Neural suppression of distractors surrounding the spotlight: Evidence from steady-state visual evoked potentials

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Received December 6, 2011; accepted January 18, 2012; published online March 22, 2012

The present study investigated the allocation of spatial attention using steady-state visual evoked potentials (SSVEPs). The SSVEP is elicited in visual cortical areas by a repetitive flicker having the same fundamental frequency as the driving stimulus. Two flickers were applied with the letter stream presented in the center of the monitor and the distractor presented on either the left or right side of the target. Participants were instructed to detect the target letter in the letter stream. The distance of the two flickers was manipulated. The results show that the amplitudes of the SSVEPs elicited by the distractor were enhanced when it was in the closest position and suppressed when it was at a farther distance. But the amplitudes rebounded at the farthest distance. Meanwhile, the SSVEP elicited by the target flicker remained stable independent of the distance of the distractor. Thus, the present study indicates that focused attention involves neural suppression surrounding the classic “spotlight”, and the SSVEP paradigms open new avenues for studying the attentional suppression mechanism.

steady-state visual evoked potential, spatial attention, neural suppression, spotlight

Citation: Zhao J B, Zhang Z J, Zhang C, et al. Neural suppression of distractors surrounding the spotlight: Evidence from steady-state visual evoked potentials. *Chin Sci Bull*, 2012, 57: 1680–1684, doi: 10.1007/s11434-012-5078-2

There are limitations to the capacity of the visual system to process multiple objects at any given moment. To obtain an accurate perception of the target object, visual attention needs to select relevant information and filter out the distractors. For decades, allocation of attention to a spatial location has been considered as analogous to a spotlight [1,2] or a zoom lens [3]. Both metaphors suppose neural enhancement or behavioral facilitation within the focus of attention and a monotonic decrease of the enhancement from the center of the attended location. But accumulating evidence indicates that attention operates through cooperative enhancement and suppression [4,5]. A number of behavioral and neural studies demonstrated that attending to a spatial location results in suppression surrounding the focus of attention [6–9]. Specifically, larger inhibitory effects were observed at spatial locations close to an attended focus than distant from it. The suppression effects were found

only when distractors were presented—not at empty locations. The spatially organized combination of enhancement and suppression may sharpen the relevant information from distractors. Yet, only a few studies have investigated the role of the suppression effect in the classic “spotlight”. Moreover, the interaction of central enhancement with surrounding suppression still remains to be clarified because the suppression effects surrounding the focus attention were also affected by sensory input in the unattended location [10].

Here, we employed steady-state visual evoked potentials (SSVEPs) to investigate deployment of spatial attention. The SSVEP is an electrical response of the visual cortex to a flickering stimulus. It has a nearly sinusoidal oscillatory waveform with the same fundamental frequency as the driving stimulus. The amplitude of the SSVEP is greater in response to the flickering stimulus at attended locations than unattended ones [11]. The SSVEP modulations are attributed to a sensory gain mechanism that amplifies the signal-to-

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noise ratio within the spotlight [11,12]. Hence, the SSVEP provides an objective electrophysiological tool to investigate the attentional resource allocation in both the attended and the unattended location concurrently. In the present study, two flickers were applied with a target presented in the center of the monitor and a distractor presented at either the left or the right side of the target. We supposed that the amplitude of the SSVEP elicited by the distractor flicker would be suppressed some distance away from the attended focus because there was a narrow suppression zone around the “spotlight”.

1 Methods

1.1 Participants

Twelve right-handed students (6 females, ages 21–28) participated in the study after giving informed consent. All had normal or corrected-to-normal vision.

1.2 Stimuli and procedure

Two gray squares appeared on a 21-inch CRT monitor (800×600 pixels; vertical refresh rate, 85 frames/s) against a white background. One square was presented in the center of the monitor, and the other square (peripheral) was presented on either side of the central square. Each square subtended a viewing angle of $1.5^\circ \times 1.5^\circ$. The distance of the two squares was manipulated with viewing angles of 0.9° , 1.8° , or 3.1° (D1, D2, or D3). The sequence of letters was presented in the central square (“A”–“G” with “E” as the target letter). Each letter was presented for 188 ms with no stimulus interval for a total stream length of 3008 ms. The letters were displayed in Arial font and subtended a viewing angle of $1.1^\circ \times 1.1^\circ$. The frequencies of 9.44 Hz (5 frames on and 4 frames off) and 12.14 Hz (4 frames on and 3 frames off) were used.

Participants were seated 80 cm in front of the monitor. As depicted in Figure 1, each trial began with the onset of a fixation cross, which appeared at the center of the screen for

500 ms. After two gray squares were presented for 800 ms, both of them began to flicker in different frequencies (9.44 Hz for the central square and 12.14 Hz for the peripheral square) for 3008 ms. Participants were instructed to press the space bar whenever they detected the target letter “E”. The next trial began after a 1-s delay. For each trial, the distractor letters were presented randomly. In the 75% trials, the targets appeared either once or twice randomly. The remaining 25% trials were catch trials in which no target was presented. Targets were not displayed in the first or last 500 ms of the stream presentation and were displayed with a minimum inter-target interval of 940 ms. Participants were instructed to attend to the central square and responded by pushing the space bar with the index finger of the right hand.

Each participant was tested in four blocks, and each block contained 48 trials. In each block, the distance of two squares (D1, D2, or D3) and the location of the peripheral square (either the left or right side of the central square) were presented randomly and equally.

1.3 SSVEP recording and analysis

Brain electrical activity was recorded from 10 scalp-site electrodes mounted in an elastic cap (Fz, FPz, Cz, POz, PO3, PO4, Oz, O1, O2, and right mastoid of the international 10–20 system). They all referenced to the left mastoid. Eye blinks were monitored with a bipolar montage positioned above and below the left eye. The horizontal electrooculogram was recorded with a bipolar electrode located on the left and right canthi. Electrode impedance was kept below 5 k Ω . The band pass of all electrodes was 0.05–100 Hz. All data were digitized at 250 Hz and stored on disk for offline analysis.

The epochs were 3008 ms from flickering onset. The blinks or other artifacts exceeding 75 μ V each epoch contained were excluded from further analysis. The averages of artifact-free epochs were algebraically re-referenced to averaged mastoids. Averages were then digitally filtered by 30 Hz low-pass filters.

The SSVEP amplitude was calculated by means of complex demodulation of the averaged epochs, which was equal to base-to-peak amplitude of the SSVEP [11,13]. The analysis selected a center frequency of 9.44 or 12.14 Hz for different flickering stimuli respectively. To avoid a visual evoked response to flickering onset in the SSVEP measurement, the first 500 ms of the epochs were excluded from our analysis.

1.4 Statistical analysis

Reaction times for three distances were submitted to an analysis of variance. The effect of attention on the SSVEP amplitude was analyzed by a repeated-measures analysis of variance with the factors of distance (D1, D2, or D3) and electrodes for target and peripheral locations separate.

Figure 1 Example sequence of events for the experiment.

2 Results

2.1 Behavioral data

Trials with incorrect responses (1.6%) and reaction times faster than 200 ms or slower than 1000 ms (3.3%) were excluded from reaction time analysis. There was no significant difference among the three distance conditions ($F(2,22)=1.35$, $P=0.28$; D1, 424.46 ± 44.90 ms; D2, 420.32 ± 46.02 ms; D3, 423.76 ± 47.61 ms).

2.2 SSVEP data

Figure 2 shows the waveforms of the SSVEPs from a representative participant. The waveforms were moving-window averages over 370 ms and thus included a 3.5 cycle of 9.44 Hz or a 4.5 cycle of 12.14 Hz [13,14].

The amplitudes of SSVEPs elicited by central and peripheral squares were analyzed respectively. Figure 3(a) shows the averaged amplitudes of the SSVEP elicited in the central location (9.44 Hz). There was no statistically significant effect of distance ($F(1,11)=0.51$, $P=0.61$). The effect of electrodes ($F(5,55)=4.61$, $P<0.01$) was significant with the largest amplitude elicited in the electrode of O1. The interaction between distance and electrodes ($F(5,55)=0.97$, $P=0.48$) was of no significance. These results indicated that the distance of the distractor could not affect attentional deployment in the attended location. For the peripheral location as

depicted in Figure 3(b) (12.14 Hz), the main effect of distance was of significance ($F(1,11)=14.73$, $P<0.01$). In detail, the amplitude was suppressed in D2 when compared with D1 ($t(11)=3.46$, $P<0.01$) and D3 ($t(11)=3.29$, $P<0.01$), and no significant difference was detected between D1 and D3 ($t(11)=1.23$, $P=0.24$). The amplitude of SSVEP for each condition was of significance across electrodes ($F(5,55)=6.49$, $P<0.01$). The interaction of distance and electrode location was not significant ($F(5,55)=1.27$, $P=0.26$). Thus, we observed a suppression of the SSVEP in the adjacent location (1.8°) when compared with the closest and farthest location, demonstrating a narrow inhibition surrounding the attended stimulus, whereas the SSVEP in the attended location remained stable.

3 Discussion

In the present study, we investigated the distribution of spatial attention using the SSVEP, which allowed us to analyze cortical activities in central and surrounding locations concurrently. The amplitude of the SSVEP elicited by peripheral distractors was enhanced when they were closest (0.9°) to the attended location and was suppressed when they were set 1.8° away from the target location. However, the amplitude rebounded in the farthest location (3.1°). The results are consistent with the study of Müller et al. [9]. In their

Figure 2 Steady-state visual evoked potential recorded from a representative participant. Recording shown is from occipital electrodes, all referenced to averaged mastoids.

Figure 3 Amplitude of the SSVEP elicited by (a) central and (b) peripheral squares.

study, the flanker effect was largest when the distractor was closest to the target letter and was not observed when placed a bit far away. Moreover, the effect was again visible when the distractor was placed farther. The suppression effect found by the SSVEP confirmed that there was a zone of suppression surrounding the central region of attention [6,10]. The result also indicated that the distribution of spatial attention with surrounding suppression can be sustained for periods because the SSVEP reflected continuous brain activities. In contrast, the SSVEP of the attended location remained stable and was not affected by the distance of peripheral distractors.

The suppression effect observed in the present study could not be because of the task demand. Although the participants were instructed to maintain attention to the central location, which might cause inhibition of the distractor actively, the enhancement effect was found as the distractors presented closest to the attended focus. But the distance between the suppression zone and the attended focus could be affected by task difficulty and the amount of attentional resource. The narrow zone of suppression was 1.8° in the present study, 1.35° in the flanker task [9], and 2.5° in the visual search task [7]. The more tasks needed processing resources, the stronger attention focused. As a result, the zone of suppression was changed correspondingly. But additional experiments, in which a similar task is employed and only difficulty is manipulated, should be conducted to explore the phenomena further.

The suppression of unattended stimuli in the present study conforms with the biased competition theory of attention [15,16]. The theory suggests that multiple stimuli compete for neural representation in the visual cortex, and the competition can be biased by top-down and bottom-up mechanisms. Attention could eliminate the competition among multiple stimuli by counteracting the suppressive influences of nearby stimuli, thereby enhancing information processing in the attended location. In other words, spatial attention counteracts suppression induced by nearby stimuli.

So, the theory implies that neural enhancement of the attended stimuli may be independent of the distance of the distractor. In the present study, the amplitude of the SSVEP induced by attended stimuli remained stable regardless of the distance of the unattended stimuli.

In conclusion, the present study indicates that focused attention involves the operation of neural enhancement and neural suppression concurrently. The findings also imply that neural enhancement of attended stimuli and suppression of unattended stimuli may cooperate in an independent way. Moreover, the SSVEP paradigms open new avenues for studying the attentional suppression mechanism.

This work was supported by the Zhejiang Provincial Natural Science Foundation of China (Y207527).

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