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The effects of stimulus-driven competition and task set on involuntary attention

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It is well established that involuntary attention—the exogenous capture of attention by salient but taskirrelevant stimuli-can strongly modulate target detection and discrimination performance. There is an ongoing debate, however, about how involuntary attention affects target performance. Some studies suggest that it results from enhanced perception of the target, whereas others indicate instead that it affects decisional stages of information processing. From a review of these studies, we hypothesized that the presence of distractors and task sets are key factors in determining the effect of involuntary attention on target perception. Consistent with this hypothesis, here we found that noninformative cues summoning involuntary attention affected perceptual identification of a target when distractors were present. This cuing effect could not be attributed to reduced target location uncertainty or decision bias. The only condition under which involuntary attention improved target perception in the absence of distractors occurred when observers did not adopt a task set to focus attention on the target location. We conclude that the perceptual effects of involuntary attention depend on distractor interference and the adoption of a task set to resolve such stimulus competition.

Introduction

The means by which attention enhances perception are varied (Carrasco, 2011); attending to a location can

lead to target signal enhancement (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Ling & Carrasco, 2006a; Yeshurun & Carrasco, 1999), noise exclusion (Dosher & Lu, 2000a, 2000b; Lu & Dosher, 1998), and distractor suppression (Awh, Matsukura, & Serences, 2003; Beck & Kastner, 2009; Desimone & Duncan, 1995). These attentional effects on perception are particularly evident when attention is directed to the target location in a goal-directed manner; when an arbitrary cue shown at fixation is predictive of the location of the subsequently presented target, perceptual identification of that target is improved.

While the effects of goal-directed attention on perception are well established (Dosher & Lu, 2000b; Giordano, McElree, & Carrasco, 2009; Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2010; Kerzel, Zarian, & Souto, 2009; Ling & Carrasco, 2006a, 2006b; Ling, Liu, & Carrasco, 2009; Lu & Dosher, 1998; Prinzmetal, McCool, & Park, 2005), there is an ongoing debate about whether perception is also enhanced by noninformative peripheral cues that guide attention involuntarily; several groups of researchers have found significant effects of involuntary attention on perception (Anderson & Druker, 2013; Barbot, Landy, & Carrasco, 2011, 2012; Herrmann et al., 2010; Luck & Thomas, 1999; Pestilli & Carrasco, 2005; Pestilli, Viera, & Carrasco, 2007; White, Lunau, & Carrasco, 2013), whereas others argued that such effects were due to nonperceptual factors (Kerzel et al., 2009; Prinzmetal,

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McCool et al., 2005; Prinzmetal, Park, & Garrett, 2005).

To be sure, involuntary attention has significant behavioral consequences (faster and more accurate responses), but it has been claimed that these effects originate from modulation of nonperceptual process, such as reduced target location uncertainty (Prinzmetal, Ha, & Khani, 2010; Prinzmetal, McCool et al., 2005; Prinzmetal, Park et al., 2005). In a model suggested by Prinzmetal, McCool et al. (2005), voluntary-but not involuntary-attention affects perceptual processing. Specifically, with an informative cue that guides attention voluntarily, capacity-limited processing resources are allocated to the cued location, enhancing the perceptual representation of the stimulus on the attended location (channel enhancement). These attentional effects on perception are mainly revealed by improved identification accuracy under perceptually challenging conditions, in which stimuli are briefly presented or degraded (data-limited conditions, see Norman & Bobrow, 1975). In addition to these perceptual effects, the voluntary cue is also thought to facilitate nonperceptual decision processes; the cued location is selected prior to uncued locations for further access to response selection or decision-making processes (channel selection). These nonperceptual effects of attention are revealed by faster reaction times for attended stimuli under conditions where accuracy is near 100%.

By contrast, a salient, noninformative cue that guides attention involuntarily only affects channel selection. That is, the salient cue primarily affects decision processes by biasing the decision toward the cued location, without affecting perceptual representation of the attended stimuli (Prinzmetal et al., 2010). Consistent with their predictions, Prinzmetal, McCool et al. (2005) and Prinzmetal, Park et al. (2005) showed that voluntary, but not involuntary, attention had significant effects on perceptual identification accuracy. According to these authors, the effects of involuntary attention on accuracy observed in previous studies could be attributed to target location uncertainty, decision bias, uncontrolled eve movements, or experimental artifacts, rather than to perceptual enhancement (Prinzmetal, McCool et al., 2005; Prinzmetal, Park et al., 2005).

In contrast to the above studies, others point to involuntary attention affecting perception. Indeed, Carrasco and colleagues (Barbot et al., 2011, 2012; Giordano et al., 2009; Grubb et al., 2013; Herrmann et al., 2010; Pestilli & Carrasco, 2005; Pestilli et al., 2007; Montagna, Pestilli, & Carrasco, 2009; White et al., 2013) reported that noninformative peripheral cues affect performance (discrimination/identification accuracy and visual acuity) through modulation of perceptual processing in conditions that had none of the confounds pointed out by Prinzmetal, McCool et al. (2005) and Prinzmetal, Park et al. (2005). Consistent with these findings, a recent electrophysiological study (Störmer, McDonald, & Hillyard, 2009) showed that the effect of involuntary attention begins to emerge at an early stage of visual information processing. Specifically, a noninformative, auditory, spatial cue elicited enhanced electrophysiological responses to the visual target within 100 ms from the target onset, and this attentional modulation was observed in the ventral visual cortex. This finding further supports the claim that involuntary attention affects early visual processing rather than nonperceptual decision processes (Carrasco, 2009).

Not only have effects of involuntary attention on early visual processing been reported in several other studies of the spatial cuing paradigm (Chanon & Hopfinger, 2011; Chica, Bartolomeo, & Lupianez, 2013; Pack, Carney, & Klein, 2013; Santangelo & Spence, 2009), they have also been observed with a singleton cuing paradigm (White et al., 2013). In this study, a feature singleton that pops out among other stimuli acted as a spatial cue. While its effect was less pronounced and more dependent on the spatial distance between the singleton and target than that of a spatial cue, the perception of a target was enhanced when it was placed at the same location as the previously presented singleton.

What factor(s) could account for the conflicting results regarding the effect of involuntary attention on perception? A review of the literature reveals that the effect of involuntary attention was robust and reliable when a target was accompanied by distractors (Giordano et al., 2009; Herrmann et al., 2010; Liu, Pestilli, & Carrasco, 2005; Pestilli & Carrasco, 2005; Pestilli et al., 2007; Störmer et al., 2009; White et al., 2013). These effects were not due to reduced uncertainty of the target location by the cue as the effects were found even when such uncertainty was eliminated by a response cue denoting the target location (Herrmann et al., 2010; Pestilli & Carrasco, 2005; Pestilli et al., 2007; White et al., 2013). These findings imply that involuntary attention plays a role in resolving competition between multiple stimuli. Specifically, in a search task in which there are several distractors, the multiple stimuli compete against each other to be represented in the visual system (Beck & Kastner, 2005, 2009; Desimone & Duncan, 1995; Kastner, De Weerd, Desimone, & Ungerleider, 1998). Such competition is resolved if a stimulus pops out among the others (Beck & Kastner, 2005), as limited perceptual resources are biased towards that stimulus in an automatic or bottom-up manner. Such resolution of competition occurs even when all the competing stimuli are task irrelevant and presented outside of goal-directed, top-down attention (Beck & Kastner, 2005). We surmise that when a target is presented at the location of a salient peripheral cue that won out the competition for processing resources, the target's perceptual processing is also enhanced. This effect of involuntary attention on perception in the presence of distractor appears to be highly robust, as it has been observed across many studies.

By contrast, when there was no distractor, the results were inconsistent across different groups; in a series of experiments by Prinzmetal, McCool et al. (2005), a noninformative peripheral cue had no effect in the perception of a target, (Prinzmetal, McCool et al., 2005), whereas others found significant effects (Anderson & Druker, 2013; Giordano et al., 2009; White et al., 2013). Importantly, the findings by Anderson and Druker (2013), Giordano et al. (2009), and White et al. (2013) showing significant effects of involuntary attention in the absence of distractors were not confounded by location uncertainty as response cues denoting the target location were used.

To account for this discrepancy, we suggest that differences in task setting across different studies should be considered. Task set has been referred to as a series of intentions to perform a task (Monsell, 2003); it configures the cognitive system to optimally carry out specific task demands (Schneider & Logan, 2007). Importantly, even if the task remains the same, task set-which specifies task demands and strategiesvaries upon the specific nature of task stimuli and their context (Monsell, 2003; Schneider & Logan, 2007). According to a study by Folk, Remington, and Johnston (1992), attentional orienting by a noninformative cue is affected by task settings (Folk et al., 1992). Specifically, attentional orienting by a peripheral cue or singleton stimulus was diminished when participants had to look for specific target features to perform the task, compared to when the target could be found by looking for any salient singleton stimulus. Several other studies have shown that the involuntary capture of attention by a salient singleton stimulus is also influenced by task demands and strategies (Bacon & Egeth, 1994; Folk et al., 1992; Johnson, McGrath, & McNeil, 2002; Kiss, Grubert, Petersen, & Eimer, 2012; Leber & Egeth, 2006, but see also Theeuwes, 1991, 1992, 2004, 2010; White et al., 2013, for an opposing view and findings).

These findings suggest that differences in task set across studies are potentially responsible for discrepant findings regarding the effect of involuntary attention in the absence of distractors. Specifically, while in Prinzmetal, McCool et al.'s (2005) work, participants were required to identify a target and report its location, no such target localization was required in other studies (Anderson & Druker, 2013; Giordano et al., 2009; White et al., 2013). It is likely that the requirement to report the target location in Prinzmetal et al.'s work further incentivizes participants to focus on the location of the target and discourage them to attend to the salient cue. By contrast, without a target localization task, participants are more likely to adopt the strategy of attending to any salient stimulus as the target is also salient, which would persist even when a response cue denoting the target location is provided; one does not need to rely upon the response cue in distractor-absent displays, as the target is the only stimulus in the display.

Noteworthily, Kiss et al. (2012) showed that under different settings of a visual search task, different task strategies are configured, modulating the effect of salient task-irrelevant stimuli. Specifically, when the target could easily be found because the target and distractors were presented until the response, there was significant attentional capture by a salient taskirrelevant stimulus. However, when the demand for the target search increased because the target display was shortly presented, participants had to focus on the target location, which eliminated the attentional capture.

In the present study, we employed a spatial cuing paradigm to test under what conditions involuntary attention can affect perceptual processing. On each trial, participants were required to identify a peripherally presented target (letter or Gabor grating), which was preceded by a peripheral cue. An informative peripheral cue was used in the first experiment to demonstrate that our cue stimulus, when it was rendered informative, was effective in eliciting a significant cuing effect. In all of the subsequent experiments, the peripheral cue did not predict the target location because the main purpose of the study was to investigate the attentional effect of a noninformative peripheral cue on target perception.

We first tested the perceptual effect of involuntary attention either in the presence or in the absence of distractors. To ensure that the observed cuing effect under distractor interference was due to enhanced target perception rather than reduced target location uncertainty by the peripheral cue (Morgan, Ward, & Castet, 1998), a different "response" cue denoting the target location was presented either at the onset or offset of the target (Dosher & Lu, 2000a, 2000b; Gould, Wolfgang, & Smith, 2007; Lu & Dosher, 1998; Luck, Hillyard, Mouloua, & Hawkins, 1996; Luck & Thomas, 1999; Shiu & Pashler, 1994). Second, we tested whether any change in task setting would affect the perceptual effect of involuntary attention. Specifically, the extent to which participants rely upon the response cue indicating the target location to perform the task was manipulated; in one experiment, the target was always presented by itself, obviating the use of response cue to locate the target, while in another experiment, the response cue was not provided.

To preview the results, significant effects of involuntary cuing were observed in the presence of distractors regardless of task settings, as we had hypothesized based upon the literature review. By contrast, in the absence of distractors, we found significant cuing effects only when participants' attention was not guided to the target location by top-down information provided by the response cue.

Experiment 1

Experiment 1 used a predictive cue to demonstrate that the peripheral cue employed in the present study can effectively affect target identification under perceptually challenging conditions. Identification accuracy was the main dependent variable because accuracy, rather than reaction time, is presumed to reflect the strength of perceptual representation under perceptually challenging conditions (Awh et al., 2003; Han & Kim, 2008; Moore & Egeth, 1998; Mordkoff & Egeth, 1993; Norman & Bobrow, 1975; Santee & Egeth, 1982). The probability that the target would be presented at the peripherally cued location was 100%. Hence, spatial attention should be deployed to the cued location, improving perceptual processing of that location (Prinzmetal, McCool et al., 2005). In addition, the local presentation of a mask following the target served as a post cue to eliminate target location uncertainty (Luck et al., 1996; Shiu & Pashler, 1994).

Methods

Participants

Twelve adults (four males, 18–25 years) with normal or corrected-to-normal vision participated for course credit or financial compensation. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

The experiment was programmed using MATLAB (MathWorks, Natick, MA) equipped with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) and ran on Mac-mini. The stimuli were presented on a 17-in. CRT monitor with a gray background. The monitor resolution was set to 1024×768 pixels, and the refresh rate was 60 Hz. The viewing distance was set to about 57 cm. Participants were required to fixate on a small white ($0.3^{\circ} \times 0.3^{\circ}$ of visual angle) dot presented at the center of the screen throughout the experiment. Four white outline squares ($1.1^{\circ} \times 1.1^{\circ}$, with a 0.06° of line thickness) were continuously present with the fixation to mark the locations where targets and distractors would be placed (Figure 1). These place holders were presented at the four corner locations of an imaginary square (6.5° from the fixation dot). The cue stimulus was a green outline square of the same size and line thickness as the place-holders. The target was a letter H or F, while distractors were chosen from T, X, K, Z, L, or R ($0.6^{\circ} \times 1^{\circ}$, Courier New font). A mask ($1.1^{\circ} \times 1.1^{\circ}$, the same size as the place holders) was created by adding 90% level of salt and pepper noise onto the symbol #.

Design and procedure

The experiment consisted of 2×3 factorial design, with factors of cue condition (valid and neutral) and target condition (single-item, four-item, and singlenoise). As shown in Figure 1, a trial started with a 300ms fixation presentation, followed by the presentation of a peripheral or neutral cue that remained visible until the onset of the mask. In the valid cue condition (50% of all trials), a green outline square appeared at the place holder location that will contain the target. In the neutral cue trials (50% of the total), all locations marked by the place holders were cued. Thus, when a single peripheral cue was presented, it always predicted the target location. A target letter was presented 120 ms after the onset of the cue and remained visible for 100 ms. Participants indicated which target letter, H or F, was presented by pressing one of two distinct buttons on a keyboard. The target was followed by the 200-ms presentation of a mask that covered only the target location, and participants were informed prior to the experiment that the target was always placed at the masked location. Thus, the mask indicated where the target was presented, eliminating uncertainty of the target location. This mask was presented in every trial, regardless of the trial types. Finally, the interval between the cue onset and the target offset (220 ms) was brief enough to preclude any eve-movement (Carrasco, Williams, & Yeshurun, 2002; Liu et al., 2005; Mayfrank, Kimmig, & Fischer, 1987; Yeshurun & Carrasco, 1999).

To demonstrate that our peripheral cue, when it was predictive of the target location, elicits significant cuing effects both in the absence and in the presence of distractors, the target was either presented alone (single-item condition) or accompanied by distractor letters (four-item condition). To address the possibility that the task in the single-item condition might be too easy to reveal a significant cuing effect due to a ceiling in performance, we also included a single-noise condition. In this condition, the target was presented alone but embedded with salt and pepper noise to make the task demanding enough to observe atten-



Figure 1. Trial design for Experiment 1. In the four-item condition, distractors were presented with the target, whereas only the target was presented in the single-item and single-noise conditions. The local mask was presented at the target location in every trial.

tional effects (Yi, Woodman, Widders, Marois, & Chun, 2004). We also added a small amount of noise to the four-item condition to ensure that accuracy in this condition was comparable to that in the singlenoise condition. The same amount of noise as in the four-item condition was added in the single-item condition so that lower accuracy in the four-item condition than in the single-item condition should be due to the presence of distractors rather than the noise, while the performance difference between the single-item and single-noise condition should be due to the difference in the amount of the salt and pepper noise. These noise levels were determined in separate sessions, prior to the main experimental session, and also adjusted after each experimental block to yield about 75% target accuracy in the neutral trials for each participant.

Different target display conditions (single-item, fouritem, and single-noise) were presented in separate, alternating blocks of trials. The order of block presentation was counterbalanced across participants. There were 12 experimental blocks, each with 64 trials. In a block, 32 valid and 32 neutral trials were randomly intermixed. Hence, for each cue (valid and neutral) by display (single-item, four-item, and single-noise) trial type, there were 128 trials. In line with previous studies Han & Marois



Figure 2. Target identification performance in Experiment 1. The informative peripheral cue enhanced identification accuracy in all the visual display conditions. Error bars represent standard error of the mean.

that utilized identification accuracy to measure the perceptual effect of attention (Han & Kim, 2008; Prinzmetal, McCool et al., 2005; Santee & Egeth, 1982), participants were instructed to respond to the target as accurately as possible without any pressure on response speed. This helps ensuring that identification accuracy reflects the strength of perceptual representation (Prinzmetal et al., 2005).

For data analysis, target accuracy and reaction time were separately entered into a repeated measure twoway analysis of variance (ANOVA) with target display (single-item, four-item, and single-noise) and cue (valid and neutral) as factors. Significant main effects and interaction were further investigated via pairwise t tests. Throughout the study, statistical thresholds for all ttests were corrected for multiple comparisons with false discovery rate (FDR) procedure.

Results and discussion

Results of Experiment 1 are shown in Figure 2. Target accuracy was entered into a repeated measure two-way ANOVA with target display (single-item, four-item, and single-noise) and cue (valid and neutral) as factors. There were significant main effects of cue, F(1, 11) = 48.32, p < 0.01, and target display, F(2, 22) =76.38, p < 0.01. The interaction between the two factors was also significant, F(2, 22) = 35.01, p < 0.01; the magnitude of cuing effect was largest in the four item condition (accuracy for the valid trials – accuracy for the neutral trials = 20%), ps < 0.01. Most importantly, pairwise t tests showed that target accuracy for the valid trials were significantly higher than for the neutral trials in all display conditions, all ps < 0.05. Reaction time data were also analyzed in the same way as accuracy data. The results revealed significant main effects of target display, F(2, 22) =

30.82, p < 0.01, and cue, F(1, 11) = 38.38, p < 0.01. That is, responses were faster for the single-item than for the four-item and single-noise conditions, and the validly cued trials also yielded faster responses. The interaction was also significant, F(2, 22) = 18.97, p < 0.01. This interaction was driven by a significantly larger cuing effect in the four-item condition than in the other two conditions, ps < 0.01.

The results of Experiment 1 showed that the currently used cue stimulus, when it was informative of the target location, affected perceptual identification of the target. In the next experiment, we tested whether the same kind of cue, when it was noninformative, would also be effective to enhance perception of the target.

Experiment 2

Experiment 2 tested the effect of involuntary attention on perceptual identification of the target. In this experiment, all the stimuli (cue, target, placeholders, and masks) and timing (cue, target, and mask durations and cue-target stimulus onset synchrony [SOA]) parameters were identical to those of Experiment 1. However, the probability that the target would be presented at the cued location was changed from 100% to chance. Participants were also informed that the cue was irrelevant to perform the task because it did not provide any information about target location or identity.

Methods

Participants

A different group of 12 adults (four males, 18–25 years) with normal or corrected-to-normal vision

participated for course credit or financial compensation. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

All stimuli and apparatus used are identical to those of Experiment 1.

Design and procedure

Details of design and procedure were identical to those of Experiment 1 except for the following. First, an invalid condition, in which the cued location and target location did not match, was included along with the valid and neutral conditions. The proportions of valid, invalid, and neutral trials were 12.5%, 37.5%, and 50%, respectively. Hence, the peripheral cue provided no information about the target location. Second, the single-item, four-item, and single-noise conditions were intermixed within a block to prevent any confound by the adoption of block-wise strategies.

Results and discussion

A repeated-measure two-way ANOVA on target accuracy with target display (single-item, four-item, and single-noise) and cue (valid, neutral, and invalid) as factors revealed main effects of target display, F(2, 22)= 26.40, p < 0.01, and cue, F(2, 22) = 48.32, p < 0.01.The interaction between the two factors was also significant, F(4, 44) = 6.55, p < 0.01. Most importantly, pairwise t tests showed a significant difference between the valid and neutral trials only in the four-item condition, t(11) = 6.26, p < 0.01, with higher target accuracy in the valid than in the neutral condition. Target accuracy for the valid trials was also significantly higher than for the invalid trials, t(11) = 5.85, p < 0.01. The difference between the neutral and invalid trials was not significant, p > 0.21, a finding that may be explained by the lesser reliability of the cost of cuing compared to its benefit (Carrasco & Yeshurun, 1998). By contrast, there were no cuing effects on target accuracy under conditions without distractors (single-item and single-noise), ps > 17.

Reaction time (RT) results showed no pattern of speed-accuracy tradeoff; there were main effects of target display, F(2, 22) = 52.75, p < 0.01, and cue, F(2, 22) = 8.64, p < 0.01, without significant interaction between these factors, p > 0.32. Specifically, the peripheral cue yielded significantly faster RT than the other two cues, ps < 0.05, and RT in the single-item condition was significantly faster than in the other conditions, ps < 0.05. Subsequent pairwise *t* tests

revealed that in the single-item condition, the RT difference between the valid and neutral trials was not significant, p > 0.15, while the mean RT for the invalid trials was significantly slower than for the valid and neutral trials, ps < 0.01. The same pattern was also observed in the four-item condition. In the single-noise condition, there was no significant difference across the cue conditions, ps > 0.14.

Thus, contrary to the accuracy data, the analysis of RT data revealed a significant main effect of cue, which did not interact with task display. One possible account for this RT effect is that it resulted from modulation of nonperceptual processes at the cued location (Han & Kim, 2008; Moore & Egeth, 1998; Mordkoff & Egeth, 1993; Prinzmetal, McCool et al., 2005; Santee & Egeth, 1982). Specifically, Prinzmetal et al. (2010) argued that a peripheral cue facilitates decision making/response selection at the cued location (Prinzmetal et al., 2010). In their framework, an involuntary attentional cue primes responses to a stimulus at the cued location, which results in faster response. Supporting this account, in the single-item condition, which showed no difference in accuracy across cue types, RTs in the valid and neutral trials were faster than in the invalid trials, with no difference between the valid and neutral trials. This might be because a cue stimulus (prime) was presented at the target location in the valid and neutral trials, whereas the target was presented at the uncued location in the invalid trials. Given that this priming could arise from the response selection stage rather than perceptual stage (Prinzmetal et al., 2010), we do not draw any conclusion regarding the perceptual effect of involuntary attention from the RT data, except to assert that there was no speed-accuracy tradeoff.

The most important aspect of these results is that target identification accuracy was improved by an involuntary cue only when distractors were present. This cuing effect cannot be explained by uncertainty (or decision noise) reduction; a local mask covered the target location immediately after the target offset in all conditions, minimizing uncertainty as to where the target was located (Luck et al., 1996; Luck & Thomas, 1999; Shiu & Pashler, 1994). In addition, the absence of cuing effect in the single-item and single-noise conditions cannot be due to the cue forward-masking the target and obscuring any advantage for the valid trials, as the same cue drove a significant effect in the fouritem conditions. A floor or ceiling account cannot explain the current results, either; the four-item condition, in which there was a significant cuing effect, vielded an intermediate level of performance compared to the single-item and single-noise conditions. It is conceivable, however, that intermixing of the task conditions and/or the presence of invalid trials-both methodological departures from Experiment 1-contributed to the absence of peripheral cuing effects in

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Figure 3. Target identification performance in Experiment 2. With the noninformative peripheral cue, there were significant cuing effects only in the four-item condition. Error bars represent standard error of the mean.

Experiment 2. These issues of task context will be analyzed further in Experiments 5 and 6 described below.

It is worth noting that the results of Experiment 2 revealed a cuing effect in the four-item condition that is smaller than that in Experiment 1 (8% vs. 20%, respectively, independent sample t test, t(22) = 3.91, p < 0.01). It is therefore possible that a cuing effect was obscured in the conditions without distractors in Experiment 2 because cuing effects were overall smaller in this experiment compared to Experiment 1. To address this possibility, we assessed whether the cuing effect in the conditions without distractors of the current experiment would be detected when the analysis was confined to participants showing relatively larger cuing effects with distractors. To do so, we performed a median split of the dataset such that participants who showed strong cuing effects in the four-item condition were selected. As shown in Figure 4, even though these participants exhibited a large cuing effect in accuracy in the four-item condition, t(5) = 17.00, p < 0.01, there was not even a trend for such cuing effect in both the singleitem and single-noise conditions (ps > 0.35). By comparison, when a subset of six participants from Experiment 1 were selected to match the cuing effect from the subgroup of Experiment 2 in the four-item condition, t(5) = 11.00, p < 0.01, see Figure 4, that subset still showed a cuing effect in the single-item, t(5) = 7.78, p < 0.01, and single-noise condition, t(5) = 3.26, p < 0.05. The analysis of RT data in the six subjects revealed that the informative cue yielded significantly faster reaction time in all target display conditions, ps < 0.01, whereas the noninformative cue had no effect, ps > 0.25, suggesting that the accuracy results were not confounded by speed-accuracy tradeoff.

Taken as a whole, these results have two significant implications. First, they strongly suggest that the absence of peripheral cuing effects in the no-distractor conditions of Experiment 2 were not a result of a lack of power. Second, they also indicate that voluntary and involuntary cuing have distinct effects on target performance in the absence of distractors (Prinzmetal et al., 2005).

Experiment 3

The conclusion that involuntary cuing affects perception under distractor interference rests on the assumption that the cuing manipulations target the perceptual stages of information processing. The presentation of a local mask at the target location in all cue manipulations of Experiments 1 and 2 helps prevent the possibility that the effect of the involuntary cue in the four-item condition consisted in reducing decision uncertainty as to where the target was located rather than facilitating perceptual processing. However, because the mask was presented after the cue and target presentations, it is possible that the cue still affected decision processes if those processes began immediately after target presentation. Thus, to provide further evidence that the effect of involuntary cues in the distractor-present condition does not consist in reducing decision uncertainty, in Experiment 3, we presented a "response cue" from target onset to indicate the location of the target in all trials (Dosher & Lu, 2000a, 2000b; Herrmann et al., 2010; Lu & Dosher, 1998; Pestilli & Carrasco, 2005; Pestilli et al., 2007; White et al., 2013). Any significant effect of the peripheral cue in the presence of the response cue would be interpreted as evidence that the peripheral cue affected target perception, not just location uncertainty.

Methods

Participants

A different group of nine adults (four males, 18–25 years) with normal or corrected-to-normal vision

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Figure 4. Effect of voluntary and involuntary cuing on target identification performance in the single-item and single-noise conditions of Experiments 1 and 2 for matched cuing effects in the four-item condition. The results of invalid trials in Experiment 1 are not shown because there are no comparable trials in Experiment 1. Error bars represent standard error of the mean.

participated for course credit or financial compensation. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

All stimuli and apparatuses used are identical to those of Experiment 1 except that the target was chosen among A, B, C, or D mapped onto button presses with the index, middle, ring, and baby fingers, respectively. This modification was applied to minimize the demand to maintain the response mapping rule of this fouralternative choice task. Distractors were chosen from the same set as Experiments 1 and 2. An arrow indicating the target location was also presented at the center of the screen.

Design and procedure

Details of design and procedure were identical to those of Experiment 1 except for the following changes

(Figure 5). First, there was only a four-item condition because this experiment aimed at investigating the source of the cuing effect observed in the four-item condition. Second, in all trials a response cue was presented at the same time as the target and distractors appeared, and it remained for 100 ms along with the target display. In addition, a local mask was presented at the target location immediately following the offset of the target display and response cue. The response cue and local mask always informed participants of the location of the target to be reported. Third, there were two types of trials in each block: In 75% of the trials, a single target and three distractors were presented (single-target trials). The other 25% of the trials contained two different targets and two distractors (dual-target trials). Because the task required reporting only the target letter indicated by the response cue, the presence of dual-target trials ensured that participants would use the response cue to perform the task. Under such setting, uncertainty regarding the target location should be completely eliminated.



Figure 5. Trial design for Experiment 3. Participants were instructed to base their decision on the location indicated by the response cue (the black arrow on the center).

Results and discussion

The results of Experiment 3 are shown in Figure 6. Target accuracy was entered into a repeated measure ANOVA with cue (valid, neutral, and invalid) and target number (single- and dual-target) as factors. The main effect of target number was not significant, p > 0.51. However, there was a main effect of cue, F(2, 16) = 45.75, p < 0.01. Pairwise t tests showed that under both single-target and dual-target conditions, the difference between the valid and neutral cue conditions was significant, t(8) = 7.01, p < 0.01, and so was the difference between the neutral and invalid conditions, t(8) = 2.56, p < 0.05. The interaction between the target number and cue was significant, F(2, 16) = 5.44, p < 0.05. This interaction was induced by a larger cuing benefit in the dual-target condition. The RT results also showed a significant main effect of cue, F(2, 16) =15.66, p < 0.01; the responses were faster for the valid than for the neutral and invalid conditions. The main effect of the target number was not significant, p > 0.08, nor was the interaction between target number and cue, p > 0.11. The overall pattern of the RT data suggests that the accuracy results were not contaminated by speed–accuracy tradeoff.



Figure 6. Target identification performance in Experiment 3. The peripheral cue affected identification accuracy in both the singletarget and dual-target conditions. Error bars represent standard error of the mean.

While the results of the single-target condition replicate those of Experiment 2, the dual-target results clearly indicate that participants made use of the response cue because accuracy for these trials was not worse than for the single-target trials. The fact that the peripheral cuing effect was still observed with distractor interference when participants used the response cue to guide their decision suggests that this cuing effect was not confounded by target location uncertainty. These results are consistent with many previous studies (Barbot et al., 2011, 2012; Herrmann et al., 2010; Montagna et al., 2009; Pestilli & Carrasco, 2005; Pestilli et al., 2007), further strengthening the notion that involuntary attention affects perception under distractor interference.

Experiment 4

This experiment examined whether the findings of the previous experiments obtained with high-contrast letter stimuli would generalize to other stimulus conditions. In particular, because it has been suggested that, at least under some circumstances, attention's modulatory power is optimal for stimuli with intermediate contrast levels (Herrmann et al., 2010; Ling & Carrasco, 2006a; Reynolds & Heeger, 2009; Reynolds, Pasternak, & Desimone, 2000), we sought to determine whether we would still only find involuntary cuing effects under the presence of distractors when Gabor gratings with one of such contrast levels (9%) are used as stimuli.

Methods

Participants

A different group of 12 adults (four males, 18–25 years) with normal or corrected-to-normal vision

participated for course credit or financial compensation. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

All stimuli and apparatus used are identical to those of Experiment 1 except for the following: The target was either a left- or right-tilted Gabor grating $(1.1^{\circ} \times 1.1^{\circ}, 9\% \text{ contrast}, 2 \text{ cycles})$, whereas distractors were Gabor gratings with vertical orientation. The magnitude of the target's tilt $(2^{\circ}-14^{\circ})$ was adjusted per each individual participant to yield about 75% accuracy for the neutral trials in the single-item condition. Finally, there was no mask, and the same response cue used in Experiment 3 was also used in the current experiment.

Design and procedure

The design and procedure of this experiment were similar to those of Experiment 2 (see Figure 7); the peripheral cue did not predict the target location, and single-item (target presented alone) and four-item (target plus three distractors) trials were randomly intermixed within a block. Cue–target SOA was also the same as Experiments 1 and 2 (120 ms). However, the target and distractors were presented only for 50 ms in order to yield about 75% accuracy without masking. A response cue appeared at the onset of the target display and remained until the response was made.

Results and discussion

The results of Experiment 4 are shown in Figure 8. A repeated measure two-way ANOVA as cue (valid, neutral, and invalid) and target display (single-item and four-item) as factors revealed main effects of target



Figure 7. Trial design for Experiment 4.

display, F(1, 11) = 15.76, p < 0.01, and cue, F(2, 22) = 15.66, p < 0.01, on target accuracy. The interaction between these factors was also significant, F(2, 22) = 9.66, p < 0.01. The RT results revealed a marginal effect of target display, F(1, 11) = 4.36, p = 0.061, and a significant main effect of cue, F(2, 22) = 3.47, p < 0.05. The interaction between these two factors also approached significance, F(2, 22) = 3.35, p = 0.054. The marginal effect of target display might result from the task demands being higher for the four-item trials than for the single-item trials. Specifically, in the former trials, even though participants' attention is guided by the response cue, the presence of distractors might evoke the demanding processes of target search and

especially distractor suppression. As for the marginal interaction, it was primarily driven by a significant main effect of cue for the four-item trials only (p < 0.01). As we mentioned in the Results and discussion section of Experiment 2, we do not draw any further conclusions from the RT data.

Most importantly, and consistent with our previous experiments, the noninformative cue only affected target performance under distractor interference; pairwise *t* tests showed that the difference between the valid and neutral conditions under distractor interference (four-item condition) was significant, t(11) = 4.14, p < 0.01, and so was the difference between the neutral and invalid conditions, t(11) = 3.10, p < 0.05. None of



Figure 8. Target identification performance in Experiment 4. There was a significant effect of the cue only with distractors present (four-item). Error bars represent standard error of the mean.

these effects was significant in the single-item condition (ps > 0.38). The RT results also showed a significant cuing effect only in the four-item conditions, ps < 0.05, while there was no significant difference across cue types, ps > 0.55. We conclude that the selective effect of involuntary cuing for distractor conditions generalize across stimulus types and contrasts.

Experiment 5

In the above experiments, the involuntary cue affected target perception only under distractor interference, while no effect of the cue was found when distractors were absent. Given that in several of these experiments, the trials with distractors were intermixed within the same blocks with trials with no distractors, it is conceivable that the effect of the involuntary cue is influenced by the trial context. That is to say, the intermixing of both types of trials may induce participants to adopt different task settings than those adopted if the distractor-present and distractor-absent trials were presented separately (see also Dalvit & Eimer, 2011).

From Experiments 2–4, we can conclude that the results for the distractor-present (four-item) trials did not depend on whether these trials were intermixed with the distractor-absent (single-item/single-noise) trials or not. That is, significant effects of the involuntary cue under distractor interference were observed regardless of whether the distractor-present trials were presented alone (Experiment 3) or intermixed with the distractor-absent trials (Experiments 2 & 4). These findings are consistent with the claim that resolving stimulus-driven competition by involuntary attention occurs independently of any top-down

control (Beck & Kastner, 2005, see also Carrasco, 2011; Lu & Dosher, 1998).

It is unclear, however, whether the results for distractor-absent trials are also independent of the trial context, as these trials have not yet been presented separately from distractor-present trials. Indeed, a study by White et al. (2013) showed that an involuntary attentional cue had significant effect on target discrimination when only distractor-absent trials were presented. It is therefore possible that the presence of trials with distractors led participants to adopt task sets or strategies that precluded involuntary cues from affecting target perception in trials that contained no distractors. To examine this issue, in Experiment 5, we included only distractor-absent (single-item) trials.

Methods

Participants

A different group of 17 adults (six males, 18–25 years) with normal or corrected-to-normal vision participated for course credit or financial compensation. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

All stimuli and apparatus used are identical to those of Experiment 4.

Design and procedure

Details of design and procedure were identical to those of Experiment 4 except that there was only the single-item condition. Han & Marois



Figure 9. Target identification performance in Experiment 5. Error bars represent standard error of the mean.

Results and discussion

The results of Experiment 5 are shown in Figure 9. Data from two participants were excluded from the analysis because accuracy for one of the cue conditions was not significantly different from chance. Remarkably, a repeated measure ANOVA with cue as factor revealed a significant effect of the noninformative cue on target accuracy in the absence of distractor interference, F(2, 28) = 16.79, p < 0.01. Pairwise t tests showed that accuracy for the valid trials was significantly higher than for the neutral trials, t(14) = 4.43, p < 0.01. The difference between the neutral and invalid trials was also significant, t(14) = 2.96, p < 0.05. The RT results also showed a significant main effect of cue, F(2, 28) = 10.46, p < 0.01. Specifically, there was no significant difference between the valid and neutral trials, p > 0.90, while responses for the invalid trials were significantly slower than for the valid and neutral trials, ps < 0.01.

The finding that the involuntary cue affected target identification even in the absence of distractors is consistent with a recent study (White et al., 2013), but contradicts our previous experiments (Experiments 2 & 4). This discrepancy could be due to an important methodological difference across experiments. As we noted, in Experiment 5 and several experiments in White et al.'s (2013) study, only distractor-absent trials were presented and a response cue was provided in each trial. In these cases, significant cuing effect surfaced in the absence of distractors. By contrast, in Experiments 2 and 4, when distractor-absent (single-item) trials were intermixed with distractor-present (multi-item) trials within a block and a response cue was provided, no cuing effect was found in the distractor-absent trials. These findings suggest that the effect of the noninformative spatial cue, often claimed to affect behavior in an involuntary or automatic way, is subject to task context (Folk et al., 1992; Kiss et al., 2012).

How could a change in task context modulate the effect of involuntary attention on target perception? We surmise that the contextual change affects the participants' strategy to perform the task (Dalvit & Eimer, 2011). Specifically, when distractor-present trials are intermixed with distractor-absent trials, participants may adopt a default strategy optimized for trials containing distractors, as those trials have additional processing load of overcoming distractor interference compared to distractor-absent trials (Butler, 1981; Garner, 1970; Han & Kim, 2008). As shown in Dalvit and Eimer (2011), participants adopt the task set for the task with highest demands when the task demands of any given trial are unpredictable. Hence, when distractor-present and -absent trials are intermixed, participants will adopt a strategy optimal for distractor-present trials; that is, locating the target by using the response cue. With this strategy, participants' attention can be correctly guided to the target location, and the noninformative peripheral cue may not affect perception of the target (Johnson et al., 2002), unless it is surrounded by competing distractors.

By contrast, when there are no distractor-present trials in the experiment, participants would not heavily depend on the response cue because the target can easily be located at its onset. In this case, they might adopt a strategy to detect the onset of a salient stimulus. With the adoption of this singleton detection mode (Bacon & Egeth, 1994), the effect of the noninformative cue, albeit a small one, is more likely to emerge. This proposition was further tested in Experiments 6 and 7.

Experiment 6

As mentioned above, it is conceivable that an involuntary cuing effect was observed in Experiment 5 because the task set did not incite participants to use the response cue to locate the target; indeed, the target could be easily located without using the response cue in every trial because there were no distractors. To test this hypothesis, in Experiment 6, the single-item condition (distractor-absent trials) was intermixed with



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Figure 10. Target identification performance in Experiment 6. Error bars represent standard error of the mean.

the four-item condition (distractor-present trials) within each experimental block as in Experiment 4, except that the response cue was also removed. Recall from Experiments 2 and 4 that when the single-item and four-item conditions are intermixed and the response cue is provided, no cuing effect is observed in distractor-absent trials. If the guidance of attention to the target location by the response cue eliminates the effect of peripheral cuing on the target when there are no distractors, then the removal of the response cue should yield significant cuing effect in distractor-absent trials even when such trials are intermixed with distractor-present trials.

Methods

Participants

A different group of 12 adults (six males, 18–25 years) with normal or corrected-to-normal vision participated for course credit. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

All stimuli and apparatus used are identical to those of Experiment 4. The magnitude of the target's tilt was independently manipulated for the single- and fouritem conditions to yield comparable performance across these conditions.

Design and procedure

Details of design and procedure were identical to those of Experiment 4 except that the response cue was not presented.

Results and discussion

The results of Experiment 6 are shown in Figure 10. A repeated measure two-way ANOVA as cue (valid, neutral, and invalid) and target display (single-item and four-item) as factors revealed main effects of cue, F(2, 22) = 75.90, p < 0.01, and target display, F(1, 11) = 25.95, p < 0.01, on target accuracy. The interaction between these factors was also significant, F(2, 22) = 15.02, p < 0.01. The RT results revealed a main effect of target display, p > 0.70. The interaction between target display, p > 0.70. The interaction between target display and cue was also significant, F(2, 22) = 6.26, p < 0.01.

Contrary to the results of Experiment 4, even though the single-item and four-item conditions were intermixed, there was a significant effect of the cue in the single-item condition, F(2, 22) = 9.42, p < 0.01. This is consistent with the findings by Giordano et al. (2009) who showed significant cuing effect in the absence of distractors (see also Carrasco, Giordano, & McElree, 2004, 2006). In this study, single-item and multi-item displays were intermixed within a block, and importantly, no response cue was provided, similar with the current experiment. In such setting, participants are likely to engage in a search for the target, thereby yielding involuntary cuing effects regardless of the presence of distractors, as shown in the current experiment. By contrast (see Experiments 2 & 4), when a response cue is provided and distractor-absent (single-item) trials are intermixed with distractorpresent (multi-item) trials, no cuing effect is found in the former trials.

Another important finding is that the removal of the response cue induced a significantly larger cuing effect (valid accuracy – invalid accuracy) in the four-item condition than when it was presented (16.9% for Experiment 6, 10.0% for Experiment 4), t(21) = 2.61, p < 0.05 (independent sample t test). This difference in cuing effect confirms that the response cue in Exper-

iments 3 and 4 effectively served to eliminate location uncertainty; when there was no response cue in target displays with distractors, in which the target location should be uncertain, the perceptual cuing effect was larger compared to when the target location was denoted by the response cue.

An alternative interpretation for this increased cuing effect with the removal of the response cue is that processing of the response cue interfered with the serial search process to locate the target, which is reflexively initiated at the location where the peripheral cue appeared. This serial search process should be terminated when the response cue is interpreted, as it should reveal the correct target location. Given that the search process is interrupted by the response cue, the effect of a peripheral cue should be attenuated when the response cue is presented, compared to when it is absent. While such serial mechanism could in principle account for the current findings, it should be noted that this account has been proposed to explain RT effects of involuntary attention, which are thought to reflect nonperceptual processes (Prinzmetal et al., 2010). Given that the current paradigm focuses on accuracy of unspeeded responses, the influence of such serial mechanism is likely to be minor. In any events, it will be valuable to assess the serial search account in future experiments, possibly by measuring target localization accuracy and estimating how the peripheral cue affects localization accuracy in a multi-item display.

Experiment 7

In this experiment, we directly tested the dependence of the involuntary cuing effect on task settings by inducing participants to adopt different task settings within the same experimental session. The experiment was divided into three phases. In the first phase, participants performed the same task as Experiment 4, in which the four-item and single-item conditions were intermixed within a block and the response cue was provided. This first phase was followed by the second phase, in which only the single-item trials were presented, as in Experiment 5. Importantly, participants were not informed of this change in trial context. In the final phase, only the single-item trials were presented as in the second phase, but the participants were informed of the trial context before the onset of that phase. We hypothesized that prior exposure to the setting in which the single- and four-item conditions are intermixed would set participants' strategy to rely upon the response cue to locate the target, which would negate any cuing effect in the single-item condition. This strategy should persist even in the second phase of the experiment when single-item trials are presented

alone. However, when explicitly instructed that there would only be single-item trials, participants may simply focus on detecting the onset of the salient stimulus, regardless of whether it is a target or cue (singleton detection mode, Bacon & Egeth, 1994). The adoption of this strategy should lead to a significant effect of the noninformative cue on target accuracy in the absence of distractors.

Methods

Participants

Twenty adults (eight males, 18–25 years) with normal or corrected-to-normal vision participated for course credit or financial compensation. The Vanderbilt University Institutional Review Board approved the experimental protocol and informed consent was obtained from each participant.

Stimuli and apparatus

All stimuli and apparatus used are identical to those of Experiment 6.

Design and procedure

There were eight experimental blocks, each of which contained 160 trials. The proportions of the valid, invalid, and neutral trials were 20%, 60%, and 20% of the total, respectively. Hence, the cue was noninformative of the target location. From the first to the fourth block, the single- and four-item conditions were randomly intermixed within each block, while there was only the single-item condition in the next two blocks (fifth & sixth-single-item-uninformed condition). Participants were not informed of this change in task setting. Finally, there were two additional blocks that were identical to the fifth and sixth blocks except that participants were informed of the change in trial context with the presentation on the screen at the onset of the seventh block that only single-item trials would be presented. To be noted, these two blocks were not immediately preceded by blocks that contain the fouritem trials, contrary to the fifth and sixth blocks that followed blocks that had the four-item trials. Other details of the experimental procedure are identical to those of Experiment 6.

Results and discussion

The results of Experiment 7 are shown in Figure 11. Data from five participants were excluded from the analysis because accuracy for any of cue condition was close to chance (lower than 60%). Including these data



Figure 11. Target identification performance in Experiment 7. Error bars represent standard error of the mean.

did not change the results. A repeated measure twoway ANOVA with cue and task set (single item, four item, single-item uninformed, and single-item informed) as factors revealed a main effect of cue, F(2,(28) = 18.43, p < 0.01. The main effect of task set was not significant, p > 0.12, though the interaction between these two factors was significant, F(6, 84) =3.32, p < 0.01. The analysis of RT data revealed significant main effects of task set and cue, ps < 0.01, and a marginal interaction, p = 0.052. This marginal interaction was driven by the fact that the RT patterns were different across task sets; specifically, in the singleitem and single-item-informed conditions, the invalid trials yielded significantly longer RT than the valid and neutral trials, ps < 0.01, while there was no RT difference between the neutral and invalid trials, p > 0.25. By contrast, in the four-item and single-itemuninformed condition, the RT for the valid trial was significantly shorter than those for the neutral and invalid trails, ps < 0.05, with no difference between the latters, p > 0.94. Most importantly, the RT results indicate that there was no speed-accuracy tradeoff.

Given that the analysis of accuracy data yielded the significant interaction between cue and task set, data

from each different task set were separately analyzed with repeated-measure one-way ANOVAs with cue as a factor to examine under which conditions the cuing effect emerged. Statistical thresholds of these four oneway ANOVAs and subsequent t tests were corrected for multiple comparisons with FDR procedure. Significant cuing effects were observed either when there were distractors or when the single-item trials were presented alone and participants were explicitly instructed that there would be no four-item trials. First, in the presence of distractors (four-item condition), the main effect of cue was significant, F(2, 28) = 15.19, p < 0.01. Specifically, target accuracy for the valid trials was higher than for the neutral, t(14) = 2.47, p < 0.05, and for the invalid trials, t(14) = 8.82, p < 0.01. The difference between the neutral and invalid trials was also significant, t(14) = 2.35, p < 0.05. Second, when the single-item condition was presented without being intermixed with the four-item condition and participants were informed of this trial context (single-item-informed), there was also a significant main effect of cue, F(2, 28) = 5.03, p < 0.05. The difference between the valid and neutral trial was not significant, p > 0.80, but there was significant

difference between the valid and invalid trials, t(14) = p < 0.05. By contrast, in the single-item and single-item uninformed conditions, there was no significant cuing effect, ps > 0.29.

From the results of Experiments 5, 6, and 7, we suggest that the effect of the involuntary attentional cue on target perception in the absence of distractors depends on task settings. When only the single-item condition is presented, and participants are aware of this trial context, there is a slight but significant effect of the involuntary attentional cue. Otherwise, the cue does not affect target identification unless distractors are presented with the target.

One caveat of these results is that the interaction between task set and cuing effect failed to reach significance when the four-item condition was excluded from the ANOVA for both accuracy and RT data (i.e., with the single-item, single-item-uninformed, and single-item-informed conditions only, ps > 0.57). This is likely due to the small effect that involuntary attention has on target perception under distractorabsent conditions and the weak power of task set to modulate that attentional effect. It is possible that once participants adopt a strategy to use the response cue at the initial phase of the experiment, they have a hard time overriding that strategy in the later phases (Leber & Egeth, 2006). It is unlikely, however, that the null effect of involuntary attention on target perception in single-item trials that were intermixed with four-item trials was due to a lack of power. Even when data from Experiments 4 and 7 were combined (N = 27, as both experiments contained similar stimulus conditions and single-item trials intermixed with four-item trials), no cuing effect was observed in the single-item condition. Specifically, there was no difference between the valid and neutral, p > 0.93, nor were there differences between the valid and invalid, and between the neutral and invalid conditions (either, ps > 0.19). Importantly, a similar pattern of result was observed for Experiment 2, which used different types of stimuli.

To further support the claim that task set plays a role in involuntary attentional cuing effects in the absence of distractors, the combined datasets of Experiments 4 and 7 above were compared to the combined datasets of the single-item trial data of Experiment 5 and 6 (N = 27). Notably, the dataset consisting of data from Experiments 4 and 7 was obtained under a task setting in which the use of the response cue was obviated or the response cue was not provided. The accuracy cuing effect in the dataset consisting of the single-item trial data from Experiments 5 and 6 was significantly larger than that in the combined datasets of Experiments 4 and 7, t(52) = 2.49, p < 0.05, independent sample t test of cuing effect (valid – invalid). No such a difference was found from RT data, p > 0.20. We conclude from these results that the effect of involuntary attention on perception of a target presented without distractors depends on the trial context, though the magnitude of both this attentional effect and its modulation by task context are moderate.

General discussion

It has recently been debated whether the effect of involuntary attention originates from enhanced perception or modulation of post-perceptual processes. We hypothesized that the presence of distractor interference and task set would be crucial to produce significant effect of involuntary attention. Consistent with our hypothesis, here we show that a noninformative peripheral cue improved perceptual identification of the target only under specific conditions. Specifically, when distractor-present (multi-item) trials were intermixed with distractor-absent (single-item) trials and a response cue was provided, involuntary cuing effects were found in distractor-present trials, but not in distractor-absent trials. By contrast, either when the experiment included only distractor-absent trials or when no response cue was provided, cuing effects were also found in the distractor-absent trials.

The involuntary cue benefits observed in the present experiments cannot be attributed to reduced location uncertainty or biased decision because participants were informed of the target location by the response cues presented either immediately after the target was removed or at the same time as the target appeared. Given that the use of the response cue has been an effective and standard way to eliminate location uncertainty (Dosher & Lu, 2000a, 2000b; Herrmann et al., 2010; Lu & Dosher, 1998; Pestilli & Carrasco, 2005; Pestilli et al., 2007; White et al., 2013), we conclude that our cuing effect took place at the perceptual stage of processing. It is nevertheless possible that the presence of multiple items introduced some decision uncertainty in the information processing system before the mask or response cues were interpreted. However, the fact that a robust cuing effect was present and similar (cf. valid vs. invalid cuing effects of Experiments 2 & 3) regardless of when a cue denoting the target location was presented strongly suggests that any potential contribution of decision noise is likely to be minor (see also Kerzel, Gauch, & Buetti, 2010).

It is also important to consider whether eye movements could account for our results because we did not use eye-tracking devices in the present study. This seems an unlikely possibility for several reasons. First, the longest interval from the onset of the cue to the offset of the target was 220 ms (Experiments 1–3), which was brief enough to preclude eye movements (Carrasco et al., 2002; Liu et al., 2005; Mayfrank et al., 1987; Yeshurun & Carrasco, 1999). Second, the pattern of results did not change even when the interval was decreased to 170 ms (Experiments 4 & 6). Third, the involuntary cues had a highly selective effect on target performance. If eye movements had occurred, there should have been significant cuing effects across all experiments. Although we cannot rule out the possibility that eye movements were made in experimental blocks that included only the relatively difficult, distractor-present trials (Experiments 1 & 3), this possibility does not affect the core finding of the study: the dependence of involuntary attention on task setting.

Another methodological point to consider is the issue of whether the cue claimed to be noninformative in the present study is truly uninformative. In the current experimental setting (except for Experiment 1), the probability that the target appears at the cued location was at chance level (25%). However, this fact also means that it is more likely that the target is presented at one of the uncued locations, which might create a bias against the cued location. While this is a critical issue for any cuing study, it does not impact any of the current findings and interpretations; even though the cue could be antipredictive of the target location, the perception of a target was enhanced at the cued location and this effect depended on task setting and distractor presence.

The crux of our study is that it revealed two conditions under which involuntary attention affects target perception. First, whether involuntary attention affects perception strongly depends on the presence of distractors. We suggest that stimulus-driven competition between the target and distractors is automatically resolved by the salient noninformative cue. When multiple stimuli are simultaneously presented in the visual field, those stimuli compete against each other to be represented in the visual system (Desimone & Duncan, 1995; Kastner et al., 1998). This competition has been known to exist regardless of whether those stimuli are attended (Scalf & Beck, 2010) or task irrelevant (Kastner et al., 1998). This stimulus-driven competition is thought to be resolved when top-down attention is allocated to one of the stimuli (Kastner et al., 1998) or when a salient object among the presented stimuli captures attention in a bottom-up fashion (Beck & Kastner, 2005). In a similar vein, a salient peripheral cue presented among targets and distractors would serve to resolve the competition by biasing perceptual processing resources toward the cued stimulus. More broadly, these results are consistent with the notion that attention, whether it is oriented in a top-down or bottom manner, works primarily to resolve competition (Desimone & Duncan, 1995; Luck & Ford, 1998; Zhang & Luck, 2009).

The second important conclusion of the present study is that whether involuntary attention affects target perception in the absence of distractors depends on task settings. As we pointed out earlier, some studies have reported perceptual effects of involuntary attention in the absence of distractors (Giordano et al., 2009; White et al., 2013), whereas others did not observe such effects (Prinzmetal, McCool et al., 2005). The findings of the present study suggest that this inconsistency may be due to differences in task sets. Specifically, involuntary attention improved the percept of targets presented alone only when the task set did not incite participants to use a concurrently presented response cue denoting the target location (Experiment 5); when only a single stimulus was presented as a target, as in Experiment 5 and several experiments by White et al. (2013), one might not rely upon the response cue because the target can be easily located. By contrast, when the strategy of participants was set to use the response cue because distractor-present trials and -absent trials were intermixed within the same block (Experiments 2 & 4), no significant cuing effect was observed unless distractors were present in the display. It is also important to note that without a response cue, significant cuing effects were found either in the presence or in the absence of distractors (Experiment 6), consistent with the results of Giordano et al. (2009). These results further support the claim that task setting related to the response cue (trial context and the presence/absence of response cue) is important to observe the effect of an involuntary attentional cue.

Recent studies also showed that the deployment of involuntary attention is heavily dependent on task settings and strategies (Dalvit & Eimer, 2011; Kiss et al., 2012). In those studies, attentional capture by a salient distractor was found when task demands were low (long presentation of target display), but not when they were high (brief presentation of target display). Importantly, this modulation of attentional capture was only observed when task demands were blocked and thus predictable for each trial. However, when high and low task demand trials were randomly intermixed, the capture effect was eliminated in the low task demand trials, presumably because participants adopted a strategy adapted to high task demand and applied it to both the high and low task demand trials (Dalvit & Eimer, 2011). It is worth noting that these results were obtained using attention capture paradigms rather than cuing paradigms (see White et al., 2013, for a direct comparison between the two). However, given that a pop-out stimulus can act as a spatial cue (White et al., 2013), it is possible that the cuing effect in the cuing paradigms is also subject to task demands and strategies. In line with this hypothesis, we showed that the effect of an involuntary attentional cue in distractor-absent trials (low task

demand) was eliminated when these trials were randomly intermixed with distractor-present trials (high task demand). As mentioned above, we surmise that participants chose a strategy set to distractorpresent trials—using the response cue to guide their attention—throughout the experimental session.

A remaining question is why the effect of the involuntary attentional cue is attenuated when participants use the response cue to perform the task. As an anonymous reviewer suggested, it is conceivable that this is due to a close interaction between top-down, goal-directed attention and bottom-up, stimulus-driven attention (Asplund, Todd, Snyder, & Marois, 2010; Chun & Marois, 2002); because these two different types of attention compete for a common pool of processing resources (Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Forster & Lavie, 2011), the effect of bottom-up (involuntary) attention should be affected by top-down processing of the response cue, which is presented shortly after the involuntary attentional cue. Specifically, when participants were set to use the response cue, some processing resources might be allocated to the eventual presentation of the response cue rather than be fully dedicated to the cued location. This account may also explain why Prinzmetal, McCool et al. (2005) found no effect of involuntary attention on target perception. In their study, participants were required to identify a target stimulus in the absence of distractors, followed by a target localization task. It may well be that this dual-task structure attenuated allocation of processing resources toward the cued location because in this setting, participants are more strongly incentivized to allocate attentional resources to the target location, thereby dissipating attentional capture by the task-irrelevant peripheral cue. Importantly, as we emphasize throughout the paper, while the effect of involuntary attention in the absence of distractors is subject to the influence of topdown factors, the resolution of competition by involuntary attention seems to be independent of such factors (Beck & Kastner, 2005).

The current findings that the effect of involuntary attention is more reliable and pronounced under distractor interference are consistent with previous studies (Carrasco & Yeshurun, 1998; Giordano et al., 2009). These also imply that involuntary attention is more effective in resolving resource-based limitations than data-based limitations of information processing. Norman and Bobrow (1975) suggested a distinction between two classes of limitations in human information processing—data-based limits that result from the limited quality of data inputed to the system and process/resource-based limits that arise from the limited processing capacity of the system. While process/resource-based limitations can be overcome by properly allocating available resources to the processing of behaviorally relevant or salient items at the expense of other items, data-based limitations cannot be surmounted by simply deploying more resources because that limitation is inherent in the data, not in the system.

A typical manipulation to induce resource-based limitations is to strain such resources by increasing the number of items to be processed (Butler, 1981; Garner, 1970), as occurs in the four-item condition of the present experiments. In this condition, behavioral performance is impaired primarily because the distractors and targets compete for processing resources. By contrast, embedding the stimuli in noise, as in the single-noise condition, is a standard way to degrade the quality of sensory input that induces data-based limitations, leaving processing demands unaffected (Norman & Bobrow, 1975). The finding that involuntary attention was especially effective in the four-item condition suggests that one important role of involuntary attention is to resolve process-based limitations by biasing the limited perceptual processing resources. That being said, we do not argue that attention has no role in resolving data-based limitation: both voluntary and involuntary attention boost weak sensory signals even without competition. However, only voluntary attention can enhance the signal regardless of task settings, whereas the effect of involuntary attention depends on this factor. While these two different types of attention compete for a common pool of processing resource (see above), they are likely to be operated by different mechanisms (Barbot et al., 2012; Chica et al., 2013; Chica & Lupianez, 2009; Giordano et al., 2009; Hein, Rolke, & Ulrich, 2006; Landau, Esterman, Robertson, Bentin, & Prinzmetal, 2007; Prinzmetal, McCool et al., 2005; Yeshurun, Montagna, & Carrasco, 2008).

In contrast to the current findings, some recent studies reported that involuntary attention does not affect perception (Kerzel et al., 2010; Kerzel et al., 2009). Specifically, Kerzel et al. (2010) failed to replicate the cuing effects that a previous study (Liu et al., 2005, see also Barbot, Landy, & Carrasco, 2011, 2012; Herrmann et al., 2010; Montagna et al., 2009; Pestilli & Carrasco, 2005; Pestilli, Viera, & Carrasco, 2007; White, Lunau, & Carrasco, 2013) reported under what seemed to be similar task settings. Instead, an involuntary cuing effect was found only when every potential target location was masked (Kerzel et al., 2010), and this effect was attributed to masking introducing target location uncertainty. Kerzel et al. (2010) argued that the results of Liu et al. (2005) could be due to data sampling bias (only six participants were recruited for the study) and/or to response-related processes as the task required speeded responses. However, all the participants in the study by Liu et al. (2005) showed the same pattern (M. Carrasco, personal communication, September 16, 2013). Furthermore, we showed that an involuntary cue has a significant effect on target perception using different stimuli and response settings that heavily emphasized accuracy over speed. Thus, it remains unclear why Kerzel et al. found no effect of involuntary attention on target perception. Presumably, the stimulus settings employed by Kerzel et al. were not identical to those of Liu et al. in a way that obscured cuing effect.

In addition to the Kerzel work, another study recently failed to show significant cuing effects of noninformative spatial cues when location uncertainty was controlled (Gould et al., 2007). However, remarkably, this study reported that even voluntary attention had no effect when the target location was marked by a response cue. This lack of cuing effect under either involuntary or voluntary attention might have been due to the fact that Gould et al. (2007) used an orthogonal discrimination task that taps on a similar process to a simple feature detection task. A recent study (Scharff, Palmer, & Moore, 2011) reported that detecting simple features (e.g., contrast increment) could proceed in parallel with unlimited capacity. If a task can be performed without the involvement of capacity-limited attentional processing, the task performance may not be affected by manipulating attention. In this case, the main factor limiting behavioral performance would be whether there is uncertainty regarding the target location. When there is uncertainty, an attentional cue will benefit performance because it reduces the target location uncertainty. Otherwise, the attentional cue should have no effect.

In conclusions, the present results illuminate the long-standing debate on whether involuntary attention affects target perception. Clearly, involuntary attention affects perception under distractor interference by resolving stimulus competition, and it does so independently of top-down control. By contrast, in the absence of distractors, the perceptual effect of involuntary attention depends on task settings: It will only enhance perception if participants' attention is not focused on a specific location. While further investigations are surely needed to fully elucidate involuntary attention, the present study highlights how such a simple and fundamental cognitive process is nonetheless subject to the complexity of the perceptual milieu and the internal mind-set of the observer.

Keywords: involuntary attention, stimulus-driven competition, task setting, perception, location uncertainty

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