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RESEARCH ARTICLE

Contingent capture and inhibition of return: a comparison of mechanisms

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Abstract We investigated the cause(s) of two effects associated with involuntary attention in the spatial cueing task: contingent capture and inhibition of return (IOR). Previously, we found that there were two mechanisms of involuntary attention in this task: (1) a (serial) search mechanism that predicts a larger cueing effect in reaction time with more display locations and (2) a decision (threshold) mechanism that predicts a smaller cueing effect with more display locations (Prinzmetal et al. 2010). In the present study, contingent capture and IOR had completely different patterns of results when we manipulated the number of display locations and the presence of distractors. Contingent capture was best described by a search model, whereas the inhibition of return was best described by a decision model. Furthermore, we fit a linear ballistic accumulator model to the results and IOR was accounted for by a change of threshold, whereas the results from contingent capture experiments could not be fit with a change of threshold and were better fit by a search model.

Keywords Attention · Inhibition of return · Contingent capture · Exogenous attention · Involuntary attention

Introduction

The goal of this research is to test accounts of contingent capture and inhibition of return (IOR), both of which are associated with involuntary attention in the spatial cueing task (e.g., Posner 1980). Our version of this paradigm is illustrated in Fig. 1. Each trial begins and ends with a fixation field that consists of gray boxes marking the potential target locations. A cue appears, which in this case is the sudden appearance of a black box, followed by a target that observers have to identify or detect (depending on the experiment). Importantly, the cue is not predictive of the target location. Nevertheless, under many circumstances, observers are faster when the target appears in the cued location compared with when the target appears in an uncued location (Jonides 1976, 1981; Rauschenberger 2003; Ruz and Lupianez 2002).

Contingent capture is the finding that the effectiveness of a nonpredictive cue is related to its physical similarity to the target and the "attentional control settings" of the subject (Folk et al. 1992, 1994). The more similar the cue is to the target, the greater the "capture". For example, cues that involve a sudden onset are effective when the target is defined by a sudden onset, but less effective if the target is defined by color. On the other hand, the sudden onset of an object will not be a particularly effective cue when the target is defined by color. The argument is that there are no stimulus attributes that capture attention in a truly automatic manner, but that it is the relationship between the cue and target that is critical. This relationship determines the "top–down" control settings. It has been argued that all automatic cueing effects arise from these top–down control settings (Burnham 2007; but see e.g., Theeuwes 2004).

IOR is the finding that when the time between the onset of the cue and onset of the target (stimulus onset

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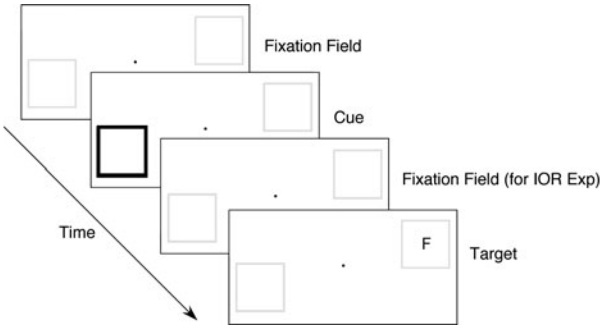


Fig. 1 The sequence of events used in the present experiments. In Experiments 1 and 2, there was no delay between the cue and target. In Experiment 3 (IOR), the delay between cue and target was manipulated

asynchrony, SOA) is increased, the facilitation in reaction time (RT) at the cued location can turn to inhibition (Posner and Cohen 1984). That is, responses to targets at the cued location are slower than at uncued locations. This effect is only observed when the cue is not predictive of the target location (Bartolomeo et al. 2007; Wright and Richard 2000). When the cue is predictive of the target location, the facilitation of RT at the cued location does not decrease as the cue-target interval increases. It may be that with a predictive cue, voluntary attention overrides IOR.

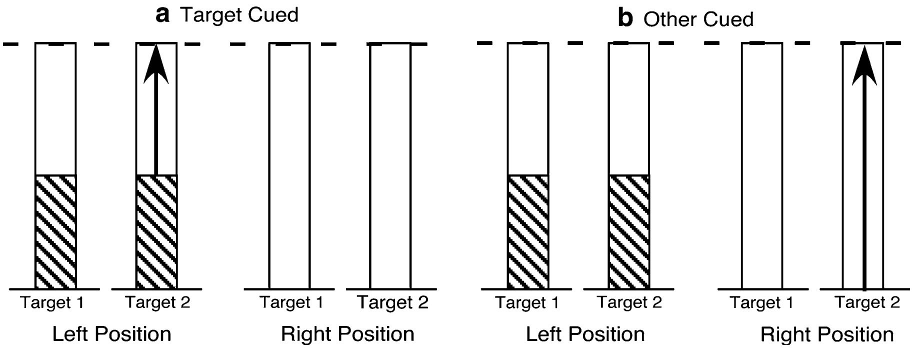
Both contingent capture and IOR are associated with involuntary attention, but not with voluntary attention. There is a plethora of research that suggests that voluntary attention and involuntary attention are caused by different mechanisms. They have different behavioral signatures (e.g., Berger et al. 2005; Funes et al. 2007; Prinzmetal et al. 2005, 2009). Furthermore, they show different patterns of neural activity both in fMRI (e.g., Esterman et al. 2008; Kincade et al. 2005) and in EEG (Landau et al. 2007).

Recently, Prinzmetal et al. (2010) provided evidence of at least two different mechanisms of involuntary attention. The first mechanism could be described as a serial search mechanism, and the second a decision mechanism. According to the serial search model of involuntary attention, display information is encoded into a memory store (e.g., visual working memory or perhaps iconic memory), and this store is searched in a more or less serial manner (Smith and Ratcliff 2009). Responses are faster when the target is in the cued location because the search tends to begin at the cued location. There is no task-relevant reason to begin the search at the cued location because the cue is nonpredictive. However, the search has to begin somewhere and the cue biases the search order. This model predicts that the more display locations, the larger the difference in RT between the target in the cued location and uncued locations. This prediction arises because when there are more display locations, it takes longer, on average, to find the target when it is in an uncued location.

The second theory involves a response-decision stage of analysis, which can be characterized as a competitive accumulator model (e.g., Usher and McClelland 2001; also see for example Brown and Heathcote 2005; Grice 1968; Smith et al. 2004). This version of the theory is illustrated in Fig. 2. The figure illustrates a situation with 2 possible target positions (labeled Left Position and Right Position) and 2 possible targets (Target 1 and Target 2). Figure 2a describes the situation where the target is cued. Figure 2b describes a situation where another location is cued. An accumulator is simply an evidence counter, and in this situation, there are four accumulators. When the evidence for one of the targets in a particular location reaches a threshold (dashed line), the observer responds. The cue activates the accumulators associated with the cued location. Cue-related activity is indicated with diagonal stripes in Fig. 2. When the target appears, the activation at its location increases until threshold is reached. Target-related activity is indicated with the arrows. On trials on which the target location was cued, the activation provided by the cue provides a head start for reaching threshold, and hence, RTs are faster for targets in the cued than in uncued location. A critical parameter in this model is the distance from the starting point to the threshold, and this parameter may be affected by cueing.

A second version of the accumulator model is that evidence accumulates more rapidly in the cued than in the

Fig. 2 The accumulator (decision) model. Striped area is the activity generated by the cue; the *arrow* is activity generated by the target. The *dashed line* is the threshold



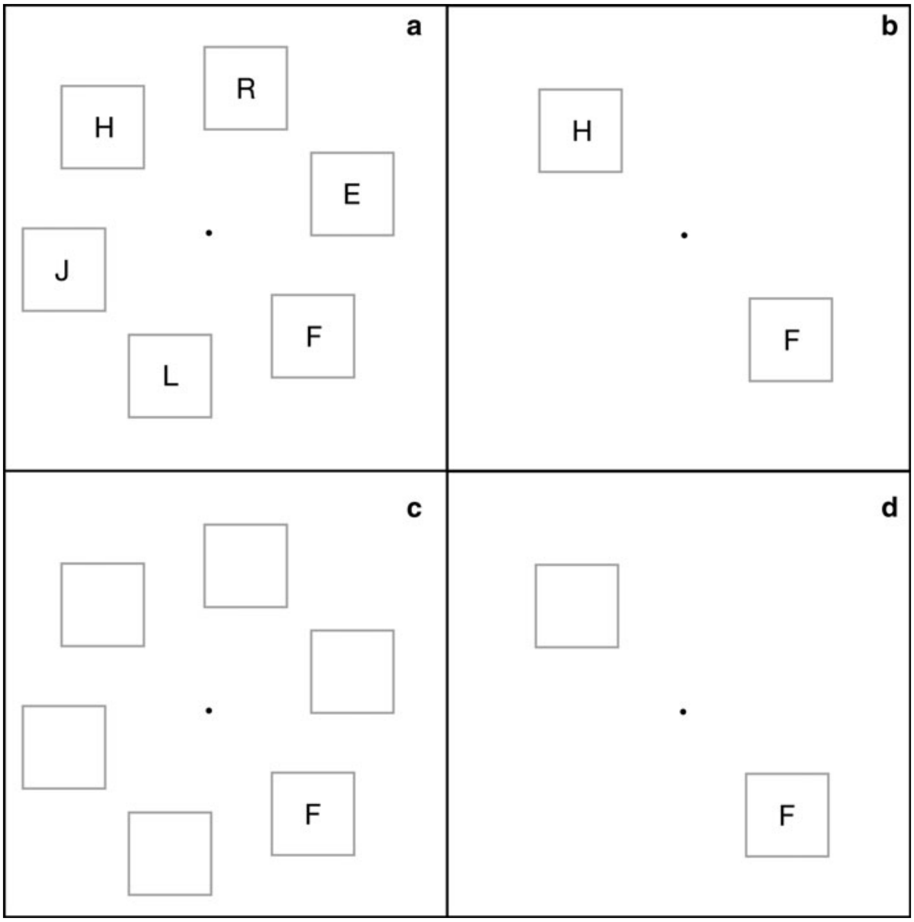


Fig. 3 The 4 stimulus conditions used in all of the experiments. There were either 2 (**b** and **d**) or 6 stimulus locations (**a** and **c**), marked with *gray boxes*, and the nontarget locations contained distractors (**a** and **b**) or there were no distractors (**c** and **d**)

uncued location, leading to a more veridical perception for the item in the cued location. A more veridical perception of items in the cued location would lead to fewer errors (FA's and misses) in the cued location. This version of the model was explicitly tested and rejected by Prinzmetal et al. (2010). They put participants under speed pressure in a go/no-go task. The response-decision version of the model predicts more false alarms (FAs) with the target in the cued location because the distance from starting point to threshold is reduced by the cue (described above). An increase in the rate of accumulation of information predicts higher accuracy in all conditions for the cued location. Prinzmetal et al. found a higher FA rate for targets in the cued location (and no change in miss rate), consistent with the decision-stage version of the model.

In contrast to the search model, the decision model predicts that the more display locations, the smaller the cueing effect. In the original version of the competitive accumulator model, the amount of competition between accumulators was a free parameter (e.g., Usher and McClelland 2001). At one extreme, any increase in activation in one accumulator leads to a decrease in activation in other accumulators, so that the total activation in the system is a constant. This assumption is shared by random walk and diffusion models (Ratcliff and Rouder 1998; Donkin et al. 2011). At the other extreme of the model, accumulators are independent. We assume some degree of competition between accumulators such that activation in any accumulator suppresses activation in other accumulators to some extent. For the purposes of our predictions, the exact amount of competition is irrelevant. Activation due to the cue will suppress activation in the other accumulators. However, with more accumulators, this suppression will be diluted and hence the cueing effect will be reduced.

Prinzmetal et al. (2010) found evidence for both the search mechanism and decision mechanism, depending on whether there were distractors in the display. Prinzmetal et al. compared the situation with either 2 display positions or 6 display positions (see Fig. 3). They found that with distractors in the display (Fig. 3a, b), the more display locations, the greater the cueing effect, consistent with the search model. Without distractors (Fig. 3c, d), there was a smaller cueing effect with 6 than with 2 display locations (search model). Without distractors, Mordkoff et al. (2008) also found a larger cueing effect with fewer display locations. With distractors, the target was difficult to locate, which led to a larger cueing effect. Without distractors, the limit on performance was deciding which target was present leading to a smaller cueing effect.

In the present paper, we examine IOR and contingent capture by varying the number of possible display locations and whether the nontarget positions contained distractors or not. The sequence of events is illustrated in Fig. 1. In the contingent capture experiments, participants decided whether the display contained the target letter "F" or "T". In the IOR experiment, they decided whether a target letter was present in the display (e.g., the letter "F"). The display conditions are shown in Fig. 3. As explained below, both theories can be adapted to account for contingent capture and IOR. With distractors in the display, the limit on performance should be finding the target. Without distractors, the limit on performance should be deciding which target was present (decision model). If the effect in question (i.e., contingent capture or IOR) is best explained by the search mechanism, it should be larger with distractors than without distractors. Furthermore, the effect should increase with the number of display positions. If the effect (contingent capture or IOR) is best described by the decision model, then it should be larger without distractors and with fewer display positions. Experiments 1 and 2 investigate contingent capture. Experiment 3 investigates IOR.

In the first description of IOR, it was associated with the automatic attention mechanism that causes facilitation at short SOAs (Posner and Cohen 1984; also see Klein and Taylor 1994; Reuter-Lorenz et al. 1996 for reviews of this idea). In many cases, the facilitation at short SOAs can be accounted for by the attentional control mechanisms that cause contingent capture (Folk et al. 1992, 1994). Following this logic, Burnham (2007) concluded that contingent capture and IOR were caused by the same mechanism.

To test whether contingent capture and IOR were caused by the same mechanism, Pratt et al. (2001) manipulated whether attentional control strategies could be used or not. With short SOA, there was greater facilitation at the target location when attentional control strategies could be used (i.e., contingent capture). This same manipulation had no effect with IOR. On the other hand, Gibson and Amelio (2000) found under some circumstances, contingent capture did affect facilitation and IOR. We do not know with certainty what accounts for these conflicting results.

We sought to find experimental variables that would lead to a double dissociation between contingent capture and IOR. Here, a double dissociation would lead to either an increase in contingent capture and a corresponding decrease in IOR, or vice versa (Reuter-Lorenz et al. 1996). To anticipate our results, we found that adding distracting letters to the display (see Fig. 3) increased contingent capture but decreased IOR. This difference was increased with more display locations.

We wanted to make IOR and contingent capture experiments as similar as possible so that if we found differences in these effects, they could be attributed to the differences in the underlying mechanisms and not peripheral aspects of the tasks. Thus, we tried to make IOR and contingent capture experiments as identical as possible except for those factors that are important to obtain these two effects. Hence to obtain IOR, we used a long SOA and a go/no-go task, whereas to study contingent capture, we varied the color of the cue and target letter. In all other respects, however, the experiments were identical in order to facilitate a comparison of these effects.

Experiment 1

Both the decision model and the serial search model can be elaborated to account for contingent capture. The decision model can account for it by claiming that only a cue that is similar to the target will activate the target accumulators resulting in a cueing effect. If the cue, for example, is completely unrelated to the target, it should not activate the target accumulators.

The search model accounts for the cueing effect by claiming that serial search usually begins at the cued location. If the target is at the cued location, the participant responds quickly. If not, the search continues. The probability of the search beginning at the target location is determined by the similarity of the target and cue. If they share features, one would have a "top–down" control setting to begin searching at the cued location (Folk et al. 1992).

Contingent capture has been studied by changing the features of the target and the cue. In this experiment, the targets were defined by color and the cue either matched the target in color or did not match the target in color (see Ansorge and Heumann 2003). Contingent capture in these experiments is the finding of a greater cueing effect when the target and cue match in color than when they do not match in color.

Method

Procedure

The procedure was almost identical to Prinzmetal et al. (2010) except that the cues and targets were colored. As shown in Fig. 1, each trial began with a cue, followed by a target. The number of locations (2 or 6) was varied between blocks, and the presence of distractors was manipulated between subjects. There were 2 or 6 possible colors when there were distractors in the display (depending on the number of locations). Samples of the stimuli, without color, are shown in Fig. 3. As in Prinzmetal et al. (2010), participants made a two-alternative forced-choice discrimination. They pressed one button if they saw the letter T and another button if they saw the letter F. For half of the participants, the target was always red, and for the remaining participants, it was always blue. In each display, there was only one target (an F or T, never both). The target matched the cue in color on half of the trials.

In a trial, we set the time between the cue and target to obtain faster RTs at the cued than at the uncued location (i.e., no IOR). A fixation field was present whenever the cue or target was not present. The fixation field consisted of a fixation point and either 2 or 6 placeholders (gray boxes, see Fig. 1). The number of potential locations was constant for a block of trials (2 or 6). The cue appeared and remained in view for 120 ms. The target appeared at the cue offset and remained in view for 240 ms. The inter-trial interval was 1 s. The cue was noninformative of the target location, so that on blocks with 2 locations, the target was cued on ½ the trials. When there were 6 locations, the target was cued on 1/6th of the trials.

Each participant had at least two practice blocks of 36 trials, and this was followed by 8 blocks of 72 trials per block alternating between 2 and 6 target locations. The order of blocks was counterbalanced across participants. When there were 2 target locations, they were always located opposite each other and this was also counterbalanced across participants.

When participants erred, the computer emitted a brief "buzz" sound. Eye movements were monitored with a video camera as described in Prinzmetal et al. (2005). When eye movements were detected, the computer-generated voice said "eye movement". At the end of each block, participants were told their accuracy and average RT for the block.

Stimuli

The stimuli were presented on a 15-inch monitor at a viewing distance of 48 cm. This distance was held constant with the use of a chin rest. Figure 3 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 degrees of visual angle. The letters were 24-point Helvetica font. The distractor letters were randomly chosen without replacement from the set L, J, E, H, K, R, and either the letter F or T (depending on the target identity). 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 colored as indicated above. There were 6 possible colors (red, blue, green, orange, brown, and magenta) for cues and distractors. The RGB values of the colors were selected to be similar in luminance. In the displays with distractors, no color was repeated.

Participants

Forty-eight participants were recruited from the University of California, Berkeley Research Participation subject pool and received class credit for participating. Twenty-four observers were run with distractors and 24 without. Three of the participants were replaced because their accuracy was below 85% in at least one condition.

Results

Trials on which observers moved their eyes were removed from the analysis (<1% of trials), trials with RTs greater than 2,000 ms and less than 100 ms (1.8% of trials) and trials on which errors were made (2.4%). The correct RTs were submitted to an ANOVA with the following factors: cue type (cued vs. uncued), number of display locations (2 vs. 6), color matching (match vs. not match), and group (distractors vs. no distractors). Not surprisingly, there were significant effects of cue type ($F(1,22) = 18.62$) and number of display locations ($F(1,22) = 7.95$, both P's < 0.01). Importantly, group significantly interacted with number of locations ($F(1,46) = 41.99$), number of locations × cue ($F(1,46) = 7.78$), and color matching ($F(1,46) = 22.57$, all P's < 0.05). Hence, the two groups were analyzed separately.

The cueing effect (uncued-cued RT) is shown separately for the no-distractor group and the distractor group in Fig. 4. In general, the cueing effects were positive, meaning that participants were faster responding to the target in the cued than in the uncued locations. First, consider the no-distractor group. There was a significant cueing effect ($F(1,23) = 14.34$, $P < 0.01$). The cueing effect was larger with 2 locations than with 6 locations, $F(1,23) = 8.24$, $P < 0.05$. This finding replicated Prinzmetal et al. (2010) and Mordkoff et al. (2008). The results are consistent with the decision model, which predicts a larger cueing effect

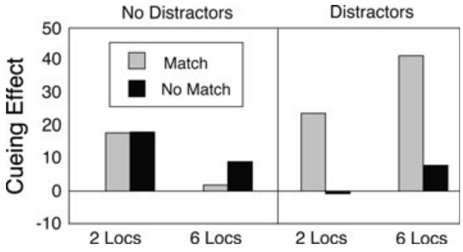


Fig. 4 The cueing effect (uncued-cued RT) in Experiment 1. The greater cueing effect for Match and No Match stimuli is the effect of contingent capture

with fewer display locations. The effect of color matching did not approach significance, $F(1,23) = 0.58$. Nor did color matching interact with any other variable. Thus, without distractors, we did not have contingent capture, at least as reflected in the cue color matching the target color.

With distractors, the picture was very different. There was a significant cueing effect, $F(1,23) = 23.34$, $P < 0.01$, and significant cue type × color matching interaction, $F(1,23) = 30.56$, $P < 0.01$. The cueing effect was larger when the color of the target and cue matched than when it did not match. Thus with distractors, we had clear contingent capture.

We obtained contingent capture with distractors, consistent with the serial model. The serial model also predicts that with distractors, contingent capture should be greater with 6 locations than with 2 locations. Contingent capture, measured with the cueing effect, was larger with 6 locations than with 2 locations (see Fig. 4). With 2 locations, the difference in cueing effect between match and mismatch was 24 ms, and with 6 locations, it was 33 ms. However, the 3-way interaction with the distractor group of cue × match × locations failed to reach significance, $F(1, 23) = 2.20$, $P = 0.15$.

In the above analysis, we considered all locations in the 6-location condition. Note that in the 2-location condition, on invalid trials, the target and cue were always opposite each other (see Fig. 3). Since the visual distance between the target and cue may affect performance, we performed an analysis that normalized the distances between items. In this analysis, for the 6-location condition, we only considered valid trials and invalid trials when the target and cue were opposite each other. Thus, the 2- and 6-location conditions were made equivalent in terms of cue-target distance. The results, in this and all subsequent experiments, were nearly identical to the initial analysis. Considering both groups together, there was a significant effect of cue ($F(1,47) = 39.88$) and display-size ($F(1,46) = 9.19$). As in the analysis with all positions, group significantly interacted with number of locations ($F(1,46) = 32.66$), number of locations × cue ($F(1,46) = 8.34$), and color matching ($F(1,46) = 22.57$, all P's < 0.05). Thus, we analyzed the two groups separately.

For the no-distractor group (only valid and opposite locations), the cueing effect was larger with 2 locations, $F(1,23) = 8.42$, $P < 0.05$. The cueing effect averaged 18 ms in the 2-location condition and 4 ms in the 6-location condition. The effect of matching did not approach significance, $F(1,23) = 0.01$, nor did it interact with any other variable. The cueing effect when the target and cue colors match and did not match was 14 and 15 ms, respectively.

For the distractor group, the results considering only the valid and opposite locations, the results were nearly identical to the initial analysis. There was a significant cue × matching interaction, $F(1,23) = 15.49$, $P < 01$. The cueing effect when the target and cue matched in color was 30 ms, and when they did not match in color, it was only 3 ms. Thus, the results were identical when controlling for the distance between the cue and target as when considering all of the display conditions.

Discussion

We found contingent capture only when there were distractors in the display. When there were no distractors in the display, there was a nonsignificant tendency to have a larger cueing effect when the cue and target were different colors (at least with 6 display locations). Our tentative conclusion is that contingent capture, as measured in this experiment, is best described by a search mechanism. Subjects are searching for a particular colored target. They have a tendency to begin their search at the location containing the cue with the color they are searching for. Note that we obtained a significant cue type effect without distractors in the display, but that effect was not influenced by whether the cue and target were the same color or not.

We are not claiming that one will never obtain contingent capture without distractors in the display. There are several cases in the literature that have some degree of capture without distractors (e.g., Ansorge and Heumann 2003). Rather, the important finding is that adding distractors increased contingent capture, a finding that is opposite to the IOR results when distractors were present (Experiment 3, below). Greater contingent capture with distractors is consistent with top–down control settings affecting search.

Before discussing the generality of this effect, we wanted to check an alternative explanation. In these experiments, the cue was not predictive of the target location. Thus, when there were 6 locations, the target was cued on 1/6 of the trials. Hence, the cue was not spatially predictive. However, the cue matched the target color on ½ of the trials. With 6 possible target locations, the cue color was not random with respect to the target color. If we had the cue color and cue location unrelated to the target color or location, the condition where the target was cued and it matched the target color would have occurred on only 1/36th of the trials. The number of trials in this condition would have been too few for statistical analysis.

Experiment 2 was a replication of Experiment 1, but we compared displays with 2 locations with displays with 4 locations. In this experiment, the target was in the cued location on ¼ of the trials and the cue matched the target color on ¼ of the trials. Hence, both the cue color and cue location were independent of the target color and location.

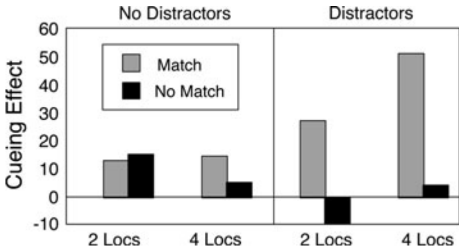


Fig. 5 The cueing effect with distractors in Experiment 2. The greater cueing effect for Match and No Match stimuli is the effect of contingent capture

Experiment 2

The goal of Experiment 2 was to investigate contingent capture when both the cue location and color were completely independent of the target location and color. The method was identical to Experiment 1 (see Fig. 1) except for the following factors. There were either 2 or 4 display locations (between blocks). When there were 4 locations, they formed the corners of an imaginary square centered on the fixation point. When there were 2 locations, they were always the diagonal corners of the square, and this was counterbalanced across subjects. To keep the difficulty about the same as Experiment 2 with 6 location, (1) distance from the fixation point to the center of the squares was increased to approximately 8.3 degrees of visual angle and (2) the exposure duration was changed to 120 ms. Twelve participants had distractors in the display and 12 had no distractors in the display. In all other respects, the method was identical to Experiment 1.

Results

In Experiment 1, the target color and the cue color were not completely independent: The target and cue color matched on half of the trials. In Experiment 2, both the cue location and cue color were completely independent of the target color and location, satisfying a strict operational definition of involuntary attention. Nevertheless, the results were similar to Experiment 1 in that we obtained contingent capture with distractors but not without distractors. The data were trimmed as in Experiment 1. Errors averaged 3.2%. The cueing effect is shown in Fig. 5.

Overall, there was a significant group × cue type × number of locations interaction, $F(1,30) = 5.71$, $P < 0.05$, which replicates Prinzmetal et al. (2010). With distractors, the cueing effect was larger with 4 display locations than with 2 locations. Without distractors, the cueing effect was larger with 2 locations than with 4 locations. There was also a significant group × cue type × color matching interaction, $F(1,30) = 12.96$, $P < 0.01$. Hence, we analyzed the two groups separately.

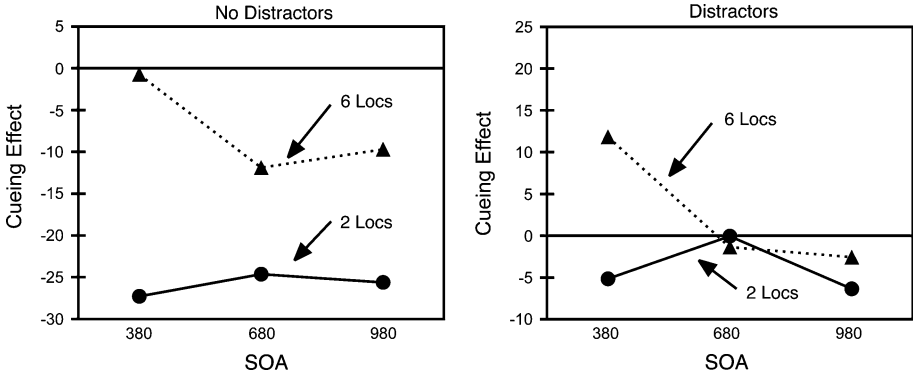
Without distractors, there was a significant cueing effect, $F(1, 16) = 11.17$, $P < 0.01$. Participants were significantly faster with the target in the cued than in the uncued location (see Fig. 5). No other effect or interactions approached significance. Without distractors, there was no contingent capture, at least as indexed by cue-target color matching.

With distractors, there was a significant cueing effect, $F(1,15) = 23.70$, and a significant effect of the number of display locations, $F(1,15) = 20.72$, both P's < 0.01. There was a significant interaction between the number of locations and cue type, $F(1,15) = 6.75$, $P < 0.05$. With distractors, the cueing effect was larger with more display locations. Most importantly, for this experiment, there was a significant cue type × color matching interaction, $F(1,15) = 20.30$, $P < 0.01$. As shown in Fig. 6, the cueing effect was larger when the cue and target matched in color. Thus, in terms of color matching, we found contingent capture when this display contained distractors, but not when there were no distractors.

Discussion

In Experiments 1 and 2, we manipulated contingent capture by having the cue and target match in color or not match in color. In both experiments, by this manipulation, we had contingent capture when there were distractors in the

Fig. 6 The cueing effect in Experiment 3. Negative values represent IOR



display, but not without distractors. The results with distractors were consistent with the search model, whereas the results without distractors were consistent with the decision model. Hence, we conclude that contingent capture is due to the serial mechanism. Without distractors, we still had significant cueing effect, but this effect was best described by the decision model.

We wanted to test whether the cue and target sharing color would automatically cause contingent capture or whether there would have to be some top–down control factor that only worked when color was relevant. With other stimuli, the results pertaining to the automaticity of contingent capture have been inconsistent (e.g., Al-Aidroos et al. 2010a, b). In order to test for this, we ran an additional experiment where the target color varied randomly from trial to trial. The task was to indicate the target identity ("F" or "T"), and participants were not informed of the target color before the trial. A consistent top–down control setting based on color would not be possible. We only ran the condition with distractors and with 4 display locations because that is the condition where we had the largest evidence of contingent capture. There were fourteen participants. There was a significant effect of the cue ($F(1,13) = 29.02$, $P < 0.01$), but the cueing effect was almost the same when the cue and target color matched (26 ms) as when they did not match (28 ms).

It seems difficult to reconcile a single mechanism to account for the results of Experiments 1 and 2 (and Prinzmetal et al. 2010). We hypothesize that there are at least 2 mechanisms of involuntary attention: a search mechanism and a decision mechanism. The similarity of the cue to the target (contingent capture) is particularly important when the limits on performance are finding the target (search). Without distractors, the fewer display locations, the smaller the cueing effect (Mordkoff et al. 2008; Prinzmetal et al. 2010; & the present experiments). With distractors, the more display locations, the larger the cueing effect. We found clear evidence for contingent capture in the latter situation.

The results of Experiments 1 and 2 were clear in that we obtained contingent capture when the target was difficult to locate and this effect was larger with more display locations. In the final experiment, we ask which mechanism of involuntary attention accounts for IOR?

Experiment 3

The serial search and decision models can potentially account for IOR. Recall that IOR is the phenomenon that as the time between the onset of the cue and the onset of the target (SOA) increases, participants become faster when the target is at an uncued location compared with a cued location. According to the serial model, ith a long SOA, attention first checks the cued location at the onset of the cue. If nothing is there, attention then moves on to search other locations. When the target subsequently appears, attention is inhibited from searching a previously visited location and hence RT is longer when the target appears at the cued location. Thus, the serial search mechanism is suggested simply by the name of the phenomenon: inhibition of return (Posner and Cohen 1984).

The decision model (accumulator model) offers two alternative accounts of IOR. First, it may be that following the cue, the rate of activation in the cued location is slower than in an uncued location. Accumulators can be thought of as summing the outputs from a large number of feature detectors. These feature detectors are activated by the cue (because the cue shares features with the target). Feature detectors are refractory. After a burst of firing, their firing rate is temporarily reduced. Hence, the rate of activation in the cued accumulators will first increase and then decrease. If the target appears in the decreased firing rate phase, RTs will be longer.

The second way the decision model could account for IOR is that the threshold for the cued location could be raised. One reason for a higher threshold in the cued location is that the cue might initiate a response, but that response is then cancelled. Canceling the response has the result of temporarily raising the thresholds for the cued accumulators (see Ivanoff and Klein 2001, for a similar explanation). The phenomenology is that it sometimes feels like you have inhibited a response to the cue, only to have the target subsequently appear in the cued location.

Recently, Ludwig et al. (2009) tested these two accumulator accounts with the inhibition of saccadic return (ISR), which is the finding that saccades to a just fixated location are slower than fixating on a new location (Maylor and Hockey 1985). They fit the data with a linear ballistic accumulator model (Brown and Heathcote 2008). ISR was best accounted for by a slower rate of accumulation for saccades to a previously fixated location. Note that we do not know whether ISR is caused by the same mechanism as IOR, but this work suggests that a decision model can explain ISR.

It is yet to be determined if IOR is better described by the decision model or the serial search model. If IOR can be described by the decision model, a subsequent issue is whether it is due to a higher threshold for the cued location or a slowing of the activation rate. If IOR is larger without distractors and with fewer display locations, we can use the linear ballistic accumulator model to determine whether the effect is in a change of rate of processing or in a change of threshold.

There is evidence for the decision model of IOR when displays do not contain distractors. Pratt et al. (1998) found that IOR decreased as the number of locations increased. However, the decision and serial search theories may not be mutually exclusive. It might be that without distractors, IOR decreases as the number of distractors increases (i.e., Pratt et al. 1998). With distractors, IOR might increase as the number of distractors increase. Pratt et al. (1998) did not compare IOR with and without distractors.

Therefore, in Experiment 3, we systematically manipulated both the number of target locations and the presence of distractors. Experiment 3 was similar to Experiment 1 with three changes. First, the cue and letters were black on a white background. Second, we chose our SOAs to try and obtain IOR (380, 680, and 980 ms). Finally, we used a go/no-go task rather than a two-alternative forced-choice task. In numerous pilot experiments, we found a robust and reliable IOR in a go/no-go task but negligible IOR with a two-alternative forced-choice task. IOR can be more robust in a go/no-go task (e.g., Lupiáñez et al. 1997) and we wanted to obtain as large an IOR effect as possible.

Method

Procedure

There were four groups of observers. Half of the observers had distractors in the display and half had no distractors. Within the distractor and no-distractor groups, half of the observers searched for the letter F and half searched for the letter T.

The number of locations (2 or 6) alternated between blocks with half of the observers beginning with 2 locations and half with 6 locations. On the 2-location blocks, the target was in the cued location on ½ the trials. On 6-location blocks, the target was in the cued location on 1/6th of the trials. Thus, there was no correlation between the cue and target location. When there were 2 locations, they always appeared directly opposite each other (see Fig. 2). For each observer, for the 2-location blocks, the same 2 locations were used, but across observers, all locations were used equally often.

The time between the onset of the cue and the onset of the target was 380, 680, or 980 ms and was varied within block. Observers pressed a button when a target appeared and withheld a response when the target did not appear. Observers were allowed 1,200 ms to respond or not to respond. For half of the subjects, the target was the letter F, and for remaining, it was the letter T. A target was present on 80% of the trials. On target-absent trials, when there were no distractors, no letter appeared. When there were distractors, letters were presented in all locations. The computer made a brief "click" sound when the target appeared or when the target would have appeared (on a target-absent trial).

Each participant was run for at least one practice block of 45 trials and 8 blocks of 90 trials. The experiment took about 50 min.

Participants

Twenty-four participants recruited as in the previous experiment. Twelve observers were run with distractors and twelve without distractors. Three of the participants were replaced because their accuracy was below 85% in at least one condition.

Results

False alarms on target-absent trials constituted only 1.2% of the trials. Misses (failures to respond by the deadline) occurred on 1.0% of trials. Trials where observers moved their eyes were removed from the analysis (<1% of trials). Correct RTs were subjected to an ANOVA with the following factors: cue type (cued vs. uncued), number of display locations (2 vs. 6), SOA (380, 680, or 980 ms), and group (distractors vs. no distractors). Group significantly interacted with cue type ($F(1,22) = 6.72$) and number of locations ($F(1,22) = 9.20$, both P's < 0.05) and so the groups (distractors and no distractors) were analyzed separately.

The cueing effect is shown separately for the two groups in Fig. 6. IOR is the finding that observers are slower in the cued location. Therefore, if an observer shows IOR, these scores will be negative. For the no-distractor group (Fig. 6), there was a significant effect of cue, $F(1,11) = 11.93$, $P < 0.01$. Observers were faster when the target appeared in the uncued than in the cued location, which is reflected in negative cueing effects in Fig. 6. Thus, we obtained IOR without distractors. Furthermore, the cue type interacted with the number of locations, $F(1,11) = 13.34$, $P < 0.01$. IOR was greater with 2 target locations than with 6 target locations, replicating Pratt et al. (1998). The main effect of SOA was not significant, nor did it significantly interact with any other variable. However, IOR was smallest at the short SOA.

When there were distractors in the display, the results were considerably different (Fig. 6). The effect of cue was not significant, $F(1,11) = 0.15$. Thus, with distractors, there was no IOR. The only other significant effects were the number of locations, ($F(1,11) = 18.79$, $P < 0.01$) and SOA ($F(2,22) = 3.58$, $P < 0.05$). Observers were faster with 2 than with 6 display locations. They were also faster with the long than with the short SOA, probably reflecting a general temporal cueing effect (Posner and Boies 1971), since it did not interact with any other variables.

As in Experiment 1, where we also compared 2- and 6-location displays, we repeated the analysis including only

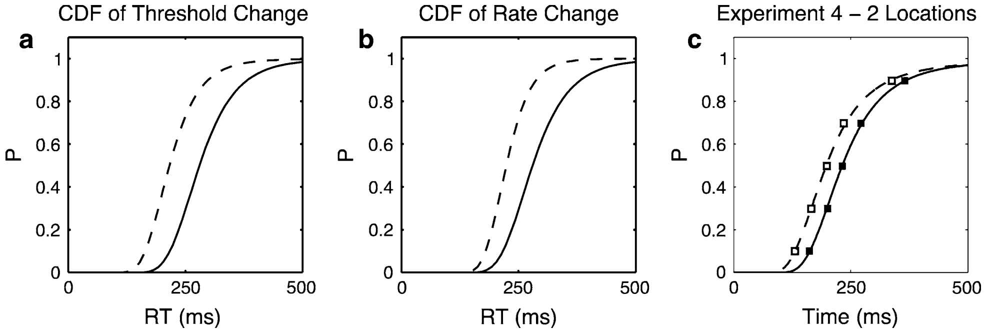


Fig. 7 Cumulative probability of reaction time. **a** A threshold model predicts faster reaction times when the threshold is decreased (*Dashed*). **b** A rate model predicts faster reaction times when the rate of accumulation is increased (*Dashed*). **c** Cumulative probability distribution of reaction time for the uncued (*open squares*) and cued (*solid squares*) for Experiment 3. The linear ballistic accumulator model estimate of the cumulative probability distribution for uncued location (*dashed*) and cued location (*solid*) for Experiment 3

the target in the cued location and the target in the opposite the cue location. In this way, the distance between the target and cue is the same for 2- and 6-location displays.

The results were the same as in the initial analysis. Group significantly interacted with cue type ($F(1,22) = 10.53$) and number of locations ($F(1,22) = 18.19$, both P's < 0.05) and so the groups (distractors and no distractors) were analyzed separately. There was a significant 19 ms IOR effect for the no-distractor group ($F(1,11) = 14.99$, $P < 0.01$). With the distractor group, there was only an average 1-ms difference between cued and uncued locations ($F(1,11) = 0.13$). Thus, when restricting the analysis to the trials where the distance between the target and cue was exactly the same for 2 and 6 location conditions, we obtained IOR only without distractors in the display.

Model

Our results suggest that IOR is consistent with a decision (accumulator) model. Implementing a decision model can often be difficult, especially in its original form as a diffusion model (Smith and Ratcliff 2009; Vandekerckhove and Tuerlinckx 2008). Recently, a linear ballistic accumulator (LBA) model, which removes the within-trial stochastic process, has been developed to account for decision processes (Brown and Heathcote 2008). LBA is much simpler, and it has been recently used to model lexical decision tasks, speed/accuracy tradeoff, and multiple alternative choices (Brown and Heathcote 2008) as well as ISR (inhibition of saccadic return, e.g., Ludwig et al. 2009). While the mathematical expression of the model is seemingly complex (see Brown and Heathcote 2008), the underlying mechanisms that may be responsible for IOR are simple. First, the threshold for targets in the cued location can be raised, slowing RT. This mechanism is indistinguishable from increasing the "starting value" or priming the uncued location. Second, information can accumulate at a faster rate at the uncued than at the cued location.

The threshold version of the model is illustrated in Fig. 2. A simple way to think of the model is to consider two runners, named "Uncued" and "Cued", and they are running time trials. They run time trials of various lengths, but usually Uncued turns in faster times than Cued. There are two reasons why Uncued generally turn in faster times.

It could be that Uncued cheats by beginning closer the to the finish line than Cued (Fig. 2). Cued can also cheat on occasion, but cheats less on average. The amount of cheating is assumed to be a random variable with a rectangular distribution; however, the mean cheating of Uncued is higher than that of Cued. In this model, the speed of the runner is also a random variable with a normal distribution but both runners have the same mean speed and variance. Thus, in threshold model, Uncued is not really faster than Cued; he simply cheats more. In contrast, in the rate model, the average amount of cheating is the same for both runners, but Uncued runs faster, on average, than Cued.

Figure 7a is the cumulative probability function of RTs (running time). This is the cumulative RT distribution divided by the longest RT for racers Cued and Uncued, generated from the model expressed above. Note that in Fig. 7a, Uncued's times are faster than Cued's times, beginning at the fastest RT. This is what one would expect if Uncued cheated by a constant average value (he had to run less far on average). He would lead by that amount regardless of whether it was a short or long race. Of course, the two curves merge on 1.0, but for most RTs, the difference is a constant.

In Fig. 7b, there is no difference in the average starting location. There is no difference in "cheating"; both Cued and Uncued run, on average, the same distance in their time trials. However, Uncued runs at a faster rate than Cued, indicated by the thicker arrow. The speeds (or rates of information accrual) are random variable with a normal distribution and the same variance. However, Uncued's mean rate is higher than Cued's. This difference in rate will

Table 1 Bold indicates cued and uncued parameters are significantly different

Parameter	Description	Experiment 4 (IOR)		Experiment 1	
		No distractors 2 Locations	No distractors 6 Locations	No distractors 2 Locations	Distractors 6 Locations
α	Rate multiplier	**1.099**	1.063	0.967	**0.916**
β	Threshold multiplier	**1.242**	1.208	**0.909**	**0.841**
v	Accumulation rate	0.004	0.005	0.004	0.003
SD	Standard deviation of rate distribution	0.001	0.001	0.001	0.001
A	Staring point boundary	0.431	0.540	0.632	0.589
T	Nondecision time (intercept)	14.919	26.865	54.650	94.793
G^2	Goodness of fit	16.638	8.843	19.710	11.133

not be so clear in the short races (fast RTs), but a difference in rate will become more evident in longer races (longer RTs). The cumulative distribution of RTs generated from a rate model is illustrated in Fig. 7b.

The example above can be formalized into the LBA model by characterizing the cumulative distribution function for each accumulator and its associated probability density function (see Brown and Heathcote 2008; Ludwig et al. 2009). For the purpose of our study, we have an accumulator for the cued location and the uncued location. Each accumulator is defined by several parameters, but of particular interest are the starting point (or threshold, b) and rate of evidence accumulation (v). The accumulator rate was free to vary between the cued and uncued locations. The threshold was set to be 1, which grounds the range of the accumulator parameters (Ludwig et al. 2009). The effect of the cue on an accumulator was implemented as a multiplier on both its rate and threshold, independently. A positive rate multiplier (α) should be interpreted as a faster rate of information accumulation in the uncued location, while a positive threshold multiplier (β) should be interpreted as a more liberal decision threshold for the uncued location. By having the cue affect the accumulator as a multiplier, we can discern the cueing effect at each location independent of the base rate and threshold of the cued and uncued locations. Thus, α greater than 1.0 means that information accumulates faster at the uncued location than at the cued location. If β is greater than 1.0, it means a lower threshold at the uncued than at cued location. Either would lead to IOR in the mean RT.

The parameters of the model (see Table 1) were estimated for each participant's data separately in the 2 and 6 locations in the no-distractor condition.[1] Two participants did not show IOR (they were faster with the target in the cued location), so they were excluded from the estimation. To have sufficient data for each participant, we combined SOAs. A cumulative probability RT distribution was calculated for each participant by placing the correct RTs into quantiles. An additional bin was added for error trials to account for the long RTs observed in error trials. The parameter estimates were solved iteratively using the simplex algorithm (Nelder and Mead 1965). To avoid local minima, we determined the range of guesses by modeling a superset of the participants' data (all participants' data stacked as a single participant). We then ensured that our final parameter estimates were insensitive to doubling or halving the values of the parameter starting values.

The parameter estimates are listed in Table 1. The fits were good, with a mean G^2 of 16.6 and 8.8 for 2 and 6 locations, respectively. The mean cumulative distribution is shown in Fig. 7c. The multiplier values for α (rate) and β (threshold) are in the top two rows, and the results from Experiment 4 are shown in the left columns. The mean is clearly consistent with the threshold model and inconsistent with the rate model in that the difference in cumulative RTs begins with relatively fast RTs and is not larger with slow RTs (see Fig. 7c). To determine whether the mean reflected individual participants, we performed a paired *t* test between the cued and uncued multiplier parameters for threshold (β) and rate (α). We found that the IOR effect arises largely from a change in the starting point (or equivalently, threshold, see Table 1). There was nearly a 25% decrease in starting point in the uncued targets for 2 locations, $\beta = 1.242$ ($t(9) = 4.976$, $P < 0.001$) and for 6 locations, $\beta = 1.208$ ($t(9) = 4.273$, $P = 0.002$). There was an inconsistent increase in the accumulation rate between 2 and 6 locations: a 10% increase when there were only 2 locations, $\alpha = 1.099$, ($t(9) = 2.345$, $P = 0.038$), and an insignificant 6% increase for 6 locations, $\alpha = 1.063$, ($t(9) = 1.457$, $P = 0.179$). Thus, although there is some suggestion of a change in rate, IOR is better accounted for by a change in starting value (or threshold).

Originally, we only planned to fit the data with the LBA only in cases that could not be described by a serial model

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[1] We used software kindly provided to us by Casimir Ludwig.

in order to address whether IOR was better described by a threshold model or a rate model (Ludwig et al. 2009). However, we thought a post hoc analysis of the clear cases of the accumulator model (Experiment 1, no distractors, 2 locations) and the serial search model (Experiment 1, distractors, 6 locations) would be informative as to why RTs are faster for targets in the cued location than in the uncued location for short SOAs.

We fit the data from Experiment 1, no distractors, and 2 locations in the same manner as we fit the data above. These are the conditions that are the most extreme examples of the decision model and the search model, respectively. The results are shown in Table 1. Note that in this experiment, participants are faster at the cued than at the uncued location. Therefore, the multipliers (α and β) should be less than 1.0 to the extent that they contribute to faster RTs at the cued location than at the uncued location.

The results for the 2-location, no-distractor condition support a lowered threshold for targets in the cued location. Only the starting value was significantly different from 1.0, $\beta = 0.909$ ($t(13) = 3.870$, $P = 0.002$). This finding is consistent with Prinzmetal et al. (2010) who found under speed pressure, more errors for targets in the cued than in the uncued location. Both the present finding and the finding of Prinzmetal et al. are consistent with a lower threshold for targets in the cued location.

We also fit the data from Experiment 1, 6-location distractor condition. The accumulator model might not be appropriate for this situation because the accumulator model assumes parallel accumulation of information at each accumulator and the results in this condition are consistent with a (serial) search model. Nevertheless, this condition should provide a comparison with data that is best fit with the threshold model. The largest effect was in the threshold parameter $\beta = 0.841$, ($t(13) = 5.40$, $P < 0.001$). However, there was also a significant effect of the rate parameter $\alpha = 0.916$ ($t(13) = 2.335$, $P = 0.036$). We do not know whether it is fair to call this effect "rate" when a serial process might be involved. As discussed below, the fact that both parameters changed in this condition indicated that more than one process is often involved: One must locate the target (search) and decide where target was present (decision).

Discussion

Both contingent capture and IOR are said to involved "involuntary attention". Unlike contingent capture, we found IOR only without distractors. Furthermore, IOR was larger with fewer display locations.

The term "IOR" seems to imply a serial process: attention checks one location and then is reluctant to return to that location. Many researchers have used the analogy of the intelligent behavior of foraging animals (e.g., Klein and MacInnes 1999). Having visited one area, the animal would be reluctant to check that location again. We found (without distractors) robust IOR and a pattern of results consistent with the decision model. However, there was little support for the serial search model when distractors were not present.

Furthermore, we were able to fit the data with an accumulator model. There are two possible explanations for IOR in the context of the decision model. IOR could affect priming (or equivalently in the model, threshold) for the cued and uncued locations. Alternatively, it could reflect a faster rate of processing in the uncued location (but see Klein and Taylor 1994). Ludwig et al. (2009) found that ISR (inhibition of saccadic return) was accounted for by a different rate of processing for return saccades compared with saccades to a new location. We found that IOR was more consistent with a difference threshold in cued and uncued locations.

We do not know whether the apparent difference in mechanism between Ludwig et al. and the present results was a consequence of the saccadic system or the task. Ludwig et al.'s task was not a cueing task, but rather one of following the target. Interestingly, Weger et al. (2008) found something akin to IOR in a task that involved following a colored target. We know that Ludwig et al.'s results are caused by a different mechanism than the present results with spatial cueing and IOR. We do not know whether the Weger et al.'s task involves the same mechanism as is responsible for IOR in the spatial cueing paradigm.

General discussion

Both contingent capture and IOR have been associated with nonpredictive spatial cues and therefore associated with involuntary attention. We compared contingent capture and IOR in similar experiments varying the same two independent variables: the number of display locations and the presence of distractors in the nontarget locations. We obtained contingent capture only when there were distractors in the display. We obtained IOR only when there were no distractors in the display.

We previously demonstrated that there were at least two forms of involuntary attention with the spatial cueing task: a serial search mechanism and a decision mechanism (based on a competitive accumulator model; Prinzmetal et al. 2010). In the present experiments, the IOR conformed to the predictions of the decision model. Furthermore, model fits were more consistent with a lowering of threshold than a change in rate (cf. Ludwig et al. 2009). Contingent capture conformed to the search mechanism. The experiments with IOR and contingent capture were identical except for those features that are necessary to obtain these different effects. Thus, differences in mechanisms are unlikely to be due to some peripheral aspect of the experiments.

Both the serial search and the decision mechanisms are members of classes of models that make similar predictions. We described the search model as a "serial" search model because the predictions are intuitive. However, there is a class of parallel search models that might make similar predictions (e.g., Dosher et al. 2004). Search models (whether serial, parallel, or something in between) account for performance when the limit on performance is finding the target (i.e., there are distractors in the display), but they do not account for the cueing effect when there are no distractors in the display.

The accumulator model is a member of a class of decision models that use the idea of data accumulation and a threshold (Ratcliff and Rouder 1998; Donkin et al. 2011). The competition in the accumulator model is a natural prediction of these models in that evidence in favor of one alternative is evidence against another alternative. Within the context of the competitive accumulator model, there are two general ways of accounting for IOR. First, it may be that the rate of information accrual is greater in the uncued than in the cued location. Second, it may be that after the cue is presented, the threshold is raised for the cued location (in the model, this is indistinguishable from priming the uncued item). This explanation is consistent with the subjective feeling that one has to inhibit responding to the cue. The model fits clearly support the later explanation.

Theoretically speaking, in all of our tasks, there are at least two computational steps: Subjects must (1) locate the target and (2) identify each character and classify its target status. Locating the target involves a search mechanism. Classifying character involves a decision. Thus, both processes are logically involved. However, without distractors in the display, the target is easy to locate and the limit on performance is deciding which target was present (or whether a target was present). As the number of locations increases, the inhibition at each location will decrease and so the cueing effect will decrease as well. When distractors are in the display, search is necessary and the limit on performance is finding the target. There are probably many cases where both processes affect RT, as exemplified by the model fits of Experiment 1 with distractors and 6 locations. Here, we found changes in both threshold and rate parameters.

Our approach is part of a general research program that is developing a taxonomy of attentional mechanisms. At the highest level of the taxonomy is the distinction between voluntary (endogenous) and involuntary (exogenous) attention. For involuntary attention, there are at least two different mechanisms (Prinzmetal et al. 2010). The first is a decision mechanism that appears to be responsible for the cueing effect when there are no distractors in the display. Under these conditions, with a sufficiently long SOA, we obtained IOR. The second mechanism is a search mechanism and it limits performance when the target is difficult to locate. As the number of display items increases, the cueing effect increases. With distractors, we obtained contingent capture.

The taxonomy is far from complete, and many issues remain. For example, it occurs to us that some cases of contingent capture, which occur with a nonpredictive spatial cue, might be mediated by the neural mechanisms of voluntary attention. Consider one case from Folk et al. (1992) as described above. Participants had to indicate whether a display contained a red "X" or red "=" among achromatic X's and ='s. The feature red is a defining feature of the target. Participants might *voluntarily* search for something red, which Bacon and Egeth (1994) called feature search mode. Feature search mode may use the neural mechanism of voluntary attention, despite the fact that the spatial cue is uncorrelated with the target location. We might define something as involuntary attention, but what is critical is how the brain is processing the information regardless of the experimental operational definition. In fact, it could be that all cases that fall under serial search are in fact mediated by the neural mechanisms of voluntary attention.

Another issue that involves involuntary attention is whether the mechanism that causes the facilitation effect at short SOAs is the same as the mechanism that causes IOR. We have described them with both a decision model and threshold change, but this model is a general formalism that could describe many processes. We do not know whether the accumulators that describe the facilitatory effect at short SOAs are the same mechanisms that cause IOR at longer SOAs.

The goal of this research is to develop theories of the mechanisms of attention, both at psychological and at physiological levels. We considered the possibility that there may be several completely different mechanisms that fall under the general heading of attention. The result not only has been a taxonomy of attention, but more importantly, explicit theories about different mechanisms that fall under the general heading "spatial attention".

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