Attentional capture is contingent on the interaction between task demand and stimulus salience

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The aim of this research was to investigate the potential impacts of task demand and stimulus salience on the stimulus-driven attentional capture effect. The participants performed an inefficient visual search task while an irrelevant luminance singleton was present. In Experiment 1, the task demand was manipulated while the stimulus salience of the irrelevant singleton was fixed. With the same salient singleton, the attentional capture effect was observed in the low-difficulty condition but disappeared in the high-difficulty condition. In Experiment 2, the stimulus salience was manipulated while the task demand was fixed. With the same task, the highly salient singleton captured attention, whereas the relatively lowly salient singleton could not. In Experiment 3, both task demand and stimulus salience were manipulated simultaneously. The stimulus-driven attentional capture effect by the irrelevant singleton increased not only as the task demand decreased but also as the stimulus salience increased. The present study might provide a way to reconcile conflicting findings in the attentional capture literature; the underlying neural mechanism is discussed.

It is well known that visual selective attention can be controlled in either a goal-directed or a stimulus-driven manner. When observers are able to orient their attention to objects and events according to their current behavioral goals and intentions, selection is said to be *goal-directed*, *top-down*, or *endogenous*. When attention is involuntarily attracted by specific objects and events irrelevant to the current goals and intentions of observers, selection is said to be *stimulus-driven*, *bottom-up*, or *exogenous*.

Although researchers have been investigating for decades what kind of stimuli have the ability to summon attention in a stimulus-driven fashion, this issue—referred to as *attentional capture*—is still quite hotly debated (for reviews, see Rauschenberger, 2003a; Simons, 2000). The literature contains three main influential theoretical accounts. First, some researchers have proposed that attention is always captured by the most salient element in the stimulus display, regardless of any top-down modulation (Theeuwes, 1991a, 1992, 1994). Second, some researchers have proposed that only stimuli matching the observer's attentional control setting are capable of capturing attention (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). Third, other researchers have proposed that attentional capture is unique to specific stimulus properties such as *abrupt onset* (Jonides &

Yantis, 1988; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). However, evidence for each approach is rather mixed. In Theeuwes's studies, the stimulus display usually contained two salient feature singletons, each unique in a different dimension. One singleton defined the target and the other served as the distractor. Theeuwes found that when the distractor was more salient than the target, reaction times (RTs) were elevated, relative to the distractor absence condition. By contrast, when the distractor was less salient, no interference effect was found, so Theeuwes concluded that when search was performed in parallel, attentional allocation depended on the relative bottom-up salience of the elements in the stimulus display, and that top-down selectivity based on target attributes was not possible. However, Bacon and Egeth (1994) claimed that when the target itself was a feature singleton, as in Theeuwes's experiments, the task might be performed using a singleton detection mode, in which the participants simply searched for a discontinuity. Thus, any additional irrelevant singleton could capture attention. When the target was instead specified by a particular value on a feature dimension, the task needed to be performed using a feature search mode, in which the participants searched for the relevant target feature. Thus, a salient distractor could no longer capture attention. This

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distinction between the two modes suggests the possibility of top-down selectivity for the relevant target feature.

Furthermore, the most important source of evidence for the top-down modulation of attentional capture is provided by Folk et al. (1992). In their study, they used the cue–target paradigm, in which a spatially uninformative cue was presented shortly before a target. Both the cue and the target were defined as either an abrupt onset singleton or a color singleton. Their results revealed that when the target was an abrupt onset, only an onset cue captured attention, whereas a color cue did not; when the target was a color singleton, however, only a color cue captured attention, whereas an onset cue did not. On the basis of such findings, Folk et al. (1992) proposed the *contingent involuntary orienting hypothesis*, which claimed that the ability of a feature singleton to capture attention was contingent on the establishment of a top-down attentional control setting for that feature (Folk et al., 1994). According to this view, attentional capture is ultimately conditional on the observer's intention and is therefore not purely stimulus-driven.

The contingent capture account is supported by the findings that feature singletons in color, luminance, or motion fail to elicit attentional capture effects in the absence of any relevant attentional setting (Folk & Annett, 1994; Hillstrom & Yantis, 1994; Jonides & Yantis, 1988; Todd & Kramer, 1994; Yantis & Egeth, 1999), but there is evidence that the abrupt onset of a new perceptual object can capture attention automatically, irrespective of the task at hand (Jonides & Yantis, 1988; Remington, Johnston, & Yantis, 1992; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). For instance, in Jonides and Yantis's serial visual search task, the participants searched for a prespecified target letter embedded among several nontarget letters. On each trial, one letter possessed a feature that differed from all the other letters. Any letter in the search display, including the target letter, had an equal chance of being the unique feature singleton. Because the feature singleton was neither consistent with the participants' adopted attentional setting for letter identity, nor predictive of the target position, there was no goal-directed incentive for the participants to attend to it. If the unique feature singleton was able to capture attention involuntarily, it would be the first one to be processed by the visual system. RTs to find the target should be independent of display size when the feature singleton happened to be the target. Thus, the singleton target function should have a zero search slope. By contrast, if the feature singleton was unable to capture attention and therefore its status was not different from that of any nonsingleton element, the singleton target slope should be steep and identical to the nonsingleton target slope. In this irrelevant feature search paradigm, the pattern of results indicative of attentional capture was obtained only in the abrupt onset condition, not in static discontinuity conditions. Therefore, Yantis and colleagues proposed the *new-object hypothesis*, which claimed that only the appearance of a new perceptual object could capture attention in a purely stimulus-driven fashion, whereas other salient feature singletons did not (Yantis, 1993; Yantis & Hillstrom, 1994). Although there has been considerable debate as to whether the capture effect associated with abrupt onset may be due to a less obvious top-down setting for other features (Franconeri, Hollingworth, & Simons, 2005; Franconeri, Simons, & Junge, 2004; Gellatly, Cole, & Blurton, 1999; Gibson & Kelsey, 1998), recent studies have demonstrated that abrupt onset indeed plays a special role in attentional guidance (Cole, Kentridge, & Heywood, 2004; Lamy & Egeth, 2003). Moreover, other recent studies have shown that some stimulus properties also appear to capture attention effectively, such as motion onset (Abrams & Christ, 2003), color change (Lu, 2006; Lu & Zhou, 2005), urgent event (Franconeri & Simons, 2003), and unique temporal change (von Mühlenen, Rempel, & Enns, 2005).

So far, most current evidence for stimulus-driven attentional capture is unique to some dynamic stimuli. Although there has been relatively little direct evidence supporting attentional capture by salient static stimuli, some recent studies have demonstrated capture effects by using indirect methods that reasonably rule out possible top-down influences (Horstmann, 2002; Theeuwes & Burger, 1998; Theeuwes & Godijn, 2002). For instance, Theeuwes, Atchley, and Kramer (2000) found that a color singleton distractor indeed interfered with the search for a shape singleton target when the distractor preceded the target by 100 msec or less, suggesting that attention might be initially drawn to the distractor position and then swiftly disengaged. Turatto and Galfano (2001) found capture effect by a salient color singleton when data were analyzed according to the distance method instead of the usual display-size method.

However, the efficiency of dynamic stimuli to capture attention is not absolutely immune to top-down modulations and bottom-up influences. Even for abrupt onset, Yantis and Jonides (1990) reported that when the subsequent target position was known in advance an abrupt onset presented elsewhere no longer captured attention (see also Juola, Koshino, & Warner, 1995; Theeuwes, 1991b). Furthermore, Martin-Emerson and Kramer (1997) showed that the capture effect by abrupt onset attenuated with an increasing number of no-onset elements in the display. Likewise, von Mühlenen et al. (2005) showed that abrupt onset was less effective in capturing attention when it occurred with other environmental changes simultaneously.

In summary, dynamic stimuli exhibit powerful potential to capture attention in a purely stimulus-driven fashion, but their potential can be modulated by both goal-directed and stimulus-driven factors. Salient static stimuli merely possess a weak ability to capture attention involuntarily, unless they receive goal-directed prioritization. Although all contemporary hypotheses in the attentional capture literature are valuable for researchers to understand the mechanism underlying stimulus-driven attentional capture, none of them is entirely compatible with all current experimental results. How are we to give a clear answer to these complicated findings in the attentional capture literature? In attentional capture experiments, the participants have to mobilize the voluntary attention mechanism to perform the task at hand, whereas the bottom-up salience of the task-irrelevant stimulus is computed by the visual system,

then triggers actively the reflexive attention mechanism. It seems likely that the efficiency of the task-irrelevant stimulus to capture attention may be jointly determined by the current task and the stimulus salience. Recently, the influences of top-down and bottom-up controls on attentional capture were investigated by Theeuwes (2004). According to his attentional window account, the size of the attentional window may be under a top-down control, but within the window salience computations occur in parallel, and no top-down control is possible. Therefore, attention always goes to the most salient element within the window in a bottom-up fashion, whereas elements outside the window will be ignored. When the target is salient enough to allow parallel search, the attentional window is set wide to encompass the whole stimulus display and any salient distractor will capture attention. When the target is not salient enough and search becomes serial, the size of the attentional window will be reduced. Consequently, any salient distractor outside the window fails to capture attention. This window account has been supported by several studies. Belopolsky, Zwaan, Theeuwes, and Kramer (2007) showed that an irrelevant color singleton was more likely to attract attention in the diffuse-attention condition than in the focused-attention condition. Furthermore, Proulx and Egeth (2006) showed that as target–nontarget similarity was increased, the salient irrelevant singleton had less impact on search.

The purpose of the present study was to further evaluate the relative impact of task demand and stimulus salience on the stimulus-driven attentional capture effect systematically, as well as their interaction. On the one hand, when the task demand was fixed, the potential of the task-irrelevant stimulus to capture attention might increase as the stimulus salience increased; on the other hand, when the salience of the irrelevant stimulus was fixed, the potential of the irrelevant stimulus to capture attention might decrease as the task demand increased. In the present study, we used a design similar to that used by Proulx and Egeth (2006), in which the participants performed a visual search task for a vertical target line among gray disks containing tilted distractor lines; one disk was brighter than the other homogeneous disks. The luminance singleton was not only uninformative about the target position but also orthogonal to the participants' adopted attentional control setting for line orientation, so that it was irrelevant to the task. The vertical-line detection task was chosen because it was relatively easier to manipulate the task demand by adjusting the degree of orientation of the distractor lines while holding the participants' attentional setting for the vertical line constant. The luminance discontinuity was chosen because it was relatively easier to manipulate the stimulus salience by adjusting the luminance contrast of the singleton element relative to nonsingleton elements. Although salient static discontinuities were usually unable to produce a zero slope for the singleton target function, it is worth noting that in many studies involving static discontinuity, the slope of the singleton target function was significantly less than the slope of the nonsingleton target function (e.g., Lu & Zhou, 2005, Experiment 2; Yantis & Egeth, 1999, Experiment 3). A conventional explanation for such a difference between the two slopes is that the singleton element enjoyed a real but small priority advantage over nonsingleton elements, suggesting that the salient static singleton had an impact on attentional deployment. Therefore, in this study, we expected a difference between the two slopes instead of a zero slope of the singleton function. Furthermore, we calculated the slope ratio (the difference in slopes divided by the nonsingleton slope), as used in Proulx and Egeth, to indicate the attentional priority of the salient singleton in the current task demand condition.

EXPERIMENT 1

The aim of Experiment 1 was to investigate the role of task demand in attentional capture. We manipulated the task demand while keeping the stimulus salience constant. The chosen vertical-line detection task was known to be an inefficient visual search task, and could produce steep search slopes as a function of target–distractor similarity (Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). Task difficulty could increase with the similarity between the target and distractors: The more similar they were, the more difficult the task was. We expected that when the task difficulty was higher, the participants would restrict attentional resources more selectively to the target-defining feature to perform the task and then the irrelevant luminance singleton would be less likely to attract attention than when the task difficulty was relatively lower.

Method

Participants. Ten college students (6 male, 4 female; age range, 20–24 years) served as paid volunteers. All had normal or corrected-to-normal vision and were naive to the purpose of the experiment.

Stimulus and Procedure. The experiment was carried out in a dimly lit and sound-attenuated room. The participants sat approximately 57 cm from the monitor. At the center of the black screen was a green fixation cross of $0.7° \times 0.7°$. On each trial, the stimulus display consisted of three or six gray disk elements ($1.2°$ in radius), equally spaced around the fixation on an imaginary circle with a radius of $5.7°$. The three disks formed an upward-pointing equilateral triangle; the six disks formed a hexagon. All the disks but one had a luminance of 3.0 cd/m^2. The luminance value of the singleton disk was fixed at 27.0 cd/m^2. Each disk contained a black line segment subtending $1.0°$ in length. The target line was vertical, whereas the degree of orientation of distractor lines from vertical was either $\pm30°$ (defined as low difficulty; see Figure 1A) or $\pm15°$ (defined as high difficulty; see Figure 1B). The stimulus display remained present until a response was made or 2,500 msec elapsed.

The participants were asked to search for the vertical target line in the stimulus display. They responded by pressing the "M" key on a standard keyboard for target present and the "C" key for target absent. They were instructed to respond as quickly as possible while maintaining accuracy. Immediate error feedback was provided by a 200-msec, 400-Hz beep. RTs were measured from the onset of the stimulus display. The participants were explicitly requested to maintain fixation throughout the entire trial. They were also informed that the target position was random and that the location of the luminance singleton disk was uninformative about the location of the target.

Design. There were three main variables: task difficulty, display size, and target type. The two task difficulties were low difficulty and high difficulty, and the two display sizes were three and six. The three target types were target present within the luminance single-
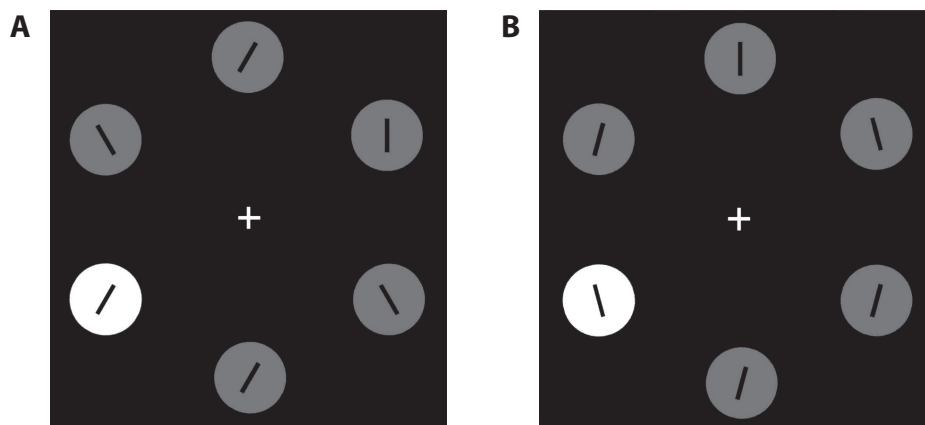
Figure 1. Sample stimulus displays for (A) the low-difficulty condition and for (B) the high-difficulty condition of Experiment 1. The participants' task was to search for the vertical target line among gray disks containing tilted distractor lines, with one disk being brighter than the other homogeneous disks. In both conditions, the luminance value of the nonsingleton disks was 3.0 cd/m² (shown here as dark gray) and the luminance value of the singleton disk was 27.0 cd/m² (shown here as light gray). In (A) the low-difficulty condition, the distractor lines had a tilt of either +30° or −30° from vertical, randomly. In (B) the high-difficulty condition, the distractor lines had a tilt of either +15° or −15° from vertical, randomly. In both conditions, the location of the target line was uncorrelated with the location of the luminance singleton disk. In this example, representing display size six, the target line is not presented inside the singleton disk.

ton disk (or, for brevity, *present singleton*), target present within another nonsingleton disk (or *present nonsingleton*), and target absent. Task difficulty conditions were run in separate blocks. In each block, each display size occurred equally often. Overall, the target was present on one half of the trials and was absent on the remainder. When the target was present, it had an equal chance of appearing within any of the disk elements; that is, when display size was three, one third of the present trials were present-singleton ones; when display size was six, however, only one sixth of the present trials were present-singleton ones. With this design, there was no incentive for the participants to deliberately attend to the luminance singleton disk, because that element was not predictive of the target position in the stimulus display. In each task difficulty block, the 3 target-type trials were combined with the two display-size conditions. The order of the trials in each task difficulty block was random. Each participant received four experimental blocks of 96 trials for each task difficulty condition. The presentation order of the eight blocks was high–high–low–low–low–low–high–high for half of the participants, and low–low–high–high–high–high–low–low for the other half. Each participant completed a corresponding practice block of 60 trials before the first experimental block of each task difficulty condition and some corresponding warm-up trials before the seventh experimental block. After each block, a short rest period was given. The experimental session took approximately 1.5 h, including breaks.

Results

In this and subsequent experiments, error trials were excluded from analysis. In addition, correct RTs of less than 300 msec or greater than 3 SDs above the mean were trimmed. This removed approximately 3.8% of the observations from this experiment.

Mean RTs in the low- and high-difficulty conditions are plotted in Figure 2, and error rates are listed in Table 1. For the overall target-present trials only, repeated measures ANOVAs were conducted on mean RT and error rate data with task difficulty (low difficulty or high difficulty), dis-

play size (three or six), and target type (present singleton or present nonsingleton) as factors. The analysis of the RT data revealed main effects of display size [$F(1,9) = 65.72$, $p < .001$] and target type [$F(1,9) = 14.25$, $p < .005$]. The main effect of task difficulty was also significant, with faster RTs in the low- versus high-difficulty condition [$F(1,9) = 65.77$, $p < .001$], indicating that the task in the high-difficulty condition was indeed harder than that in the low-difficulty condition. There was a significant interaction between task difficulty and display size [$F(1,9) = 44.28$, $p < .001$], but no other interactions (all ps $> .14$). In addition, the analysis of error rate revealed main effects of task difficulty [$F(1,9) = 19.96$, $p < .003$] and display size [$F(1,9) = 12.44$, $p < .007$], and a significant interaction between task difficulty and display size [$F(1,9) = 6.15$, $p < .036$]. The three-way interaction was also significant [$F(1,9) = 5.61$, $p < .043$]. Neither the main effect of target type [$F(1,9) = 0.40$, $p > .50$] nor any other two-way interaction (all ps $> .40$) approached significance. The error rate pattern paralleled the RT data pattern, excluding any speed–accuracy trade-off. Of main interest was the role played by task difficulty in attentional guidance. Therefore, the target-present data in each task difficulty condition were entered into separate ANOVAs, with display size and target type as factors.

In the low-difficulty condition, the analysis of the RT data yielded significant main effects of both display size [$F(1,9) = 26.81$, $p < .002$] and target type [$F(1,9) = 9.86$, $p < .013$]. The interaction between the two variables was significant as well [$F(1,9) = 6.13$, $p < .036$], indicating that there was a difference between the slopes of the two target-present functions. Furthermore, the slope of the present-singleton function was 27.0 msec/item, which was significantly greater than zero [$t(9) = 3.30$, $p <$
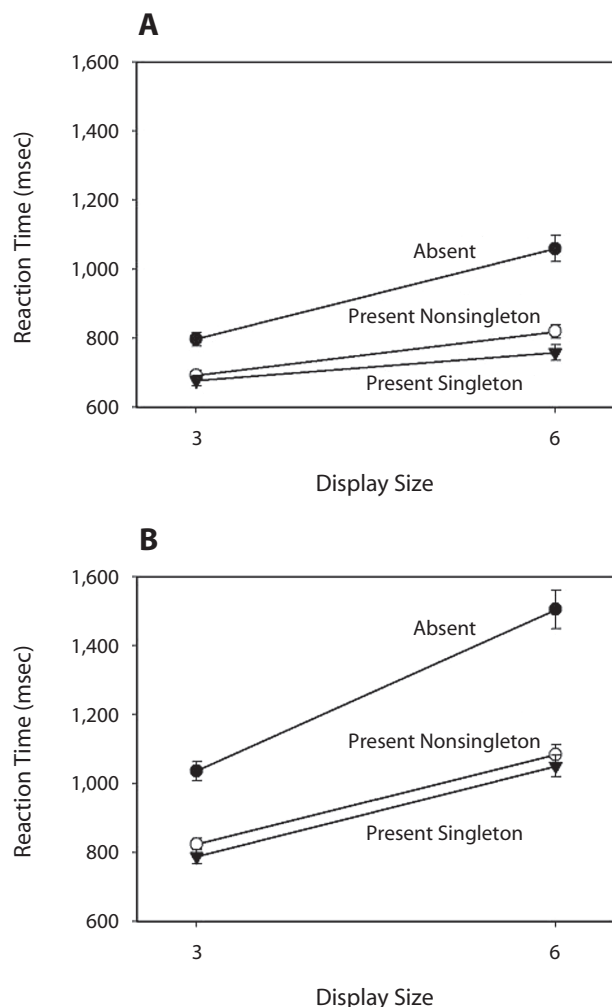
Figure 2. Mean reaction times in (A) the low-difficulty condition and in (B) the high-difficulty condition of Experiment 1, plotted as a function of display size for target-absent, target-present nonsingleton, and target-present singleton trials.

.010]. The slope of the present-nonsingleton function was 42.3 msec/item. The mean slope ratio averaged across all participants was 0.43. In addition, the analysis of error rate did not reveal any significant effect.

Table 1
Error Rates (Percentage) by Display Size
and Target Type in the Low-Difficulty and
High-Difficulty Conditions for Experiment 1

Trial Type	Display Size	
	3	6
Low Difficulty		
Absent	2.3	0.7
Present nonsingleton	2.0	5.4
Present singleton	2.5	2.5
High Difficulty		
Absent	1.8	4.0
Present nonsingleton	4.7	10.0
Present singleton	3.1	11.3

In the high-difficulty condition, the analysis of the RT data yielded a significant main effect of display size [$F(1,9) = 76.77, p < .001$], but no effect of target type [$F(1,9) = 4.18, p > .070$]. The interaction between the two variables did not reach significance [$F(1,9) = 0.01, p > .923$], indicating that the slopes of the two target-present functions did not differ. Furthermore, the slopes were 87.3 msec/item for the present-singleton function and 86.5 msec/item for the present-nonsingleton function. The mean slope ratio was -0.06, which was significantly smaller than that in the low-difficulty condition [$t(9) = 2.27, p < .050$]. In addition, the analysis of error rate revealed only the main effect of display size [$F(1,9) = 11.47, p < .009$].

Discussion

The design and results of Experiment 1 were similar to those of Proulx and Egeth (2006). In the low-difficulty condition, we observed a reliable difference between the slopes of the two target-present functions, suggesting that the irrelevant luminance singleton did somewhat guide attention to the singleton position, despite the failure to capture attention fully. In the high-difficulty condition, however, such a difference between the two target-present slopes disappeared, suggesting that the same salient stimulus in the low-difficulty condition was unable to guide attention in a harder search task. The significant reduction in the slope ratio showed that the salient irrelevant singleton received less attentional priority in the high- versus low-difficulty condition. The results of Experiment 1 suggested that with a certain stimulus salience, the potential of the task-irrelevant stimulus to capture attention decreased with the task demand. These results replicated the findings of Proulx and Egeth, in which target–nontarget similarity could modulate the stimulus-driven shift of attention to an irrelevant luminance singleton. Proulx and Egeth explained their results according to Theeuwes's (2004) attentional window account. Likewise, this window notion can account for the present results: As the task demand increased, the attentional window became smaller. Thus, the salient irrelevant singleton would be less likely to fall within the window and be less likely to attract attention.

EXPERIMENT 2

The aim of Experiment 2 was to investigate the role of stimulus salience in attentional capture. We manipulated the bottom-up stimulus salience of the irrelevant luminance singleton while keeping the task demand constant. Stimulus salience of one element could increase with the differences between it and the neighboring elements. Thus, although the luminance level of nonsingleton elements was fixed, the brighter the luminance singleton was, the greater stimulus salience it had. We expected that when the stimulus salience of the luminance singleton was higher, the irrelevant singleton would be more likely to attract attention than when the stimulus salience was relatively lower.

Method

Participants. Ten college students (4 male, 6 female, age range, 21–30 years) served as paid volunteers. All had normal or corrected-to-normal vision and were naive to the purpose of the experiment.
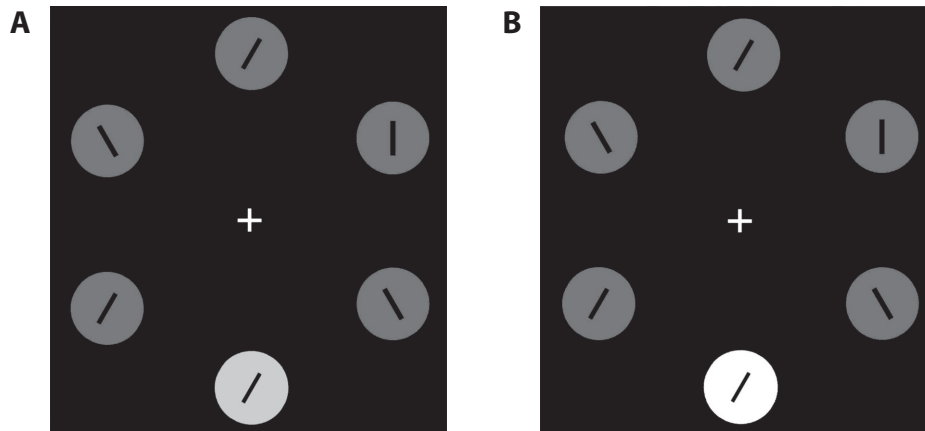
Figure 3. Sample stimulus displays for (A) the low-salience condition and for (B) the high-salience condition of Experiment 2. In both conditions, the distractor lines had a tilt of either $+30^{\circ}$ or -30° from vertical, randomly, and the luminance value of the nonsingleton disks was 3.0 cd/m² (shown here as dark gray). In (A) the low-salience condition, the luminance value of the singleton disk was 9.0 cd/m² (shown here as medium gray). In (B) the high-salience condition, the luminance value of the singleton disk was 27.0 cd/m² (shown here as light gray). In both conditions, the location of the target line was uncorrelated with the location of the luminance singleton disk. In this example, representing display size six, the target line is not presented inside the singleton disk.

Stimulus and Procedure. The stimulus and procedure were the same as those in Experiment 1, with a few exceptions. First, the degree of orientation of distractor lines from vertical was fixed at $\pm 30^{\circ}$. Second, although all nonsingleton disks had a luminance of 3.0 cd/m², the luminance value of the singleton disk was either 9.0 cd/m² (defined as low salience; see Figure 3A) or 27.0 cd/m² (defined as high salience; see Figure 3B). Note that the stimuli in the high-salience condition were identical to those in the low-difficulty condition of Experiment 1.

Design. There were three main variables: singleton salience, display size, and target type. The two singleton saliences were low salience and high salience, the two display sizes were three and six, and the three target types were target-present singleton, target-present nonsingleton, and target absent. Within each block, each singleton salience and each display size occurred equally often, and the three target-type trials were combined with the two singleton salience conditions and the two display-size conditions, producing 12 different types of trials. The order of the trials was random. Each participant received a practice block of 60 trials and six experimental blocks of 144 trials. Other aspects of the design were identical to those of Experiment 1.

Results

In this experiment, approximately 3.2% of the observations were removed. Mean RTs in the low-salience and high-salience conditions are plotted in Figure 4, and error rates are listed in Table 2. For the overall target-present trials only, separate ANOVAs were conducted on mean RT and error rate data with singleton salience (low salience and high salience), display size (three and six), and target type (present singleton and present nonsingleton) as factors. The analysis of the RT data revealed main effects of display size [$F(1,9) = 39.14, p < .001$] and target type [$F(1,9) = 19.09, p < .003$], as well as a significant three-way interaction [$F(1,9) = 9.20, p < .015$]. Neither the main effect of singleton salience [$F(1,9) = 0.06, p > .800$] nor any two-way interaction (all $ps > .10$) approached significance. In addition, the analysis of error rate revealed only a significant main effect of display size [$F(1,9) =$

10.85, $p < .010$. Of main interest was the role stimulus salience played in attentional guidance. Therefore, the target-present data in each singleton salience condition were entered into separate ANOVAs, with display size and target type as factors.

In the low-salience condition, the analysis of the RT data yielded a significant main effect of display size [$F(1,9) = 27.58, p < .002$] but no effect of target type [$F(1,9) = 3.78, p > .080$]. The interaction between the two variables did not reach significance [$F(1,9) = 0.07, p > .800$], indicating that the slopes of the two target-present functions did not differ. Furthermore, the slopes were 32.2 msec/item for the present-singleton function and 34.0 msec/item for the present-nonsingleton function. The mean slope ratio averaged across all participants was approximately zero. In addition, the analysis of error rate did not reveal any significant effect.

In the high-salience condition, however, the analysis of the RT data yielded significant main effects of both display size [$F(1,9) = 53.89, p < .001$] and target type [$F(1,9) = 11.25, p < .009$]. The interaction between the two variables was significant as well [$F(1,9) = 11.13, p < .010$], indicating a difference between the slopes of the two target-present functions. Furthermore, the slope of the present-singleton function was 15.9 msec/item, significantly greater than zero [$t(9) = 4.17, p < .003$]. The slope of the present nonsingleton function was 34.5 msec/item. The mean slope ratio was 0.49, significantly greater than that in the low-salience condition [$t(9) = 3.48, p < .008$]. In addition, the analysis of error rate revealed only a main effect of display size [$F(1,9) = 5.34, p < .047$].

Discussion

In the low-salience condition, we did not observe a difference between the slopes of the two target-present functions, suggesting that the irrelevant luminance singleton
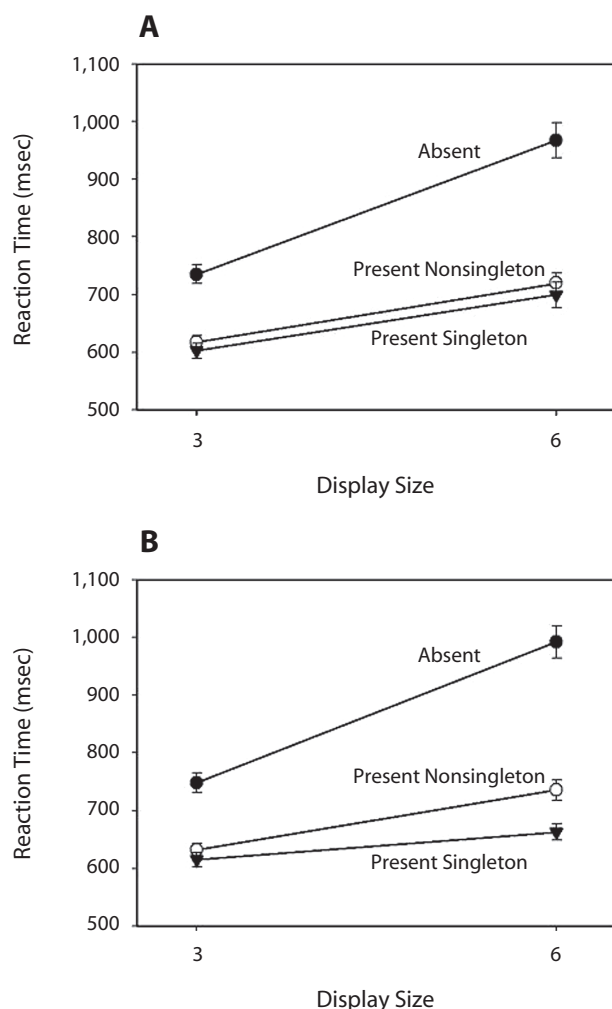
Figure 4. Mean reaction times in (A) the low-salience condition and in (B) the high-salience condition of Experiment 2, plotted as a function of display size for target-absent, target-present nonsingleton, and target-present singleton trials.

with low salience received no priority advantage over any other nonsingleton element. In the high-salience condition, however, we observed such a difference between the two target-present slopes again, replicating the results of the low-difficulty condition in Experiment 1. The sig-

Table 2
Error Rates (Percentage) by Display Size and Target Type in the Low-Salience and High-Salience Conditions for Experiment 2

Trial Type	Display Size	
	3	6
Low Salience		
Absent	2.7	2.1
Present nonsingleton	3.2	5.3
Present singleton	4.2	6.1
High Salience		
Absent	2.0	1.9
Present nonsingleton	2.8	5.6
Present singleton	2.5	4.4

nificant elevation in the slope ratio showed that the irrelevant singleton received more attentional priority in the high- versus low-salience condition. The results of Experiment 2 suggested that with a certain task demand, the potential of the task-irrelevant stimulus to capture attention increased with the bottom-up salience of the stimulus. These results seemed not fully compatible with the prediction of Theeuwes's (2004) attentional window account, that attention always went to the most salient element within the window. In Experiment 2, the size of the attentional window in the two singleton salience conditions should be identical because of the same task. Thus, the irrelevant singleton, whether of low or high salience, should have equal likelihood to intrude into the window and attract attention, according to the window account. Despite this discrepancy, the results of Experiment 2 suggest that stimulus salience should be considered another necessary factor in attentional capture. Although the importance of stimulus salience has been well documented in parallel search tasks, in which the attentional window might be very wide (e.g., Theeuwes, 1992, 1994), the present results further confirm the role of stimulus salience, even in serial search tasks in which the window might be relatively narrow.

EXPERIMENT 3

The roles of task demand and stimulus salience in attentional capture were investigated in Experiments 1 and 2, respectively. The results of the two experiments suggested that the potential of the irrelevant stimulus to capture attention not only decreased with the current task demand but also increased with the bottom-up stimulus salience. To examine the role of the interaction between task demand and stimulus salience in attentional capture, in the present experiment, we manipulated the two potentially causal factors at the same time.

Method
Participants. Ten college students (4 male, 6 female; age range, 19–26 years) served as paid volunteers. All had normal or corrected-to-normal vision and were naive to the purpose of the experiment.

Stimulus, Procedure, and Design. Four within-subjects factors were used: task difficulty (low difficulty or high difficulty), singleton salience (low salience or high salience), display size (three or six), and target type (present singleton, present nonsingleton, or absent). Each participant performed in two sessions on 2 different days. Each session consisted of two blocks of 192 trials for each task difficulty condition. Half of the participants had the high–low–low–high presentation order of the four blocks in Session 1 and the low–high–high–low order in Session 2, and the other half had the opposite. In each task difficulty block, the three target-type trials were combined with the two singleton salience conditions and the two display-size conditions, producing 12 different types of trials. The order of the trials in each task difficulty block was random. Other aspects were identical to those of Experiments 1 and 2.

Results
In this experiment, there were four combinations of task difficulty and singleton salience: low difficulty with low salience, low difficulty with high salience, high difficulty with low salience, and high difficulty with high salience.

Overall, approximately 4.1% of the observations were removed. Mean RTs in the four combination conditions are plotted in Figure 5, and error rates are listed in Table 3. For the overall target-present trials only, separate ANOVAs were conducted on mean RT and error rate data with task difficulty (low difficulty or high difficulty), singleton salience (low salience or high salience), display size (three or six), and target type (present singleton or present nonsingleton) as factors. The analysis of the RT data revealed main effects of task difficulty [$F(1,9) = 245.42$, $p < .001$], singleton salience [$F(1,9) = 9.47$, $p < .014$], display size [$F(1,9) = 78.05$, $p < .001$], and target type [$F(1,9) = 7.76$, $p < .022$]. There was a significant interaction between task difficulty and display size [$F(1,9) = 70.00$, $p < .001$], a significant interaction between singleton salience and display size [$F(1,9) = 13.78$, $p < .006$], and a significant interaction between singleton salience and target type [$F(1,9) = 11.80$, $p < .008$]. The three-way interaction between singleton salience, display size, and target type was also significant [$F(1,9) = 5.49$, $p < .045$]. No other interactions approached significance (all $ps > .070$). In addition, the analysis of error rate revealed main effects of task difficulty [$F(1,9) = 14.78$, $p < .005$] and display size [$F(1,9) = 18.54$, $p < .003$].

Of main interest was the interaction effect of task difficulty and singleton salience in attentional guidance. Therefore, the target-present data in each combination condition were entered into separate ANOVAs, with display size and target type as factors. In all combination conditions, the analysis of the RT data yielded significant main effects of display size (all $Fs > 28.57$, $ps < .001$). The main effects of target type were significant in the low-difficulty, high-salience condition [$F(1,9) = 40.11$, $p < .001$] and in the high-difficulty, high-salience condition [$F(1,9) = 10.19$, $p < .012$], and were not significant in the other two combination conditions ($ps > .50$). Only in the low-difficulty, high-salience condition was the interaction between display size and target type significant [$F(1,9) = 16.04$, $p <$
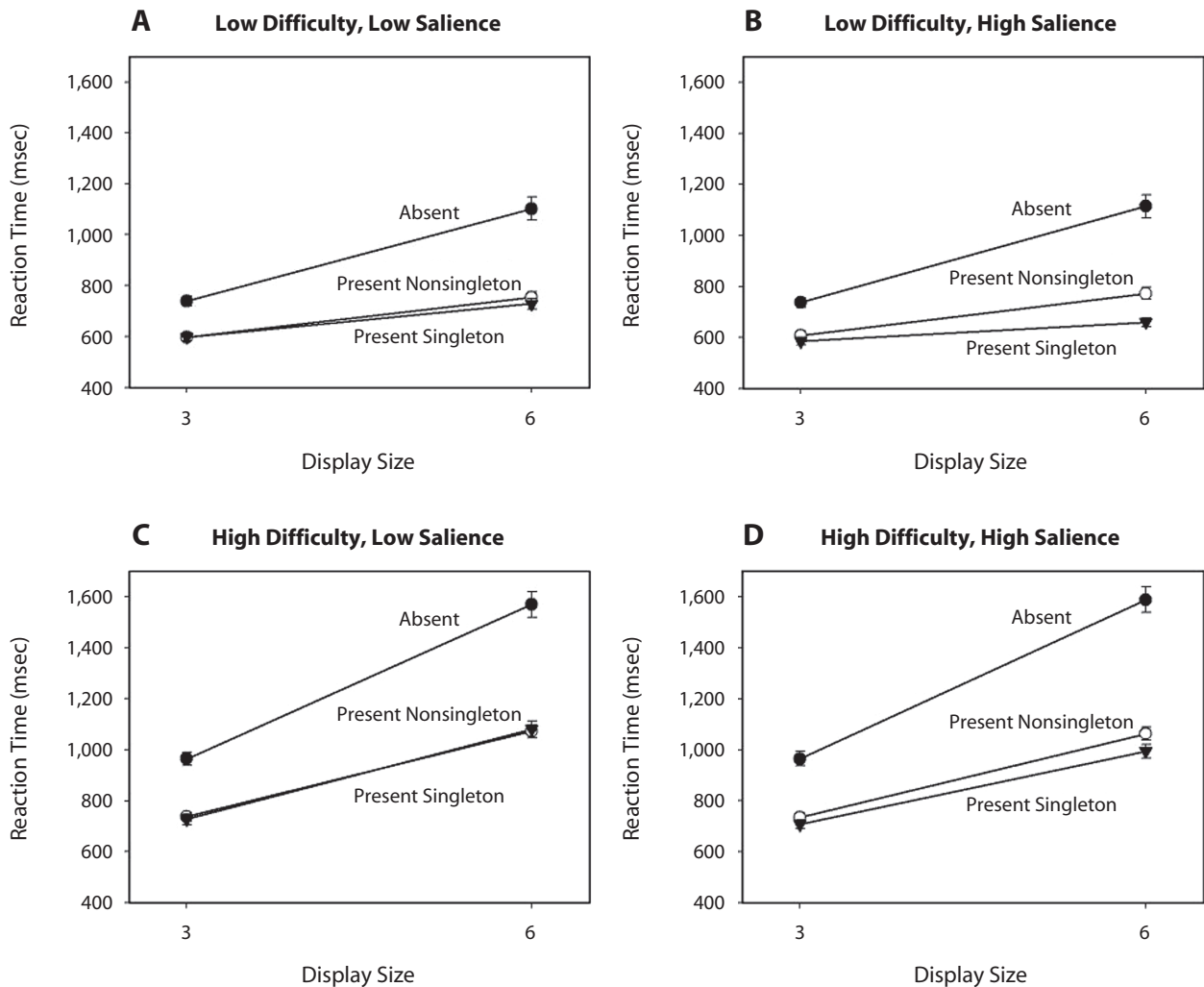

Figure 5. Mean reaction times in (A) the low-difficulty, low-salience condition, in (B) the low-difficulty, high-salience condition, in (C) the high-difficulty, low-salience condition, and in (D) the high-difficulty, high-salience condition of Experiment 3, plotted as a function of display size for target-absent, target-present nonsingleton, and target-present singleton trials.

Table 3
Error Rates (Percentage) by Display Size and Target Type in Each Combination of Task Difficulty and Singleton Salience for Experiment 3

Trial Type	Display Size	
	3	6
Low Difficulty, Low Salience		
Absent	2.0	0.9
Present nonsingleton	2.7	3.9
Present singleton	2.2	5.6
Low Difficulty, High Salience		
Absent	1.5	1.6
Present nonsingleton	2.8	3.9
Present singleton	1.3	5.6
High Difficulty, Low Salience		
Absent	1.5	6.5
Present nonsingleton	3.9	9.0
Present singleton	4.7	10.6
High Difficulty, High Salience		
Absent	1.6	8.4
Present nonsingleton	3.8	9.0
Present singleton	4.7	8.8

.004], indicating a difference between the slopes of the two target-present functions. The interactions between the two variables in other combination conditions were not significant ($ps > .095$). The analysis of error rates revealed only significant main effects of display size in all combination conditions (all $Fs > 4.76$, $ps < .05$).

Mean search slopes and the respective mean slope ratios averaged across all participants in the four combination conditions are listed in Table 4. Furthermore, the slope ratio data were entered into an ANOVA with task difficulty and singleton salience as factors. The main effect of task difficulty was significant [$F(1,9) = 20.97$, $p < .002$], indicating that the slope ratio in the low-difficulty condition was greater than that in the high-difficulty condition. The main effect of singleton salience was also significant [$F(1,9) = 6.98$, $p < .028$], indicating that the slope ratio in the high-salience condition was greater than that in the low-salience condition. Interestingly, the interaction between task difficulty and singleton salience was significant as well [$F(1,9) = 7.53$, $p < .024$], indicating that the disparity between slope ratios of the two singleton salience conditions was greater in the low- versus high-task difficulty condition, and the disparity between slope ratios of the two task difficulty conditions was greater in the high- versus low-singleton salience condition.

Table 4
Search Slopes (in Milliseconds) by Target Present Type and Respective Mean Slope Ratio in Each Combination of Task Difficulty and Singleton Salience for Experiment 3

Condition	Target Present Type		Slope Ratio
	Nonsingleton	Singleton	
Low difficulty, low salience	52.04	43.34	0.11
Low difficulty, high salience	54.70	24.88	0.54
High difficulty, low salience	111.93	117.68	−0.04
High difficulty, high salience	109.52	95.46	0.09

Discussion

In this experiment, task difficulty and singleton salience were manipulated simultaneously, producing four combinations of the two critical factors. The present results showed that the difference between the two target-present slopes was evident in the low-difficulty, high-salience condition, but disappeared in both the high-difficulty, high-salience condition and the low-difficulty, low-salience condition, replicating the results of both Experiments 1 and 2. In addition, such a difference was not observed in the high-difficulty, low-salience condition. Furthermore, the analysis of slope ratio showed that the potential of the task-irrelevant singleton to capture attention could increase not only as a function of the decreasing task difficulty but also as a function of the increasing singleton salience. The reliable interaction effect between task difficulty and singleton salience indicated that the irrelevant singleton had relatively more impact on visual search when the task was relatively less demanding and the stimulus was relatively more salient. Thus, the most attentional prioritization in the present experiment took place in the low-difficulty, high-salience condition.

GENERAL DISCUSSION

The goal of the present article was to investigate the potential influences of both task demand and stimulus salience on attentional capture. Experiment 1, replicating the findings of Proulx and Egeth (2006), showed that the specified task-irrelevant stimulus was less likely to capture attention when the task became more difficult. Experiment 2 showed that for the specified task, the ability of the irrelevant stimulus to capture attention increased with the stimulus salience. Experiment 3 further showed that the ability of the irrelevant stimulus to capture attention was jointly determined by task demand and stimulus salience. The three experiments together demonstrate that both task demand and stimulus salience should be the two critical factors in determining the occurrence and magnitude of attentional capture by an irrelevant stimulus. On the basis of the present findings, we suggest that attentional capture may reflect a dynamic interaction between voluntary attention determined by the task demand and reflexive attention evoked by the stimulus salience. Although previous research has documented the roles of task demand (e.g., Lavie, 2000) and stimulus salience (e.g., Theeuwes, 1994), respectively, the present article considers the role of the interaction between the two critical factors in attentional capture.

On the one hand, when the target becomes less salient and the search task becomes more difficult, the participants have to focus their attentional resources more selectively on the target-defining feature in order to perform the task, resulting in a higher demand for attentional resources. If the task is relatively easy and does not consume all resources, there may be some resources available for the visual system to assign priority to the irrelevant stimulus; the irrelevant stimulus therefore appears to be able to guide attention automatically. If the task is much harder and requires more resources, there may be no resources

available to process the irrelevant stimulus, so the irrelevant stimulus fails to guide attention. As Lavie (2000) showed, the irrelevant stimulus can be processed if the primary task does not consume all available resources.

On the other hand, when a stimulus becomes more salient its bottom-up activation in the salience map becomes higher, resulting in an increasing potential to summon attention automatically (Wolfe, 1994). If an irrelevant stimulus is inconspicuous, it has no impact on attentional guidance in an inefficient search task, so there is no difference between the two steep target-present slopes. If the stimulus is relatively more salient, it receives higher attentional priority, so the stimulus somewhat guides attention to its position, pulling the singleton target slope toward flat. If the stimulus is salient enough, it captures attention effectively, producing a flat singleton target slope. Therefore, attentional capture may not be interpreted as an all-or-none phenomenon, but as a matter of degree. Furthermore, the stimulus salience may be modulated by top-down influences. The salience of the stimulus that matches the attentional setting may be evaluated, whereas the salience of the stimulus outside the relevant setting may be reduced (Folk et al., 1992; Theeuwes et al., 2000). For example, attentional capture by target-colored distractors was accompanied by increased activity in corresponding visual cortical areas (Serences et al., 2005), whereas resistance to capture by same-salient but non-target-colored distractors was mediated by inhibitory processes (Lamy, Leber, & Egeth, 2004). Although Lamy et al. revealed some role of perceptual salience of stimuli within the attentional setting, the present article suggests for the first time a much more central role for bottom-up salience of stimuli outside any relevant attentional setting.

In summary, our findings suggest that attentional capture may be neither unique to specific stimuli (e.g., dynamic events) nor fully contingent on top-down control settings. It seems to be more appropriate to interpret attentional capture as a quantitative mechanism rather than as an all-or-none phenomenon. The extent of the attentional capture effect jointly depends on both the intensity of voluntary attention determined by task demand and the intensity of reflexive attention evoked by stimulus salience. As Berger, Henik, and Rafal (2005) suggested, both voluntary attention and reflexive attention were separate mechanisms that competed for shared or partly shared resources. Under low task demand, the two mechanisms had additive and independent orienting effects and even contradicted each other. In contrast, under high task demand, voluntary attention seized most resources, and reflexive attention no longer interfered with voluntary attention. Therefore, a strong form of attentional capture may be considered a competitive result that under appropriate conditions (i.e., the diffuse attention state induced by the relatively easy task and the high salience of the irrelevant stimulus), the reflexive mechanism activated by the irrelevant stimulus wins the voluntary mechanism induced by the task, resulting in an attentional orienting to the irrelevant stimulus.

Our suggestion that the interaction between reflexive attention determined by stimulus salience and voluntary attention determined by task demand influences the efficiency of the irrelevant stimulus to capture attention may imply a way to understand conflicting results and hypotheses in the attentional capture literature. First, dynamic stimuli may possess higher salience than static stimuli. In nature, dynamic stimuli may have high ecological significance, because organisms may have evolved to be sensitive to environmental changes that require immediate attention. The occurrence of dynamic stimuli needs organisms to make a corresponding action, thereby capturing attention. Thus, most direct evidence for stimulus-driven attentional capture comes from studies involving dynamic stimuli (e.g., Franconeri & Simons, 2003; Jonides & Yantis, 1988), whereas only some indirect evidence reveals relatively weak capture effects by static stimuli (e.g., Horstmann, 2002). Second, even the most potential dynamic stimulus—abrupt onset—fails to elicit capture effects, both when the participants' attention is highly focused (e.g., Yantis & Jonides, 1990) and when the salience of abrupt onset is lowered by adding greater environmental noise (e.g., Martin-Emerson & Kramer, 1997). Third, static stimuli have an impact on attentional capture, both when the task at hand is relatively easy and efficient (e.g., Theeuwes, 1992) and when the static stimuli are of higher salience (e.g., Turatto & Galfano, 2001). We reason that the capture effect that Turatto and colleagues observed may have been due to some factors of the design rather than methodological differences between the display-size method and the distance method (Turatto, Galfano, Gardini, & Mascetti, 2004). Actually, color discontinuity in their studies was more noticeable than that in previous studies (e.g., Jonides & Yantis, 1988). Moreover, other findings in the literature also appear to be compatible with our suggestion. For instance, regarding the reflexive attention aspect: In Rauschenberger's (2003b) study, when participants were set for new object onset, large luminance changes might be considered to be highly salient, so they captured attention, whereas small luminance changes might be considered to be relatively low salient, so they failed to capture attention. Regarding the voluntary attention aspect, in Theeuwes and Burger's (1998) study, the congruency effect associated with a salient but to-be-ignored color distractor was eliminated only when participants were fully informed about the colors of the target and the distractor.

Recent progress in physiological studies may shed light on the neural mechanism. The thalamus, as is well known, serves as a gate through which the flow of sensory inputs passes to the neocortex, and this gate is controlled by neuromodulators from the brainstem reticular formation (Sherman & Koch, 1986). Castro-Alamancos and Oldford (2002) showed that when rats were highly aroused, sensory-evoked responses were suppressed in the neocortex by weakening the efficiency of the thalamocortical connection. Moreover, Swadlow and Gusev's (2001) study suggested that when rabbits were in a relaxed state, their thalamocortical connections were enhanced after the emergence of thalamic bursts. These studies may point to the neural mechanism underlying the relation between voluntary attention and reflexive attention. When the in-

tensity of voluntary attention is high, the brain is kept in a highly aroused state, resulting in a reduced efficiency of the thalamocortical connection. In this case, the thalamus gate seems to be "narrow," so the visual system is able to process relevant information more selectively. Unless it is salient enough to enter and be processed, irrelevant information seems to be blocked outside the thalamus gate, making the observer appear insensitive to external events. When the intensity of voluntary attention is relatively low, the brain is kept in a relaxed state, resulting in enhanced efficiency of the thalamocortical connection. In this case, the thalamus gate seems to be "wide open," so that a great amount of sensory information, both relevant and irrelevant, can enter that gate and be processed by the visual system. Therefore, the intensity of reflexive attention is relatively high, and the observer appears to be susceptible to external events in the environment. Furthermore, using event-related potential measures, Handy, Soltani, and Mangun (2001) found that when the perceptual load of foveal target was increased, the occipital P1 amplitude evoked by a parafoveal stimulus was decreased. Using functional brain-imaging techniques, O'Connor, Fukui, Pinsk, and Kastner (2002) found that at the human thalamic level, neural responses to attended stimuli were enhanced and those to unattended stimuli were attenuated. These studies may suggest that the interaction between voluntary attention and reflexive attention occurs during the relatively early stage of visual processing.

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