

The role of top-down spatial attention in contingent attentional capture

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Abstract

It is well known that attentional capture by an irrelevant salient item is contingent on top-down feature selection, but whether attentional capture may be modulated by top-down spatial attention remains unclear. Here, we combined behavioral and ERP measurements to investigate the contribution of top-down spatial attention to attentional capture under modified spatial cueing paradigms. Each target stimulus was preceded by a peripheral circular cue array containing a spatially uninformative color singleton cue. We varied target sets but kept the cue array unchanged among different experimental conditions. When participants' task was to search for a colored letter in the target array that shared the same peripheral locations with the cue array, attentional capture by the peripheral color cue was reflected by both a behavioral spatial cueing effect and a cue-elicited N2pc component. When target arrays were presented more centrally, both the behavioral and N2pc effects were attenuated but still significant. The attenuated cue-elicited N2pc was found even when participants focused their attention on the fixed central location to identify a colored letter among an RSVP letter stream. By contrast, when participants were asked to identify an outlined or larger target, neither the behavioral spatial cueing effect nor the cue-elicited N2pc was observed, regardless of whether the target and cue arrays shared same locations or not. These results add to the evidence that attentional capture by salient stimuli is contingent upon feature-based task sets, and further indicate that top-down spatial attention is important but may not be necessary for contingent attentional capture.

Descriptors: Top-down spatial attention, Feature selection, Contingent attentional capture, N2pc, Spatial cueing paradigm

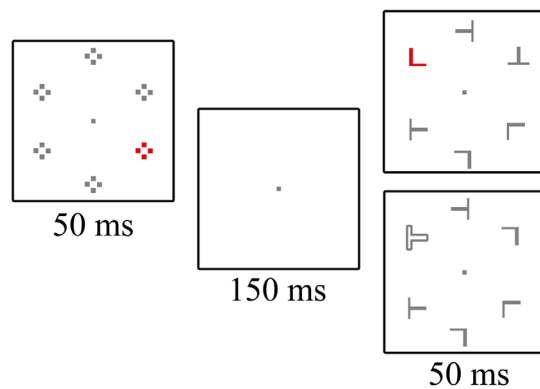
The human brain is able to focus on goal-relevant objects and discard irrelevant information in most situations. Sometimes, however, our attention may be attracted by salient but goal-irrelevant stimuli. Although the distinction between goal-directed and stimulus-driven attention has been discussed (for a review, see Corbetta & Shulman, 2002), whether attention can be captured in a purely bottom-up fashion remains controversial. It has been claimed that attentional capture is determined by low-level sensory properties of the stimuli in a display, and the most salient item captures attention automatically (Theeuwes, 1991a, 1994). Such stimulus-driven attentional capture is considered to be influenced by parallel/serial search strategy (Gaspelin, Ruthruff, Lien, & Jung, 2012; Theeuwes, 2004). Alternatively, the hypothesis of contingent attentional capture holds that attentional capture is always mediated by top-down control, and salient objects capture attention only when they possess task-relevant features (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994).

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Recently, studies of ERPs played an important role in the debate about top-down versus bottom-up control of attentional capture. In particular, researchers adopted the N2pc (N2-posterior-contralateral; Luck, 2012; Luck & Hillyard, 1994) component as an electrophysiological marker for the allocation of visual attention to reveal the mechanism of attentional capture. For example, Hickey, McDonald, and Theeuwes (2006) investigated attentional capture under an additional singleton paradigm in which a search array contained a highly salient distractor singleton (i.e., color singleton) and a less salient target singleton (i.e., shape singleton). They found that both the target and distractor singletons elicited N2pc components successfully, and the distractor-elicited N2pc preceded the target-elicited N2pc. This result indicated that spatial attention was initially oriented to the highly salient distractor and was considered to reflect automatic attentional capture (but see McDonald, Green, Jannati, & Di Lollo, 2013, for a different opinion). However, a sizeable number of other ERP studies have shown evidence for the hypothesis of contingent attentional capture, especially under a spatial cueing paradigm (e.g., Eimer & Kiss, 2008; Kiss & Eimer, 2011; Kiss, Grubert, Petersen, & Eimer, 2012; Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, Goodin, & Remington, 2008). In the spatial cueing paradigm, a cue array that contained a spatially uninformative peripheral singleton cue was presented preceding the display of the target. The behavioral spatial cueing effect (i.e., shorter reaction time [RT] to the target at the cued location relative to the

A. Peripheral tasks



B. Central tasks

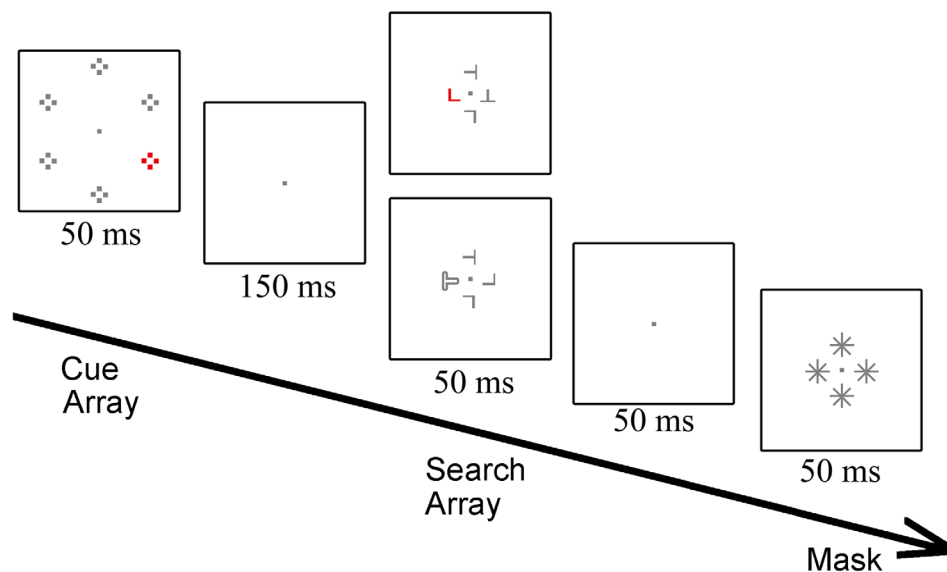


Figure 1. Task design in Experiment 1. For both the peripheral and central VS tasks, a cue array that contained a color singleton was presented for 50 ms and was followed by a target array (50-ms duration) after a 150-ms interval. Participants were asked to report the character of the target letter. The target letter was a red letter among gray letters in the color tasks or an outlined letter among gray letters in the outlined tasks. Cue arrays were always presented at the peripheral locations with an eccentricity of 4.3° . In the peripheral VS tasks (A), the target array appeared at the same positions as the cue array, whereas in the central VS tasks (B), the target array appeared near the central fixation with an eccentricity of 0.48° . A mask display was employed in the central tasks to match the difficulties between the peripheral and central tasks. The background was black throughout the experiment. The stimuli are not drawn to scale.

uncued location) was accompanied by a cue-elicited N2pc, indicating attentional capture by the salient singleton cue. Crucially, such behavioral spatial cueing effect and the cue-elicited N2pc component were observed only when the singleton cue possessed the same feature as the target (e.g., a color cue preceding a same-color target), but absent when the features of the singleton cue and the target were mismatched (e.g., a color cue preceding a shape target), suggesting that attentional capture is contingent on top-down feature selection.

Compared with the extensive ERP studies concerning the role of feature selection in attentional capture, only a few investigated whether the attentional capture by salient irrelevant items is dependent on endogenous spatial attention. In one study, Seiss, Kiss, and Eimer (2009; Experiment 1) used central cues to manipulate the focus of top-down spatial attention. In each trial, a salient

color singleton (either target singleton or nontarget singleton) would appear on either the cued or uncued side, and participants were asked to respond to the target singleton appearing on the cued side. Nontarget color singletons were found to elicit comparable N2pc components regardless of whether they appeared on the cued or uncued side. In another study, Leblanc, Prime, and Jolicoeur (2008) asked participants to search for a colored digit among a rapid serial visual presentation (RSVP) stream of heterogeneously colored nontarget digits, which were presented at a fixed central location. A pair of peripheral distractors were presented, one on each side of the RSVP stream, 117 ms preceding the target digit. One of the peripheral distractors was found to elicit an N2pc component when it was in the target color. These two studies indicated that attentional capture by salient irrelevant stimuli (indexed by the N2pc component) may happen outside the focus of endogenous

attention. One might argue, however, that the experimental design of these studies could not rule out the possibility that partial top-down spatial attention was still allocated to the to-be-ignored locations. In the Seiss et al. (2009) study, the direction of top-down spatial attention was manipulated in a trial-by-trial manner, so participants had to shift their attention frequently throughout the experiment. Although the lateralized ERP components (i.e., the anterior directing attention negativity and the late directing attention positivity) indicated that participants used the cues to direct attention, it remained possible that top-down spatial attention did not efficiently and completely switch across the fixation point due to frequent attentional shifts. In the Leblanc et al. (2008) study, although the RSVP paradigm was used to maintain sustained attention to a central location, the peripheral distractors were only about 1° of visual angle away from the central stream (from edge to edge). As was argued by Theeuwes (2010), these distractors might be still near the observer's attentional window and the observed N2pc component could not be recognized without doubt as a marker of attentional capture outside the concurrent attentional focus. Therefore, there is still a lack of conclusive electrophysiological evidence as to whether top-down spatial attention is important or even necessary for a salient irrelevant stimulus to capture visual attention.

The aim of the present study was to investigate whether attention capture by an irrelevant color singleton will be attenuated or even disappear when the singleton is located outside the focus of top-down spatial attention. Through a spatial cueing paradigm, we manipulated the focus of top-down spatial attention by adjusting the eccentricity of the target array while keeping that of the peripheral cue array unchanged. Specifically, in a peripheral visual search (VS) task, the target array was presented at the same locations as the peripheral cue array with an eccentricity of 4.3°. For a central VS task, however, the target array was set to be very close to the central fixation with an eccentricity of only 0.48°, so that the spatial distance between peripheral cues and central targets was over 3° of visual angle (from edge to edge). Such spatial distance between the attended and unattended stimuli has been frequently used to investigate the role of spatial selective attention (e.g., Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Ding, Martinez, Qu, & Hillyard, 2014; Di Russo, Martínez, & Hillyard, 2003; Martínez et al., 1999). In addition, a block design was adopted to avoid frequent shifts of top-down spatial attention. With such a design, the peripheral cue arrays would be continuously within the participants' attentional window for the peripheral task, and be continuously outside the attentional window for the central task. For both the peripheral and central tasks, we measured the behavioral spatial cueing effect and the N2pc elicited by peripheral color singleton cues to investigate their capacities of attentional capture. The direct comparison between the peripheral and central tasks allowed us to examine whether and how top-down spatial attention modulates attentional capture by a salient color cue. We also manipulated feature-based task sets (i.e., whether the target was a colored or a shape singleton) to investigate whether attentional capture by spatially attended/unattended color cues is contingent on these task sets. The schematic representation of this experimental design is illustrated in Figure 1.

Experiment 1

Method

Participants. Twelve volunteers (mean age = 23 years, 6 males) were recruited as paid participants in Experiment 1, and informed

consents were obtained before the experiment. All participants were right-handed except one, and all had normal or corrected-to-normal vision.

Stimuli and procedure. In each trial, a cue display (50-ms duration) was followed by a target display (50-ms duration) after a 150-ms interval. The cue display consisted of a circular array of six sets of four closely aligned dots (each set subtending $0.8^\circ \times 0.8^\circ$). The center of each set of dots was presented at a constant distance of 4.3° from a central fixation point. One set of dots was red (i.e., color singleton cue), whereas the other sets were gray. The color singleton cue was presented randomly and equiprobably at one of the four left and right locations, but never at the top or bottom location. In peripheral VS conditions, target arrays were presented at the same locations as the cue arrays. To investigate whether attentional capture was contingent upon feature-based task set, two types of target letters were used in separate tasks. For the color task, a red letter was presented at one of the four lateral locations and five gray letters were presented at the other five locations. For the outlined task, the red letter was replaced by an outlined one. The size of each letter was $0.8^\circ \times 0.8^\circ$. The character (*L* or *T*) and rotation angle (0° , 90° , 180° , or 270°) varied randomly across trials (Figure 1A).

In central VS conditions, cue displays were identical to those of the peripheral conditions. To match the crowding or lateral masking of the peripheral conditions, target arrays in the central conditions used a smaller set size of four instead of six. Each target array consisted of one target letter (red or outlined) and three gray distractor letters, with the target letter appearing randomly and equiprobably at one of four locations (left, right, top, and bottom). The letters were presented at a distance of 0.48° from the central fixation point. The size of each letter was $0.54^\circ \times 0.54^\circ$, and its character (*L* or *T*) and rotation angle (0° , 90° , 180° , or 270°) varied randomly across trials. To match the difficulties of the central and peripheral VS tasks, in the central VS conditions, the target display was followed by a mask display (50-ms duration) after a 50-ms interval. The mask consisted of four gray bars ($0.54^\circ \times 0.09^\circ$, with orientations of 0° , 45° , 90° and 135°) and occupied the same locations as the target array (Figure 1B).

In summary, there were four kinds of tasks (peripheral color VS task, peripheral outlined VS task, central color VS task, and central outlined VS task) in Experiment 1, each consisting of six successive blocks of 64 trials. For each task, participants were asked to identify the target letter by pressing a left or right response key within a random interstimulus interval (ISI) from 1,200 to 1,600 ms. In all four tasks, color singleton cues were uninformative with respect to the target location. All red and gray stimuli were isoluminant (11 cd/m^2) against a black background (0.06 cd/m^2). A small gray fixation dot ($0.23^\circ \times 0.23^\circ$) was continuously presented at the screen center throughout the experiment. The order of tasks and mappings of target characters to response hands were counterbalanced across participants.

In previous studies, a standard approach to compute the behavioral spatial cueing effect would be to directly compare RTs at cued locations (i.e., in trials where cues and targets occupy the same location) and at uncued locations (i.e., in trials where cues and targets were presented at different locations). However, this approach could not be applied to the present central VS tasks because none of the central targets were presented at cued locations. Here, we used an alternative approach by defining two categories of trials, namely, near trials and far trials, based on the spatial distance between the color singleton cues and the

subsequent targets. While near trials consisted of the trials in which targets were nearest to the color singleton cues, far trials were those whose targets were farthest from the color singleton cues. Consider the trials whose color singleton cues appeared in the upper-right quadrant, for example: In the peripheral tasks, the near trials were those in which targets appeared in the upper-right quadrant and the far trials were those in which targets appeared in the lower-left quadrant. The trials whose targets appeared in the upper-left or lower-right quadrant were discarded from this analysis because these targets were neither nearest to nor farthest from the cues. In the central tasks, the near trials were those whose targets appeared on the upper vertical midline and the right horizontal midline (notice that the cue location was equidistant from these two target locations) and the far trials were those whose targets appeared on the lower vertical midline and the left horizontal midline. We hypothesized that the behavioral spatial cueing effect would be reflected by shorter RTs for the near trials than for the far trials.

Electrophysiological recording and data analysis. An ANT EEG/ERP acquisition system with a Refa-8 72-channel DC amplifier was used in EEG recordings. The EEG was recorded from 58 scalp sites (including FP1, FPZ, FP2, AF3, AFZ, AF4, F7, F3, FZ, F4, F8, FC5, FC3, FC1, FCZ, FC2, FC4, FC6, T7, C5, C3, C1, CZ, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPZ, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, I5, I3, Iz, I4, and I6 from the 10/10 system), as well as from the left and right mastoids. The horizontal and vertical electrooculograms (EOGs) were recorded as well. The EEG was recorded with a common average reference online, and was then algebraically rereferenced to the average of the left and right mastoids. Electrode impedances were kept below 5 k Ω . The EEG analog signals were digitized at a 512-Hz sampling rate, and a digital antialiasing filter of $0.27 \times$ the sampling rate was applied at the time of recording. After filtering the EEG signals with a digital 40-Hz low-pass filter and then a 0.1-Hz high-pass filter, epochs were extracted that included 200 ms of prestimulus baseline and 1,000 ms of poststimulus EEG. Trials contaminated by eye blinks, eye movements, or muscle potentials exceeding $\pm 70 \mu\text{V}$ at any electrode were excluded before averaging. Overall, 13% of trials were rejected due to these artifacts. ERPs were then averaged from EEG epochs time-locked to the presentation of the cue displays. The baseline for ERP measurements was the mean voltage over the 200-ms precue interval. Separate ERPs were calculated for each combination of color singleton cue location (left or right) and task type (peripheral color, peripheral outlined, central color, or central outlined VS task). The N2pc elicited by the color singleton cue was defined as the difference ERP between the contralateral and ipsilateral posterior scalp sites with respect to the cue location. The mean amplitudes of N2pc were measured at P7/8 and PO7/8 sites in the 180–230 ms interval after cue onset, at which scalp sites and time window the N2pc showed maximum amplitudes. In addition, to determine the time at which the averaged N2pc wave deviated significantly from the baseline, successive *t* tests were carried out with a sliding window of ~ 20 ms (10 time points) in steps of ~ 10 ms (5 time points). A similar analysis was used to examine differences in N2pc amplitude between conditions as a function of time.

Mean ERP amplitudes and behavioral measurements (error rates and RTs) were analyzed in two-way analyses of variance (ANOVAs) with factors being target type (color vs. outlined) and task location (peripheral vs. central). The behavioral spatial cueing effects were analyzed in three-way ANOVAs with factors being target type, task location, and trial category (near vs. far).

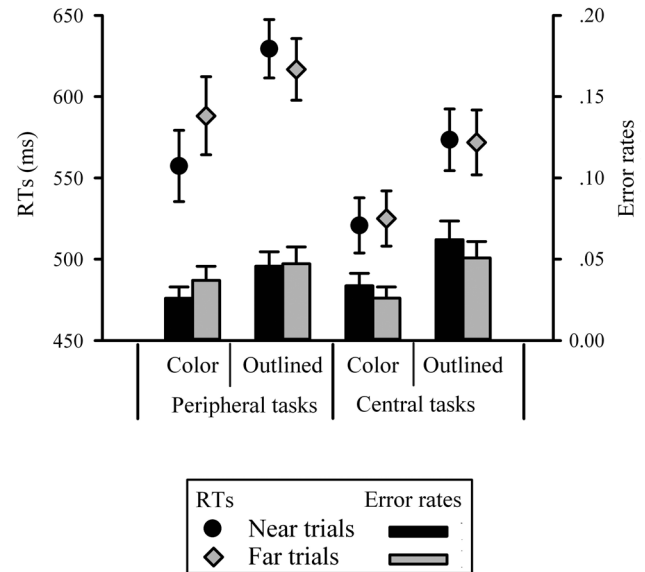


Figure 2. Behavioral results in Experiment 1. Error rates (bars) and RTs (dots) for both near trials (black bars and black round dots) and far trials (gray bars and gray diamond dots) in four different visual search tasks are shown. The results of RTs showed the spatial cueing effects for the color targets in both the peripheral and central tasks, with a larger effect in the former. By contrast, no spatial cueing effect was found for the outlined targets in either the peripheral or central task. Error bars indicate standard errors of the mean.

Results

Behavior. Trials with no or invalid responses (i.e., participants pressed a key that was not defined in the task) were excluded from further analysis (less than 0.6% of trials). For the peripheral color VS task, central color VS task, peripheral outlined VS task, and central outlined VS task, error rates were $4.1 \pm 0.8\%$, $3.2 \pm 0.7\%$, $5.2 \pm 0.8\%$, and $5.7 \pm 1.0\%$ (mean \pm SE), respectively. A two-way repeated measures ANOVA was performed of Target Type (color vs. outlined) \times Task Location (peripheral vs. central). Results revealed a significant main effect of target type, $F(1,11) = 12.521$, $p = .005$, $\eta_p^2 = .532$, indicating that the color VS task was a little easier than the outlined VS task. Neither the main effect of task location, $F(1,11) = 0.264$, $p = .618$, $\eta_p^2 = .023$, nor the interaction of Task Location \times Task Type, $F(1,11) = 1.688$, $p = .220$, $\eta_p^2 = .133$, was found to be significant, indicating that the difficulties of the central and peripheral tasks were well matched.

In order to investigate the behavioral spatial cueing effects, we then analyzed error rates and RTs for the near trials and far trials in all four tasks (i.e., peripheral color VS task, central color VS task, peripheral outlined VS task, and central outlined VS task). The results are illustrated in Figure 2. For the error rates, neither the main effect of trial category (near vs. far) nor any interaction involving the factor of trial category was significant, $F(1,11) < 3.101$, $ps > .106$, η_p^2 s $< .220$. For the RTs, a significant interaction of Target Type \times Task Location \times Trial Category was found, $F(1,11) = 30.745$, $p < .001$, $\eta_p^2 = .736$. We then analyzed the spatial cueing effects (reflected on RTs) of the peripheral and central tasks separately. In the peripheral tasks, a significant interaction of Target Type \times Trial Category, $F(1,11) = 29.491$, $p < .001$, $\eta_p^2 = .728$, indicated that the spatial cueing effects differed between the color target and the outlined target. For the color target, RTs were much faster for the near trials than for the far trials

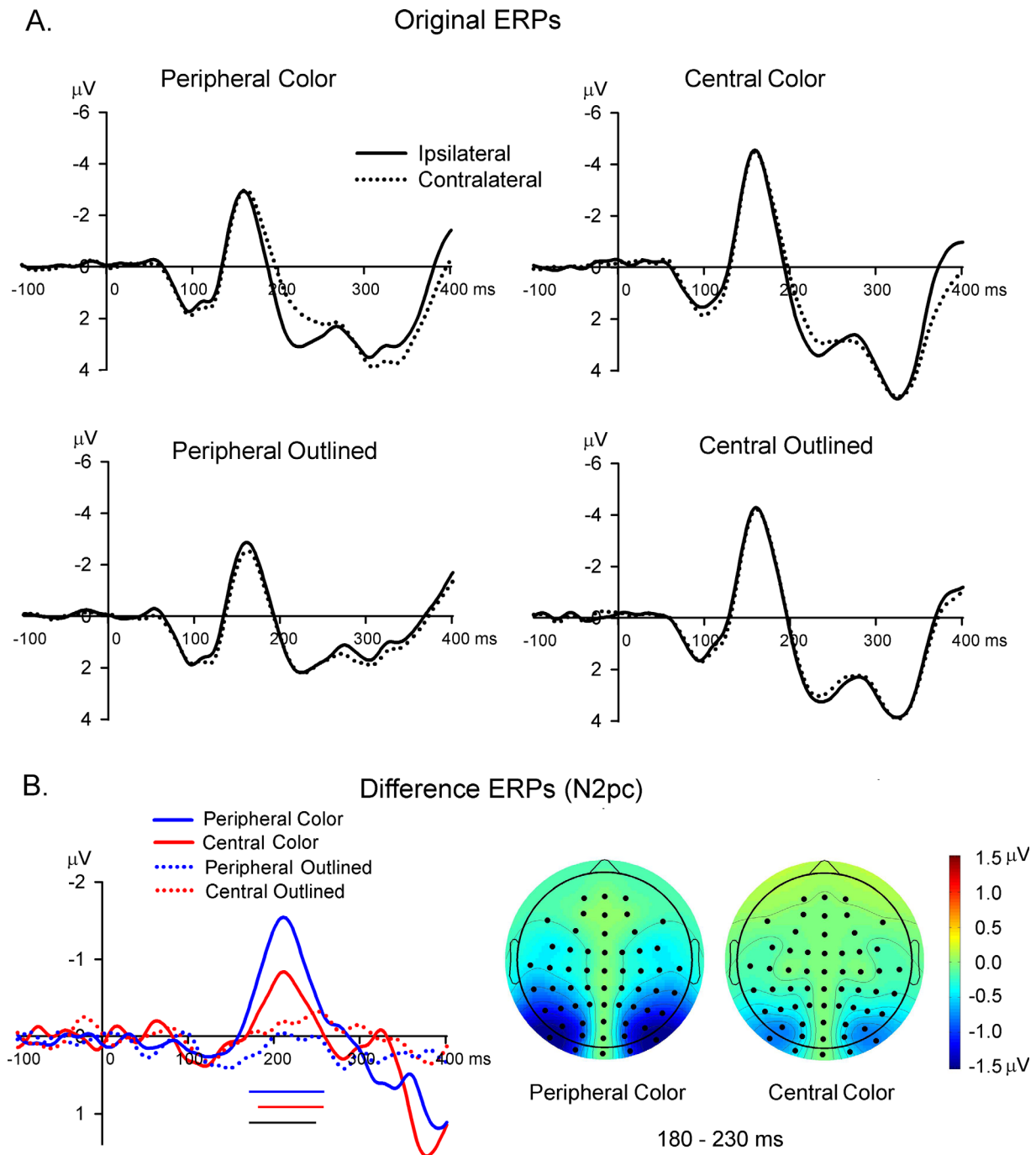


Figure 3. ERP results of the four kinds of VS tasks in Experiment 1. **A:** The original ERP waveforms elicited by the color singleton cues at posterior electrode sites (collapsed across P7/8 and PO7/8) ipsilateral (solid lines) and contralateral (dotted lines) to the visual hemifield where the color singleton cue was presented. Negative plotted upwards. **B:** The N2pc elicited by the color singleton cues. The left panel shows the N2pc waveforms collapsed across P7/8 and PO7/8 sites. The color singleton cues elicited significant N2pc components for both the peripheral color (blue solid line) and central color (red solid line) VS tasks, with a larger amplitude in the former task condition. By contrast, no significant N2pc was found in either the peripheral outlined (blue dotted line) or central outlined (red dotted line) VS task. Time windows of significant N2pc amplitudes are indicated as colored lines below. The gray line indicates the time window for the significant difference in N2pc amplitudes between the peripheral and central color VS tasks. The right panel shows the voltage topographical maps of the N2pc during the 180–230 ms time interval. The N2pc was mainly distributed over occipital areas for both the peripheral and central color VS tasks.

(far – near = 30.9 ± 6.1 ms, mean \pm SE; $t(11) = 5.069$, $p < .001$), whereas for the outlined target, RTs were a little slower for the near trials than for the far trials (far – near = -12.7 ± 3.7 ms; $t(11) = 3.483$, $p = .005$). In the central tasks, a marginal significant interaction of Task Type \times Trial Category was found,

$F(1,11) = 4.574$, $p = .056$, $\eta_p^2 = .294$. Further paired t tests indicated that the spatial cueing effect was significant for the color target (far – near = 4.3 ± 1.8 ms; $t(11) = 2.334$, $p = .040$) but not for the outlined target (1.6 ± 2.5 ms; $t(11) = 0.658$, $p = .524$). Further analysis showed that, for either the peripheral or central color VS

task, the error rate of near trials was not significantly different from that of far trials (far – near, peripheral task: $1.1 \pm 0.6\%$, $t(11) = 1.734$, $p = .111$; central task: $-0.7 \pm 0.5\%$, $t(11) = 1.541$, $p = .151$). These results suggested that, for both the peripheral and central VS tasks, spatial cueing effects were presented for color targets but not for outlined targets, and the spatial cueing effects for color targets were not due to a speed-accuracy trade-off. Moreover, for the color target, a significant Task Location \times Trial Category interaction was also found on RTs, $F(1,11) = 20.345$, $p = .001$, $\eta_p^2 = .649$. This interaction resulted from the fact that the spatial cueing effect for color targets was much more robust in the peripheral task (~ 31 ms) than in the central task (~ 4 ms), suggesting that the magnitude of the spatial cueing effect was modulated by task locations.

ERPs. Figure 3 shows the ERPs elicited by salient color singleton cues in all four tasks. The mean N2pc amplitude (180–230 ms post-stimuli) was computed from the difference waveforms (contralateral to the color cue minus ipsilateral to the color cue) and then analyzed in a two-way repeated measures ANOVA with factors being target type and task location. The main effect of target type, $F(1,11) = 34.344$, $p < .001$, $\eta_p^2 = .757$, and the interaction of Target Type \times Task Location, $F(1,11) = 8.143$, $p = .016$, $\eta_p^2 = .425$, were significant. In addition, the main effect of task location was marginally significant, $F(1,11) = 4.767$, $p = .052$, $\eta_p^2 = .302$. Further t tests revealed that the N2pc elicited by the color cue significantly differed from baseline in both the peripheral (mean amplitude during 180–230 ms: -1.292 ± 0.202 μ V, mean \pm SE; $t(11) = 6.411$, $p < .001$) and the central (-0.651 ± 0.154 μ V; $t(11) = 4.238$, $p = .001$) color VS tasks, whereas no significant N2pc was observed in either the peripheral or central outlined VS task (both $t(11) < 1.051$, both $ps > .316$). Moreover, a significant difference in N2pc amplitude was found between the peripheral and central color VS tasks, $t(11) = 3.028$, $p = .011$, indicating that the salient color cue elicited a larger N2pc in the peripheral task than in the central task.

Discussion

In Experiment 1, a cue-elicited N2pc component, accompanied by a behavioral spatial cueing effect, was found not only when the color singleton cue was presented at spatially relevant or to-be-attended locations (i.e., in the peripheral color VS task), but also when it was presented at spatially irrelevant or to-be-ignored locations (i.e., in the central color VS task). As the N2pc component is widely accepted as an electrophysiological marker of attentional capture under the spatial cueing paradigm (e.g., Eimer & Kiss, 2008; Kiss & Eimer, 2011; Kiss et al., 2012; Lien et al., 2008, 2010), the present results provide both behavioral and neural evidence supporting that attentional capture by a salient stimulus could exist regardless of whether it is located within the focus of top-down spatial attention or not. On the other hand, both the magnitude of the behavioral spatial cueing effect and the amplitude of the cue-elicited N2pc component were attenuated when the cue arrays appeared at unattended locations relative to attended locations, indicating that top-down spatial attention still plays an important role for attentional capture.

The behavioral spatial cueing effect and the N2pc elicited by a color singleton cue were found only in the color tasks but not in the outlined tasks, which was consistent with the hypothesis of contingent attentional capture (Eimer & Kiss, 2008; Folk & Remington, 1998; Folk et al., 1994; Kiss & Eimer, 2011; Kiss et al., 2012; Lien

et al., 2008, 2010). These results also ruled out the possibility that the N2pc observed in the color tasks merely reflected sensory imbalance between visual hemifields. The fact that the N2pc in response to singleton cues was modulated by both voluntary spatial attention and feature selection supports that attentional capture by salient stimuli is not driven purely by bottom-up salience but is subject to top-down control.

In Experiment 1, by using an untraditional method (i.e., comparing the RTs of near trials vs. far trials) to reveal the behavioral spatial cueing effects, we found a small but significant effect in the central color VS condition (~ 4 ms), which was much smaller than that in the peripheral color VS condition (~ 31 ms). One might argue that it may be unfair to compare behavioral capture effects by cues under peripheral and central conditions. In central target blocks, the near cues appeared at a nearby location with respect to the subsequent targets. By contrast, in peripheral target blocks, the near cues appeared just at the subsequent target location, which might facilitate target processing (e.g., Folk & Remington, 1998). To rule out this “unfair comparison” possibility, we carried out a complementary behavioral experiment. The design of this experiment was the same as that of Experiment 1 with two modifications. First, for the peripheral VS conditions, the target array was presented at an eccentricity of 3.1° instead of 4.3° , so that the target and the preceding singleton cue would not share a same location. Second, for the central VS conditions, the target array (as well as the following mask) was rotated 45° clockwise, so that each of the four letters was presented in one of the four quadrants. With such a design, we could measure the behavioral spatial cueing effects with a traditional method (i.e., comparing the RTs of trials at cued vs. uncued quadrants) in both the peripheral and central conditions. Each of the four conditions (peripheral color, central color, peripheral outlined, central outlined) consisted of four blocks of 64 trials. Fourteen subjects participated in this experiment. Again, we found a small but significant spatial cueing effect in the central color VS condition (uncued – cued: 7.7 ± 2.9 ms; $t(13) = 2.605$, $p = .022$), which was significantly weaker than the effect in the peripheral color VS condition (33.0 ± 8.6 ms, $t(13) = 3.846$, $p = .002$; central vs. peripheral: $p = .008$). The error rate results demonstrated that neither of these spatial cueing effects was due to a speed-accuracy trade-off (uncued – cued: central, $-0.4 \pm 0.6\%$, $t(13) = 0.560$, $p = .585$; peripheral, $1.4 \pm 0.9\%$, $t(13) = 1.501$, $p = .157$). By contrast, no significant spatial cueing effect was found for either the peripheral or central outlined VS condition (RT: both $t(13) < 1.153$, $ps > .270$; error rate: both $t(13) < 0.185$, $ps > .856$). These results replicated the behavioral results of Experiment 1 and confirmed the small behavioral spatial cueing effect in the central color VS condition. More importantly, these results ruled out the possibility that the effect of attentional modulation was due to an unfair comparison between the peripheral and central conditions, because in this supplementary experiment the singleton cues and the subsequent targets did not occupy the same locations under either condition.

Experiment 2

In Experiment 1, a significant (although attenuated) N2pc component was successfully induced by the peripheral color singleton cue in the central color VS task, suggesting that top-down spatial attention may not be an essential factor to evoke contingent attentional capture. However, one might argue that top-down spatial attention was necessary to attentional capture per se, and that even the central color VS task in Experiment 1 could not preclude leaking of

Central RSVP tasks

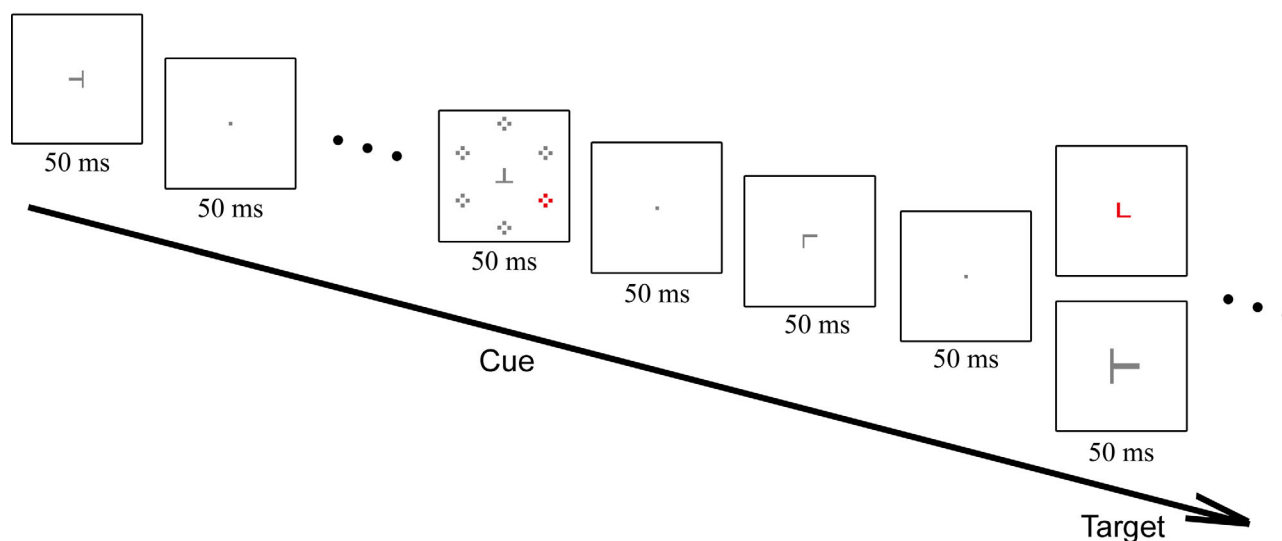


Figure 4. Illustration of the central RSVP tasks used in Experiment 2 and 3. The central RSVP stream consisted of a series of successively presented letters (rotated T or L). Each letter was presented at the center of the screen for 50 ms with an ISI of 50 ms. A cue array that contained an spatially uninformative color singleton cue was presented for 50 ms and was followed by a red (Experiment 2 and 3, upper exemplar) or a larger (Experiment 3, lower exemplar) target letter after a 150-ms ISI. As in Experiment 1, the cue arrays were always presented at the peripheral locations with an eccentricity of 4.3°. The background was black throughout both experiments. The stimuli are not drawn to scale.

top-down spatial attention to the peripheral locations. In the central color VS task, the target's location remained a little uncertain, so top-down attention was still in a slightly distributed state, which may be essential for the observed effect of attentional capture (Theeuwes, 1991b; Yantis & Jonides, 1990). Also, the attentional load of the central color VS task was relatively low (error rate 3.2%), so that participants may not need to focus their attention on the central target array to accomplish this task (Ding et al., 2014; Lavie, 1995). Taken together, top-down spatial attention might have leaked to the peripheral locations to some extent and induced the observed effect of attentional capture in Experiment 1. To investigate this alternative hypothesis of attentional leak, in Experiment 2 we made two manipulations to minimize the possible leaking of top-down spatial attention. First, the central color VS task was replaced by a central color RSVP task in which top-down spatial attention is required to be highly focused on a fixed central location rather than slightly distributed over a surrounding area. Meanwhile, the central color RSVP task in Experiment 2 was designed to be more difficult than the central color VS task in Experiment 1. We are interested in whether the peripheral color singleton cue would still induce a significant N2pc wave under such a condition. If the N2pc observed in the central color VS task of Experiment 1 was completely due to attentional leak, little N2pc might be observed in the current central color RSVP task. Otherwise, the appearance of an N2pc triggered by the peripheral color singleton cue would provide strong neural evidence supporting that top-down spatial attention may not be necessary for contingent attentional capture.

Method

Participants. Twelve volunteers (mean age = 22 years, 4 males) were recruited as paid participants in Experiment 2, and informed

consents were obtained before the experiment. All but one of the participants were right-handed, and all had normal or corrected-to-normal vision.

Stimuli, procedure, data recording, and analyses. Participants completed a peripheral color VS task and a central color RSVP task in Experiment 2. The peripheral color VS task was identical to that of Experiment 1. In the central color RSVP task, each trial consisted of a series of successively presented letters ($0.41^\circ \times 0.41^\circ$). Letters were L or T, and their rotation angle (0° , 90° , 180° , or 270°) varied randomly from letter to letter; no identical stimuli were presented consecutively. Each letter was presented at the center of the screen for 50 ms with an ISI of 50 ms. All letters appeared gray with the exception of the target letter, which was red. All gray and red stimuli were isoluminant (11 cd/m^2) against a black (0.06 cd/m^2) background. The number of pretarget letters was chosen randomly for each trial and varied between seven and 10. There were always four letters following the target letter. At the end of the letter stream, a central fixation dot was presented, and participants were asked to identify the character of the red target letter by pressing a left or right response key. After a response, a random ISI from 600 to 1,000 ms was presented with a blank display. As in the peripheral color VS task, a peripheral cue array, which contained an uninformative color singleton cue, was presented 200 ms before the target for 50 ms (Figure 4, upper exemplar). Each task consisted of six successive blocks of 64 trials. The order of tasks and mappings of target characters to response hands were counterbalanced across participants. Data recording and analysis were identical to Experiment 1, except that the RTs of the central color RSVP task were not considered. Behavioral spatial cueing effects and the N2pc amplitudes were analyzed using *t* tests.

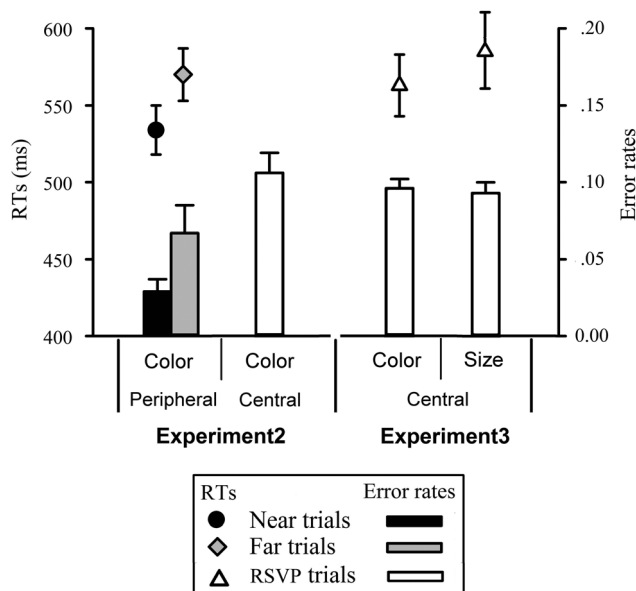


Figure 5. Behavioral results in Experiment 2 (left) and Experiment 3 (right). Error rates (bar) and RTs (dot) for near trials (black bars and black round dots) and far trials (gray bars and gray diamond dots) in Experiment 2, and for RSVP trials (white bars and white triangle dots) in Experiment 2 and 3 are shown. In Experiment 2, both the RT and error rate results revealed significant spatial cueing effects for the color targets in the peripheral VS task. In Experiment 3, RTs were a little shorter in the color task than in the size task, whereas error rates did not differ between these two tasks. Error bars indicate standard errors of the mean.

Results

Behavior. Trials with no or invalid responses were excluded from further analysis (less than 0.4% of trials). The error rate of the peripheral color VS task ($6.6 \pm 1.4\%$, mean \pm SE) was comparable to that in Experiment 1 ($4.1\% \pm 0.8\%$, $t(22) = 1.523$, $p = .142$), whereas the error rate of the central color RSVP task ($10.6 \pm 1.3\%$) was significantly higher than that of the central color VS task in Experiment 1 ($3.2\% \pm 0.7\%$; $t(22) = 4.955$, $p < .001$). This result confirmed that the difficulty manipulation of the central color RSVP task in Experiment 2 was successful.

We then analyzed the behavioral spatial cueing effect for the peripheral color VS task. Error rates and RTs of the near and far trials were illustrated in Figure 5 (left panel). The error rates were significantly less (far – near = $3.8 \pm 1.4\%$, mean \pm SE; $t(11) = 2.732$, $p = .020$) and the RTs were significantly shorter (far – near = 35.9 ± 11.5 ms; $t(11) = 3.124$, $p = .010$) for the near trials than for the far trials, indicating a significant spatial cueing effect.

ERPs. Figure 6 shows the ERPs elicited by the salient color singleton cues in the two tasks. Significant N2pc components were observed in both the peripheral color VS task ($180\text{--}230$ ms: -1.236 ± 0.264 μ V, mean \pm SE; $t(11) = 4.688$, $p = .001$) and the central color RSVP task (-0.737 ± 0.239 μ V; $t(11) = 3.084$, $p = .010$). The N2pc found in the central color RSVP task indicated that, even when spatial attention was highly concentrated to the central location, peripheral salient cues with a task-relevant feature could still capture attention. Moreover, the N2pc amplitude was significantly larger in the peripheral color VS task than in the central color RSVP task, $t(11) = 2.563$, $p = .026$, suggesting once

more that attentional capture by color singleton cues could be modulated by top-down spatial attention. Further two-way ANOVAs with factors being experiment (1 vs. 2) and location of color task (central vs. peripheral) revealed that the modulation effect of top-down spatial attention in Experiment 2 was comparable to that in Experiment 1 (interaction of Experiment \times Location of Color task: $F(1,22) = 0.243$, $p = .627$, $\eta_p^2 = .011$).

Discussion

Compared to the central color VS task in Experiment 1, the current central color RSVP task required top-down spatial attention to highly focus on the central location of the visual display. In addition, the central color RSVP task was more difficult than the central color VS task. Thus, little if any top-down spatial attention would have been deployed to the peripheral locations in the current central color RSVP task relative to that in the central color VS task of Experiment 1. According to the hypothesis of attention leak as mentioned earlier, no or at least an attenuated N2pc would have been observed. However, the N2pc elicited by the color singleton cue was still apparent in the central color RSVP condition, and its amplitude was comparable to that of the central color VS task in Experiment 1 (amplitude: -0.681 μ V in Experiment 2 vs. -0.618 μ V in Experiment 1; $t(22) = 0.302$, $p = .765$). These results indicated that the observed effects of attentional capture by the peripheral color cues might not be completely due to attention leak, suggesting that the top-down spatial attention may not be necessary for attentional capture.

Moreover, the modulation effect of top-down spatial attention on attentional capture was again observed in Experiment 2. Though no behavioral spatial cueing effect could be calculated, the attenuated amplitude of N2pc in the central color RSVP task revealed that the peripheral color cues caused a significantly weaker effect of attentional capture when located at unattended locations. These results were in accordance with the findings of Experiment 1 and further demonstrated that top-down spatial attention can modulate the magnitude of attentional capture.

Experiment 3

In Experiment 2, the peripheral color cues elicited a significant N2pc wave even when top-down spatial attention was highly focused on a known fixed location in the central visual field and the peripheral color cues were located more than 3° of visual angle away. One might argue that it may be partly due to the fact that, in Experiment 2, half of the participants performed the peripheral task before the central task. There might be some sort of fast or short-term effects of perceptual learning induced by previous blocks (e.g., Ding, Song, Fan, Qu, & Chen, 2003; Qu, Song, & Ding, 2010; Qu et al., 2014; Vatterott & Vecera, 2012), and this prior experience may account for the fact that previously spatially relevant salient stimuli captured attention to some extent even when they became spatially irrelevant (see also Awh, Belopolsky, & Theeuwes, 2012). To rule out this possibility, in Experiment 3, we only adopted the central RSVP task, keeping the peripheral color cues spatially irrelevant throughout the experiment. To further confirm that attentional capture was contingent upon feature selection, two kinds of tasks (color task vs. size task) were introduced. We expected that the peripheral color singleton cues would still trigger a significant N2pc wave in the central color RSVP task, but not in the central size RSVP task.

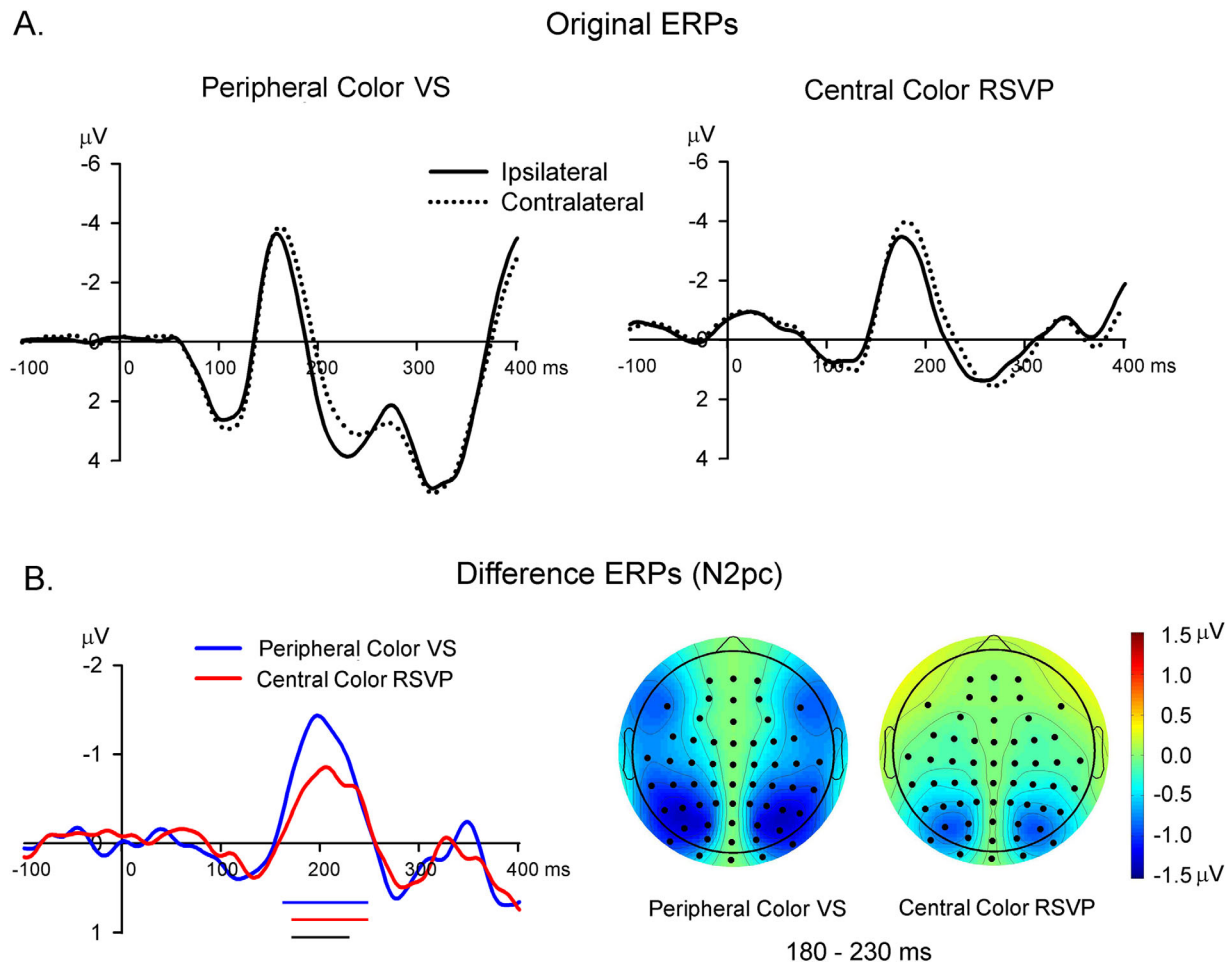


Figure 6. ERP results in Experiment 2. **A:** The original ERPs elicited by the color singleton cues at posterior electrode sites (collapsed across P7/8 and PO7/8) ipsilateral (solid lines) and contralateral (dotted lines) to the visual hemifield where the color singleton cue was presented. Negative plotted upwards. **B:** The N2pc elicited by the color singleton cues. The left panel shows the N2pc waveforms collapsed across P7/8 and PO7/8 sites. The color singleton cues elicited significant N2pc components in both the peripheral color VS task (blue line) and the central color RSVP task (red line), with a larger amplitude in the former task condition. Time windows of significant N2pc amplitudes are indicated as colored lines below. The gray line indicates the time window for the significant difference in N2pc amplitudes between the peripheral color VS and central color RSVP tasks. The right panel shows the voltage topographical maps of the N2pc during the 180–230 ms time interval. The N2pc was mainly distributed over occipital areas for both the peripheral color VS task and the central color RSVP task.

Method

Participants. Twelve volunteers (mean age = 21 years, 7 males) were paid to participate in Experiment 3, and informed consents were obtained before the experiment. All but one of the participants were right-handed, and all participants had normal or corrected-to-normal vision.

Stimuli, procedure, data recording, and analyses. Participants completed two tasks in Experiment 3. The central color RSVP task was the same as that of Experiment 2 except that the visual angle of central letter streams varied from $0.18^\circ \times 0.18^\circ$ to $0.45^\circ \times 0.45^\circ$ across participants to maintain each individual's error rate at about 10% (Figure 4, upper exemplar). In the central size RSVP task, the target was a relatively large letter among a gray letter stream. The distractor letters always subtended $0.36^\circ \times 0.36^\circ$, and the size of the target letters varied from $0.52^\circ \times 0.52^\circ$ to $0.56^\circ \times 0.56^\circ$ across participants to keep a comparable task difficulty as in the central color RSVP task (Figure 4, lower exemplar). Each task consisted of six successive blocks of 64 trials. The order of tasks and mappings

of target characters to response hands were counterbalanced across participants. Different from Experiment 2, participants were asked to respond to the target letter as accurately and immediately as possible. Error rates and RTs were recorded. The electrophysiological recording and analysis were identical to those in previous experiments. The behavioral (error rates and RTs) and ERP (N2pc amplitudes) data were analyzed with paired *t* tests or one-sample *t* tests.

Results

Behavioral. The error rates of the central color RSVP task and the central size RSVP task were $9.6 \pm 0.6\%$ and $9.3 \pm 0.7\%$ (mean \pm SE), respectively. And the RTs were 563 ± 20 ms and 585 ± 24 ms, respectively (Figure 5, right panel). Paired *t* tests showed that the error rates did not differ between these two tasks, $t(11) = 0.624$, $p = .545$, and that the RTs were a little shorter in the color task than in the size task, $t(11) = 2.361$, $p = .038$.

ERPs. Figure 7 shows the ERPs elicited by the peripheral color singleton cues in the two tasks. A significant difference of the

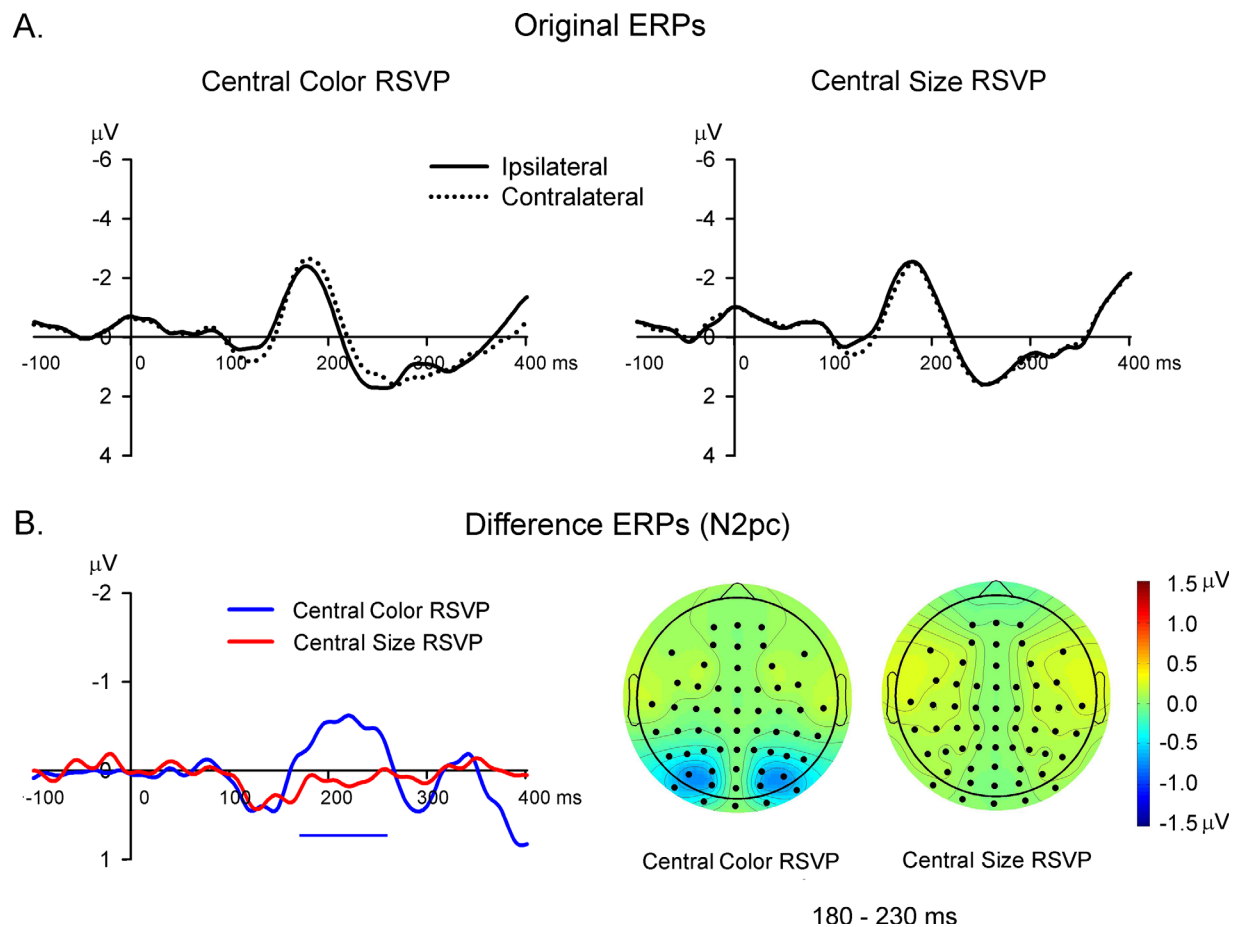


Figure 7. ERP results in Experiment 3. **A:** The original ERPs elicited by the color singleton cues at posterior electrode sites (collapsed across P7/8 and PO7/8) ipsilateral (solid lines) and contralateral (dotted lines) to the visual hemifield where the color singleton cue was presented. Negative plotted upwards. **B:** The N2pc elicited by the color singleton cues. The left panel shows the N2pc waveforms collapsed across P7/8 and PO7/8 sites. The color singleton cues elicited a significant N2pc component in the central color RSVP task (blue line) but not in the central size RSVP task (red line). The time window of significant N2pc amplitudes for the central color RSVP task is shown as a blue line below. The right panel shows the voltage topographical maps of the N2pc during the 180–230 ms time interval. The N2pc of the central color RSVP task was mainly distributed over occipital areas.

mean amplitude during the N2pc time window (180–230 ms) between the two tasks was found, $t(11) = 4.748$, $p = .001$. One sample t tests revealed that a significant N2pc component was observed in the central color RSVP task (180–230 ms: $-0.530 \pm 0.139 \mu\text{V}$, mean \pm SE; $t(11) = 3.813$, $p = .003$), whereas a slight but significant positive deflection was found in the central size RSVP task ($0.123 \pm 0.044 \mu\text{V}$; $t(11) = 2.762$, $p = .019$).

Discussion

The principal purpose of Experiment 3 was to test the possibility of whether the cue-elicited N2pc observed in the central color RSVP task of Experiment 2 was due to the prior experience of previously spatially relevant salient stimuli. Our results showed that, even when the color singleton cues were always spatially irrelevant, they elicited a significant N2pc in the central color RSVP task, ruling out this explanation.

Again, attentional capture was found to be contingent upon top-down feature selection. That is, the salient color singleton cues captured attention only when they shared the defining feature of the target (i.e., in the central color RSVP task), but not when they were totally task irrelevant (i.e., in the central size RSVP task). The

positive-going deflection found in the central size RSVP task might suggest suppression to the peripheral color singleton cues when they are task irrelevant (see Hickey, Di Lollo, & McDonald, 2009; the positive deflection within the N2pc time window was interpreted as an electrophysiological index of distractor suppression).

General Discussion

In the present study, the N2pc component was adopted as an electrophysiological marker of attentional deployment to investigate how top-down attention influences the attentional capture by salient color stimuli. Using modified spatial cueing paradigms, we varied the eccentricity of the targets to manipulate the focus of top-down spatial attention. In the peripheral VS tasks of Experiment 1 and 2, the peripheral cues shared the same possible locations as the peripheral targets, and therefore were located within the scope of top-down spatial attention. In the central VS task of Experiment 1 and the central RSVP task in Experiment 2 and 3, however, the peripheral cues and central targets were never presented at the same locations, and the distances between the cues and targets were over 3° of visual angle (edge to edge). Especially, the RSVP tasks in Experiment 2 and 3 required top-down attention to be

highly focused on a fixed central location. Even under these central tasks, the peripheral spatially irrelevant color singleton cues consistently elicited apparent N2pc components in the color tasks, suggesting that attentional capture may exist outside the focus of top-down spatial attention. Interestingly, this attentional capture by spatially irrelevant salient color stimuli seemed not sensitive to the specific type and difficulty of the central color task. That is, the peripheral color singleton cues triggered comparable N2pc components in both the relatively easy central color VS task (Experiment 1) and the relatively difficult central color RSVP tasks (Experiment 2 and 3). Further analysis confirmed that, although the difficulties were significantly different, $F(2,33) = 19.162$, $p < .001$, $\eta_p^2 = .537$, no significant difference was found in N2pc amplitude across these three conditions, $F(2,33) = 0.323$, $p = .726$, $\eta_p^2 = .019$. These results suggested that spatially irrelevant salient stimuli captured visual attention in a very general and robust way.

Although top-down spatial attention seems to be not necessary for attentional capture, it plays a significant role. In Experiment 1, the behavioral spatial cueing effect induced by the peripheral color cue was larger in the peripheral color VS task than in the central color VS task, indicating that attention capture is modulated as a function of the spatial distance between the cue array and the target array. This finding is in accordance with a recent behavioral study (Leonard, Balestreri, & Luck, 2015) where Leonard et al. varied the locations of peripheral cue arrays in a color RSVP task and found that the interference of performance by the color cues became smaller when the cues were put farther away from the target. More importantly, here we provide consistent ERP results showing that the cue-elicited N2pc (180–230 ms, occipital sites) was much stronger when the cue array and target array shared same locations (peripheral color VS tasks in Experiment 1 and 2) than when they were far away from each other (central color VS task in Experiment 1 and central color RSVP task in Experiment 2). These N2pc effects, with maximum amplitudes over the occipital areas and at ~ 200 ms after the stimulus onset, further confirmed that attentional capture by spatially irrelevant salient items is derived from relatively early visual cortical processing, but not from high-level late processing (such as decision making, which involves frontal cortical regions). Thus, our study provided both behavioral and electrophysiological evidence supporting that top-down spatial attention can modulate attentional capture by salient peripheral cues.

In a previous study, Seiss et al. (2009) reported that the N2pc elicited by a nontarget color singleton was unaffected by top-down spatial attention when the target was defined by a different color feature (Experiment 1 of Seiss et al.). The different manipulations of top-down spatial attention between the current study and Seiss et al. (2009) might account for the disparate results. Through central cues, Seiss et al. manipulated spatial attention in a trial-by-trial manner. Participants might not completely and efficiently deploy their attention to the cued side during attention shifting, and redundant top-down spatial attention might be available on the uncued side, especially when attention is not highly demanded for the task (error rate $< 4\%$ in Experiment 1 of Seiss et al.). In the present study, however, the peripheral and central tasks were manipulated in a block design. In the blocks of the peripheral VS task, top-down spatial attention was continuously allocated to the locations of the cue arrays where the target would be presented. In the blocks of the central VS task and the central RSVP task, however, little (if any) top-down spatial attention was allocated to the peripheral cue arrays. This block design maximized the difference of the top-down attentional deployment on the same peripheral cue arrays

between the central and peripheral task conditions and, accordingly, a significant modulation effect of top-down spatial attention was revealed in the present study. Consistently, in Experiment 2 of Seiss et al. (2009) where task demand was increased and stimulus salience was reduced, they also found the modulation effect of top-down spatial attention on the nontarget-elicited N2pc, probably resulting from an enlarged imbalance of spatial attention deployment between the attended and unattended locations under this situation.

Although salient color cues can capture attention even when spatially unattended, this effect is contingent on a feature-based task set. In the present study, when the color cues were outside of the focus of spatial attention, the cue-elicited N2pc, as well as the behavioral spatial cueing effect, was found only when the targets were color singletons but not when they were outlined or larger ones. These results reinforce the essential role of feature selection in attentional capture and are in line with the findings from previous RSVP tasks that peripheral distractors preceding targets decreased the identification of a central target (Folk, Leber, & Egeth, 2002) and elicited the N2pc (Leblanc et al., 2008) when the distractors possessed the target-defining features. Also, our results suggest that feature selection can take effect outside of the focus of top-down spatial attention, which is consistent with the findings of previous single unit recordings (Martinez-Trujillo & Treue, 2004; Motter, 1994; Treue & Martinez-Trujillo, 1999) and fMRI studies (Saenz, Buracas, & Boynton, 2002).

Based on the present results and the literature, we propose that top-down feature attention and spatial attention may have distinctive roles in attentional capture. Whereas feature attention determines whether attentional capture happens or not, spatial attention modulates the magnitude of attentional capture. We infer that, when a certain feature is selected, neurons tuned to that feature are globally activated, and those neurons whose receptive fields overlap with the focus of spatial attention might be further enhanced. Thus, the N2pc elicited by featurally relevant but spatially irrelevant cues might be due to the global effect of feature selection (e.g., Andersen, Hillyard, & Muller, 2008; Andersen, Fuchs, & Muller, 2011; Melcher, Papathomas, & Vidnyánszky, 2005), and the enlarged N2pc elicited by both featurally and spatially relevant cues might reflect the summation of the global effect of feature selection and the local enhancement by spatial attention. This proposal may also shed insights into the relationship between feature-based attention and space-based attention. While some studies (e.g., Anllo-Vento & Hillyard, 1996; Hillyard & Munte, 1984) showed that attention to features is dependent on attention to locations, some others (e.g., Liu & Mance, 2011; Serences & Boynton, 2007) suggested that feature-based attention can act in a location-independent manner. According to our proposal, however, while feature selection (as indexed by contingent attentional capture in the present study) may exist outside the focus of spatial attention, its magnitude can still be modulated by top-down spatial attention, suggesting that top-down spatial attention is not essential but has significant influence on feature selection.

In the present study, to reveal the effect of attentional capture by spatially unattended cues and the modulation effect of top-down spatial attention on attentional capture, the spatial distance between the unattended locations (i.e., the cue array) and the attended locations (i.e., the target array) was set to be $\sim 3\text{--}4^\circ$ of visual angle, and the attended locations were at the central area while the unattended locations were at the peripheral area. Further studies are needed to investigate whether the salient featurally relevant stimulus can capture attention in other spatially unattended conditions, such as

when an increased distance is introduced between the attended and unattended locations, or when both the attended and unattended locations are at peripheral areas. Moreover, it must be admitted that, besides the spatial relevance of the cue, the spread of attentional focus might also contribute to the present effect of attentional modulation, since the task with a spatially relevant cue adopted a diffuse attentional window (i.e., peripheral task) and the task with a spatially irrelevant cue adopted a focused attentional window (i.e., central task). Further studies are needed to investigate whether only one of these two factors or both contributes to the modulation effect of spatial attention, such as when the task with a spatially relevant cue adopts a focused attentional window while the task with a spatially irrelevant cue adopts a diffuse attentional window, or

when these two tasks adopt the same spreading level of attentional windows.

In summary, the present study provides both behavioral and electrophysiological evidence showing that a salient color feature can capture visual attention regardless of whether it is located within the focus of top-down spatial attention or not. This attentional capture is subject to top-down control in that it is contingent on top-down feature selection and can be modulated by top-down spatial attention. These results dissociate the roles of feature- and space-based attention in attentional capture, and suggest that top-down spatial attention is important but may not be necessary for contingent attentional capture.

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