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Early ERP effects on the scaling of spatial attention in visual search

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Abstract

This article describes the examination of the spatial ‘scaling’ effect of visual attention with the technique of event-related potential (ERP). Eighteen participants were involved in a visual search task in which the cue-target paradigm was used. The search array was three concentric circles consisting of randomly selected English letters that were equally distributed in each circle. The behavioral and ERP data were recorded, respectively. The behavioral results showed that the response time increased and the response accuracy decreased with the increase of precue size. The ERPs amplitude of P1 and N1 components evoked by search array increased with the reduction of precue size. However, the latencies of these ERP components did not show significant differences between conditions. The hierarchical data of both behavioral assessment and ERPs provided evidence for the spatial ‘scaling’ effect of visual attention. The amplitudes of P1 and N1 components may be used as indices to examine the effect of spatial ‘scaling’. In different tasks, the display-set size of stimuli and the task complexity may be important factors that affect the attention allocation.

Keywords: Visual search; Spatial attention; ‘Scaling’ effect; Event-related potential

1. Introduction

In the 1980s, Posner used the classic ‘cue-target’ paradigm to investigate the allocation of attention in visual space. Besides the behavioral result which proved that the target detection in attended areas is faster than that in unattended areas, most importantly, he also provided evidence from event-related potentials (ERPs) demonstrating that the amplitudes of early components of visual attention (P1 and N1) evoked by validly cued targets are larger than those evoked by invalidly cued targets [1,2], which has been supported by other studies during the following years [3,4]. This attention effect of visual space is considered as ‘spotlight’ [5], which facilitates the processing of all stimuli that fall within the attended region [3]. If the ‘spotlight’ effect describes the attention allocation between attention and inattention, the ‘zoom-lens’ model proposed by Erikson and St. James will describe the spatial ‘scaling’ effect under attended condition, which considers that people can dynamically adjust their attention, extend or contract, according to the objects or tasks [6]. Greenwood and his colleagues [7,8] set a series of attention scope with different sizes in their experiments. Through comparing the behavioral data of visual searching within different attention scopes, they drew the conclusion that the size and density of visual attention might adjust according to the task demand. They called this effect the ability of ‘scaling’.

Since 2001, a series of ERP studies have been conducted by our group to investigate the underlying mechanism of attention ‘scaling’ effect in visual space. Luo et al. [9] divided the attentional space by three different cue sizes, which were large, medium and small, respectively. In their experiment, subjects were asked to search for the target

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stimuli within the area indicated by precue. The result showed that the amplitudes of P1 components increased whereas the N1 amplitude decreased with the increase of the attentional scope. They concluded that the increase in P1 amplitude reflected the ‘additional computations’, whereas the decrease in N1 amplitude might reflect a broadening of the spatial gradient of attention. Since the precues were presented randomly in different locations during this experiment, this result could be confounded by the random spatial location. In the following studies, the location of precue presented was fixed in order to purify the spatial ‘scaling’ effect of visual attention. Results from these following studies suggested that spatial ‘scaling’ effect was reflected by the amplitudes of P2 and N2 components, rather than P1 and N1 components [10]. The problem in these studies was that the attentional scopes could not be divided clearly, that is, subjects could well search for target stimuli ignoring the indication of precues. This might be the reason why ‘scaling’ effect did not show among early ERP components in their studies. Following them, Song et al. [11,12] used randomly selected English letters composing three concentric circles as the search arrays in their experiments to improve the indication of precues. Subjects were asked to search for a target letter among other non-related letters within the indicated scopes. The results showed that spatial ‘scaling’ effect of visual attention was reflected by the amplitudes of P1 and N1 components. In their experiments, the amplitudes of P1 and N1 components increased with decreased attentional scope. They considered this effect as facilitation for visual processing under more valid indication of precue, that is, with the decrease of attentional scope, the validity of indication by precues increased, which facilitated the input of visual sensory signals. As a result, the amplitude of the P1 component increased. However, this result is inconsistent with Luo’s studies in the P1 amplitude effect. Recently, Fu et al. [13] divided attentional scopes into two grades, and got similar results with Song’s studies in P1 amplitude effect. Therefore, it is necessary to conduct further studies to investigate the underlying mechanism of attention ‘scaling effect’ in visual space.

In Song’s studies, the stimuli were distributed differently in three concentric circles. In the present study, the search arrays were three concentric circles with randomly selected English letters equally distributed in each circle. The precues were circles that were equal to search arrays in size. The behavioral data and ERPs evoked by both precues and search arrays were recorded, respectively. We expected further understand about the mechanism of visual spatial attention based on the comparison with previous studies.

2. Method

2.1. Subjects

Eighteen students (8 male and 10 female) ranging in age from 19 to 24 years (mean 21) from the Chinese Agricultural University participated as paid volunteers. All subjects were healthy, right-handed, and had normal or corrected to normal vision. All of them were first-time participants in an electroencephalogram (EEG) experiment.

2.2. EEG recording

The EEG was recorded by the NEURO SCAN recording system with 64 channeled scalp electrodes. The electrodes’ distribution was set according to the international standard 10–20 sites system. The references were placed on mastoid of both sides. The vertical and horizontal electrooculogram (EOG) was recorded at the same time. Horizontal eye movements (HEOG) were monitored by placing two electrodes lateral to the left and right orbits. Vertical eye movements (VEOG) and eye blinks were measured by placing two electrodes 1.5 cm below and above the left eye. The impedances of all electrodes were maintained below 5 kΩ. The EEG from each electrode site was digitized at 500 Hz and was filtered with a band-pass of 0.05–100 Hz.

2.3. Stimuli

All stimuli were presented on a 14-in. monitor. A search array was preceded by a precue that indicated the subsequent target location. A white cross located in the center of the screen was used as fixation. As shown in Fig. 1, the precue was a circle with three sizes, which were small (2.9°), medium (5.7°), and large (8.6°), respectively. The search array was three concentric circles composed by randomly selected English letters, which were distributed equally in each circle, i.e., the distance was equal between every two adjacent letters in the same circle. Eight, 16 and 24 letters were distributed in the small, medium and large circles, respectively. The target was a letter ‘T’ located in one of the three concentric circles among other letters.

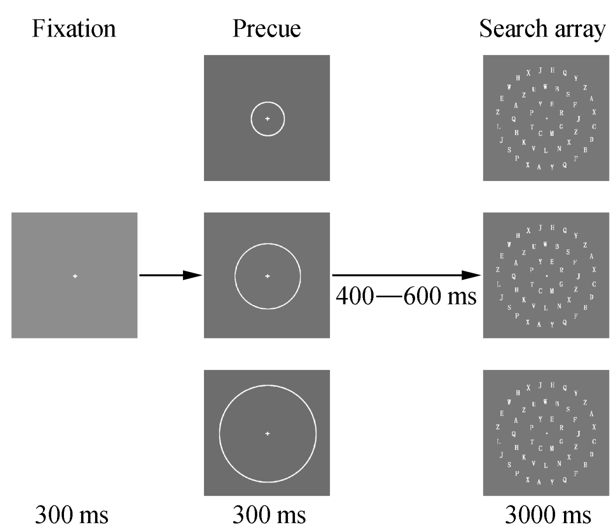

Fig. 1. The procedure and stimuli.

For the small precue size, the target 'T' only appeared in the small circle. For the medium precue size, the target 'T' could appear only in the small or medium circle. For the large precue size, the target 'T' could appear in any one of the circles. The precues were always of the same size as the search arrays. The background was black, and the fixation, precues, and search arrays were all white.

2.4. Procedure and task

Following presentation of the fixation for 300 ms, one of the three precues appeared randomly for another 300 ms. When the precue disappeared, after an interval varying from 400 to 600 ms, the search array was presented for 3000 ms to ensure that subjects had enough time to complete the searching (Fig. 1).

During the interval between two trials, a black background was presented. Subjects were asked to search for a letter 'T' among other non-related letters within the precued area, and to make a response as fast as possible by pressing the left key using their left index finger when letter 'T' appeared on the left side of the screen or pressing the right key using their right index finger when letter 'T' appeared on the right side of the screen. The probability of letter 'T' appearing on the left or right side of the screen was balanced. Ten-percent trials in which letter 'T' appeared nowhere in the search array were used as a control mechanism to check whether subjects completed their task seriously. The data showing that subjects responded strongly to these no-'T' trials were excluded from further analysis. These trials themselves were also excluded from the data prior to analysis.

2.5. Data analysis and statistics

E-Prime and SCAN software was used to present stimuli and to record and analyze behavioral and EEG data. Prior to averaging the EEG, trials with EOG artifacts (mean EOG voltage exceeding $\pm 80\ \mu V$) and those contaminated with artifacts due to amplifier clipping, bursts of electromyographic (EMG) activity, or peak-to-peak deflection exceeding $\pm 80\ \mu V$ were excluded. ERPs for the precues and search arrays were averaged from the time point of their onset. A 1100-ms epoch including a 100-ms pre-stimulus baseline was used for average. Peak-to-peak detection for amplitudes and latencies was used for statistical analysis.

Behavioral data were analyzed by means of repeated measurement of variances (ANOVAs) with two factors: precue size (large, medium, or small), and visual field (left or right). For electrophysiological data analysis, the electrodes and the hemisphere (left or right) factors were also included. The Greenhouse–Geisser method was used when it was necessary to rectify the degree of freedom and P value. According to the previous studies and working experiences, the posterior sites Pz, P3/P4, P5/P6, POz, PO5/PO6, PO7/PO8, Oz, O1/O2, and the anterior sites Fz, F1/F2, F3/F4, FCz, FC1/FC2, FC3/FC4 were selected for statistical analysis. At the posterior scalp sites, the windows for defining P1, N1, P2, and N2 peak latency and amplitude were 50–120 ms, 120–190 ms, 190–250 ms, and 250–350 ms, respectively. At the anterior scalp sites, the windows for defining N1 and P2 peak latency and amplitude were 50–150 ms and 150–260 ms, respectively. For the unpaired electrodes located on the middle line of scalp, the statistical analyses were conducted separately without hemisphere factor.

3. Results

3.1. Behavioral measures

Under the conditions of large, medium, and small precues, the response accuracies of subjects were 86%, 98%, and 100%, respectively. Covariance was used to exclude the factors of different response accuracy when response time was analyzed. Subjects responded faster to the search array indicated by small precue than to those by medium and large precues [$F(2,44) = 46.8$, $p < 0.001$]. The modified means of response under these three conditions were 1066.2 ± 37.87, 854.9 ± 23.51, and 604.3 ± 26.34 ms, respectively. The main effect between the left and right visual fields where the target stimulus appeared was of no significance. Also, there was no significant interactive effect among the three precue sizes.

3.2. ERP measures

More than 80 trials were included when each condition was averaged. The grand average of ERPs and brain distribution elicited by precue and search array are shown in Fig. 2. Significances existed only among the ERPs of posterior P1 and N1 components. There was no significance in the ERPs of P2, N2, and the anterior early ERPs in the present experiment. Therefore, only P1 and N1 components at posterior site are introduced here.

3.2.1. ERPs elicited by the precues

There was no significant difference in both the latency and the amplitude of P1 components elicited by the precues of three different sizes. For the N1 component, the latency increased with the increase of precue size [151.0 ± 3.27, 155.3 ± 3.40, 164.6 ± 4.16 ms; $F(2,30) = 24.87$, $p < 0.01$, $\varepsilon = 0.596$]. Under three conditions the N1 amplitudes were of no significance. There was no significant difference left and right hemispheres in the latency and amplitudes of P1 and N1.

3.2.2. ERPs elicited by search arrays

For the P1 component, the amplitudes increased with the decrease of precued area (see Fig. 2) [4.42 ± 0.52, 5.07 ± 0.58, $5.00 \pm 0.58\ \mu V$; $F(2,30) = 5.19$, $p < 0.05$]. The hemisphere main effect was significant [left: $4.43 \pm 0.56\ \mu V$, right: $5.90 \pm 0.61\ \mu V$; $F(1,15) = 9.01$,

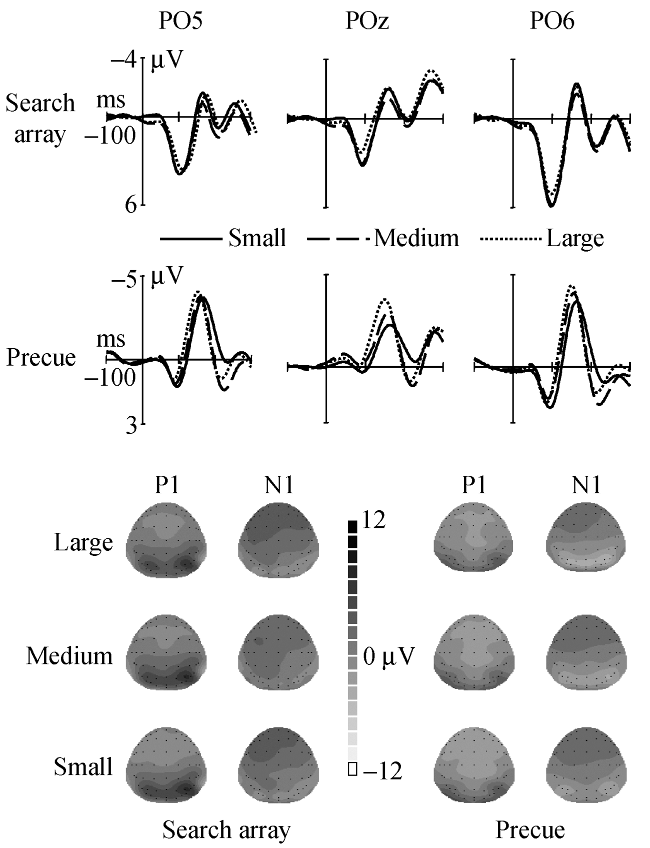

Fig. 2. The grand average ERP waveforms (upper) and topographies (lower) of P1 and N1 components evoked by the search array and precue.

$p < 0.01$] in the amplitude of P1. The main effect of P1 latency and the interaction of precue size and hemisphere were of no significance.

For N1 component, the amplitudes increased with the decrease of precued area (see Fig. 2) [7.46 ± 0.72, 7.41 ± 0.81, 8.24 ± 0.81 μV; $F(2,30) = 3.42$, $p < 0.05$]. The hemisphere main effect was significant [left: 6.09 ± 0.82, right: 9.32 ± 0.89 μV; $F(1,15) = 15.66$, $p < 0.01$] in the amplitude of N1. The main effect of N1 latency and the interaction of precue size and hemisphere were of no significance.

4. Discussion

To date, there has been consistency in the behavioral results of previous studies of spatial 'scaling' effect of visual attention [7–9,11,12,14–16], that is, when the indication of precue is always valid, subjects need a longer time to search for targets in a larger attentional scope. The result from the present study is also consistent with this.

The ERP results in the present study showed that the amplitudes of early visual components (P1 and N1) increased with the decrease of attentional scope, which was also the case in Song's studies [11,12]. Even in Luo et al.'s [9] and Fu et al.'s [13] studies, it is obvious that there is a hierarchical change in P1 and N1 amplitudes within the attentional scopes of different size. All of these results suggest that the spatial 'scaling' effect of visual attention is reflected by the amplitudes of early visual ERPs (P1 and N1).

In the classic selective visual attention paradigm, the precues are always defined as valid and invalid precues, or neutral precue sometimes. When validly precued, target stimulus always appears within the attended area. As a result, compared with invalid precue, the response under valid precue is improved. Our ERP results showed that the amplitudes of early components increased more obviously when validly precued than when invalidly precued. However, the latencies of these components did not change in this way. This type of effect was considered to reflect a mechanism of sensory 'gain control' by which the sensory signals arising from attended (i.e., valid) stimuli are enhanced relative to unattended stimuli [2].

In the present study, the precues of three different sizes were all used validly, which could be interpreted as the precue validity increasing with the precue size decreasing. In fact, those valid precues used in classic selective visual attention paradigms could also be considered to reduce attentional scope by half, which was also a kind of increase in the precue validity. In the present experiment, the amplitudes of P1 and N1 components increased with the decrease of attentional scope, which might reflect that the precue validity increases with the precued area decreasing because the target stimuli are indicated more precisely by the smaller precue. This effect might be considered as a 'hierarchical amplifier', which means that the sensory 'gain control' could function in a hierarchical way. With the decrease of attentional scope, the sensory signals within the smaller attended area could be much more amplified. As a result, the neuron activities related to the amplified sensory signals are enhanced, or the synchrony of these neuron activities gets enhanced [17], which are reflected by the increase in the amplitudes of early ERPs. However, when the attentional scope is extended, the amplifying function might reduce a lot. In the present study, the large precue indicates the whole visual search field. The decrease in the amplitudes of early ERPs might reflect the dysfunction of attentional amplifying. Furthermore, the data have shown that the 'hierarchical amplifier' effect was only reflected by the ERPs amplitudes evoked by search array rather than those evoked by precue. This suggests that, instead of the different size of precue itself, the hierarchical results of early ERPs amplitudes are related to the different attentional scope during the visual search.

The concept that the attentional capacity is limited has been generally accepted. Numerous studies showed that, when targets differ from non-targets along a simple and substantial featural dimension, many elements could be processed in parallel without evident capacity limits. However, capacity limits could be evident when subjects were required to discriminate the targets defined by complex discriminations [18]. Therefore, whether the attentional capacity limitation occurs (i.e., whether the maximum of attentional capacity has been reached) depends on the specific task involved in experiments.

In some previous experiments, fewer stimuli were used and the tasks for subjects to complete were relatively easier. As a result, the attention allocation needed in these experiments does not have to match the maximum of attentional capacity. In Luo et al.'s [9] experiment, there was only one stimulus within the area indicated by small precue. Even in the large precued area, there were nine stimuli at most at one time. The task in this experiment was to discriminate the direction of a vertical crescent among other horizontal ones, which was easier to complete (compared with discriminating a certain English letter among others). Therefore, the attentional capacity limitation might well not be reached when completing these tasks. This means that attention allocation can keep increasing with the increase of attentional scope. The amplitude of P1 component increased under these experimental conditions may reflect the increase of attention allocation [9,13,19–21]. In Fu et al.'s [13] experiment, compared with large precued condition, the P1 amplitude evoked by target stimuli increased under small precued condition. However, he considered that more attention resources were allocated under a small precued condition in his experiment.

In the present experiment, however, the amount of stimuli within the small precued area has already reached eight. There were 48 stimuli distributed within the large precued area. Subjects were asked to search for a letter 'T' among other non-related English letters, which was a more complex task compared with the tasks mentioned above. Therefore, the attention resources needed in this experiment could have reached or exceeded the attentional capacity limitation. This means that, with further increases of attentional scope, attention allocation could not increase anymore. As a result, the 'attention density' distributed in each stimulus within the attentional scope decreases. The decrease of P1 amplitude with the increase of attentional scope in the present experiment and Song's experiment could be a result of the reduction of 'attention density'. Of course, the mechanism of 'attention density' we mentioned here would only function when, and after, attentional capacity limitation occurs. The 'hierarchical amplifier' should also function mainly in this stage.

This spatial 'scaling' effect of visual attention may be understood with the help of 'zoom-lens'. When there are fewer stimuli and the task is relatively easier, less attention resources are needed. With the increase of attentional scope, more stimuli are involved and the tasks become more difficult, which demands more attention resources to ensure the completion of the task. However, the attention resources that can be exploited are limited. Once the attentional capacity limitation has been reached, with further increase of attentional scope, the 'attention density' has to decrease to ensure that all stimuli that fall into the attentional scope are attended, which results in the increase in response time and errors. Certainly the mechanism we described here does not apply to all experiments. For example, it might not be the case when the stimulus amount does not increase with the increase of attentional scope. The related brain mechanism still expects further exploration.

It is interesting that, compared with medium and small attentional scope, the amplitudes of P1 and N1 evoked by target stimuli decreased in large attentional scope. In Song's experiment [11,12], however, there was no significant difference in the amplitudes between medium and large attentional scope. The significance in her experiments lay in the amplitudes between small and medium attentional scope. The difference between Song's and the present experiment is the equal distribution of all English letters with the aim to avoid the potential influence on spatial 'scaling' effect by the unequal distribution of stimuli in different circles. The phenomenon that different search array results in different ERPs significance confirms the deduction that the distribution difference of stimuli may affect the spatial 'scaling' effect. Besides, there is no significant difference in the amplitudes of P1 and N1 between small and medium attentional scopes in present experiment, for which the random presentation of three different precues may account. Subjects may not allocate their attention resources systematically to each precue size, especially when different precues are randomly presented [19]. Further studies are required to explore how the stimuli distribution and the presenting order of different conditions can influence the spatial 'scaling' effect.

In the present experiment, the spatial 'scaling' effect of visual attention is reflected by the increased amplitudes of both P1 and N1 components. Although the amplitudes of P1 and N1 both reflect the early processing involved in visual attention, they are not supposed to reflect the same process. The dissociation between P1 and N1 effect has been observed in many studies [2,22,23]. A more acceptable opinion is that the P1 effect reflects a facilitation of the stimuli located in attended areas during the early perceptual processing stage [22,24] whereas the N1 effect reflects the further discrimination of the stimuli located within the attended area [23]. In the present study, the latency of N1 evoked by precues reduced with the increases of precue size. This may reflect the further discrimination of different precues themselves. Besides, the brain distribution of these two components varies. The maximum of P1 amplitude is distributed at lateral occipital site, whereas the maximum of N1 amplitude is distributed in the lateral occipital and occipital-parietal area. Both of these two components have predominance in the right hemisphere, which demonstrates that visual spatial attention is dominant in the right hemisphere.

References

[1] Handy TC, Green V, Klein RM, et al. Combined expectancies: event-related potentials reveal the early benefits of spatial attention that are obscured by reaction time measures. J Exp Psychol: Hum Percep Perform 2001;27(2):303–17.

[2] Mangun GR, Hillyard SA. Modulation of sensory-evoked brain potentials provide evidence for changes in perceptual processing during visual–spatial priming. J Exp Psychol 1991;17:1057–74.
[3] Handy TC, Mangun GR. Attention and spatial selection: electrophysiological evidence for modulation by perceptual load. Percept Psychophys 2000;62:175–86.
[4] Luck SJ, Hillyard SA, Mouloua M, et al. Effects of spatial cuing on luminance detect-ability: psychophysical and electrophysiological evidence for early selection. J Exp Psychol: Hum Percep Perform 1994;20:887–904.
[5] Posner MI. Orienting of attention. Quart J Exp Psychol 1980;32:3–25.
[6] Eriksen CW, St. James JD. Visual attention within an around the field of focal attention: a zoom lens model. Percept Psychophys 1986;40:225–40.
[7] Greenwood PM, Parasuraman R. Scale of attentional focus in visual search. Percept Psychophys 1999;61:837–59.
[8] Greenwood PM, Parasuraman R. The scaling of spatial attention in visual search and its modification in healthy aging. Percept Psychophys 2004;66(1):3–22.
[9] Luo YJ, Greenwood PM, Parasuraman R. Dynamics of the spatial scale of visual attention revealed by brain event-related potentials. Cogn Brain Res 2001;12(3):371–81.
[10] Gao W, Wei J, Peng X, et al. Brain dynamic mechanisms on the visual attention scale with Chinese characters cues. Chin Sci Bull 2002;47(19):1644–9.
[11] Song W, Gao Y, Luo YJ. Early scale effect and hemisphere superiority on the visual spatial attention: from the electrophysiological evidence of ERP. Prog Nat Sci 2004;14(10):875–9.
[12] Song W, Li XY, Luo YJ, et al. Brain dynamic mechanisms of scale effect: in visual spatial attention. Neuroreport 2006;15(17):1643–9.
[13] Fu Shimin, Caggiano DM, Greenwood PM, et al. Event-related potentials reveal dissociable mechanisms for orienting and focusing visuospatial attention. Cogn Brain Res 2005;23:341–53.
[14] Muller NG, Bartelt OA, Donner TH, et al. A physiological correlate of the "zoom lens" of visual attention. J Neurosci 2003;23:3561–5.
[15] Castiello U, Umilta C. Size of the attentional focus and efficiency of processing. Acta Psychol (Amsterdam) 1990;73:195–205.
[16] Turatto M, Benso F, Facoetti A, et al. Automatic and voluntary focusing of attention. Percept Psychophys 2000;62:935–52.
[17] Steinmetz PN, Roy A, Fitzgerald PJ, et al. Attention modulates synchronized neuronal firing in primate somatosensory cortex. Nature 2000;404:187–90.
[18] Pashler HE. The psychology of attention. Cambridge: MIT Press; 1998, p. 218.
[19] Handy TC, Soltani M, Mangun GR. Perceptual load and viscocortical processing: event-related potentials reveal sensory-level selection. Psychol Sci 2001;12(3):213–8.
[20] Handy TC. Capacity theory as a model of cortical behavior. J Cogn Neurosci 2000;12:1066–9.
[21] Han S, He X, Woods DL. Hierarchical processing and level-repetition effect ad indexed by early brain potentials. Psychophysiology 2001;37:817–30.
[22] Luck SJ, Heinze HJ, Mangun GR, et al. Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P1 and N1 components. Electroencephalogr Clin Neurophysiol 1990;75:528–42.
[23] Vogel EK, Luck SJ. The visual N1 component as an index of a discrimination process. Psychophysiology 2000;37:190–203.
[24] Luck SJ, Hillyard SA, Mouloua M, et al. Mechanisms of visual–spatial attention: resource allocation or uncertainty reduction. J Exp Psychol: Hum Percep Perform 1996;22:725–37.