the left or right visual field (LVF or RVF) with equal probability (see **Figure 1 (b)**). After the displaying period of visual search array, there would be a 1000 ms interval from trial to trial for participants to blink and relax.

Experimental paradigm was presented using the Psych-toolbox 3.0 package in MATLAB software. Participants were seated 75 cm from a 27-inch monitor with a spatial resolution of 1920 by 1080 pixels. In formal experiment, all participants completed 720 trials of 20 sessions. Prior to this, they performed one or more training sessions to become familiar with task. For the purpose of investigating modulation effect of RVS on visuo-spatial selective attention, key-pressing behavior, and EEG data of all participants in formal experiment were recorded for following analysis.

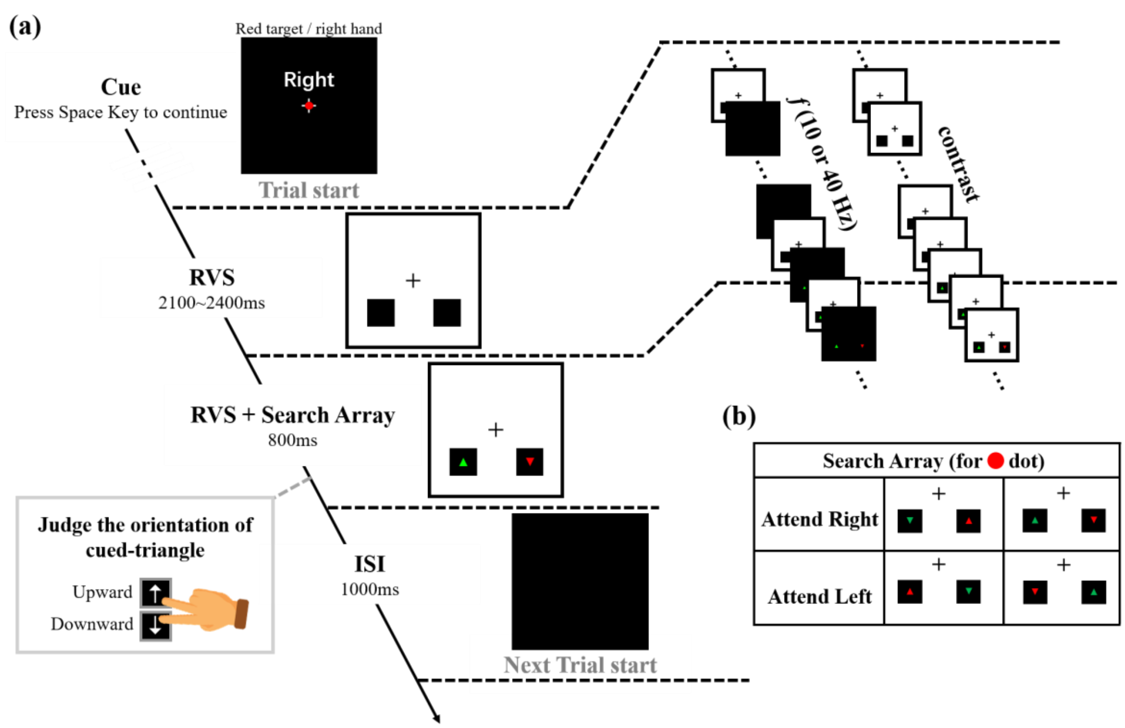

Figure 1 (a) Experimental stimulation sequence. (b) Example of cuing red triangle as target. There are four possible types of search array including attending target in RVF versus LVF and responding with upward versus downward key.

C. Experimental paradigm and procedure

The EEG signals were acquired by a Neuroscan Synamps2 system with a 60-channels scalp based on the international 10-20 system. The EEG sampling rate was set at 1000 Hz. A bandpass filter ranging from 0.01 to 100 Hz and a notch filter at 50 Hz were utilized to remove baseline wander, high-frequency noise and power frequency interference online. The electrode site between CZ and CPZ was regarded as reference. Eye movements and blinks were monitored by a pair of horizontal electrooculogram (HEOG) channels placed at the left and right outer canthi and a pair of vertical electrooculogram (VEOG) channels placed above and below the left eye.

In offline pre-processing, the raw EEG signals were filtered by a Butterworth third-order bandpass filter ranging from 1 to 50 Hz. Then we carried out two removal operations on the EEG data. On the one hand, for trials with wrong response or manual reaction times (RT) were not in the range of 200 to 800 ms (including no key-pressing reaction), removal measures were taken. On the other hand, to minimize eye movements' impact on EEG data, trials with HEOG fluctuations in the top 10% were removed. Subsequent data analysis was entirely based on trials after above preprocessing operations.

D. Data Processing and Analysis

1) Behavioral analysis

Despite that the spatial location of target-triangle was unrelated with orientation discrimination, stimulus-response compatibility effect might influence task performance in spatial selective attention [12]. Therefore, we instructed participants to perform the attention task with both hands and combined 2 executive hands conditions in the following analysis. Grand-averaged RTs and detection accuracies were computed for 3 RVS conditions (0: control group; 10: 10 Hz RVS; 40: 40 Hz RVS) respectively. A three-way repeated measure analyses of variance (ANOVA) was applied to investigate the influence of RVS backgrounds on task performance estimated by RT and detection accuracy.

2) EEG spectrum analysis

We concentrated on the displaying period of visual search array to investigate RVS modulation on brain activities following target onset. Therefore, the preprocessed EEG data was segmented into epochs of 900 ms, from 100 ms before onset of search array to 800 ms after. The initial 100 ms was used to perform baseline correction. For a better understanding of the modulation effect of RVS on attention-related brain oscillations, fast Fourier transform (FFT) analysis, which enabled the calculation of the intensity of amplitude spectra in a specific frequency band [13], was applied to the segmented EEG epochs of three RVS conditions respectively to obtain the scalp EEG amplitude spectrum. A paired t-test was applied to test the differences of EEG amplitude spectrums among multiple conditions.

III. RESULTS

A. Behavioral results

Figure 2 showed the grand-averaged RTs and detection accuracies of all participants in control, 10 Hz and 40 Hz RVS conditions. In formal experiment, on average, participants responded 86.3% ± 0.5% (mean ± standard error) of all trials effectively. Statistical analysis revealed no significant difference in detection accuracies among multiple conditions. Interestingly though, there was a significant main effect of RVS frequency on RTs ($F (2, 30) = 11.529$, $p < .000$, $\eta 2 = .435$). Specifically, compared with control group (539.96 ± 12.11 ms), 40 Hz RVS led to significantly shorter RTs (533.76 ± 11.43 ms) while 10 Hz RVS (541.54 ± 11.63 ms) did not impact the speed of visuo-spatial information processing significantly. The above observations indicated that RVS background can impact task performance in selective attention. Moreover, the modulation effect was correlated with the frequency parameter of RVS backgrounds.

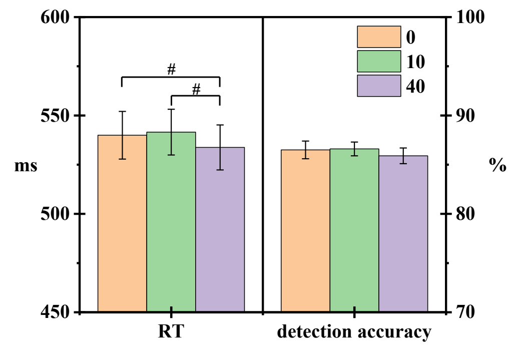

Figure 2. Grand-averaged RTs and detection accuracies in 3 RVS backgrounds conditions. The mark "#" indicate significant differences between two RVS conditions linked by a square bracket (p<0.01 after Bonferroni correction, estimated by one-way ANOVA)

B. EEG spectrum

The EEG amplitude spectrums at alpha (10 Hz) and gamma (40 Hz) frequency point were shown as **Figure 3**. From a topographic perspective, comparing to control group, the brain underwent a global modulation effect on the 10 Hz amplitude value in 10 Hz RVS condition. Regarding 40 Hz amplitude value, both 10 and 40 Hz RVS led to higher 40 Hz amplitude value in posterior brain regions. Furthermore, comparing to 10 Hz RVS condition, the amplitude modulation induced by 40 Hz RVS also appeared in anterior brain areas.

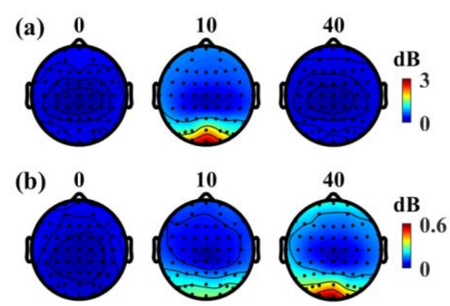

Figure 3 The topographic distributions of EEG amplitude spectrum at (a) 10 Hz and (b) 40 Hz frequency point.

To further illustrate the difference of EEG spectrum between 10 Hz and 40 Hz RVS condition, we put emphasis on the EEG spectrum of channel FPZ and OZ. As shown in **Figure 4**, for channel FPZ, compared with control group (0.07 ± 0.02 dB), 40 Hz RVS condition (0.21 ± 0.03 dB) induced a remarkably larger 40 Hz amplitude value ($T (15) = -4.775$, $p = 0.000$) of EEG spectrum. It's worth noting that there was also slight difference between control and 10 Hz RVS group (0.10 ± 0.02 dB, $T (15) = -2.111$, $p = 0.052$). For channel OZ, the 40 Hz amplitude for 10 Hz RVS condition was 0.24 ± 0.03 dB, which was slightly less than 40 Hz RVS condition (0.46 ± 0.11 dB) even though there was no significant difference between them ($T (15) = -1.974$, $p = 0.067$).

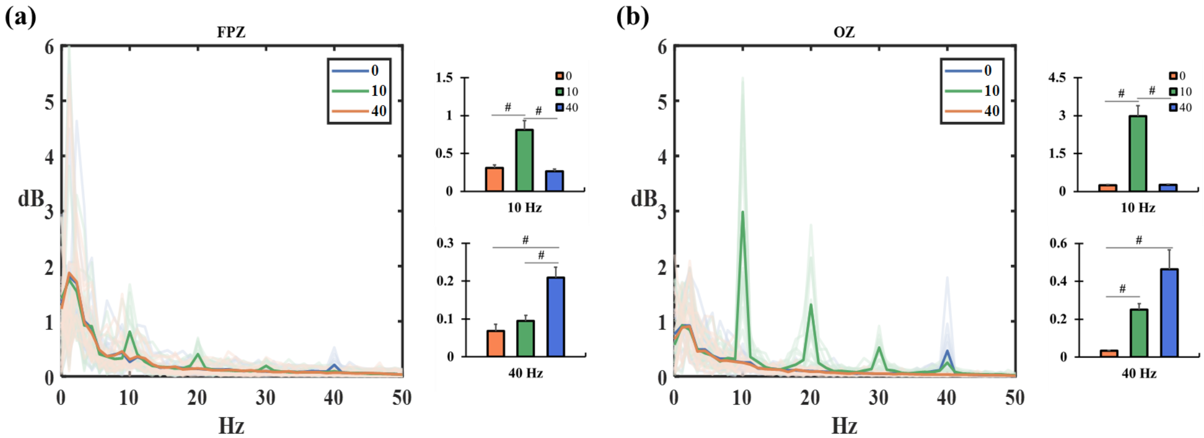

Figure 4 EEG amplitude spectrums of three RVS conditions obtained from (a) channel FPZ in anterior cortex and (b) channel OZ in posterior cortex. The light lines in the left column of each sub-figure represent the SSVEP spectrums of every single individual. The histograms in the right column of each sub-figure show the amplitude values at 10 Hz (top) and 40 Hz frequency point (bottom).

Associated with behavioral outcomes, these findings indicated that higher 40 Hz amplitude might correspond to faster information processing speed because of the close relationship between gamma oscillations and enhanced attention ability [14]. However, 10 Hz RVS made no contribution to this behavior advantage despite there was also higher 40 Hz amplitude. This is most probably because 10 Hz RVS also led to higher 10 Hz amplitude which was always thought to correspond to selective cortical inhibition [15]. Besides, the attention processes involved in current study was comprehensive and required multiple brain regions' cooperation. Thus, there are still many studies needed to illustrate the inner correlation between RT performance and attention-related brain oscillations.

IV. Conclusion

In summary, by treating different RVSs as visual backgrounds of selective attention task, we have investigated the effective frequency parameter of RVS in modulating attentional performance. Behavioral analysis revealed that 40 Hz RVS had a remarkable promotion effect on the processing speed of target discrimination. However, 10 Hz RVS did not bring such enhancing effect and even brought slight counter-effects to the RT performance, which demonstrated that RVSs could modulate attention-related performance with effective but totally diverse effects. In addition, compared to control and 10 Hz RVS conditions, we found significant higher amplitude of 40 Hz SSVEP in frontal and occipital cortex, which might be essential for target discrimination in selective attention. We suggest that these novel findings can serve as a guide for attention enhancement researches with RVS in gamma band.

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