

The Mechanisms of Involuntary Attention

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We tested 3 mechanisms of involuntary attention: (1) a perceptual enhancement mechanism, (2) a response-decision mechanism, and (3) a serial-search mechanism. Experiment 1 used a response deadline technique to compare the perceptual enhancement and the decision mechanisms and found evidence consistent with the decision mechanism. Experiment 2 used a multiple-targets paradigm to compare the decision and serial-search mechanisms. The results favored the decision mechanism. Experiment 3, which varied the display size and whether distractors were present in the display, found that when locating the target was easy, the results conformed to the decision mechanism. However, when locating the target was difficult, the serial-search mechanism was favored. Thus, there appears to be at least 2 mechanisms of involuntary attention. The serial-search mechanism accounts for involuntary attention when the target is difficult to locate, whereas the decision mechanism accounts for results when the target is easy to locate.

Keywords: accumulator model, attention mechanisms, exogenous attention, involuntary attention, stimulus-driven capture

The prevailing view has long been that there are at least two kinds of attention. For example, Wundt commented that attention could be controlled either voluntarily or involuntarily (Wundt, 1897).¹ Posner discussed the exogenous and endogenous control of attention (Posner, 1978). Similarly, in a colorful manner, Jonides discussed the “voluntary versus reflexive control of the mind’s eye’s movement” (Jonides, 1976).

The present article is concerned with the mechanisms of involuntary attention. To study involuntary attention, we used the spatial-cueing paradigm that was developed by Michael Posner and his colleagues (Posner, 1978, 1980; Posner, Snyder, & Davidson, 1980) and adapted for studying involuntary attention by John Jonides (Jonides, 1976, 1980, 1981). A typical trial with this paradigm is shown in Figure 1. Each trial begins with a fixation point (Figure 1A). Typically, there are faint placeholders (squares) to mark potential target locations. One of the placeholders thickens as a cue (Figure 1B). A short time later, a target appears (Figure 1C).

Operationally, voluntary and involuntary attention can be distinguished by whether the cue is predictive or not predictive of the target location. When a spatial cue is presented and it is not predictive of the target location, there is no reason to voluntarily allocate attentional resources to the cued location. Thus, any effect of the cue is said to involve involuntary attention (e.g., Prinzmetal, McCool, & Park, 2005; Wright & Richard, 2000). It is important to note that, to study involuntary attention in all of the experiments

reported here, the cues are not predictive of the target location. Thus, if there are two possible target locations, the probability of the target appearing in the cued location is 0.5. Even with non-predictive cues, observers are typically faster to identify the target when it appears in the cued location than when it appears in an uncued location (Jonides, 1976, 1980, 1981). The involuntary-attention effect can even occur under some circumstances when the cue is antipredictive; that is, the target is less likely to occur in the cued than an uncued location (Posner, Cohen, & Rafal, 1982; Prinzmetal & Landau, 2008; Rafal & Henik, 1994; Sereno & Holzman, 1996; Warner, Juola, & Koshino, 1990). This anticueing effect occurs when the time between the stimulus and target (stimulus-onset asynchrony; SOA) is relatively short.

For a while, it was thought that the main difference between voluntary and involuntary attention was whether the cue appeared at the fixation point or in the periphery (e.g., Briand & Klein, 1987), but recent studies have demonstrated that nonpredictive central cues can have a similar effect on performance as the effect of nonpredictive peripheral cues (e.g., Gibson & Bryant, 2005; Ristic, Friesen, & Kingstone, 2002; Tipples, 2002). Rather than cue eccentricity, what distinguishes voluntary and involuntary attention is whether the cue is predictive of the target location or random with respect to the target location. Observers are faster to respond to targets in the cued location rather than the uncued location for both predictive and nonpredictive cue experiments, but there are numerous differences in behavior between predictive and nonpredictive cues (e.g., Berger, Henik, & Rafal, 2005; Juola, Koshino, & Warner, 1995; Prinzmetal, Leonhardt, & Garrett, 2008; Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, &

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¹ In this article, we use the terms *voluntary* and *involuntary* attention because they have a historical precedent. However, by voluntary, we do not mean necessarily under conscious control (Bartolomeo et al., 2007) but rather the strategic allocation of processing resources to achieve specific goals.

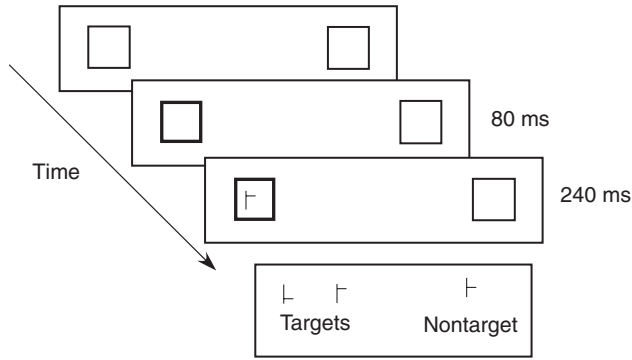


Figure 1. Panels A, B, and C show the sequence of trial events in Experiment 1. The lower panel illustrates the targets and the nontarget.

Garrett, 2005; Wright & Richard, 2000). Furthermore, there are also marked differences in physiological responses between predictive and nonpredictive cues, even when exactly the same stimuli are used (e.g., Esterman et al., 2007; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005; Landau, Esterman, Robertson, Bentin, & Prinzmetal, 2007).

The goal of the research reported here is to test three mechanisms of involuntary attention. The first mechanism is that involuntary attention enhances the perceptual representation of the target. If perception is considered a process whereby information from the environment is sampled by the visual system, attention may operate by having more samples from an attended location than from an unattended location (e.g., Bonnel & Miller, 1994; Luce, 1977; Prinzmetal, 2005). By this view, more perceptual information is gathered from the attended than from the unattended location, and/or information is gathered more quickly in the attended location. This corresponds to what Doshier and Lu (2000) termed *signal enhancement*. This mechanism is probably appropriate for voluntary attention (Doshier & Lu, 2000; but see Lu & Doshier, 1998), but there is evidence, discussed later, that signal enhancement might not be an appropriate explanation of involuntary attention. However, an appeal to parsimony suggests considering a single mechanism for both voluntary and involuntary attention.

The second mechanism attributes the involuntary-attention effect to a decision stage of analysis. We characterize this with the

competitive leaky accumulator model of Usher and McClelland (2001; see also, e.g., Brown & Heathcote, 2005; Klein & Hansen, 1990). Figure 2 illustrates this model in a two-alternative forced-choice spatial-cueing task with two possible target positions. Accumulators are simply evidence counters. In this model, there are four accumulators: (1) Target 1-related activity on the left, (2) Target 2-related activity on the left, (3) Target 1-related activity on the right, and (4) Target 2-related activity on the right. We assume that evidence for the alternative targets accumulates separately for each display position. This assumption is equivalent to the claim that independent decisions are made for targets at each location. There is considerable evidence in support of this assumption (Shaw, 1982).

When any accumulator reaches the response threshold (dashed line in Figure 2), the observer responds. In the trial illustrated, the left location is cued and Target 2 is presented. The cue preactivates both accumulators corresponding to the cued location (striped rectangles). When the target appears, evidence then accumulates (arrow) until the threshold is reached. In other words, the cue primes responses to anything (similar to the target) that appears in the cued location. Note that, in the model, the activation provided by the cue is a random variable (with a mean and variance) so that it might not be exactly the same from trial to trial. Also the rate of accrual of information (arrow in Figure 2) is a random variable that varies from trial to trial. This aspect of the model is important in predictions in Experiment 2.

On target-cued trials (left panel in Figure 2), the cue-generated activity gives a headstart to the target, and reaction times (RTs) will be faster than when a target appears in an uncued location. On trials in which the target appears in an uncued location (right panel), the target accumulator is not primed by the cue-related activity. The accumulator mechanism predicts that when observers are not under speed pressure, there should be no difference in accuracy between cued and uncued trials because target-related evidence (arrow in Figure 2) accumulates at the same rate on cued and uncued trials. However, when the stimuli are easy to perceive but observers are under speed pressure, more errors may be made on uncued than on cued trials. The reason for this is that, under speed pressure on an uncued trial, activation from the cue alone may trigger a response. Such responses must be at chance because there is no target-generated activity in the cued location on uncued trials.

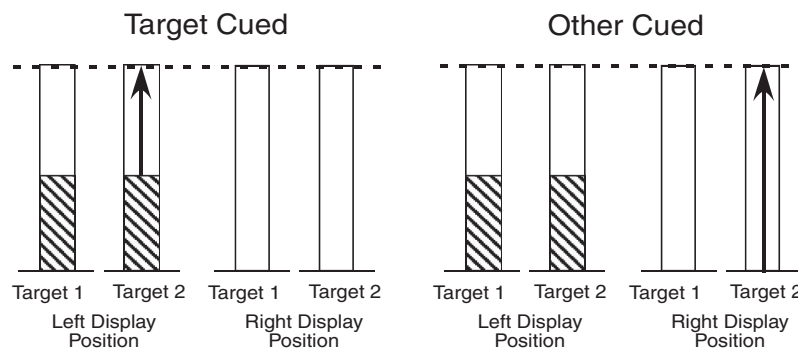


Figure 2. The accumulator model. Striped areas indicate cue-related activity, and the arrows indicate target-related activity. The horizontal dashed line represents the response threshold.

The competitive leaky accumulator model has some nice properties. The accumulators are “leaky” so that cue-related activity will quickly leak away. For the cue to speed responses, the target must follow the cue closely in time. Research has shown that, for a nonpredictive cue to facilitate responses at the cued location, the target must follow the cue closely in time (e.g., Posner et al., 1982; Warner et al., 1990). The accumulators are also competitive: Activation in any accumulator sends a certain amount of suppression to other accumulators. The competitive nature of the accumulator model is important for accounting for results in experiments that have neutral cues (which do not indicate a unique location), as well as cued and miscued trials. RT on neutral-cue trials is often between target-cued and other-location cued trials (e.g., Posner et al., 1980). The competitive nature of the accumulators accounts for this pattern of results because activity in the cued location suppresses activity in other possible target locations. Neutral cues do not differentially affect the accumulators. The competitive nature of the accumulators will be important later in making predictions that contrast the serial-search and decision mechanisms. The amount of competition is a parameter and, as the competition increases, the accumulator model becomes similar to a diffusion model (Ratcliff & Rouder, 1998). Thus, this account of involuntary attention is part of a general class of decision mechanisms.

The third mechanism involves serial search. It is similar to Rauschenberger’s (2003) idea of a processing queue. It is assumed that information about all display locations is perceptually encoded to the same degree into a representation that includes spatial information. This information store might be the same as visual working memory. Items are read out of this store serially. There is a tendency to begin the readout at the cued location. Thus, on average, if the target is in the cued location, RT will be faster than if the target is in another location. The access to this store need not be strictly one at a time, but there may be partly overlapping processes (Harris, Shaw, & Bates, 1979; McClelland, 1979). There is considerable evidence for something like a serial search in many circumstances (e.g., Neisser, 1964; Treisman, & Gelade, 1980; cf. Doshier, Han, & Lu, 2004).

In this article, we compared these three theories of the involuntary-attention cueing effect. Experiment 1 compared perceptual enhancement with the decision mechanism, and the results favored the decision mechanism. Experiment 2 compared the decision and serial-search mechanisms, and the results again favored the decision mechanism. Finally, in Experiment 3, we tested the hypothesis that, if the target is easy to locate, the decision mechanism will account for the involuntary-attention effect, and if the target is difficult to locate, the serial-search mechanism will account for the effect. In Experiment 3, we varied the number of possible target locations. In Experiment 3A, the target was relatively easy to locate because there were no distractors, and the results favored the decision mechanism. In Experiment 3B, the limit on performance was on finding the target within a display of distractors, and the results favored the serial-search mechanism. Thus, we conclude that there are at least two mechanisms of involuntary attention, and which mechanism accounts for the involuntary-cueing effect depends on whether the target is easy or difficult to locate.

Experiment 1

In Experiment 1, we compared the decision mechanism to the perceptual enhancement mechanism. According to the decision mechanism, the cueing effect is due to priming accumulators associated with the cued location. This architecture makes a unique prediction: Under speed pressure, there should be more false alarms (FAs) to nontargets presented in the cued location than in the uncued location.

This prediction arises because, in the accumulator model, speed pressure is equivalent to lowering the threshold (dashed line in Figure 2). If the threshold is sufficiently low, then cue-related activity alone might reach threshold and trigger a response on some trials. We tested this by using a combination of a two-alternative forced-choice experiment and a go/no-go procedure.² On 75% of the trials, one of two targets was presented and observers were to respond by pressing one of two buttons. On 25% of the trials, a nontarget was presented and observers were to refrain from responding. The targets and nontargets were similar to each other, but they could be discriminated easily without speed pressure. To increase speed pressure, we instructed observers to try to beat a deadline (150 ms). When they did not beat the deadline, the computer uttered the words “too slow.”

The decision mechanism predicts that observers would make more FAs to a nontarget when the nontarget appeared in the cued location than in the uncued location. The theory that attributes the involuntary-attention effect to enhanced perceptual processing would make the opposite prediction: Fewer FAs in the cued than in the uncued location. This prediction arises because observers would perceive the nontarget more veridically when it appeared in the cued location and would, therefore, be more likely to correctly classify nontargets and not respond to them.

Method

Procedure. Each trial began with a fixation point (see Figure 1A). A cue (darkening and thickening of a placeholder) was presented in one of the two locations for 80 ms (see Figure 1B), followed by the onset of one of the two targets or the nontarget in one location for 240 ms (see Figure 1C). The gray placeholders then reappeared. Figure 1 illustrates a target-cued trial. The targets, when present, consisted of a vertical line with a horizontal line near the top or bottom. The nontarget consisted of a vertical line with the horizontal line in the middle. Figure 1 (bottom panel) illustrates the targets and the nontarget. If a target was present, observers were to press one of two keys on a numeric keypad. The keypad was arranged so that the two response keys were vertically aligned. The “upper” key (further from the observer) indicated the target with the horizontal line near the top, and the “lower” key (closer to the observer) indicated the target with the horizontal line near the bottom. On target-present trials, if a response was longer than 150 ms from the offset of the target, a computer voice (Macintosh voice “Victoria”) uttered the words “too slow.” On target-present trials, if no response was made within 1,500 ms from the target offset, the computer said “too slow,” and the next trial began. On target-absent trials, if the observer did not respond for 1,500 ms, the next trial began. No accuracy feedback was

² We thank Richard B. Ivry for suggesting this experiment.

given. The purpose of these procedures was to generate errors, particularly in target-absent trials. Eye movements were monitored with a video camera as described in Prinzmetal, McCool, and Park (2005). When eye movements were detected, the computer-generated voice said "eye movement."

In each block of trials, 75% were target-present trials and 25% were target-absent trials. On half of the trials in each block, the target or nontarget location was cued, and on the other half, the other location was cued. The target identity and target location was randomly determined on each trial.

Each observer began the experiment with a minimum of one block of 32 trials of practice, with the target-present deadline set to 1,000 ms. If the observer was below 90% correct, we repeated practice until the observer completed a practice block with at least 90% correct. This was done to ensure that our observers could accurately discriminate the targets and nontarget. This practice was followed by an additional practice block of 32 trials, with the deadline lowered to 150 ms. Observers were told to try to beat the deadline and that speed was more important than accuracy. At the end of each block, observers were told their average RT for that block. After practice, data were collected in eight blocks of 64 trials per block.

Stimuli. The stimuli were presented on a 15-in. (38.1-cm) monitor, set to 800×600 pixels, controlled by a Macintosh G4 computer at a viewing distance of 48 cm. This distance was held constant with the use of a chin rest. Figure 1 is drawn to scale. The distance from the fixation point to the center of the target or nontarget subtended 8.3° of visual angle. The targets and nontargets were drawn in lines 2 pixels wide, and the cue was 5 pixels wide. The lines of the target and cue were black on a white monitor. The placeholders were gray (50% luminance of maximum monitor luminance).

Observers. Twelve observers were recruited from the University of California, Berkeley, Research Participation subject pool and received class credit for participating. One observer was replaced because of extremely inaccurate performance (34% correct in the target-absent condition). However, the results were almost identical with and without the replaced observer.

Results

In this and all of the experiments reported in this article, trials with eye movements occurred on an average of less than 1% of the trials, and these trials were removed from analysis.

The critical theoretical comparison in this experiment is the FA rate for target-absent trials. The decision model predicts a higher FA rate in the cued location than in the uncued location. The FA rate was significantly higher in the cued than in the uncued location (62.8% vs. 55.7%), $t(11) = 2.47$, $p < .05$ (two-tailed). Thus, in terms of the FA rate, the cue caused observers to be less accurate. This result is consistent with the decision mechanism, but it is the opposite of what would be expected from a theory proposing that involuntary attention enhances perception.

On target-present trials, there are two kinds of errors: Observers can make an incorrect response (i.e., respond to Target 1 when Target 2 was present) or fail to respond (i.e., a miss). Observers made significantly fewer incorrect responses when the target was in the cued than in the uncued location (14.2% vs. 19.8%), $t(11) =$

3.65, $p < .05$. However, there was no significant difference in miss rate between the cued and uncued locations (7.8% vs. 6.7%), $t(11) = 0.82$.

We analyzed RTs on target-present trials. On correct trials, observers were significantly faster on target-cued than other location-cued trials, (166 ms vs. 186 ms), $t(11) = 5.36$, $p < .05$ (two-tailed). Thus, in terms of RT, our experiment resembles the typical involuntary-attention cueing experiment.

The average RT for the errors in the target-absent trials was 134 ms. For 11 of the 12 observers, the average FA reaction time was faster than the average target-present correct response, indicating that errors were due to premature responses.

These results are consistent with the decision mechanism and inconsistent with the perceptual enhancement account. If involuntary attention enhanced perceptual processes, one would expect a pattern of FA rates opposite from what we obtained. Observers should have had fewer FAs for the nontarget in the cued location than the noncued location, because observers should be more likely to correctly classify the nontarget and not respond. The results were inconsistent with a perceptual enhancement account of involuntary attention.

If the effect on the FA rate was due to involuntary attention, and involuntary attention decreases with increased SOA, then our FA effect should be reduced or eliminated with a longer SOA. To determine whether this was the case, we conducted a follow-up experiment with 12 observers. The experiment was identical to Experiment 1, except that the SOA was changed to 1,000 ms. The percentages of FAs for the cued and the uncued nontargets were 53.0% and 54.2%, respectively, and this difference was not reliable, $t(11) = 0.37$, *ns*. Thus, when we increased the SOA, the cueing FA effect on nontargets disappeared. The difference in RTs for the target-present trials between cued and uncued trials also disappeared. The RTs, calculated as shown earlier, for cued and uncued target-present trials were 151 ms and 155 ms, respectively, $t(11) = 1.31$, *ns*. Thus, increasing the SOA eliminated the effect both in terms of FA and RT.³

Discussion

If involuntary attention enhances the perceptual representation, observers should make fewer FAs when the target was cued than when it was not cued. The decision mechanism predicts that observers would make more FA for targets in the cued than uncued location, and this is what we found.⁴

One might speculate that the higher FA rate in the cued location compared with the uncued location is because the extra lines from the box make it more difficult to distinguish between the target and

³ One may wonder why we did not observe inhibition of return with the long SOA. We think that a possible reason is that inhibition of return is less likely when the cue remains in view until the target appears (Tassinari, Aglioti, Chelazzi, Peru, & Berlucchi, 1994).

⁴ This is the third replication of the effect with similar stimuli. The first, reported at the annual Psychonomics meeting (Prinzmetal, 2005) has similar stimuli but with a smaller eccentricity and a shorter exposure duration. The second, reported at the Cognitive Science Association for Interdisciplinary Learning (Prinzmetal & Ha, 2007), had no placeholders and a distractor in the nontarget location (the letter O). In each case, at short SOAs, observers made significantly more FAs in the cued location than in the uncued location.

nontarget stimuli in the cued location. In this version of the experiment (see Footnote 3), the cue remained on with the target. However, even if the cue had returned to a gray box before the target appeared, one could still speculate that some kind of forward masking from the cue made the targets less perceptible in the cued location and caused the FA effect (worse performance on target-cued trials). We believe that this explanation is unlikely. Note that on target-present trials, observers were significantly more accurate on cued than on uncued trials. Considering accuracy on all trials (correct rejections and correct target classifications), observers were equally accurate on cued and uncued trials (79.3% correct for both). If the cue were causing some kind of perceptual interference, observers should have been overall less accurate on cued trials, and they were not.

Klein and Hansen (1990) proposed a model similar to our accumulator model to account for some of their results. They had two targets (stimulus became darker or lighter). One target was much more likely to occur in one of the locations than the other. For example, the dark stimulus might occur more often in the left location than the right location. Observers were faster when a target appeared in its high-probability location than when it appeared in its low-probability location. They accounted for this probability manipulation with a model similar to our accumulator model. However, they attributed the basic cueing effect to greater sensitivity for targets in the cued than in the uncued location, consistent with the enhanced perceptual processing account, even when the cues were not spatially informative (Experiment 5). Our results were inconsistent with the perceptual enhancement mechanism.

The account that is closest to our decision model was proposed by Hawkins, Shafto, and Richardson (1988). They explicitly proposed that there might be situations in which there would be a higher FA rate with the target in the cued than in the uncued location. However, there are two problems with Hawkins et al.'s proposal. First, they based their conjecture on a simple detection task and signal detection theory. Within this framework, there is no way to account for the spatial-cueing effect with a two-alternative forced-choice task and multiple possible target locations. The accumulator model that we present could be considered an extension of simple detection theory to account for two-alternative forced-choice tasks. Second, Hawkins et al. did not distinguish between voluntary and involuntary attention. There are at least three pieces of behavioral evidence that suggest that, whereas involuntary attention (nonpredictive spatial cues) does not enhance perception, voluntary attention (predictive spatial cues) does.

First, Prinzmetal, McCool, and Park (2005) compared predictive and nonpredictive spatial cues. Both types of cues affected RT similarly (i.e., faster when the target appeared in the cued location). However, when the tasks were made difficult (e.g., using very small letters as targets) and observers were urged to be as accurate as possible, only voluntary attention affected accuracy. They found this pattern of results with different stimuli and discriminations (e.g., letters, line orientation, and faces), different cues (e.g., boxes brightening as described earlier or sounds coming from the left or right), different numbers of target locations (2 or 4), with or without poststimulus masks, and with different SOAs (0 ms to 300 ms; see also Prinzmetal, Park, & Garrett, 2005). Recently, the same pattern of results has been found with gaze-direction cues and nonpredictive-central arrow cues (Prinzmetal et

al., 2008; Stevens, West, Al-Aidroos, Weger, & Pratt, 2008). This pattern of results led Prinzmetal, McCool, and Park (2005) to conclude that voluntary attention enhances perceptual processing, leading to more veridical perception, whereas involuntary attention affects RT through nonperceptual mechanisms such as the decision mechanism or the serial-search mechanism.

One might wonder whether the high accuracy for target-present trials for the cued than for the uncued trials is counter to the findings of Prinzmetal, McCool, and Park (2005), who claimed that involuntary attention did not affect accuracy. This is not the case. Prinzmetal et al. demonstrated that a nonpredictive cue did affect accuracy when observers were under speed pressure (Experiment 5, Prinzmetal, McCool, & Park, 2005) but not when observers were not under speed pressure. The observers in Experiment 1 were urged to respond quickly. We know that the errors that observers made were due to speed pressure because in practice, without speed pressure, all observers had at least one block in which their accuracy was over 90%. Thus, the accuracy results for the target-present trials are consistent with Prinzmetal et al.

The second kind of evidence that involuntary attention does not enhance perception involves a manipulation of perceptual processing difficulty. If voluntary attention affects perceptual processing, then it should have a larger effect in a perceptually demanding task than a perceptually easy task. On the other hand, if involuntary attention does not affect the perceptual representation, then increasing perceptual difficulty should not increase the cueing effect. This prediction was tested in a series of experiments designed around RT (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, 2009). Increasing target discrimination difficulty increased RT as expected with both voluntary and involuntary attention. In addition, with voluntary attention, the cueing effect was larger with the difficult than with the easy task. However, with involuntary attention, increasing difficulty decreased the attention effect. Thus, changing perceptual difficulty had the opposite effect with voluntary and involuntary attention.

Finally, Funes, Lupiáñez, and Milliken (2007) also found a double dissociation in RT between voluntary and involuntary attention. They compared a central predictive cue to a peripheral nonpredictive cue in a situation that involved a spatial Stroop task. The task was to indicate whether a target arrow pointed to the left or right, and the target could appear on the left or right. If the target location and identity were the same (e.g., ← on the left), then the trial was spatially congruent. If the identity and location of the target were different (e.g., ← on the right), then the trial was spatially incongruent. For voluntary attention, the congruency effect was larger for target-cued than for target-uncued trials. This is to be expected if voluntary attention enhances perceptual processing of the objects in the cued location. However, for involuntary attention, the pattern of results reversed. Recently, Halvorson, Hazeltine, and Prinzmetal (2007) found similar results comparing predictive and nonpredictive peripheral cues. Given the results from Experiment 1 and the previous evidence against the perceptual enhancement account of involuntary attention, we believe perceptual enhancement to be an unlikely account of involuntary attention.

There is an interesting parallel to our finding of more FAs with nontargets in the cued location in the phenomenon of inhibition of return. Inhibition of return is the finding that when the SOA is long, observers can be slower to respond when the

target appears in the cued location than when it appears in an uncued location. This effect only occurs when the cue is non-predictive (Bartolomeo, Decaix, & Siéroff, 2007; Wright & Richard, 2000). If inhibition of return is caused by the same mechanism that causes the facilitation in RT at short SOAs, one might expect that at long SOAs there would be greater FAs at the uncued location than at the cued location. In an experiment with a long SOA in a situation that yielded inhibition of return, Ivanoff and Klein (2004) found more FAs with nontargets in the uncued location than in the cued location. They argued that inhibition of return, which only occurs with nonpredictive cues, was not due to a perceptual mechanism.

In Experiment 1, we tested a prediction of the decision mechanism: Higher FA rate to nontargets in the cued compared with the uncued location. This is the opposite prediction of a theory that attributes involuntary attention to perceptual enhancement. The serial-search model does not make a prediction for FAs. Experiment 2 tests a unique prediction of the serial-search mechanism.

Experiment 2

According to the serial-search mechanism, RT is faster when the target is in the cued location because the serial search has a tendency to begin in the cued location. On trials on which the target appears in the uncued location, the search must shift to the uncued location and responses are slower. Note that the cueing effect arises because the serial processor must shift location when the target is not in the cued location.

We tested this theory by having a target in each location on half of the trials (multiple-target trials). The strategy of having multiple targets had been successful in discriminating serial and parallel models (e.g., Thornton & Gilden, 2007). On multiple-target trials, there was a target in each display location. On multiple-target trials, observers could respond to the target in the cued or uncued location. On these trials, the serial-search mechanism predicts no difference in RT to responses to a target in the cued location compared with a target in the uncued location.

To understand this prediction, consider a situation in which the observer checks the cued location first on 80% of the trials and the uncued location first on 20% of the trials. On trials when there is a target in each position, if the serial search begins on the cued location (80% of the trials), a target will be found immediately and the response will be relatively fast. If the serial search begins on the uncued location (20% of the trials), it will also find a target immediately and responses will also be fast. On multiple target trials, observers should be more likely to report the target in the cued than the uncued location. More important, regardless of whether the search begins at a cued or uncued location, responses will be equally fast. Hence, the serial-search model predicts that RT should *not* be faster when the observer responds with the target in the cued location compared with a target in the uncued location, because there is no reason to shift attention to another location on multiple-target trials. Wherever the serial processor begins, there is a target and a fast response can be executed.

Predictions of the decision model are a little more subtle. As with the serial-search model, the decision model predicts that,

on multiple-target trials, observers will be more likely to respond with the target in the cued location than with the target in the uncued location. Observers' responses will be determined by which accumulator reaches threshold first. This will usually be a target in the cued location because these accumulators are primed. However, occasionally, the uncued target will pass threshold first. This is because the amount of cue-related activation changes from trial to trial, as does the rate of the acquisition of target-related information (arrows in Figure 2). On some trials, the cue will provide relatively little activation, and the processing of the target in the uncued location will be faster than in the cued location. On these trials, observers will respond with the target in the uncued location. However, unlike the serial-search model, the decision model predicts that, on average, when observers respond with the target in the cued location, RTs will be faster than when they respond with the target in the uncued location, and the activation generated by the cue will make responses to the cued location not only more likely but also faster.

Method

Procedure. The sequence of events and stimuli are shown in Figure 3. Each trial began with a fixation point and two dim square placeholders. A cue (a darkened square) was presented for 160 ms. Eighty milliseconds after the cue, either one target or two targets was presented for 160 ms. The targets were the letters A, B, C, and D. On half of the trials, there was a single, randomly chosen, target (as shown in Figure 3). On half of the trials, there were two targets, one in each location, chosen with the constraint that they were different letters. Observers responded by pressing the keyboard digits 1, 2, 3, or 4 for Targets A, B, C, and D, respectively. On two-target trials, observers were instructed to press the button corresponding to *either* target; both were correct responses. They were told that we did not care about the target to which they responded, just that they be as fast as possible (see Prinzmetal & Taylor, 2006, for a similar procedure). When observers responded to a target that was not presented, the computer emitted a brief "buzz" sound. Observers were urged to be as fast as possible but to try to be over 90% correct. Eye movements were monitored as

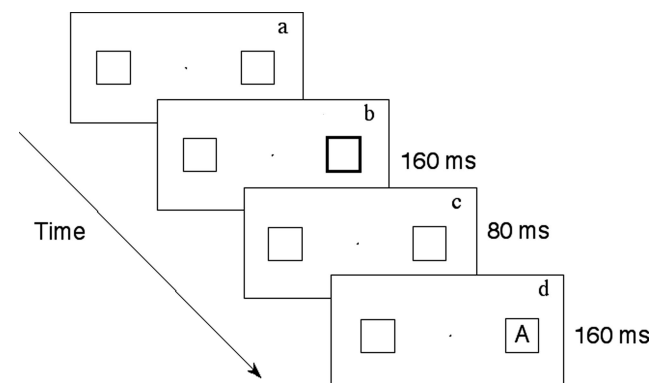


Figure 3. Panels A to D show the sequence of trial events in Experiment 2.

in Experiment 1. At the end of each block, observers were given their average percentage correct and RT.⁵

Each observer was given two blocks of 32 practice trials, followed by five blocks of 64 trials on which data were collected. The experiment took approximately 30 min.

Stimuli. The stimuli were presented on a 15-inch (38.1-cm) monitor controlled by a Macintosh G4 computer at a viewing distance of 48 cm. This distance was held constant with the use of a chin rest. Figure 3 is drawn to scale. The distance from the fixation point to the center of the squares subtended approximately 2.4°. The target letters were 28-point Helvetica font. The placeholder boxes were 1 pixel wide and gray (50% of the maximum monitor luminance). The cue was 5 pixels wide and black.

Observers. Twelve observers were recruited from the University of California, Berkeley, Research Participation subject pool and received class credit for participating.

Results and Discussion

On each condition (one-target cued trials, one-target uncued trials, and two-target trials), observers averaged 95% correct. Thus, there was no difference in accuracy between conditions.

Correct RTs on one-target trials replicated previous spatial-cueing results. Observers were faster when the target was in the cued location than when it was in the uncued location (423 ms vs. 452 ms), $t(11) = 5.10, p < .01$ (see Figure 4). On two-target trials, when observers responded with the target in the cued location, they were significantly faster than when they responded with the target in the uncued location (477 ms vs. 509 ms), $t(11) = 3.53, p < .01$.

The serial-search mechanism predicts that the cue should have no effect when there is a target in each position. Clearly, that was not the case. The effect of the cue was about the same magnitude when there was one target versus two targets. Observers were significantly slower when there were two targets versus one target, $F(1, 11) = 63.24, p < .01$; perhaps because of some indecision as to the target to which observers should respond. Overall, observers were faster to respond to the target in the cued location than to that in the uncued location, $F(1, 11) = 49.69, p < .01$. However, the

interaction shown in Figure 4 does not approach significance, $F(1, 11) = 0.15$.

Overall, when there were two targets, observers were more likely to respond with the target in the cued location than with the target in the uncued location (66.4% vs. 33.6%), and this was true of each observer. Both theories predict that observers will respond to a target in the cued location more than in the uncued location. The decision mechanism predicts this because the cued location will more often reach threshold first. The search mechanism predicts this because there is a tendency to begin the search in the cued location. However, the critical result is the RTs in the cued and uncued locations on the two-target trials. The search mechanism predicts that there will be no difference in RT when observers respond with the target in the cued location versus uncued location. This was not the case.

Experiments 1 and 2 were consistent with the decision mechanism. Nevertheless, we believe that there are situations in which the search mechanism may provide a better account of the cueing effect than the decision mechanism. In Experiment 3, we compared the decision and search mechanisms in an experiment in which the two mechanisms make opposite predictions. We found that which model provides the better account of the involuntary-cueing effect depended on whether the limit on performance was deciding which target was present or whether the limit on performance was finding the target. The former situation favors the decision mechanism, and the latter favors the serial-search mechanism.

Experiment 3

A clear prediction of the serial-search mechanism is that the more display positions, the larger the cueing effect. This prediction arises because, on trials in which a nontarget location is cued, if there are only a few display positions, the serial processor will find the target quickly. However, if there are many display positions, on average, the serial processor will take longer to find the target, as it has to search more locations.

The decision mechanism makes the opposite prediction: The larger the display size, the smaller the cueing effect. This prediction arises because, when any accumulator is activated, it sends inhibition to the other accumulators. It is a "competitive" accumulator. As the number of display locations increases, the inhibition from any activated accumulator is divided over more accumulators and, thus, inhibition to any one accumulator is decreased. This scenario is illustrated in Figure 5. In Figure 5A, there are two display locations. The inhibition from the cued location goes to the other two other accumulators (for the uncued location). In Figure 5B, the same inhibition is divided between six accumulators (three uncued locations). Hence, the difference in RT between target-cued and -uncued trials should be greater with fewer display positions, because inhibition is greater.

The dilution of competition is a corollary of one construal of the accumulator model. Activation of any accumulator at a moment in

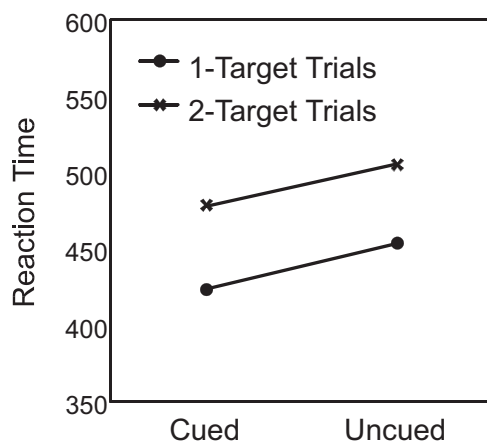


Figure 4. Reaction times on one- and two-target trials from Experiment 2.

⁵ This experiment was similar to one reported by Prinzmetal and Landau (2008) with multiple targets. The main difference was that, in the 2008 experiment, observers responded verbally, triggering a voice-operated relay. The present results were almost identical to those results.

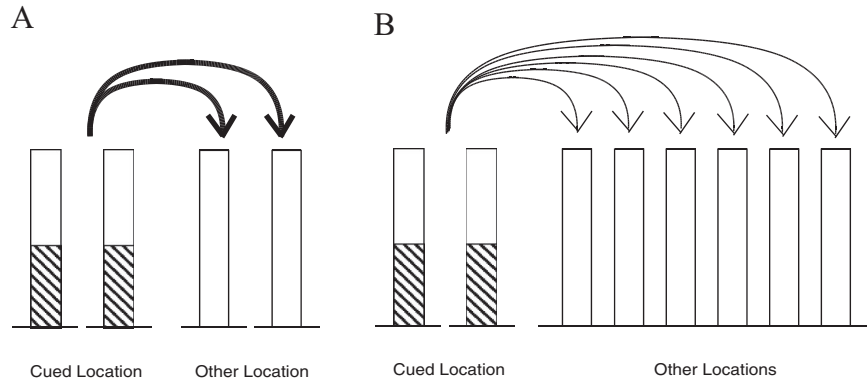


Figure 5. Competition in the accumulator model is related to the number of display locations.

time could be considered the likelihood (i.e., probability) of that accumulator exceeding the threshold and triggering a response. Thus, before the trial begins, all accumulators are equally likely to trigger a response. After the cue appears in one location, the likelihood of accumulators associated with that location triggering a response will increase. The accumulators associated with other locations will decrease in likelihood of triggering a response. Because probabilities sum to 1.0, increasing the activation a certain amount in the cued location will decrease the activation in the uncued locations. The more of these there are, the less each will decrease.

This experiment was inspired by a recent report by Mordkoff, Halterman, and Chen (2008), who varied display size in a detection task with nonpredictive spatial cues. They compared the effect of a nonpredictive cue with two, three, or four display locations in a detection task. They found that, as the number of display locations increased, the cueing effect decreased. This finding is consistent with the decision mechanism and opposite the prediction of the serial-search mechanism.

Experiment 3A is a replication of Mordkoff et al.'s (2008) study, with several differences. First, we used a two-alternative forced-choice task instead of a detection task. Second, we compared two locations to six locations (see Figure 6, Panels A and B). Otherwise, Experiment 3A was a standard spatial-cueing experiment with a single target presented on each trial that observers had to identify.

It occurred to us that our Experiments 1, 2, and 3A and Mordkoff et al.'s (2008) study did not involve conditions in which one would expect serial search. Finding the target in all of these experiments was fairly easy. In Experiment 1, the nontarget location was blank; thus, locating the target would be easy. In Experiment 2, on one-target trials, the nontarget location was blank. On two-target trials, both positions contained a target, so no search was necessary. Finally, in our Experiment 3A and in Mordkoff et al.'s study, the nontarget locations were blank. Again, finding the target would not be difficult, so a search would not be necessary.

In Experiment 3B, we created a need to search for the target by filling the nontarget locations with distractor letters that were similar to the targets (see Figure 6, Panels C and D). If serial search is necessary with distractors in the nontarget locations, we would expect a larger cueing effect with six possible target locations than with two possible target locations.

Method

Procedure. The sequence of events was similar to that in Experiment 2. Each trial began with either two or six dim grey squares that marked the potential target positions (placeholders) and a fixation point. The cue consisted of one of the squares becoming thicker and darker and was nonpredictive of the target's location. The cue remained in view for 80 ms, and then the fixation field returned for 40 ms. The target letter (F or T) was then displayed for 160 ms, followed by the fixation field. The observers' task was to identify the target by pressing one of two buttons on a keypad. When observers erred, the computer emitted a brief "buzz" sound. Eye movements were monitored as before.

The display size (2 or 6) alternated between blocks, with half of the observers beginning with a display size of 2 and half with a display size of 6. On the Display Size 2 blocks, the target was in the cued location on half of the trials. On the Display Size 6

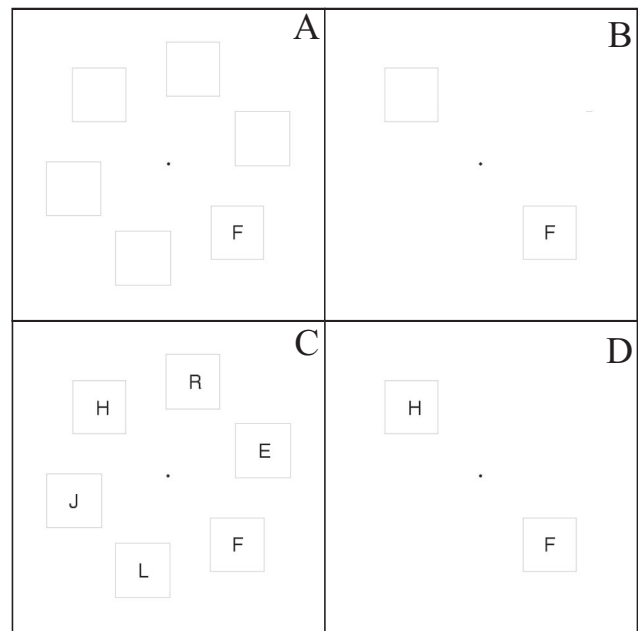


Figure 6. Sample stimuli in Experiment 3. Boxes A and B refer to Experiment 3A, and boxes C and D refer to Experiment 3B.

blocks, the target was in the cued location on 1/6 of the trials. Thus, there was no correlation between the cue and target location. When there were two locations, they always appeared directly opposite each other (see Figure 6B). For each observer, for Display Size 2 blocks, the same two locations were used, but across observers, all locations were used equally often.

In Experiment 3A (no distractors), the nontarget locations were blank. In Experiment 3B, the nontarget locations contained distractors, randomly chosen from the set L, J, E, H, K, and R. In Display Size 2 trials, one of these letters was randomly selected. In the Display Size 6 trials, five distractor letters were randomly selected without replacement.

Each observer began with at least one practice block of 36 trials with the same display size condition, on which they were to be tested first. This was followed by eight blocks of 72 trials per block, alternating between display size conditions. The target identity (F or T) and the target location were randomly selected on each trial.

Stimuli. Figure 6 illustrates the stimulus conditions and is drawn to scale. The distance from the fixation point to the center of the squares subtended approximately 2.9° of visual angle. The letters were 24-point Helvetica font. The gray placeholder squares were 1 pixel thick and had RGB values of 88% of the screen background (white). The cues were 5 pixels thick and black.

Observers. A different group of 12 observers participated in Experiments 3A and 3B. Observers were selected from the same pool as that used in Experiments 1 and 2.

Results

The mean correct RT and error rates are shown in Table 1. In Experiment 3A (no distractors), there was a significant main effect of the cue, $F(1, 11) = 12.46, p < .05$; and a significant Cue \times Display Size interaction, $F(1, 11) = 5.28, p < .05$. The effect of the cue (uncued RT – cued RT) was 16 ms, with a display size of 2 and only 3 ms with a display size of 6. The display size effect by itself was not significant, $F(1, 11) = 1.0$. These results replicate those of Mordkoff et al. (2008). This finding is consistent with the decision mechanism and inconsistent with the serial-search mechanism.

The results from Experiment 3B (distractors) are also presented in Table 1. In Experiment 3B, there was also a significant main effect of the cue, $F(1, 11) = 17.86, p < .01$; and a significant Cue \times Display Size interaction, $F(1, 11) = 5.77, p < .05$. However, the form of the interaction was exactly the *opposite* of

the no-distractor group: The cueing effect (uncued RT – cued RT) was larger with Display Size 6 than with Display Size 2 (40 ms vs. 14 ms, respectively). This finding is consistent with the search mechanism but not with the decision mechanism. With distractors, there was also a significant main effect of display size, $F(1, 11) = 31.02, p < .01$.

We also conducted an omnibus ANOVA that included both groups. In that analysis, of particular importance, was the significant interaction of Group (distractors vs. no distractors) \times Cue \times Display Size, $F(1, 22) = 10.01, p < .05$. This interaction is depicted in Figure 7. Without distractors, the cueing effect is larger with Display Size 2. With distractors, it is larger with Display Size 6.

Discussion

In Experiment 3, we found evidence for both the decision and the serial-search mechanisms. The serial-search mechanism is concerned with finding the target. The decision mechanism is concerned with deciding which target was present. Both mechanisms can account for the effect of a nonpredictive cue. Computationally, one must both locate the target and decide which target was present. Which mechanism best describes a particular experiment depends on whether the limits on performance are more on finding the target or on deciding which target is present. If the display contains distractors that are similar to the target, then the limit on performance is on finding the target. Under these circumstances, the serial-search mechanism best describes performance. When finding the target is easy because there are no distractors, the limits on performance are less on finding the target and more on deciding which target was present. In this case, the decision mechanism best describes performance.

We based the predictions of the decision model on the idea that competition from the cued locations is diluted when there are many noncued locations (i.e., 6 locations vs. 2 locations). There are probably other ways of accounting for this effect within the decision framework. For example, one might suppose that the facilitation of the cue is greater when there are fewer locations. This prediction would arise from a difference in the cue–target relation when there are two versus six locations. When there are two locations, the probability of a target following the cue is .5. When there are six locations, this probability is .167 (see Mordkoff et al., 2008, for a similar discussion). Perhaps the system is sensitive to this difference in contingencies, and therefore, it provides more activation in the cued location when there are only two locations.

At this point, we favor the dilution of inhibition account because most of the change in the cueing effect (without distractors) from two to six locations is in the uncued trials. When the target location was cued, the difference between two and six locations was 3 ms. When the target location was not cued, the difference was 11 ms (see Table 1). The facilitation account would predict that the difference would mostly be in the cued trials. Thus, the inhibition account fits the data better than the facilitation account, but undoubtedly there are more theoretical possibilities. What is clear is that there are two different mechanisms: The pattern of cueing effects is the opposite with and without distractors.

Table 1
Mean Correct Reaction Times and Error Rates for Experiment 3

Experiment and distractor status	<i>n</i> (and %) for target cued	<i>n</i> (and %) for target not cued
Experiment 3A		
No distractors		
Display size 2	295 (97)	312 (97)
Display size 6	298 (97)	301 (97)
Experiment 3B		
Distractors		
Display size 2	373 (97)	393 (96)
Display size 6	478 (94)	520 (92)

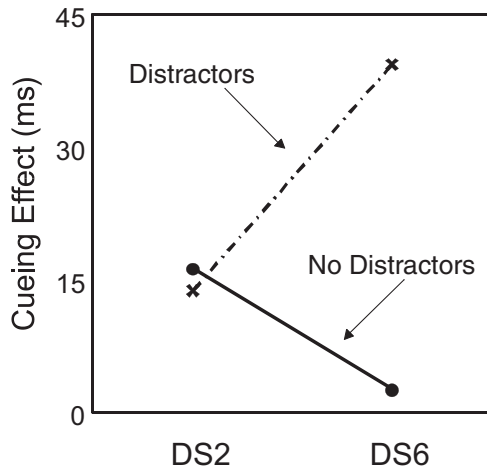


Figure 7. The cueing effect (uncued RT – cued RT) as a function of distractors at Display Size 2 (DS2) and Display Size 6 (DS6).

General Discussion

We hypothesized that three mechanisms could account for involuntary attention in the spatial-cueing paradigm. The first was that involuntary attention affects performance by perceptual enhancement. The second account was a decision mechanism, described in terms of a leaky competitive accumulator model (Usher & McClelland, 2001). By this account, the effect of the cue is to prime responses to anything (similar to the target) that appears in the cued location. Finally, we proposed a serial-search mechanism whereby display items are searched in a serial manner for the target, with a tendency to begin the search at the cued location.

Experiment 1 compared the perceptual enhancement account with the decision model. The perceptual enhancement account predicted that observers should be more accurate in identifying items in the cued than in the uncued location. The decision model predicted that there should be more FAs to nontargets in the cued location. The results clearly favored the decision model. The results were consistent with other evidence suggesting that, although perceptual enhancement might be a good account for voluntary attention, it does not account for involuntary attention (see, e.g., Prinzmetal & Landau, 2009, for a review).

The second experiment compared a prediction of the search model with a prediction of the decision model. The search model predicted that, if there was a target in every location, the cueing effect should be eliminated. The decision model predicted that the cueing effect should not be eliminated. The results favored the decision model.

The final experiment considered the possibility that the decision and search models both account for involuntary attention, but in different circumstances. The decision model accounts for the involuntary attention effect when the target is easy to locate, and the search model accounts for it when the target is difficult to locate. The models make different predictions for varying the number of target positions. When there were distractors in the display and the target was difficult to locate, the results favored the search model. When there were no distractors in the display, the results favored the decision model. Thus, there are at least two different mechanisms for involuntary attention.

There are theoretical alternatives for our two involuntary-attention mechanisms. An equivalent decision model is to lower the threshold for responding for the cued accumulators. Similarly, the decision mechanism could be described as a random walk or diffusion model (Ratcliff & Rouder, 1998). Competition in the competitive accumulator model is a parameter; as it increases, the accumulator model becomes more like a diffusion model. A diffusion model also predicts that competition will be diluted as the number of display locations increases. Consider a two-decision bounds model. Any one-unit drift toward one bound is a unit drift away from the other bound. However, as the number of decision bounds increases, any one-unit drift toward one bound is not an *average* of one drift away from all other decision bounds. Also note that predictions of the search model can be mimicked by certain unlimited-capacity parallel models (Doshier et al., 2004). Thus, there are different ways of describing these processes.

What seems to be clear, however, is that more than one mechanism will be required to account for the involuntary-attention data in Experiment 3. It is difficult to imagine a single mechanism that could account for the double dissociation in these results without being overly complex. Thus, although there are different ways of describing our decision and search mechanisms, the results of Experiment 3 are difficult to rectify with a single mechanism (e.g., Burnham, 2007).

One may wonder how the two mechanisms we propose work together. We describe one possibility. At a functional level, one must both locate the target and identify the target. When the target is easy to find—either because there are no distractors or because the target is defined by a single feature—the target might be located in parallel (Treisman & Gelade, 1980). The decision model provides a mechanism for this parallel processing. Furthermore, cueing primes responses to any item in the cued location through accumulator activation. When the target is difficult to find, a serial search takes place, considering each display item, one at a time, usually beginning at the cued location. Each item is classified as a target or nontarget with an accumulatorlike mechanism. However, when one is considering one item at a time, all relevant responses are either primed (cued trial) or not primed (uncued trial). Thus, the cueing effect with distractors is mostly determined by the search order, not by priming responses to a target in a particular location. By this account, if it is immediately apparent where the target is located, the decision model will account for performance. If the target is difficult to find, then the serial model will take over. Additionally, Awh, Matsukura, and Serences (2003) demonstrated that the expectation that a trial will or will not have distractors can change an observer's performance.

Evidence for two different mechanisms of involuntary attention raises several questions. There are several phenomena associated with involuntary attention, such as inhibition of return (Posner & Cohen, 1984), contingent capture (Folk, Remington, & Johnston, 1992) and the object effect (Egley, Driver, & Rafal, 1994). Inhibition of return, as previously discussed, is the finding that, as SOA increases, the cueing effect can reverse. Contingent capture is the finding that the more similar the cue and target, the greater the cueing effect. The object effect is the finding that cueing one part of an object can facilitate responses to a target in another part of that object. All of these effects have been obtained with nonpredictive spatial cues and therefore are associated with involuntary

attention.⁶ For each of these effects, one can ask whether the decision mechanism or the serial-search mechanism provides a better explanation. Experiment 3 provides a blueprint for investigating these issues. We can vary the difficulty of finding the target by including distractors in the display. Furthermore, we have a method to determine whether a cueing effect is best described by the serial-search mechanism or the decision mechanism. If the effect is greater with few display locations, then the decision mechanism is a better descriptor. If the effect is greater with more display locations, then the serial-search mechanism is a better descriptor of the phenomenon in question.

Note that the mechanisms are not mutually exclusive. Consider inhibition of return, which we are now investigating with the crucible used in Experiment 3. If inhibition of return is due to the decision stage (accumulator mechanism), then it should occur without distractors and it should be greater with fewer display locations. However, if inhibition of return is due to serial search (as the name suggests), then it should occur with distractors and be larger with more display locations. Pratt, Adam, and McAuliffe (1998) varied the number of display positions from two to six in a spatial-cueing task, in which the nontarget locations were blank. They found that the amount of inhibition of return decreased as the number of display locations increased, a pattern consistent with the decision mechanism. Furthermore, Ivanoff and Klein (2004), in an inhibition-of-return experiment found fewer FAs for nontargets in the cued location, also supporting the decision mechanism. However, we do not know whether we would also obtain inhibition of return in conditions that engender serial search (i.e., including distractors in the display). It is possible that, with distractors, inhibition of return increases as the number of display positions increases. Inhibition of return could be multiply determined (Klein & Taylor, 1994), and the paradigm in Experiment 3 could help answer this question.

One may wonder whether there are more than the two mechanisms for which we found evidence. We do not know the answer to this. For example, visual attention to the perceived location of a limb might be different than the forms of involuntary attention that we have explored (e.g., Reed, Grubb, & Steele, 2006); or voluntary attention, when one is aware that the cue location predicts the target location, might be different than when one is unaware of this relationship (cf. Bartolomeo et al., 2007; Lambert, Naikar, McLachlan, & Aitken, 1999). However, hypothesizing separate mechanisms is not parsimonious unless there is evidence of, for example, a double dissociation between the hypothesized forms of attention. In hypothesizing different voluntary- and involuntary-attention mechanisms, we found double dissociations between predictive and nonpredictive cues, both in behavior (e.g., Prinzmetal et al., 2009) and neurophysiology (e.g., Landau et al., 2007). In asserting that there are two forms of involuntary attention, we found the opposite pattern of cueing effects with display size, depending on whether the target was easy or difficult to find (see Figure 7). We do not want to hypothesize additional separate mechanisms without compelling evidence.

In addition, it may be that some effects that involve serial search, even with nonpredictive cues, invoke voluntary-attention mechanisms. Consider, for example, an experiment by Folk et al. (1992) on contingent capture. Observers had to indicate whether a display contained a red X or red equal signs among black Xs and black equal signs. The most effective cue consisted of red dots. The location of the cue was irrelevant, but the color of the cue was

relevant. The task required observers to find the red letter. Perhaps observers set themselves to search for something red. Such a situation could evoke the same neural mechanism as with a predictive cue. Not all contingent-capture experiments have the conditions that would lead to serial search (e.g., Ansoorge & Heumann, 2003). The challenge will be to find empirical methods to determine whether voluntary-attention mechanisms affect performance in some nonpredictive cue situations.

We have followed a *divide et impera* approach to understanding the mechanisms of spatial attention. Previous behavioral and neurophysiological evidence suggests that there are different mechanisms for voluntary and involuntary attention. We considered three possible mechanisms of involuntary attention. We found that a decision mechanism and a search mechanism can both account for involuntary attention but in different situations. Instead of thinking of involuntary attention as a unitary concept, it is more accurate to think of involuntary attention in terms of specific mechanisms.

⁶ There is some controversy as to whether the object-based effect is related to involuntary attention (see, e.g., Abrams & Law, 2000). However, we know that the object-based attention effect can be obtained with nonpredictive spatial cues (e.g., He, Fan, Zhou, & Chen, 2004).

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