

Top-down directed attention to stimulus features and attentional allocation to bottom-up deviations

Risa Sawaki

Graduate School of Education, Hokkaido University,
Sapporo, Japan, &
Japan Society for the Promotion of Science, Japan



Jun'ichi Katayama

Faculty of Education, Hokkaido University, Sapporo, Japan



One highly controversial issue with respect to visual selective attention concerns the degree to which the top-down attentional mechanism modulates attentional allocation to bottom-up deviation. We investigated whether top-down directed attention to a stimulus feature modulates attentional allocation to task-irrelevant, bottom-up deviation. The P3 event-related potential was measured as an electrophysiological marker of attentional allocation. Target and non-target objects were serially presented in random order. Bottom-up deviations occurred as a change in task-irrelevant features of target or non-target objects, or as the appearance of task-irrelevant distractor objects around target or non-target objects. When task-irrelevant features were changed, the P3 deviant effect was greater in target than in non-target trials. In contrast, when distractor objects appeared, the P3 deviant effect was smaller in target than in non-target trials. These findings suggest that top-down directed attention to a stimulus feature modulates attentional allocation to bottom-up deviation such that attentional allocation is enhanced when bottom-up deviation and an attended feature share the same object but is inhibited when bottom-up deviation occurs outside an object with an attended feature. Thus, the top-down attentional mechanism has a strong influence even for deviant processing and provides a competitive advantage for objects with an attended feature.

Keywords: top-down attentional mechanism, bottom-up attentional mechanism, selective attention, stimulus feature, task-irrelevant deviation, event-related brain potential, P3

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Introduction

In our visual world, we are faced with a vast amount of both spatial and temporal information. However, our cognition is limited with regard to its processing capacity, and therefore, we need to select important information from among what we see. Selective attention contributes to this selection process, and it has been proposed that there are “top-down” and “bottom-up” attentional mechanisms (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Egeth & Yantis, 1997; Kastner & Ungerleider, 2000; Theeuwes, 1991a; Yantis & Egeth, 1999). The top-down attentional mechanism selects information in favor of behavioral goals or task demands. When we have knowledge about a target, we can find it among multiple non-targets more easily. In contrast, the bottom-up attentional mechanism selects information based on the properties of the stimuli themselves, for instance, physical salience or stimulus deviation. Our attention is often allocated for deviant information such as objects with a unique color in the spatial (Theeuwes, 1991a) and temporal (Dalton & Lavie, 2006) contexts or objects with an abrupt onset (Egeth & Yantis, 1997; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984), even when it is irrelevant to ongoing activity.

In the literature on visual attention, there is a debate concerning the degree to which the top-down attentional mechanism modulates attentional allocation to bottom-up deviation (Theeuwes & Burger, 1998). One view is that such attentional allocation is entirely determined by the physical properties of the stimuli and there is no top-down influence (e.g., Hickey, McDonald, & Theeuwes, 2006; Theeuwes, 1994, 2004). The other view is that attentional allocation is dynamically modulated by a top-down attentional mechanism (e.g., Bacon & Egeth, 1994; Folk & Remington, 1998, 1999; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Sawaki & Katayama, *in press*; Yantis & Jonides, 1990). Several studies using visual search tasks have shown evidence that supports top-down modulation. For instance, when observers have knowledge about where a target is likely to appear, a distractor could be ignored even though it has a high stimulus salience (Theeuwes, 1991b; Yantis & Jonides, 1990). Furthermore, the observer’s search mode for target detection affects attentional allocation to deviant distractors (Bacon & Egeth, 1994; Lamy & Egeth, 2003). When observers adopt a “singleton search mode,” in which attention is strategically set to respond to a deviation in general, attention is allocated not only to deviant targets but also to deviant distractors. In contrast, when they adopt a “feature search mode,” in which

attention is directed to a particular feature of the target (e.g., circle), deviant distractors can be ignored.

Recent studies have indicated that spatial attention is an important factor in these top-down modulations: attentional allocation to bottom-up deviation is modulated by the extent of the spatial attention that is controlled by the top-down mechanism (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Theeuwes, 2004). Knowledge regarding where a target is likely to appear generates focused spatial attention on the anticipated target location and a deviant distractor consequently falls outside the attentional focus, which results in the elimination of attentional capture to the deviant distractor. Similarly, a feature search mode results in a serial search with a narrow focus of spatial attention, and thus, a distractor falls outside the attended region. In contrast, a singleton search mode induces a parallel search with a widely distributed spatial attention, and thus, a deviant distractor inevitably falls within the attended region. Therefore, attention is not allocated to a deviant distractor in the feature search mode but in the singleton search mode. This assertion is consistent with a recent electrophysiological study, which demonstrated that attentional allocation to a deviant distractor is increased within an attentional focus but decreased outside its focus (Sawaki & Katayama, [in press](#)).

According to these previous studies, top-down controlled “spatial” attention can modulate attentional allocation to bottom-up deviation. However, it is unclear whether or not top-down directed attention toward “a particular stimulus feature belonging to an object” modulates attentional allocation to bottom-up deviation. As an effect of top-down visual attention toward an object, it has been proposed that the processing of an unattended feature is enhanced when it belongs to an object with an attended feature, and consequently, the object gains a competitive advantage in selective attention (Desimone & Duncan, 1995; Duncan, Humphreys, & Ward, 1997). Evidence to support this theory has been reported following several approaches. For instance, psychophysics studies have shown that selective attention toward the color of a dot field modulates the processing of motion of the same dot field (e.g., Sohn, Pappathomas, Blaser, & Vidnyánszky, 2004). The processing of unattended motion is modulated even when the perception of motion is subthreshold (Melcher & Vidnyánszky, 2006). Furthermore, fMRI studies have demonstrated that neural activities for the processing of unattended features are modulated by top-down visual attention toward an object (McMains, Fehd, Emmanouil, & Kaster, 2007; O’Craven, Downing, & Kanwisher, 1999). Several neural areas (e.g., fusiform area) respond to a specific stimulus feature (e.g., face), and their activities are enhanced when attention is directed to their preferred feature but attenuated when attention is drawn away from it. However, even when attention is directed to an unpreferred feature, the neural activities of these signal-specific areas are enhanced if their preferred features belong to an object with the

attended feature. In addition, an electrophysiological study has reported that color-related components of event-related potentials (ERP) and magnetoencephalograms are enlarged when an unattended color signal belongs to an attended moving surface (Schoenfeld et al., 2003).

These previous studies suggest that when the object contains a top-down attended feature, the processing of not only attended but also unattended features of the same object is facilitated. Is attentional allocation to bottom-up deviation enhanced when this deviation belongs to objects with an attended feature, or is the attentional allocation to bottom-up deviation independent of top-down directed attention toward the object and entirely determined by the bottom-up mechanism? The present study examined if attentional allocation to bottom-up deviation is modulated according to whether bottom-up deviation and a top-down attended feature share the same object. Furthermore, although the top-down attentional mechanism provides a competitive advantage for an object with an attended feature, the bottom-up attentional mechanism also provides a competitive advantage for an object with stimulus deviation. Is attentional allocation to bottom-up deviation inhibited when deviant distractor objects appear around an object with an attended feature, or do objects with an attended feature have no advantage when they compete with distractor objects which have bottom-up deviation? The present study also examined whether attentional allocation to bottom-up deviation is modulated according to whether deviant distractor objects appear around an object with or without a top-down attended feature.

To answer these questions, the P3 component of the ERP, which is a positive-going deflection over the parietal scalp for target and over the central scalp for non-target with a peak latency of about 300–600 ms, was measured as an electrophysiological marker of attentional allocation (Donchin, 1981; Kok, 2001; Sawaki & Katayama, 2006a, 2006b, 2007, 2008; Sutton, Braren, Zubin, & John, 1965; Verleger, 1997). It has been proposed that the degree of attentional allocation is greater toward deviant stimuli than non-deviant, frequent stimuli. This increase in attentional allocation toward deviant stimuli is reflected by a larger P3 response for deviant stimuli than for frequent stimuli (i.e., P3 deviant effect). The P3 response can be elicited by stimuli regardless of whether they evoke a behavioral response. Therefore, the degree of attentional allocation can be directly evaluated by the P3 response even when there are no observable behavioral responses.

The present study used a simple visual discrimination task in which circle- and triangle-shaped objects were serially presented at the central location of a display with equal probability. Participants were asked to respond to objects that had a target-defined shape (circle or triangle), regardless of infrequent deviation. For frequent stimuli, we expected that attentional allocation would be facilitated more for a target object than for a non-target object because the target object contained a top-down attended feature (i.e., target-defined shape; circle or triangle).

Therefore, a larger P3 response would be observed in target, compared to non-target, frequent trials.

In the *change* condition, bottom-up deviation occurred infrequently as a change in task-irrelevant features (stimulus color and size) of target or non-target objects. This condition was provided to examine the hypotheses that attentional allocation to bottom-up deviation is modulated according to whether bottom-up deviation and a top-down attended feature share the same object. If attentional allocation to bottom-up deviation is enhanced when bottom-up deviation and an attended feature share the same object, the P3 deviant effect should be increased in target, compared to non-target, trials. In the *appearance* condition, task-irrelevant distractor objects were presented around either target or non-target objects. The distractor objects had bottom-up deviation since they appeared abruptly at a blank location (e.g., Egeth & Yantis, 1997; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). This condition was provided to examine the hypotheses that attentional allocation to bottom-up deviation is modulated according to whether deviant distractor objects appear around an object with or without a top-down attended feature. If attentional allocation to bottom-up deviation is inhibited when deviant distractor objects appear around an object with an attended feature, the P3 deviant effect should be decreased in target, compared to non-target, trials. However, if attentional allocation to bottom-up deviation is not modulated by top-down directed attention to a stimulus feature, there should be no differences in the P3 deviant effect between target and non-target trials in either condition.

defined by the shape of the stimulus (circle/triangle): for half of the participants, the circle was target and the triangle was non-target, and for the other half, the triangle was target and the circle was non-target. Two conditions were defined by two types of deviation: in the change condition, target or non-target objects were changed with regard to their stimulus size and color, and in the appearance condition, distractor objects appeared on the sides of frequent target or non-target objects.

At a viewing distance of 1 m, stimuli were presented in a random series, once every 1.2 s for a duration of 120 ms on a gray background. For frequent stimuli in both conditions, a blue circle (1.15° wide \times 1.15° tall) or a blue triangle ($1.32^\circ \times 1.15^\circ$) was presented at the center of the display. For deviant stimuli in the change condition, a large red circle ($2.29^\circ \times 2.29^\circ$) or a large red triangle ($2.63^\circ \times 2.29^\circ$) was presented at the center of the display. For deviant stimuli in the appearance condition, frequent target or non-target objects were presented at the center of the display and two red squares (both $2.03^\circ \times 2.03^\circ$) were presented on both sides of the frequent object; the center-to-center distance between the central frequent object and the surrounding square was 2.16° . The stimuli in each condition are summarized in Figure 1 for the case in which the target is a circle. The participants were instructed to respond to the target by pushing a button with the right thumb as quickly and accurately as possible, regardless of its color and size changes (change condition) or distractor appearance (appearance condition). A practice series was presented before each condition. The order of the two conditions was randomized across participants.

Methods

Participants

Twelve young adults (7 men, 5 women) with normal or corrected-to-normal visual acuity and normal color vision served as participants ($M = 20$ years, $SD = 1.8$ years, age range = 18–23 years). All participants were right-handed (self-report) and they reported being free of neurological or psychiatric disorders and provided written, informed consent.

Stimuli and procedure

Participants performed 510 trials for each condition (see below), consisting of frequent target, deviant target, frequent non-target, and deviant non-target with probabilities of 40%, 10%, 40%, and 10%, respectively. Thus, target and non-target trials occurred with the same probability (50%), and a bottom-up deviation occurred with a probability of 20%. Target and non-target were

	Change		Appearance	
	Frequent (80%)	Deviant (20%)	Frequent (80%)	Deviant (20%)
Target (50%)				
Non-target (50%)				

Figure 1. Stimulus characteristics for each task condition for the case where the target is a circle. For half of the participants, the circle was target and the triangle was non-target, and for the other half, the triangle was target and the circle was non-target. Circles and triangles for frequent stimuli in both conditions and deviant stimuli in the appearance condition were blue. Circles and triangles for deviant stimuli in the change condition and squares for deviant stimuli in the appearance condition were red.

Recording and analysis

Electroencephalographic (EEG) activity was recorded with an electrode cap using Ag/AgCl electrodes from 30 electrode sites at Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, and O2, according to the modified 10-20 System. Voltage changes caused by eye movements and blinks were monitored with EEG recordings from forehead sites (Fp1 and Fp2). A common reference electrode was placed at the nose tip, and impedance was kept at 10 k Ω or less. The EEG signals were amplified with a bandpass of 0.05–100 Hz and digitized at 500 Hz.

The EEG was digitally low-pass filtered off-line at 30 Hz (6 dB/octave) with a finite impulse response (FIR) analog simulation filter. Averaging epochs were 900 ms, beginning 100 ms before stimulus onset. Waveforms were averaged, such that trials with a response error or those in which the EEG exceeded $\pm 100 \mu\text{V}$ were rejected automatically. P3 was defined as the largest positive-going peak that occurred within the time window between 300 and 700 ms after stimulus presentation. To estimate the reliable peak amplitude and peak latency, averaged waveforms were digitally low-pass filtered at 8 Hz (24 dB/octave) with an FIR zero-phase filter. Peak latencies were measured from the time of stimulus onset at Pz for target P3 and at Cz for non-target P3. These electrodes were chosen for latency analysis because target P3 and non-target P3 were maximal at Pz and Cz, respectively. Peak amplitudes were measured relative to the prestimulus baseline at the Pz (target) and Cz (non-target) peak latency points. The deviant effect for a P3 response was defined as the difference in the peak amplitude between frequent and deviant stimuli. To reduce the number of statistical comparisons, the data from three midline electrodes (Fz, Cz, Pz) were analyzed statistically. All analyses of variance (ANOVAs) used Greenhouse–Geisser corrections to the degrees of freedom, and only the corrected probability values are reported.

Results

Behavioral results

The behavioral data are summarized in Table 1. A two-way ANOVA performed on the reaction times for target as a function of condition (change, appearance) and deviancy (frequent, deviant) revealed a main effect of deviancy, $F(1, 11) = 17.7$, $p = 0.001$, indicating that the reaction time for the deviant target was longer than that for the frequent target. The same analysis of hit rate for target revealed no significant effects. A two-way ANOVA performed on the false positive rates for non-target as a

	Change		Appearance	
	Frequent	Deviant	Frequent	Deviant
Reaction time (ms)	301	321	300	316
SD	40	37	34	45
Hit targets (%)	99.6	99.1	99.2	99.1
SD	0.5	2.3	1.8	2.6
False positive rate (%)	3.3	4.9	1.8	9.4
SD	2.9	4.9	2.2	7.2
P3 peak latency (ms)				
Target	390	397	382	395
SD	53	27	33	26
Non-target	390	394	383	398
SD	47	37	34	32

Table 1. Mean reaction times, performance rates, and P3 peak latencies for target (Pz) and non-target (Cz) stimuli for each task condition.

function of condition (change, appearance) and deviancy (frequent, deviant) revealed a main effect of deviancy, $F(1, 11) = 12.9$, $p = 0.004$, however, this effect was qualified by two-way interactions with condition, $F(1, 11) = 13.7$, $p = 0.003$. Post hoc comparisons revealed that there was no significant difference in the false positive rate between frequent and deviant non-target in the change condition, whereas the false positive rate for deviant non-target was higher than that for frequent non-target in the appearance condition ($p = 0.001$).

ERP results

Figure 2 shows the grand averaged ERPs from the three midline electrodes at frontal (Fz), central (Cz), and parietal (Pz) sites for each stimulus type. Figure 3 shows topographic maps taken at the latency of the peak P3 amplitude for the target and non-target stimuli in each task condition.

The P3 amplitude data from the midline electrodes (Fz, Cz, and Pz) were assessed with a four-factor ANOVA as a function of condition (change, appearance), stimulus category (target, non-target), deviancy (frequent, deviant), and electrode (Fz, Cz, Pz). Main effects of condition, $F(1, 11) = 20.0$, $p = 0.001$, deviancy, $F(1, 11) = 40.9$, $p = 0.001$, and electrode, $F(1, 11) = 29.5$, $p = 0.001$, were obtained. These effects were further modified by interactions of stimulus category \times electrode, $F(1, 11) = 18.5$, $p = 0.001$, $\epsilon = 0.78$, deviancy \times electrode, $F(1, 11) = 10.4$, $p = 0.004$, $\epsilon = 0.64$, and condition \times stimulus category \times deviancy, $F(1, 11) = 28.9$, $p = 0.001$.

Post hoc comparisons revealed that the P3 amplitude of both target and non-target trials was larger for deviant stimuli than for frequent stimuli in both conditions (change condition: target $p = 0.001$, non-target $p = 0.002$; appearance condition: target $p = 0.01$, non-target

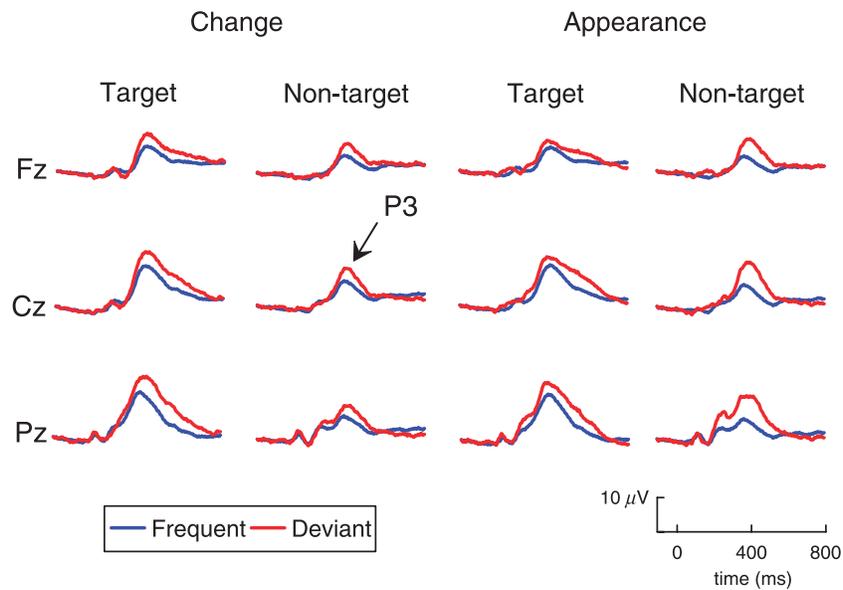


Figure 2. Grand averaged ERPs for each condition from three midline electrodes at frontal (Fz), central (Cz), and parietal (Pz) sites ($N = 12$).

$p = 0.001$). Therefore, a deviant effect was obtained regardless of the stimulus category in both conditions. In addition, for frequent stimuli, the P3 amplitude was larger for target than for non-target trials in both conditions (change condition: $p = 0.001$; appearance condition: $p = 0.001$). For deviant stimuli, the P3 amplitude was larger for target than for non-target trials in the change condition ($p = 0.001$), whereas there was no significant difference in the appearance condition.

Most importantly, the P3 deviant effect (the difference in the peak P3 amplitude between frequent and deviant stimuli) for the target versus non-target stimuli showed an opposite pattern for the change and appearance conditions. Figure 4 shows the P3 deviant effect in the change and appearance conditions, collapsed across midline electrodes

(Fz, Cz, and Pz). In the change condition, the deviant effect was significantly larger for target than for non-target trials ($p = 0.026$). In contrast, in the appearance condition, the deviant effect was significantly larger for non-target than for target trials ($p = 0.02$).

As for the scalp distribution, target P3 had a more parietal distribution compared to non-target P3. The P3 amplitude was larger for target than for non-target at Cz and Pz electrode sites (Cz: $p = 0.006$, Pz: $p = 0.001$), while there was no significant difference at the Fz electrode site.

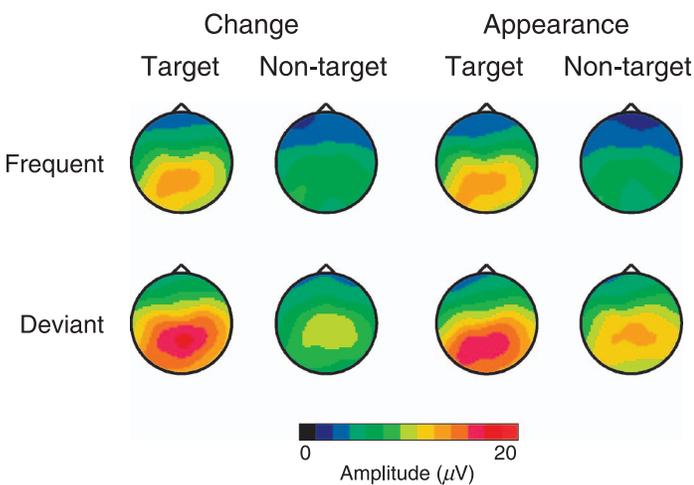


Figure 3. Topographic maps taken at the P3 peak latency from the target and non-target in each task condition.

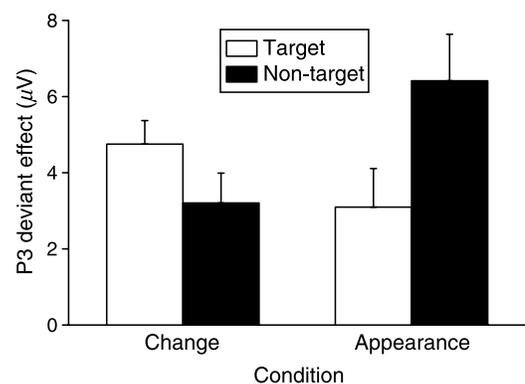


Figure 4. P3 deviant effect (the difference in the peak P3 amplitude between frequent and deviant stimuli) for each trial in the change and appearance conditions, collapsed across midline electrodes (Fz, Cz, and Pz). Error bars indicate standard errors of the means. For the change condition, the deviant effect was larger in target than in non-target trials. In contrast, for the appearance condition, the deviant effect was larger in non-target than in target trials.

P3 latencies for target and non-target in each condition are summarized in Table 1. A three-factor ANOVA (2 Conditions \times 2 Stimulus Categories \times 2 Deviancies) of the latency found neither main effects nor interactions.

Discussion

The present study examined whether top-down directed attention to a stimulus feature of an object modulates attentional allocation to a bottom-up deviation. To examine the issue that attentional allocation to bottom-up deviation is modulated according to whether bottom-up deviation and a top-down attended feature share the same object, infrequent deviation occurred as a change in the task-irrelevant features of the target or non-target object in the change condition. Furthermore, to examine the issue that attentional allocation to bottom-up deviation is modulated according to whether deviant distractor objects appear around an object with or without a top-down attended feature, infrequent deviation occurred as the appearance of task-irrelevant distractor objects around either the target or non-target objects in the appearance condition. The P3 response was used as an electrophysiological marker of attentional allocation.

In both conditions, the P3 response for frequent stimuli was larger in target than in non-target trials. This result can be understood as a basic effect of top-down directed attention toward a stimulus feature (Desimone & Duncan, 1995; Duncan et al., 1997). In the present study, the target and non-target objects were continuously presented in a stimulus sequence and a behavioral response was required only for target objects. This task demand resulted in selective bias toward the attended feature. Accordingly, attention was allocated more toward target objects that have the attended feature.

With regard to the P3 deviant effect in target and non-target trials, the present study found an opposite pattern between the change and appearance conditions. In the change condition, the P3 deviant effect was larger for target than for non-target trials. This result reflects that attentional allocation to bottom-up deviation is enhanced when bottom-up deviation and an attended feature share the same object. In contrast, the P3 deviant effect was smaller for target than for non-target trials in the appearance condition. This result reflects that attentional allocation to bottom-up deviation is inhibited when deviant distractor objects appear around an object with an attended feature. These findings suggest that attentional allocation to bottom-up deviation is modulated by top-down directed attention toward a stimulus feature such that an object with an attended feature gains a competitive advantage, even when there is a bottom-up deviation.

In the literature on selective attention, it has been proposed that our visual processing is biased by two

different attentional mechanisms (Hopfinger, Buonocore, & Mangun, 2000; Hopfinger & Mangun, 1998). The top-down mechanism selects information based on a behavioral goal and facilitates the processing of information with an attended signal. As an effect of the top-down selective attention mechanism, it has been reported that top-down directed attention toward a stimulus feature facilitates the processing of unattended features when they belong to an object with an attended feature (McMains et al., 2007; Melcher & Vidnyánszky, 2006; O'Craven et al., 1999; Schoenfeld et al., 2003; Sohn et al., 2004) and provides a competitive advantage for objects with an attended feature (Desimone & Duncan, 1995; Duncan et al., 1997). In the bottom-up mechanism, information is selected based on its physical properties and is preferentially processed, regardless of whether it is related to a behavioral goal. Previous studies have demonstrated that these two mechanisms are not exclusive but rather have mutual influences because attentional allocation to bottom-up deviation is modulated by the extent of spatial attention, which is controlled by the top-down attentional mechanism (Belopolsky et al., 2007; Sawaki & Katayama, *in press*; Theeuwes, 2004). However, it has not yet been elucidated whether top-down directed attention to a stimulus feature of an object modulates attentional allocation to bottom-up deviation. The results of the present study suggest that the modulation of the processing of an unattended feature occurs even for an unattended bottom-up deviation, and objects with an attended feature gain an advantage in selection even when they compete with bottom-up deviation.

Spatial attention is modulated by several factors such as observers' search mode (Bacon & Egeth, 1994; Lamy & Egeth, 2003) or perceptual load (Lavie, 1995, 2005; Lavie & Tsal, 1994). In the present study, target and non-target trials occurred randomly, and thus, there were no differences in the influence from search mode between these trials. In addition, stimulus configuration of the display was the same between target and non-target trials; therefore, the perceptual load was equal between these trials. Thus, the observed difference between target and non-target trials in the present study cannot be explained by top-down controlled spatial attention. This notion was supported by the fact that significant differences in early visual components of the ERP (e.g., P1 and N1), which is altered by spatial attention, were not observed between target and non-target trials.

The reaction time for target was delayed for deviant compared to frequent stimuli in both conditions. This reflects the notion that attention is allocated to bottom-up deviation, and this results in distraction from task-relevant processing (Schröger & Wolff, 1998). Although there was no significant difference in the false positive rate between frequent and deviant non-target trials in the change condition, the false positive rate for deviant non-target was higher than that for frequent non-target trials in the appearance condition. These results suggest that a large

amount of attention was allocated toward distractor objects, which led to an impulsive response for irrelevant distractors.

Conclusions

Previous studies of visual selective attention have investigated the relationship between the top-down and bottom-up attentional mechanisms, and it has been reported that top-down controlled spatial attention can modulate attentional allocation to bottom-up deviation. The present study revealed that top-down directed attention to a stimulus feature dynamically modulates attentional allocation to bottom-up deviation: attentional allocation to bottom-up deviation is enhanced when bottom-up deviation and an attended feature share the same object, and attentional allocation is inhibited when deviant distractor objects appear around an object with an attended feature. Top-down directed attention to a stimulus feature has a strong influence even for deviant processing and provides a competitive advantage for objects with an attended feature. This finding significantly contributes to the further understanding of the top-down and bottom-up attentional mechanisms, which are not exclusive but rather have mutual influences.

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Corresponding author: Risa Sawaki.

Email: sawaki@edu.hokudai.ac.jp.

Address: Graduate School of Education, Hokkaido University, Kita-11 Nishi-7, Kita-ku, Sapporo 060-0811, Japan.

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