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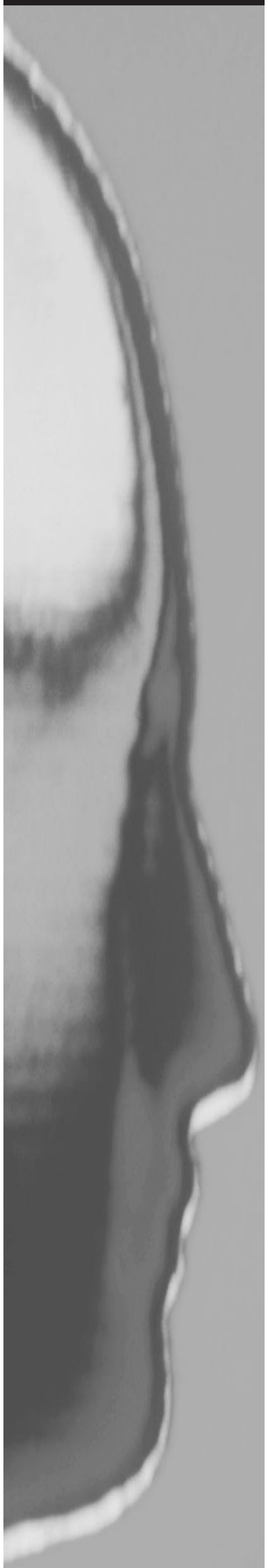

Inhibition of return

Raymond M. Klein

Immediately following an event at a peripheral location there is facilitation for the processing of other stimuli near that location. This is said to reflect a reflexive shift of attention towards the source of stimulation. After attention is removed from such a peripheral location, there is then delayed responding to stimuli subsequently displayed there. This inhibitory aftereffect, first described in 1984 and later labeled 'inhibition of return (IOR)', encourages orienting towards novel locations and hence might facilitate foraging and other search behaviors. Since its relatively recent discovery, IOR has been the subject of intensive investigation, from many angles and with a wide variety of approaches. After describing the seminal contribution of Posner and Cohen ('Who'), this review will discuss what causes IOR and, once initiated, what effects IOR has on subsequent processing ('What'). The time course ('When') and spatial distribution ('Where') of IOR, and what is known about IOR's neural implementation ('How') and functional significance ('Why') are also discussed.

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Orienting is one of the most primitive functions of living things. Even the leaves of a plant orient towards sunshine; the roots towards moisture. In more complex organisms more complex systems have evolved to orient the various receptors reflexively either towards or away from signal sources in the environment and to prepare the organism to select from a repertoire of behavioral actions[1]. Whereas the efficiency and rapidity provided by reflexive control of orienting would be critical in predation and defense, voluntary control over the orienting reflexes has undoubtedly been an important evolutionary development. Efficient foraging for food (or other desirable objects, places, playmates) involves not only voluntary control over orienting but also the use of information stored in memory about one's previous orienting behavior. Once discovered, the locus of a food source that is not exhausted should be remembered as a place to return to. By contrast, places one has searched and not found what one is looking for, or places that have been stripped bare, should be remembered to be avoided. A mechanism that encourages orienting towards novel locations would be useful in these

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latter situations. Inhibition of return (IOR) is such a mechanism. The initial response to a peripheral visual event is facilitation of the processing of nearby stimuli, presumably owing to a reflexive shift of attention towards the source of stimulation. However, when the event is not task-relevant and attention has had time to disengage from it, an inhibitory after-effect can be measured in delayed responding to stimuli subsequently displayed at the originally cued location. This is a prototypical example of IOR as it has been studied.

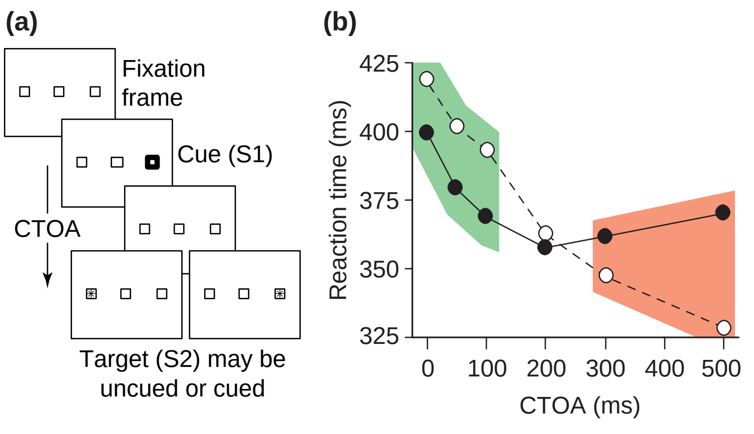

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Fig. 1. A prototypical demonstration of IOR. (a) The sequence of events in a typical trial. A fixation display is followed by the first stimulus (S1, cue): the brightening of one of the two peripheral boxes. After varying intervals (cue–target onset asynchronies, CTOAs) from the onset of the cue, a target (S2), shown here as an asterisk, is presented at the cued (right) or uncued (left) location. The observer's task is to make a speeded detection response as soon as the asterisk is detected. Catch trials with cues but no targets are included to discourage anticipatory responses and measure their frequency in the form of false alarms. **(b)** The data from such an experiment, by Posner and Cohen[2]; responses to cued targets, filled circles; responses to uncued targets, open circles. Faster responding to cued targets at the shorter intervals (green) reflects the facilitatory effect of reflexive orienting of attention toward the cue. IOR is reflected in the slower responding to targets at the cued location at the longer intervals (red).

Who: discovery and early characterization

It is a testament to the scientific ingenuity and rigor of its authors that so much of what we know about IOR was first demonstrated in Posner and Cohen's seminal paper[2], and so many questions that have subsequently been pursued were anticipated there. In their experiments, following a peripheral cue that did not predict the location of a subsequent peripheral target (see Fig. 1a), two different procedures were used to discourage attention from remaining at the cued location: either targets were more likely to appear at fixation than at the two peripheral locations, or the fixation stimulus was flashed before target presentation.

Implicit in these manipulations is the belief that the inhibitory effect might not be seen if attention were maintained at the cued location, either because facilitation and inhibition are both initiated by the cue or because the inhibition begins when attention leaves the cued location. Reaction time (RT) was faster to targets at the cued location than it was to uncued targets, when the interval between the onset of the cue and onset of the target (stimulus-onset asynchrony; SOA) was short, and slower when the SOA was long. The crossover point – where facilitation changed to inhibition – was between 200–300 ms following cue onset. Nearly identical results were obtained whether the cue was the brightening or dimming of one of the peripheral boxes, suggesting that this pattern was not purely sensory in origin. By interposing eye movements between the cue and the target IOR was shown to be coded in environmental rather than retinal coordinates. Although a shift of attention towards and then away from the cued location seemed strongly implicated, IOR did not follow a shift of attention that was directed endogenously (voluntarily) by an arrow presented at fixation. These are some of the key characteristics of IOR that were unveiled by its discoverers.

What: cause and effect

By naming the poorer performance at previously cued locations 'inhibition of return', Posner *et al.*[3] implied both a cause and an effect (see Ref. 4 for a review of causes and effects of IOR). The cause of IOR was attributed to orienting of attention towards a location and the subsequent removal of attention from that location. The effect was to discourage attention from re-orienting back to the originally attended location.

Refining this story, Rafal *et al.*[5] demonstrated the importance of oculomotor programming in causing IOR. They presented arrows at fixation or luminance changes in the periphery to signal the observer to execute or prepare an eye movement (saccade) or to shift visual attention without shifting gaze (Table 1). On some trials a flash at fixation was used to change the task, and, depending on the condition, this flash drew the eyes or attention back to fixation, or cancelled the saccade preparation. On these probe trials, a target was presented at the 'cued' or opposite location with equal probability, and the subject's task was to make a simple manual button press when this target was detected. A delayed response to this target was found if it was presented at locations that subjects had planned to fixate or actually had just fixated, whether the cue to do so had been central or peripheral. By contrast, when the cues were used to direct attention and the subjects were instructed to keep their eyes fixed, the inhibitory effect was observed following peripheral cues (which also tend to activate the oculomotor system). However, as in Posner and Cohen's original experiment[2], it was *not* observed following central cues (which can generate attention shifts independently of oculomotor programming[6]). Thus, those conditions in which Rafal *et al.*[5] observed IOR suggest that it is caused by activation of the machinery responsible for eye movements.

Once IOR is initiated, what effect or effects does it have? Broadly speaking, investigators have questioned whether IOR affects sensory/perceptual, motor or attentional stages of

Table 1. Conditions that elicit inhibition of return

	Cue type	
Condition	**Peripheral (Exogenous)**	**Central (Endogenous)**
Execute saccade	Yes[+]	Yes
Prepare saccade	Yes	Yes
Attend	Yes	No

[+] *'Yes' indicates that inhibition was significant at the cued (previously fixated, prepared to fixate, attended) location.*

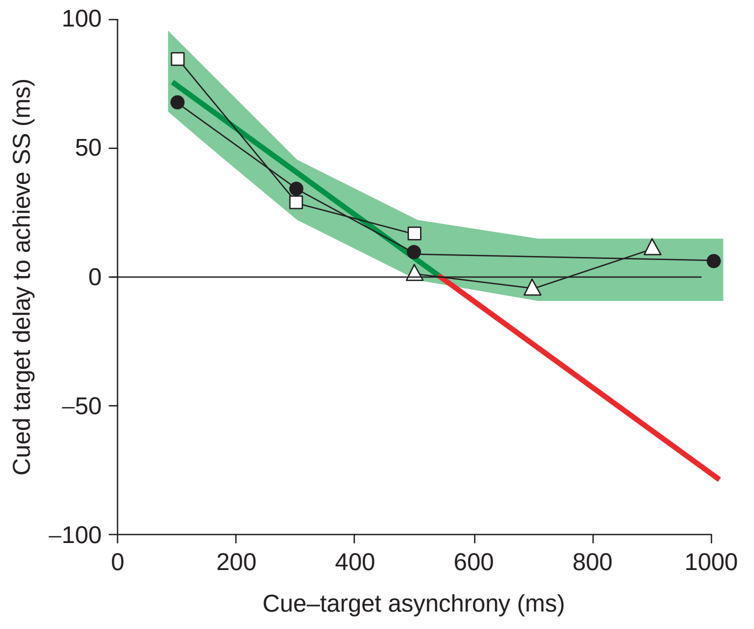

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Fig. 2. Peripheral cues advance perceptual arrival times, but IOR does not delay them. Shortly after a peripheral cue, if two targets are presented simultaneously on opposite sides of fixation, with one at the previously cued location and subjects are asked to judge which one was presented first, there is a strong tendency to perceive the cued target as having been presented first. In order for the two targets to be perceived as simultaneous (subjective simultaneity, SS) when the cue–target SOA is 100 ms, the target at the cued location must be delayed by about 80 ms (shown as a positive value on the y axis). The accelerated perception that this delay cancels is presumed to reflect the facilitative effect of attention upon stimuli at the cued location. If IOR had the opposite effect on perceptual arrival times, then at longer cue–target SOAs, when IOR operates, the effect should reverse. The target at the cued location, now retarded by IOR, will need to be presented before the uncued target in order for them to be perceived as simultaneous. This prediction of the sensory/perceptual locus of IOR is illustrated by the red portion of the diagonal line in the figure. However, the data from studies of the effect of uninformative peripheral cues on temporal order judgments[9,10] do not confirm this prediction. Closed circles, data from Ref. 9; open squares, data from Ref. 10, Expt 1; open triangles, data from Ref. 10, Expt 2. (Graph redrawn from Ref. 11.)

processing. Converging evidence suggests that IOR delays both motor responses and the return of attention[7,8].

A motoric locus was implicated in one of the earliest studies of IOR (Ref. 3). Following a peripheral cue and a return cue at fixation, two targets were presented in rapid succession, one at the cued peripheral location and one at another peripheral location. When subjects were instructed to make a saccade to whichever of the two locations seemed ‘more comfortable’, there was a significant tendency to make saccades away from the cued location. This tendency might reflect delayed perception at the cued location or a bias against making motor responses (eye movements) towards the cue. However, there was no bias when subjects were asked to make the temporal order judgment (TOJ), ‘which of the two targets was presented first’, which strongly supports a motor locus of the effect. Subsequent TOJ studies[9,10] confirm this demonstration that IOR does not affect the speed with which the sensory/perceptual machinery extracts information from a previously cued location (Fig. 2; for a review, see Ref. 11, and for evidence using a different approach, see Ref. 12).

Posner *et al.*[3] also demonstrated that saccades made in response to a central arrow (pointing either left or right) were delayed in the direction of a previous peripheral cue. Because, in this case, there was no peripheral event to detect, this finding provides support for a motoric basis for IOR when the response is an eye movement. Abrams and Dobkin replicated this finding[13] but also reported that IOR was significantly larger when the final saccade was made in response to a peripheral event than when it was made in response to a centrally presented arrow. Although this pattern is often cited as supporting a perceptual component, there are at least two reasons to reserve judgment. The additional IOR when saccades are made to peripheral targets might merely reflect the fact that the superior colliculus, thought to be important in mediating IOR (see ‘How’ section below) is more involved in executing target-directed saccades than in executing voluntary saccades in the absence of a visual target (Ref. 11, footnote 5). Also, as noted by Taylor and Klein[8], Abrams and Dobkin’s peripherally directed saccades were made in the absence of a fixation stimulus, whereas there was an arrow at fixation when saccades were elicited centrally. As IOR has been shown to be larger when the fixation stimulus is removed[14] the extra inhibition with peripheral targets that Abrams and Dobkins attributed to perceptual processing could have been caused instead by fixation removal.

Although early sensory/perceptual processing may not be directly affected by IOR, indirect effects could be attributable to delayed orienting of attention towards the cued location – as in the original proposal. Klein and Taylor[15] rejected such an ‘inhibited attention’ view, noting that IOR had been observed with simple detection, manual localization and saccadic responses, but had not been obtained when the task involved a non-spatial discrimination (of form, color or size; e.g. Ref. 16). Attention affects such discriminations, hence Klein and Taylor concluded that attention was not inhibited by IOR. They advanced instead a motor bias view: ‘...IOR is a reluctance to respond to an event at the inhibited location (in other words, IOR is more closely associated with responding than with attention)’[15]. Subsequently, however, numerous investigators have found IOR with non-spatial discrimination tasks(e.g. Refs 17–19). How can the varied findings with discrimination tasks be explained? It appears that the timing of IOR depends on the difficulty of the target discrimination (see ‘When’ section) and that when measured at the location of a previous target rather than cue[16], IOR might be obscured by benefits associated with a response-repetition strategy (see Ref. 20, pp. 91–93). The likelihood of use (and magnitude of benefit) of such a strategy increases with task difficulty[21]. Converging evidence for the original proposal that one effect of IOR is to impede a shift of attention back to recently attended locations[22] comes from recent studies of the effects of IOR on target detection[23] (using a bias-free measure of perceptual sensitivity, d prime) and on early components of the brain’s electrical response to a target[24].

Fuentes and colleagues have suggested that IOR is a bias against connecting perceptual representations with their usual conceptual or motor representations[25]. For example, when presented at a previously cued location, where inhibition would be expected to operate, irrelevant distractors and priming stimuli have an opposite effect from that expected (conflicting distractors help performance; related primes hurt performance). At first sight this effect does not appear to be straightforwardly classifiable according to the sensory/attentional/motor scheme we use here. Nevertheless, the results are quite consistent with the proposal that one effect of IOR is to inhibit responses that are normally associated with stimuli.

To observe IOR, investigators must satisfy two conditions: they must use a combination of methods that elicit or cause the inhibition and they must look for it using a task whose performance includes one or more stages of processing that are affected by the inhibition. While implementing this strategy it must be borne in mind that IOR is inferred from poorer performance with targets at some locations than at others. It is possible that inhibition is present but will not be seen in performance because its effects are obscured by other processes (such as facilitation or a response-repetition advantage) operating at the same time as the hypothesized inhibition. (Similarly, the facilitation that is usually present for short cue–target SOAs might be masked by procedure-dependent perceptual, decision or response processes that delay responses to cued targets[26]). Thus, when IOR is not obtained it could be that it was: (1) present but the task used to measure it was not sensitive to the inhibition; (2) present and measurable, but obscured by an accompanying effect in the opposite direction; or (3) not present in the first place. Discriminating amongst these alternatives is one challenge to researchers of IOR.

When: time course of IOR

IOR appears to last for several seconds, but when does it begin? In a simple luminance-detection task, Posner and Cohen varied the interval between the onset of the cue and the onset of the target to adress this question (Fig. 1b). If the marker for the onset of IOR is taken as the crossover point where RT at the cued location becomes slower than RT at the uncued location, then it could be said that, from these results, IOR begins at a cue–target SOA of 225 ms (Fig. 1b).

One factor underlying the onset of IOR appears to be related to the attentional demands of performing the task (to determine target identity or discriminate between targets and catch trials). Lupiáñez *et al.*[18], for example, showed that IOR occurred later when the task was color discrimination rather than detection. IOR also begins earlier when saccadic responses are made than when manual responses are required[27] (e.g. compare Fig. 1b with Fig. 3).

The concept of an attentional control setting (ACS) can be used to explain why the onset of IOR might vary with the difficulty of the task[28]. Let us assume that at the start of a trial the observer sets internally the level of attention that will be allocated to a target in order to perform the task: low intensity for a simple detection task; high intensity for a difficult discrimination. The peripheral cues are uninformative, and hence should not be voluntarily attended. Nevertheless, just as task switching requires time, so too does changing the attentional control setting. Therefore, the control setting selected to process the target will be in place before the onset of the cue. The higher its intensity, the more attended the peripheral cue will be because the attentional setting for the target will apply to the cue. Under the assumption that the more intensely attention is allocated to the cue the longer attention will dwell on it[29], facilitation due to the allocation of attention towards the cued location will last longer the more target processing is required for successful performance (Fig. 4). A similar proposal has been made by Lupiáñez (pers. commun.).

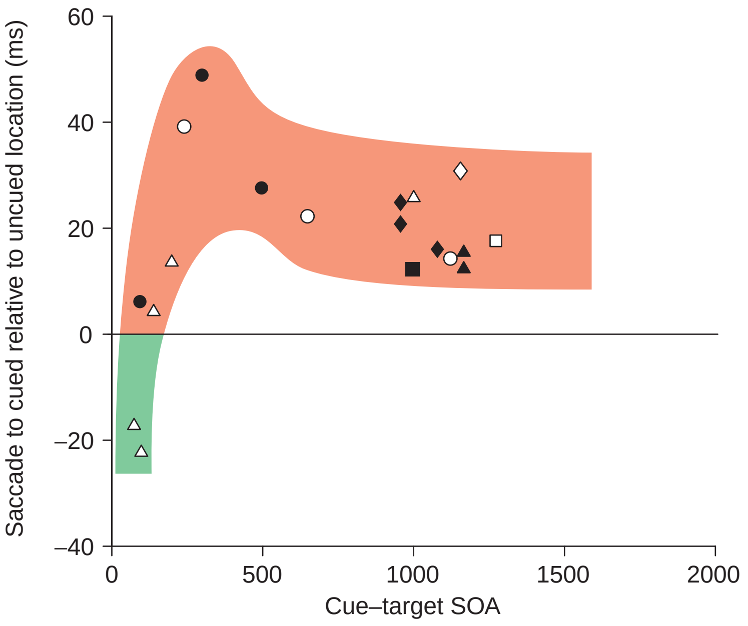

Fig. 3. The time course of IOR. Data from studies using a cue–saccade paradigm, with the difference (cued minus uncued) in saccadic reaction time shown as a function of cue–target stimulus-onset asynchrony (SOA). Note that facilitation (green) at short cue–target intervals (SOAs) turns into inhibition (red) somewhere between 100 and 200 ms. ○ Ref. 51, data from four monkeys. The remaining data are from normal human observers: ● Ref. 9; △ Ref. 27; ■ Ref. 8; □ Ref. 61; ▲ Ref. 13; ♦ Ref. 14; ◊ Ref. 22.

Target discrimination difficulty is not the only variable that might affect the time course of IOR via control settings. For example, consider the presence versus absence of a distractor accompanying the target. In a block of trials where the target is never accompanied by a distractor, the target is located by its discrete onset. A control setting to find onsets

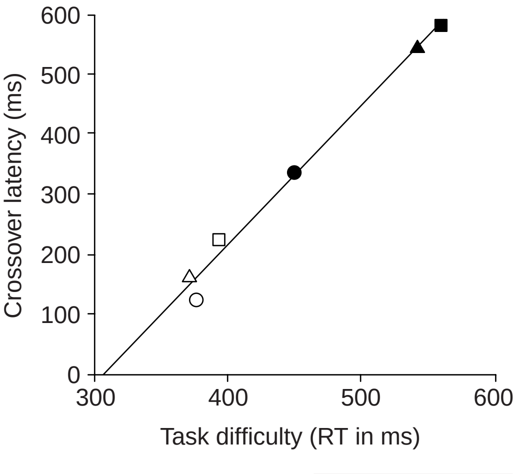

Fig. 4. IOR onset as a function of target task difficulty. The crossover point (measured by the cue–target SOA) where facilitation changes to inhibition is shown as a function of reaction time (RT) to the target (at this crossover point, when available) from three studies[18,27,30] that manipulated the difficulty of the target task and used a range of SOAs sufficient to determine the crossover point with confidence. Circles show localization data from Ref. 27 (open circles, saccadic; filled circles, manual); squares show manual detection (open) and discrimination (filled) data from Ref. 18; triangles show manual detection (open) and discrimination (filled) data from Ref. 30.

Box 1. Hypothetical temporal dynamics of facilitation and inhibition

The data from Posner and Cohen's seminal study (Ref. a) are plotted in Fig. I. From performance patterns such as these cognitive psychologists infer hypothetical inhibitory and facilitatory processes. Two different construals of the time course of these processes are illustrated.

Reference

a Posner, M.I. and Cohen, Y. (1984) Attention and performance, In *Attention and Performance Vol. X* (Bouma, H. and Bouwhuis, D., eds), pp. 531–556, Erlbaum

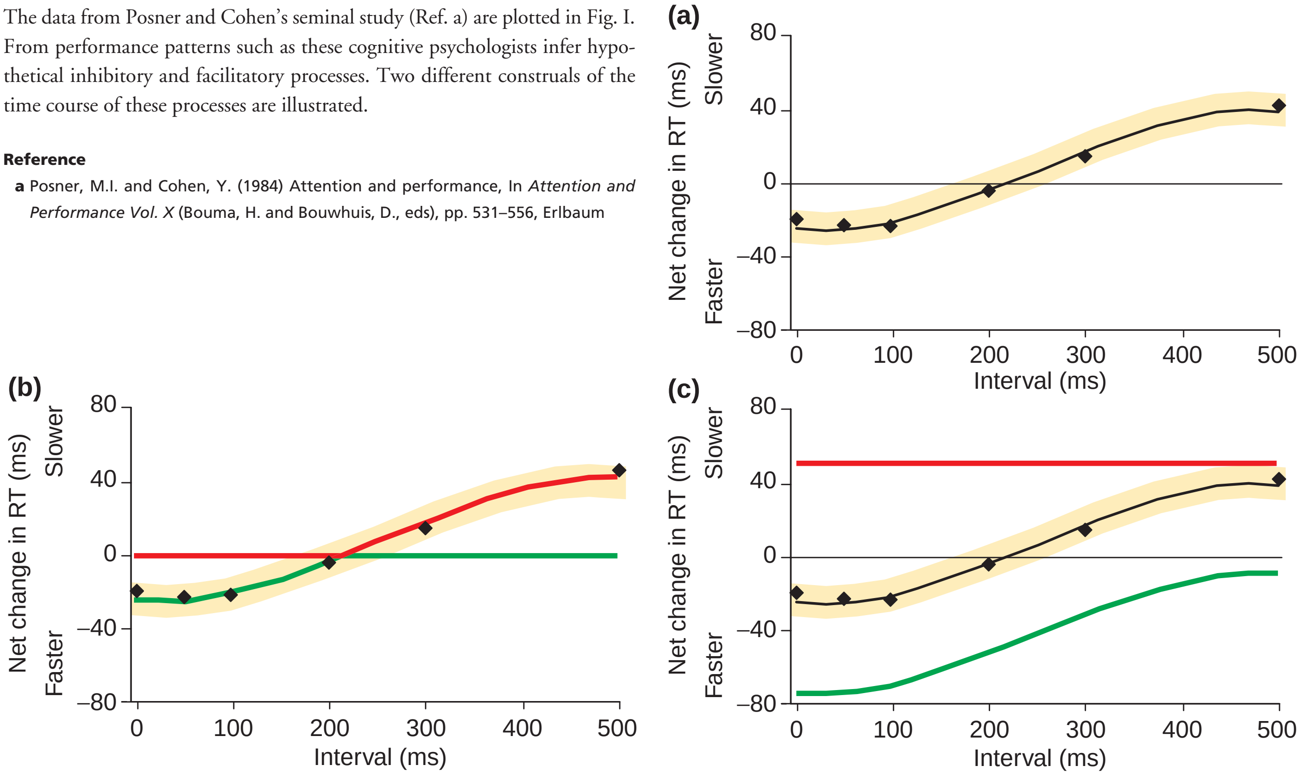

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Fig. I. Results from Posner and Cohen's original study (Ref. a). (a) Data are plotted as a difference score (data points are cued minus uncued reaction times; RTs). A negative score reflects a net facilitation at the cued location (faster RTs), whereas a positive score reflects a net inhibition (slower RTs) at the cued location. The black line and yellow background represent a hypothetical time course function fitted to these data. **(b)** One construal of the time course of two such processes, attentional facilitation at the cued location (plotted in green) and inhibition of return, also acting at the cued location (and plotted in red). Here, it is assumed that facilitation follows rapidly, if not immediately, after presentation of the cue and that when attention has been withdrawn from the cued location (which here takes just over 200 ms), an inhibitory process (IOR) grows in its place. Facilitation and inhibition are assumed to add linearly yielding the performance function highlighted in yellow (also in graph c). **(c)** A different construal of the time course of similar facilitatory and inhibitory processes. Here, it is assumed that the inhibition starts, like the facilitation, when the cue appears; and that inhibition remains constant (red), whereas the facilitation decreases over time (green). At first, there is greater facilitation than inhibition, hence the net effect on performance (black) is a faster RT at short cue–target intervals. However, net facilitation switches to net inhibition at the interval where their absolute values are equal.

would apply also to the onset of the cue, thus causing a strong attentional engagement, a long dwell time, and hence a late onset of IOR. By contrast, when the target is always accompanied by a distractor, luminance onset no longer provides the signal that will locate the target. Hence, the control setting needed to locate the target is less likely to result in strong attentional capture, and IOR will appear sooner. Finally, when the probability of a distractor is neither zero nor one but somewhere in between, the onset of IOR should depend more on this probability than on whether there is or is not a distractor. Precisely these findings have been reported by Lupiáñez and Milliken[30].

In a typical IOR study the cue is uninformative. Thus, while there is no particular incentive to attend to the cued location, neither is attending to this location particularly inappropriate – the target is as likely to occur here as at any of the other possible locations. If the time course of IOR is affected by attentional dwell time, as described above, then IOR should appear sooner if the observer is motivated to remove attention from the stimulated location, a prediction that was recently confirmed by Danziger and Kingstone[31]. Although demonstrating that the appearance of IOR can be accelerated by shifting attention away from the cue sooner, this important finding does not distinguish between the view that IOR begins when attention moves away from the cued location and the view that IOR begins when the cue is presented while the early, attentionally mediated, facilitation obscures it (see Box 1).

Where: spatial distribution and coding of IOR

How is IOR distributed spatially and in what frame of reference is it coded? Posner and Cohen demonstrated that IOR is not coded in retinal coordinates but is attached to environmental locations. By interposing saccadic eye movements between the initial attention-capturing cue and the final target, the delay in responding was seen for targets appearing at the initially cued location on the screen, not on the retina. Maylor and Hockey confirmed this finding while also demonstrating a gradient in the magnitude of IOR, with inhibition declining with increasing angular distance from the originally cued location[32]. A similar gradient for both amplitude and angle has been demonstrated in the monkey using a cue–saccade paradigm (Fig. 5).

Is inhibition of return a purely visual phenomenon, or is it represented in crossmodal spatial maps? Considering that IOR is caused by oculomotor programming and that it delays

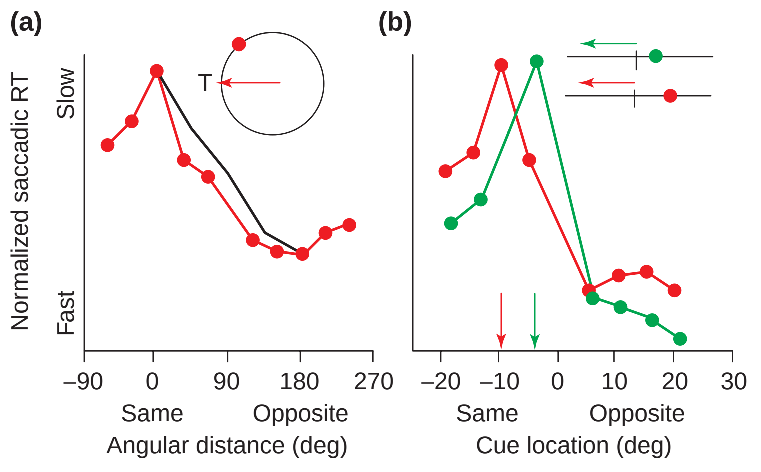

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Fig. 5. The spatial distribution of IOR. Saccadic reaction time (RT) is shown as a function of **(a)** the angular distance between the location of the cue and target, and **(b)** the relative amplitude of cue and target. The cue and target were presented either in the same or opposite halves of visual space, as indicated. The colored data are from two monkeys in a cue–saccade paradigm[51]. Data from human observers making manual responses[60] are shown in (a) as a black line. In (b), saccadic RT is shown as a function of cue direction and amplitude (x-axis) for targets presented at either 10 degrees (red) or 5 degrees (green) to the left of fixation (shown by vertical arrows).

responses and reorienting of attention towards the inhibited location, it is reasonable to expect IOR in other spatial modalities and perhaps even between modalities. Indeed this is the case: IOR has been observed in the auditory[33–35] and tactile modalities[36] and also crossmodally (for a review, see Ref. 37).

Posner and Cohen[2] and Klein[38] realized that the coding of IOR in environmental coordinates would allow it to assist visual search in static scenes by discouraging orienting (whether overt or covert) towards locations that had previously been inspected (see 'Why' section). In the real world, however, objects move. Suppose you enter the daycare or nursery looking for your child. As you inspect each small humanoid shape to determine if it 'belongs to you', some might be stationary, but some are moving. A tagging system that merely inhibited environmental locations in the nursery would not optimize search in such a dynamic scene. Tags would need to be attached to objects in the scene and to move with them to be helpful in this real-world situation[39]. Tipper *et al.*[40] were the first to demonstrate that IOR could be attached to objects in a scene with moving elements, and this finding has since been replicated and extended[13,41,42].

How: neural implementation

Converging evidence supports the view that a midbrain oculomotor structure, the superior colliculus, plays an important role in IOR. Individuals with damage to the superior colliculus (SC)[3,43,44] show reduced or no IOR, while conversely, one hemianopic patient with visual cortex damage but an intact colliculus showed IOR to cues presented in his blind field[45]. IOR is greater for stimuli presented (monocularly) in the temporal hemifield, which has a stronger collicular representation than the nasal hemifield[5] and IOR interacts with the gap effect[14], which is mediated by disinhibition of oculomotor programming in the superior colliculus[46]. Finally, IOR occurs in infancy, prior to complete cortical development[47–50], which is further evidence for collicular involvement.

In order to explore precisely how the superior colliculus might be involved in the generation of IOR, Dorris *et al.*[51] first demonstrated IOR in the monkey (Fig. 5). They then tested monkeys in a cue–saccade paradigm while recording the activity of identified cells in the superior colliculus[52]. It was found that targets presented at the cued location elicited greatly reduced responses compared with targets presented at the opposite, uncued, location. Although this exciting finding definitively establishes that neurons in the SC reflect IOR, the question remains whether structures in the SC are directly inhibited, or are merely receiving reduced inputs. An indirect answer was available from an examination of pre-target background (build-up) activity, which was greater for neurons that had been stimulated (cued) than for those on the opposite side, which had not. If a neuron's reduced responses to visual targets were caused by inhibition of that neuron, then build-up activity shown by these cued neurons should have been suppressed. Because this was not observed, we tentatively conclude that the SC is not itself inhibited in the region of the cue; rather it receives reduced inputs from other brain systems representing that region.

A possible source of these reduced inputs is the parietal cortex, because of its important role in exogenous visual orienting, its rich interconnections with the colliculus, and its role in spatial working memory and manual responding. Consistent with this proposal, one study of IOR in two split-brain individuals[53] suggests that the coding of IOR in object coordinates is dependent on cortical structures being intact. Danziger *et al.* have suggested that, 'While IOR may be generated through the retino-tectal pathway, the colliculus may not, itself, maintain a spatiotopic representation. Rather, the inhibitory tag generated in the midbrain may need to be transmitted to the parietal cortex through the pulvinar to be encoded in spatiotopic coordinates' (Ref. 45, p. 306). Thus, whereas an intact superior colliculus may be a necessary condition for IOR, it might not be sufficient in order for IOR to be observed – machinery in the cortex seems to be responsible for computing the spatial code and generating the inhibited signals.

Why: IOR functions as a foraging facilitator

What is the functional significance of this mechanism that biases orienting and other responses away from recently inspected locations? Klein reasoned that if IOR biases orienting away from previously inspected locations in the environment then it could serve to facilitate visual foraging behavior – that is, visual search[38]. Although subsequent challenges to Klein's foraging proposal were so convincing that Klein later rejected it (see Ref. 15, p. 139–143), other investigators (particularly Tipper and colleagues) recognized the validity of that proposal. All of the challenges have since been rebutted (see Box 2).

Recently, Klein and MacInnes explored IOR using overt orienting during search of a complex visual scene for camouflaged targets[54] (Box 3). After several saccades, the original fixation stimulus reappeared; at the same time the scene was either removed or maintained, and participants were required to locate the fixation probe by foveating it. When the probe was located by the first saccade after its presentation, RT was slower for probes in the general region of a previous fixation. This dependence of probe RT on the angular distance between the probe's location and a recent fixation was eliminated if

Box 2. The foraging facilitator proposal

The rationale, method and findings from Klein's study (Ref. a) are illustrated in Fig. I. According to Treisman and Gelade (Ref. b) attention is required to perform a serial search task, and, by hypothesis, inhibitory tags will have been left at the location of each item after a 'target absent' decision. However, as attention is not required in parallel search, display locations containing items should not receive inhibitory tags. If this functional explanation is correct, following serial search, reaction times (RT) to probes presented where there had just been a distractor (On) should exceed those to probes at previously empty locations (Off), by more than they do following parallel search. This is indeed what Klein found (Ref. a).

Three challenges to Klein's functional explanation of IOR appeared in subsequent years. Each has recently been rebutted.

(1) When one location and then the other was cued, Pratt and Abrams (Ref. c) reported that IOR was obtained only at the most recently cued location. In visual search, if inhibition were only maintained at the most recently attended location then IOR would not be a particularly effective foraging assistant. Subsequent studies (Refs d,e) demonstrated that IOR can be observed at more than one location, and, as illustrated in Fig. II, Snyder and Kingstone (Ref. f) showed significant IOR when up to four cues intervened between a cue and a subsequent target presented at the same location.

(2) Klein and Taylor (Ref. g) concluded that attention was not inhibited in IOR because inhibition had not been observed in studies at that time using non-spatial discrimination tasks and such tasks should be affected by attention. As described in the 'What' section of this article, effects of IOR upon discrimination tasks have since been amply demonstrated.

(3) Wolfe and Pokorny (Ref. h) and later Klein and Taylor (Ref. g) reported failures to replicate the original pattern reported by Klein (Ref. a). This discrepancy has recently been resolved by Takeda and Yagi (Ref. i) and Müller and von Mühlenen (Ref. j), who showed that the original pattern depends on delivery of the probe while the search array is still present (see Fig. I, bottom). When the findings of Tipper *et al.* (Ref. k) and others are considered, that demonstrate that IOR is attached to objects, this dependence is quite understandable: following a scene change signalling a new search environment it would not be functional for IOR to be maintained.

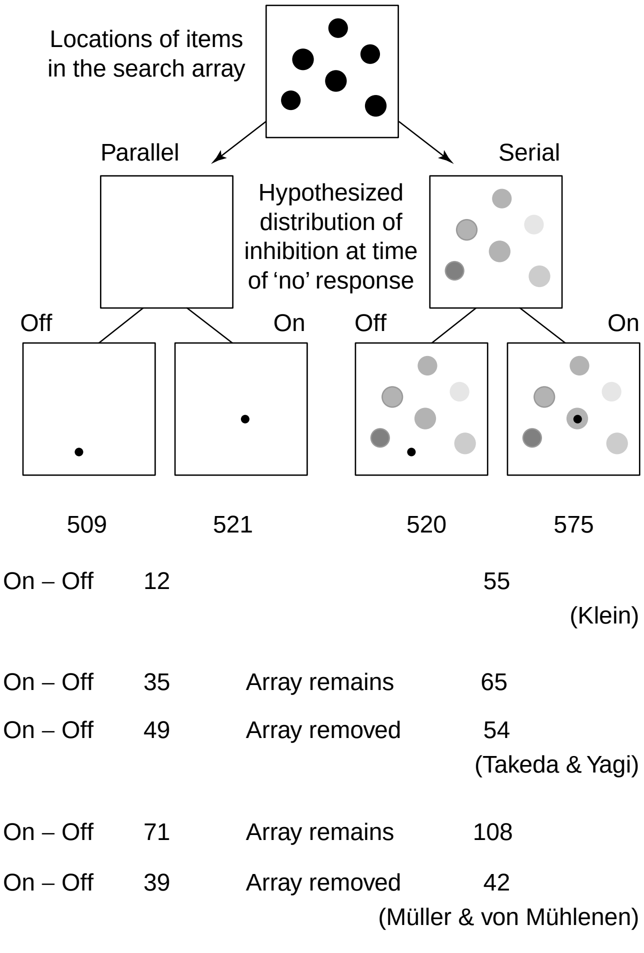

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Fig. I. Functional explanation of IOR. Klein hypothesized that, in parallel search, the difference between reaction times (RTs) to probe targets presented at distractor locations (On) and empty locations (Off) should be less than in serial search, as in the latter, inhibitory 'tags' will be left at each location attended to. This hypothesis was borne out by the experimental data (RT differences are given as On minus Off), and it was shown later, by two other groups, that this result is dependent on whether the search array remains present or is removed when the probe target is presented.

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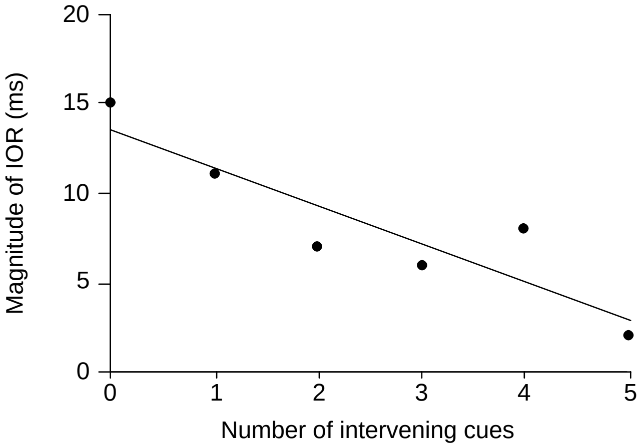

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Fig. II. IOR with intervening cues. Data showing that significant IOR is still observed when up to four intervening cues are presented between a given cue and a subsequent target at the same location. (Adapted from Ref. f.)

the search array was removed when the probe was presented, confirming other recent studies showing that IOR following visual search depends upon maintenance of the search array. Pre-probe saccades showed a strong directional bias away from a previously fixated region, probably reflecting IOR. Together with recent studies that replicate the finding of inhibition at distractor locations following serial but not parallel visual search – so long as the search array remains visible[55] – these data strongly support the proposal that IOR functions to facilitate visual search by inhibiting orienting to previously examined locations.

What's in a name?

As presented here, IOR is generated within a system that is normally responsible for orienting of gaze direction. IOR inhibits orienting of covert attention, of gaze direction and, more generally, of spatial responses towards tagged locations and objects. By biasing orienting away from already inspected items IOR functions to make search of the environment more efficient. The presentation in this review of IOR, from its discovery by Posner and Cohen in 1984 to the present day, is perhaps more integrated than might be intuited from an exhaustive survey of studies that lay claim to the term. Some investigators have observed inhibitory effects for non-spatial attributes of irrelevant pre-cues (e.g. repeating colors at fixation[56]; repeating a particular pitch at any location[34]), which they assume exemplify IOR. Similarly, Houghton and Tipper's[57] computational model of negative priming (presumably an inhibition of the features of irrelevant distractors) can also generate IOR from irrelevant cues. In contrast to these possible over-extensions of the term[58] Watson and Humphreys[59] have demonstrated a marking process during visual search that appears to function like IOR, but they believe, perhaps too restrictively, that visual marking is distinct from IOR. As our knowledge of the characteristics of IOR and its neural implementation grows, there will hopefully be increasing agreement on the use of the term. In the meantime, it is important to be careful but open-minded when choosing terms to divide up the psychological–biological realm.

Outstanding questions

- Is the removal of attention from a 'cued' location the signal for IOR to begin there, or is IOR timelocked to the appearance of the cue?
- To establish firmly that IOR delays attention, it would be useful to measure the time course of attentional shifts (under exogenous and endogenous control) towards previously cued versus uncued locations.
- If parietal cortex and the superior colliculus jointly implement IOR, how is this achieved?
- Once caused, does IOR have separable effects on oculomotor and attentional responses? For example, would the inhibition observed by Klein and MacInnes in their camouflaged search task[54] generalize to non-oculomotor responses?
- What is the relationship between IOR and other effects with a surface similarity (visual marking, repetition blindness, attentional momentum, negative priming, foveal IOR)? How might these different effects be implemented in the brain?

Box 3. IOR of eye movements during search

The observer fixates a small black disk at the center of an empty screen when the image to be searched (a picture from the Where's Waldo™ series of books) is presented. After several saccades were made (illustrated with blue arrows in Fig. Ia) as the observer searched for Waldo or another item, the fixation stimulus reappeared unexpectedly at carefully selected locations (indicated by black circles) while the search array remained (Fig. Ib) or was removed (Fig. Ic). The task was to foveate this target as rapidly as possible. Arrows illustrate a saccade to the target in the 0 deg. condition. In one experiment this target was presented at the most recently fixated location or other locations around an equi-eccentric circle (one back). Shown in Fig. Id are the data from the experiment where the penultimate fixation (labeled 0 here) was used to generate target locations (two back). Saccadic reaction time when the target was located by the first post-target saccade (as in b and c) increased with increases in the target's proximity to a previously fixated region, but only when the scene was maintained.

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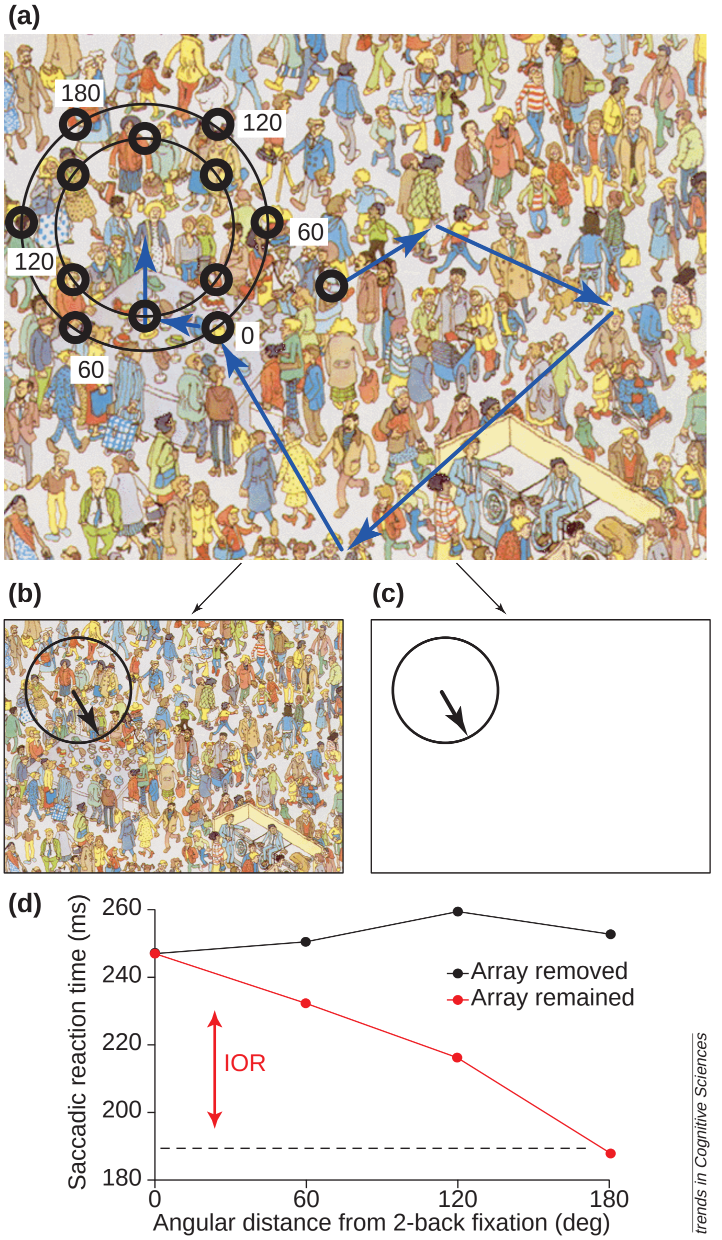

Fig. I. IOR during visual search. (See text for details; adapted from Ref. a.) (Illustration from Where's Waldo © 1987, 1997 Martin Handford. Reproduced by permission of Walker Books Ltd., London. Published by Candlewick Press Inc., Cambridge, MA, USA.)

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Attentional capture and inattentional blindness

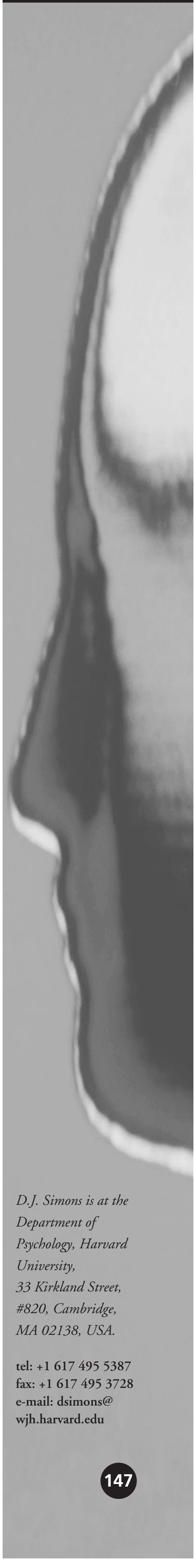
Daniel J. Simons

Although we intuitively believe that salient or distinctive objects will capture our attention, surprisingly often they do not. For example, drivers may fail to notice another car when trying to turn or a person may fail to see a friend in a cinema when looking for an empty seat, even if the friend is waving. The study of attentional capture has focused primarily on measuring the effect of an irrelevant stimulus on task performance. In essence, these studies explore how well observers can ignore something they expect but know to be irrelevant. By contrast, the real-world examples above raise a different question: how likely are subjects to notice something salient and potentially relevant that they do not expect? Recently, several new paradigms exploring this question have found that, quite often, unexpected objects fail to capture attention, a phenomenon known as 'inattentional blindness'. This review considers evidence for the effects of irrelevant features both on performance ('implicit attentional capture') and on awareness ('explicit attentional capture'). Taken together, traditional studies of implicit attentional capture and recent studies of inattentional blindness provide a more complete understanding of the varieties of attentional capture, both in the laboratory and in the real world.

In order to study whether unattended stimuli can capture attention, researchers must first operationally define a way to measure the capture of attention. Two classes of definitions have been used in the study of attentional capture. 'Explicit attentional capture' occurs when a salient and unattended stimulus draws attention, leading to awareness of its presence. 'Implicit attentional capture' is revealed when a salient and irrelevant stimulus affects performance on another task, regardless of whether or not subjects are aware of the stimulus. The first, explicit attentional capture, is perhaps the more intuitive conception: when someone across a room says our name or waves at us vigorously, the stimulus signal segregates itself from the background and we become aware of its source. Typically, studies adopting the explicit approach determine whether capture has occurred by asking subjects whether they noticed the critical stimulus. Although reporting the presence of an unexpected object may not conclusively demonstrate attentional capture, the failure to notice it suggests that the object failed to capture attention explicitly. Several recent studies of explicit attentional capture have found that when observers are focused on some other object or event, they often fail to notice salient and distinctive objects, a phenomenon that is termed 'inattentional blindness'. Although the use of explicit reports was one of the first approaches used to study attentional capture (in the study of divided and selective attention), and despite a recent resurgence of interest in inattentional blindness, most recent studies have focused on implicit attentional capture. That is, such studies make the critical stimulus irrelevant to the primary task and infer capture based on different patterns of response times or eye movements. This review considers evidence for attentional capture in both implicit and explicit paradigms. Together, these findings raise the intriguing possibility that salient stimuli, including the appearance of new objects, might not always capture attention in the real world.

Implicit measures of attentional capture

Most recent studies of attentional capture have adapted methodologies used extensively in the study of visual search. Four distinct paradigms have been used to explore implicit



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