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Investigating interactions between search mechanisms in the control of visual attention

Brian J. White
Wilfrid Laurier University

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Investigating Interactions Between Search Mechanisms in the Control of Visual Attention

by

Brian J. White

BA Psychology, Sir Wilfred Grenfell College,

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Abstract

Olds, Cowan and Jolicoeur (2000) showed that although the mechanisms underlying visual search have traditionally been assumed to be independent, in fact they interact. Using coloured disk stimuli, they interrupted pop-out search (target plus D1 distractors) by adding more distractors (D2s) of a different colour to the display before pop-out processes were able to find the target. In short, partially completed pop-out processes facilitated subsequent difficult search processes ("search assistance"). The present study investigated hypotheses for this interaction. In Experiments 1 and 2, we used methods aimed at determining where the bulk of attentional resources are allocated during search of a visual display assumed to produce search assistance (by measuring the effect of inhibition of return [IOR] between D1 and D2 locations). In Experiment 1, we first presented observers with a search task that has been shown to produce search assistance (using coloured disks; see Olds et al., 2000). Immediately following target response, observers had to determine as quickly and accurately as possible whether a small probe-dot (that appeared on one of the disks) was present or absent. The results of Experiment 1 provided tentative support for a *negative prioritisation hypothesis* which proposed that some initial distractors (D1s) are eliminated from consideration during the second portion of the display. The sequence of events in Experiment 2 were identical to that of Experiment 1 except that, following target response, observers had to make a temporal order judgement (TOJ) as to which of two physically simultaneous lines (one on a D1, and one on a D2) appeared first. The results of Experiment 2 did not support either of the hypotheses regarding the nature of search assistance. Experiment 3 examined the effect of spatial cues on difficult search by attempting to eliminate the effect of negative prioritisation while measuring the effect of positive prioritisation. The results of Experiment 3 provided evidence in support of a *positive prioritisation hypothesis* which proposed that the initial items are more likely to be searched in the second portion of the display. Future research is discussed.

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Investigating Interactions Between Search Mechanisms in the Control of Visual Attention

The amount of information that hits the retina far exceeds what can be processed in-depth by the visual system. Consider, for example, the multitude of colours, shapes and textures that appear in your visual field at a given moment in everyday life. Only a small portion of this information is of major importance at any given moment, so to process the entire visual field would simply be a waste of valuable resources. The visual system, therefore, only selects portions of the entire visual field that merit further processing, while filtering out the remaining information.

The mechanisms that guide visual selection are integral to almost every aspect of visual processing. Whenever we are faced with the task of trying to find a target object amongst a background of distractor information (e.g., looking for a particular car in a crowded parking lot), the visual system is engaged in a complex set of processes called visual search. Traditionally two types of visual search have been identified, each of which is assumed to be governed by a specific set of mechanisms: "Pop-out" search and difficult search. The distinction between the two can be better understood if we consider the unique pattern of results that each type of search produces. In pop-out search, response time (RT) for target detection is fast, and is relatively unaffected by the number of items in the display ("set size"). It is often assumed that this type of search operates in parallel because the entire set of items would have to be processed at once in order for RT to be unaffected by set-size. In contrast, target detection is slower for difficult search, and RT tends to increase linearly with the number of items in the display. Some researchers have interpreted this pattern as evidence that difficult search is performed serially; i.e., we attend to each item one at a time until the target is detected (or not).

What determines whether a given search display will result in pop-out versus difficult search? A display in which the distractors differ from the target in terms of a single feature (e.g., colour or shape) can result in pop-out (e.g., finding a blue target-letter "H" amongst blue "A" distractor letters [see Treisman & Gelade, 1980]). However, a display in which the distractors differ from the target on a conjunction of relevant features (e.g., both colour and shape) can result in difficult search (e.g., a blue target-letter "H" amongst green "H"s and blue "A"s [see Treisman & Gelade, 1980]).

However, a difficult search display can be created using a single feature as well. For example, distractor colours can be chosen to fall on a line with a target in *CIELuv* colour space such that the distractor colours fall on either side of the target (see Figure 1). In this case, no single line can be drawn that will separate both distractors from the target in colour space; i.e., the target is not linearly separable from the distractors (see D'Zmura, 1991; Bauer, Jolicoeur & Cowan, 1996). The result is a difficult search array. Pop-out search is only possible for targets that are linearly separable from the distractors (e.g., in displays with distractors of a single colour and a target of a different colour, or where all distractors are on one side of the target in colour space).

The mechanisms underlying pop-out and difficult search have been traditionally assumed to be independent (Treisman & Gelade, 1980). However, Olds, Cowan and Jolicoeur (2000) have provided evidence that these mechanisms may interact under certain conditions. Using coloured disks as search stimuli, they interrupted pop-out operating in a display consisting of an orange target plus distractors of one colour (D1s; see Figure 2) by adding more distractors of a different colour (D2s) to the display. This interruption occurred after various delays (stimulus onset asynchronies or SOAs). At some shorter SOAs (e.g., 50ms), the interruption occurred before pop-out processes had time to detect the target (or determine that it was absent).

RT distributions for intermediate SOAs (50, 100, 150, 200, 250, 300, and 1000 ms) were compared to control distributions (SOA = 0 and SOA = ∞). For trials with SOA = 0, the second set of distractors was always present, and for trials with SOA = ∞, the second set of distractors never appeared. Therefore, these trials represented the "pure" difficult, and "pure" pop-out control conditions, respectively. The logic behind this approach is that if the search mechanisms do not interact, either the mechanisms responsible for pop-out will find the target, or the mechanisms responsible for difficult search will find the target. As such, RT distributions for intermediate SOAs ought to be linear combinations of the two control distributions. That is, the intermediate distributions would be the result of sampling from the two control distributions in different proportions. For example, for some intermediate SOA, if pop-out detected the target before interruption by additional distractors 60% of the time, difficult search would be required to detect the target on the remaining 40% of trials when pop-out failed. The resulting distribution should look as if we had randomly sampled 60% of RTs from the pop-out control distribution, and 40% of RTs from the difficult control distribution.

However, analysis of RT distributions showed that the intermediate distributions could not have been created by sampling from the two control distributions. Olds et al. (2000) concluded that the mechanisms are not independent (i.e., they interact). When pop-out failed to detect the target (or determine that the target was absent) in the first portion of the display, difficult search was facilitated by partial information provided by the mechanism(s) responsible for pop-out before interruption by the D2 distractors.

This paper is concerned with the nature of the information that pop-out transmits to difficult search during search assistance. Olds et al. (2000) demonstrated that moving the target mid-trial eliminated search assistance. This result suggested that the information is spatial in nature (it involves the *location* of the target). In addition, since partial pop-out assisted difficult search on target-absent trials as well (in experiments where the target did not move), Olds et al. (2000) concluded that search assistance might involve information about where the target *is not* (possibly in addition to information that suggests where the target *is*).

Hypotheses Regarding the Nature of Search Assistance

Positive prioritisation hypothesis. This hypothesis proposes that pop-out assists difficult search by encoding initial item locations (target plus D1 distractors) before the onset of the second set of distractors (D2s; Olds, Punambolam, & Degani, 2001; see Figure 3). Therefore, initial items are prioritised for search during the second portion of the display. Since observers know the target will always appear in the initial portion of the display (in experiments where the target does not move), difficult search might be facilitated by visiting only these initial items.

Positive prioritisation could occur by way of simple spatial cuing of possible target locations. Palmer (1995) presented observers with search displays preceded by spatial cues. Some of these cues (black crosses) indicated potential locations where a subsequent target, when present, could appear ("relevant set"), whereas the other cues (white crosses) did not indicate a potential target location ("irrelevant set"). By holding constant the total set-size while varying the number of cues that indicated potential target locations, the effect of this "relevant set-size" could be measured. Palmer found that the effect of the "relevant set-size" was nearly identical to the actual display set-size effects found in experiments that did not employ cues. This makes spatial cuing a particularly probable explanation for search assistance. Search assistance (Olds et al., 2000) might be made possible because the initial items act as cues to a smaller search set that contains the target (when present). This would be consistent with a positive prioritisation hypothesis.

Negative prioritisation hypothesis. This hypothesis states that partial pop-out assists difficult search by eliminating from consideration some initial D1 distractors (Olds et al., 2001; see Figure 4). This strategy would require some form of deprioritisation of some initial items determined to be distractors prior to the onset of the second set of distractors (D2s). Search is facilitated in the second portion of the display by ignoring those items found to be distractors during the first portion of the display.

Deprioritisation of initial distractors could be accomplished via visual marking (Watson & Humphreys, 1997). Visual marking is an inhibitory mechanism that allows observers to eliminate from consideration old search items once new items are added to the display. Watson and Humphreys (1997) demonstrated visual marking by having participants perform a search task in 3 conditions (see Figure 5). In the *single feature condition*, observers had to find a blue "H" target amongst a set of blue "A" distractors. This was essentially a pop-out search task because the target differed from the distractors on only one feature, shape. In the *conjunction baseline condition*, observers had to find a blue "H" target amongst a set of green "H", and blue "A", distractors. This condition was a difficult search task because the target differed from the distractors on a combination of features (colour and shape). Finally, a third condition involved a short (1000ms) presentation of an initial display of green "H" distractors before filling in the empty locations with blue items (blue "A" distractors, plus the blue "H" target on half the trials). This was called the *gap condition*. Note that the target (when present) only appeared in the second portion of the display (i.e., there was no target with the initial set of distractor items). The second portion of the display in the gap condition was identical to the conjunction display.

Watson and Humphreys (1997) found that performance in the gap condition was comparable to that in the single feature baseline condition, and better than that in the conjunction condition. That is, results for the gap condition (like the single-feature baseline) were indicative of pop-out search. The authors argued that observers were able to ignore the initial distractors in the gap condition by a top-down inhibitory mechanism they called visual marking. In addition, observers were somehow able to keep ignoring the initial green items once the blue items (which included the target) appeared.

Partial pop-out may assist difficult search by marking some initial distractors (Olds et al., 2001). Note that, Watson and Humphreys (1997) have shown that full marking requires 400ms to complete. While the research demonstrating search assistance (Olds et al., 2001) employed SOAs shorter than 400ms, some form of partial marking may have occurred. That is, the delay before the onset of the second portion of the display may have allowed the mechanisms responsible for pop-out to mark at least some of the D1 distractors. This may have facilitated difficult search by enabling observers to search for the target only amongst the unmarked items (as illustrated in Figure 4).

Hybrid hypothesis. It is possible that both hypotheses are true, but at different SOAs (Olds et al., 2001). In an experiment by Olds et al. (2001), the target was moved (either replacing a D1 location, or moved to a previously empty location), when the D2 distractors were added, on 25% of the target-present trials. On the remaining 75% of target present trials the target remained in the same position when the D2s were added. If observers are able to encode initial item locations before the D2s are added, then RT should be faster when the target is moved to an initial item location. It is possible that the encoding of initial locations might occur quickly, and that this might occur at short SOAs. Alternatively, if observers are able to reject from search some initial distractor locations before the D2s are added (via "marking"), then RT should be slower, on average, when the target is moved to an initial item location. Marking is likely slower than encoding of initial locations, so this might occur at longer SOAs. Interestingly, Olds et al. (2001) found that at a short SOA (53ms), RT was faster when the target moved onto a D1 location, supporting the positive prioritisation hypothesis. However, at a longer SOA (160ms), RT was slower when the target was moved onto a D1 location providing tentative support for the negative prioritisation hypothesis (the interaction of SOA and onto-D1-location versus onto-empty-location approached significance, $p = .07$).

Rationale Underlying the Experiments

The goal of this research is to extend the research of Olds et al. (2000) by attempting to determine how partial pop-out facilitates difficult search. The general assumption underlying each of the following experiments is that search assistance involves focusing the bulk of attentional resources on one set of distractor items over the other (D1s versus D2s) during the difficult search portion of the display. That is, search assistance involves confining attention to a smaller proportion of the display that primarily consists of one set of distractors. As was described in the previously mentioned hypotheses regarding search assistance, this might occur by either positively or negatively prioritising initial items.

To test the hypotheses of search assistance, three types of experiments were employed: 1) Using inhibition of return to determine the locus of attention. 2) Using temporal-order judgements to determine the locus of attention. 3) Measuring the effect of initial placeholders on difficult search.

Using Inhibition of Return to Determine the Locus of Attention

What is Inhibition of Return?

Posner and Cohen (1984) had observers fixate at a central box that was flanked by a box on either side (see Figure 6). On a trial, the outline of one of the three boxes would flash for a brief time (150ms), quickly summoning attention to that location. After a variable delay (0ms to 1500ms), a target stimulus would then appear in one of the three boxes. The task was to press a key as quickly as possible when the target was detected. Because the target usually appeared in the central box (with a probability of 0.6), attention was likely to return there following the cue. Posner and Cohen found that for targets in the peripheral boxes a biphasic RT pattern emerged: At short cue-target SOAs (150ms or less) a peripheral cue facilitated detection of a target that fell at the cued location (i.e., faster RT). However, at longer SOAs (300ms to 1500ms), target detection was inhibited at the cued location (i.e., slower RT). Posner and Cohen termed the latter effect inhibition of return (IOR) suggesting that its purpose is to inhibit attention from returning to old locations, in favour of novel locations.

At first glance, IOR appears similar to visual marking (Watson & Humphreys, 1997). However, Watson & Humphreys (1997) showed that this is not the case. They presented observers with a brief display (750msec) of initial green "H" distractors. These then disappeared for 250ms after which they reappeared in the same positions with additional blue items (blue "A" distractors and the blue target "H" on 50% of trials) filling in the remaining locations. Recall that the gap condition was the same as this condition with the exception that, in the gap condition, the initial items (green "H" distractors) did not disappear for 250msec, but instead remained present for the duration of a trial. Target detection in the gap condition was easy. If the gap effect is essentially the result of IOR, then the initial items (green "H" distractors) also ought to be inhibited after a brief delay of 250msec, so target detection ought to be easy in this case as well. However, the results showed that target detection was more difficult in this case than the gap condition. As such, Watson & Humphreys (1997) concluded that IOR and marking are not the same.

What is inhibited in IOR?

Three general hypotheses have been proposed to explain what is inhibited in IOR: Sensory, Motor, and Attentional Hypotheses (see Kwak, 1995; Taylor & Klein, 1998).

The *Sensory Hypothesis* states that IOR is a masking or habituation phenomenon that operates at the level of the retina (Kwak, 1995; Taylor & Klein, 1998). As such, IOR is presumed to have retinotopic coordinates (see Posner & Cohen, 1984). However, current research has generally ruled out this possibility mainly because IOR has been shown to last much longer than typical masking effects (e.g., Snyder & Kingstone, 2000, showed an inhibitory effect up to 4800msec following the first cue). Currently the debate revolves around motor and attentional explanations of IOR (see Kingstone & Pratt, 1999; Kwak, 1995; Taylor & Klein, 1998).

One simple version of the *Motor Hypothesis* states that IOR is a general motor response bias. The argument here is that at cue-target SOAs greater than 150ms inhibition of responding to the cue is transferred to the target (see Kwak, 1995). That is, inhibition of return results from a carryover of inhibition of responding to the cue (a sort of interference effect) since the cue is of little predictive value. However, at cue-target SOAs of less than 150ms, target detection is facilitated because attention is presumably still there (exogenously). However, this general hypothesis is currently not believed to be the case (see Kwak, 1995). A more specific version of the Motor Hypothesis states that IOR is the result of an oculomotor bias against making eye-movements towards the cued location, since observers know the target rarely appears at a cued location (Kwak, 1995; Taylor & Klein, 1998). This has been demonstrated in the work of Rafal, Calabresi, Brennan, and Sciolto (1989). The idea here is that while the presentation of a cue automatically orients attention towards the cue (resulting in target facilitation at cue-target SOAs < 150ms), targets appearing at the cued location after longer SOAs (e.g., 300ms or greater) are inhibited as a result of a mechanism inhibiting eye-movements from cued locations. In short, IOR is the direct result of inhibited eye-movements.

Finally, the *Attentional Hypothesis* states that IOR is a genuine attentional bias against responding to targets at a previously cued location, irrespective of eye movements. In addition, IOR is assumed to have environmental coordinates (versus retinal coordinates as suggested by the Sensory Hypothesis).

Research clearly demonstrates a motor component of IOR (see Taylor & Klein, 1998, for a review). However, there is evidence for an attentional component as well (see Gibson & Egeth, 1994; Kingstone & Pratt, 1999; Reuter-Lorenz, Jha, & Rosenquist, 1996). The debate surrounding this issue is beyond the scope of this research. The main issue here is that the present experiments are based on the assumption that IOR operates in visual search, whether IOR involves an attentional component, an oculomotor component, or both.

Inhibition of Return in Visual Search

Klein (1988) was the first to extend Posner and Cohen's (1984) notion of inhibition of return (IOR) to the visual search paradigm (see Figure 7). He used a dual task visual search paradigm whereby observers had to detect a small probe-dot immediately following a serial or parallel search task (set sizes of 2, 6 or 10 items).

Klein (1988) found impaired probe-dot detection following a serial search task when the dot was placed where a search item had previously been (versus an empty location where no search items had been). This effect was not found following a parallel search task. Consequently, Klein (1988) suggested that IOR might be a mechanism designed to facilitate serial/difficult search by inhibiting attention from revisiting previously inspected item locations. Otherwise, target detection might take an infinitely long time if attention were to keep revisiting previously inspected locations. Since then, several researchers have been seeking evidence to support (or refute) this claim.

IOR in multiple cuing paradigms. In order for IOR to operate in difficult search as a facilitory mechanism (Klein, 1988), it ought to occur for multiple locations and last for a reasonable amount of time. Research employing multiple cues has examined these issues.

Pratt and Abrams (1995) were among the first to employ multiple cues to IOR. Their paradigm consisted of only two successively cued spatial locations, which is more like traditional IOR studies (with the exception of using multiple cues) than a visual search paradigm. Nonetheless, they found IOR in only the most recently cued location, and they claimed that subsequent exogenous cues displaced any inhibition that might have affected the previously attended location. Tipper Weaver and Watson (1996) challenged Pratt and Abrams' (1995) claim by introducing four possible cue locations such that the locations (cue boxes) formed an imaginary circle around a central fixation. On a given trial, three of the boxes were cued in succession followed by the target dot that could land in any of the four possible locations. In contrast to Pratt and Abrams (1995), Tipper et al. (1996) found IOR at all three of the cued locations, but only when adjacent locations were cued (which they argue is a more likely serial search pattern).

In a sequential search paradigm (see Danziger, Kingstone, & Snyder, 1998), observers have to track multiple cues that appear randomly along an imaginary circle. What separates this from traditional multiple-cueing paradigms (as employed by Pratt & Abrams, 1995; Tipper et al., 1996), according to Danziger et al., is uncertainty as to when the target will appear. Danziger et al. (1998) argued that in the previous traditional precuing paradigms, such as the one employed by Tipper et al. (1996), observers did not need to inspect the initial cued locations because the target always appeared after a fixed number of cues. Therefore, Danziger et al. (1998) introduced uncertainty as to when the target would appear, 1) by varying the number of cues that precede the target from one to five, and 2) by having target onset occur with the same SOA as each of the cues rather than cueing fixation prior to target onset (which had traditionally been done in precuing paradigms).

Each trial started with a central fixation ("+"), and five grey outline boxes surrounding the fixation along an imaginary circle equidistant from the "+". These stimuli remained present for the entire duration of each trial. Then, one to five of these locations would illuminate in succession, acting as peripheral cues, and the target could appear after any number of cues. Therefore, observers had to inspect each cue since they could not be sure at what point the target would appear. In contrast to Tipper et al. (1996), Danziger et al. (1998) found IOR in up to three non-adjacent locations, and the inhibitory effect was found to last nearly 5sec.

Snyder and Kingstone (2000) have extended the number of inhibited locations to as many as six using the same paradigm as Danziger et al. (1998). As well, inhibition was found to decline in a very linear fashion from the most recent cue to the earliest (i.e., IOR was highest for most recently cued locations and IOR declined linearly from each earlier cued location). At present, it is unknown whether this limit can be exceeded, and whether the decline is affected by the number of items inhibited, or a decay based on the passage of time.

Although multiple-cuing paradigms are not identical to visual search, they provide a controlled method of investigating IOR as a visual search phenomenon. In particular, the sequential search paradigm (Danziger et al., 1998) does appear to facilitate scanning each and every item in search for the target. This makes it particularly useful for testing both the number of inhibited items/locations, and the decay of IOR for two reasons: 1) It forces observers to attend to every item in a controlled sequence, and 2) it allows us to make comparisons of the relative amount of inhibition associated with each location. Furthermore, the research surrounding this paradigm provides fairly convincing evidence that IOR operates in visual search.

IOR in the dual task visual search paradigm. There have been several attempts to replicate Klein's (1988) initial findings using the dual-task visual search paradigm (Müller & von Mühlenen, 2000; Takeda & Yagi, 2000; Wolfe & Pokorny, 1990). Wolfe and Pokorny (1990) failed to replicate Klein (1988). They instead found impaired probe detection in all item locations in comparison to empty locations, irrespective of the search display type (serial versus parallel). Wolfe and Pokorny argued that the effect they found is more likely a forward-masking effect than IOR.

Nonetheless, others have found results similar to Klein's (1988) but only when the search display remained visible during the probe detection task (see Müller & von Mühlenen, 2000 [see Footnote 2 for details]; Takeda & Yagi, 2000).

To further support the role of IOR in serial visual search, Klein and MacInnes (1999) had observers search complex scenes for a camouflaged target (Waldo from the "Where's Waldo?" books). The purpose of this research was to test IOR as an oculomotor phenomenon, versus an attentional phenomenon (see Rafal et al., 1989). As well, Klein and MacInnes wanted to replicate the finding that IOR in visual search depends on persistence of the search stimuli during the probe task (supporting object-based IOR).

Following the removal of the fixation stimulus (same stimulus that acted as a probe), observers searched the complex scenes for Waldo, and after a short number of saccades, the probe (which was essentially the same stimulus used for fixation) would appear. Observers had to then locate the probe by simply moving their eyes towards it (saccadic RT was measured by an eye tracking device). The scene would either disappear, or remain present during the probe task. The probe was placed along an imaginary circle surrounding the current fixation such that one of the possible probe locations was at a preceding fixation location (one-back for Experiment 1, and two-back for Experiment 2).

Klein and MacInnes (1999) found impaired saccadic reaction time to detect a probe that was closest to preceding fixation locations, and this finding did not occur when the scene was removed during the probe detection task. This again demonstrates the importance of keeping the display visible during the probe detection task. In addition, it provides further support of IOR as a mechanism designed to facilitate search in a visually complex environment.

Rationale Behind Using IOR to Determine the Locus of Attention

Theoretically, IOR can be used to determine where attention was focused during difficult search. Accordingly, we should see impaired RT to a probe-dot at recently searched locations relative to other locations. The goal here was to use IOR to determine where attention is focused during the difficult search portion of the display in an experiment demonstrating search assistance (e.g., Olds et al., 2000).

In Experiment 1, the search display consisted of coloured disks like those used by Olds et al. (2000). Following target response, a small probe-dot could appear at either a D1 or a D2 location (see Figure 8). Any difference in probe-dot detection between these two locations should tell us where the bulk of attentional resources were allocated during the difficult search portion of the display. Impaired RT to a probe-dot at a D1 (relative to a D2) location would suggest that attention was focused at D1 locations, on average, during search. A result such as this would provide support for the positive prioritisation hypothesis (i.e., encoding initial item locations). Alternatively, impaired RT to a probe-dot at a D2 (relative to a D1) location would suggest that attention was instead focused at D2 locations, on average, during search. A result such as this would provide support for the negative prioritisation hypothesis (e.g., marking initial distractors). This is essentially what Experiment 1 tested.

Experiment 1

Method

Observers. Eleven students (6 females and 5 males) attending Wilfrid Laurier University took part in Experiment 1. Eight of the eleven participants were naive as to the nature of the experiment. All observers were tested for normal colour vision using Ishihara plates, and all had normal, or corrected to normal visual acuity. All observers were paid for participating.

Equipment. The experiments were programmed and run using MATLAB software on a Macintosh G-3. The monitor (a Sony Trinitron Multiscan 220GS) was calibrated using the Minolta Chroma Meter CS-100 (see Olds, Cowan & Jolicoeur, 1999, for monitor calibration technique).

Stimuli. All stimulus colours were chosen using *CIELuv* colour space which corresponds to actual perceptual colour distances (see Bauer et al., 1996). The circular disks were 8mm (28 pixels) in diameter, and occupied 0.75° of visual angle. All the stimuli and the background were isoluminant at 20.0 candelas/m^2. The target colour was orange with chromaticity values of $x = 0.416$, and $y = 0.364$. The coloured disks were presented on a grey background with chromaticity values of $x = 0.327$. and $y = 0.332$. The distractor colours were chosen to fall along a line in *CIELuv* space with the target colour such that the distractor colours fell an equal distance on either side of the target. Therefore, the target was not linearly separable from both distractors (see D'Zmura, 1991; Bauer et al., 1996). As such, when both sets of distractors were present, search for the target was difficult, but with only one set of distractors present, search was easy.

The distance of the distractors from the target in colour space was varied depending on the sensitivity of each observer. Colours were chosen so the homogenous display (only one set of distractors) showed a pattern indicative of pop-out search, and the heterogeneous display (both sets of distractors) showed a pattern indicative of difficult search. Each observer took part in preliminary test sessions with various target-distractor colour distances in order to determine their optimal colour distance. This took approximately 5 hours of testing per observer before actual experiments were run.

Finally, the probe-dot stimulus had the same chromaticity and luminance values as the background, and was placed directly in the center of the coloured disk.

Therefore, it appeared as a hole in the coloured disk. The size of the probe-dot varied (from 5 to 9 pixels in diameter) with eccentricity from the target. So a probe-dot appearing closer to the target was smaller in diameter than a probe-dot further in the periphery to roughly equate its visibility.

Procedure. Each trial (see Figure 8) began with a 400ms fixation stimulus that also acted as feedback for target response on the previous trial (e.g., "+" = correct, "-" = incorrect). The fixation stimulus was followed by a 400ms blank screen, after which the initial stimulus array appeared. This initial display always consisted of one set of distractors (D1s), plus the target, when present (on 50% of trials). After a short SOA (80ms), a second set of distractors (D2s) appeared. Therefore, pop-out was interrupted after 80ms by the addition of the second set of distractors. Recall that Olds et al. (2000) found search assistance most apparent at SOAs of between 50ms and 150ms (Olds et al., 2000). We therefore chose a single intermediate SOA of 80ms. As well, no control SOAs (SOA = ∞, or SOA = 0) were used in this experiment because of a potential reduction of power. As such, it is possible that on some trials, pop-out processes found the target before the onset of the D2s. We had no way of alleviating this potential problem. However, by using a short SOA (80ms), it is likely that, for most trials, target response occurred after the second set of distractors appeared (that is, most trials showed search assistance).

The full array consisted of 18 items, nine of which were D1s (except on target-present trials where one of the D1s was replaced by the target), and nine were D2s. The coloured disks were randomly placed within a 6 X 6 display field (7.6°

across) with a slight random variation (one-seventh of a disk in diameter) both horizontally and vertically from the grid locations. Using their right and left index fingers for the "yes" and "no" keys respectively, observers had to indicate whether the target was present or absent. Observers were encouraged to respond as quickly as possible while maintaining an error rate below 10%.

Immediately following target response, the probe-dot appeared (on 50% of the trials) on one of the distractors. The coloured disk array remained on the screen until response to the probe-dot was made. Observers were encouraged to respond as quickly as possible by pressing the "yes" key if the probe-dot was present, and the "no" key if the probe-dot was absent (probe-dot present on 50% of trials). Incorrect responses to the probe-dot were signalled by a tone from the computer. Following response to the probe-dot, a new trial would begin. Each observer completed 1200 trials over 4 sessions. The computer recorded RTs and the decision on each trial for target responses and probe-dot responses (the proportion correct was later calculated from the decision data).

Results and Discussion

RT outliers of more than 3 standard deviations for both target and probe-dot responses were removed from the analyses. As well, average errors were below 10%. RT to the orange target for both target absent trials ($\underline{M}$ = 2650ms, $\underline{SE}$ = 230) and target present trials ($\underline{M}$ = 1175ms, $\underline{SE}$ = 100) showed a pattern indicative of difficult search (i.e., RTs were well above the normal range of that which is typically indicative of pop-out search). Thus, the search task did not appear to be too easy.

Figure 9 shows the average RTs (and standard errors) to a probe-dot when on a D1 versus a D2 location, for both target present and target absent trials. Analyses included probe present trials only. A 2 X 2 repeated measures analysis of variance was conducted with target (present/absent) and probe-dot (onto D1/onto D2) as factors. The dependent measure was response time to the probe-dot. The target by probe-dot interaction was not significant, ($F < 1$). This suggests that any potential difference in probe RT was not dependent upon whether the target was present or absent. The main effect of RT to the probe-dot when on a D1 (M = 633ms, SE = 29ms) was also not significantly different from RT to the probe-dot when on a D2 (M = 643ms, SE = 31ms), $F(1, 10) = 2.87$, $p = .12$.

One possibility for the lack of an effect here could simply be due to the fact that IOR effects are subtle (typical IOR effects range from 20-30ms according to Law, Pratt & Abrams, 1995). It may have been in our best interests to only analyse target absent trials alone, rather than running an ANOVA (because of the loss of power analysing more conditions). Note that Klein (1988) argued that IOR would be weaker for target present trials since the target would, on average, be detected after only half the items had been inspected (therefore, only half the items, on average, would have inhibition associated with them). Klein (1988) therefore only analysed target absent trials. Thus, analysis of target absent trials alone might have been a wiser decision by increasing the power of our test, especially in light of the large amount of 'noise' in the data. We considered this possibility and tested the effect of target absent trials alone.

Figure 10 shows the difference scores between the RT to a probe-dot on a D2 minus the RT to a probe-dot on a D1 for target absent and target present trials separately (Note that this difference is presumably due to IOR. Therefore, we refer to it hereafter as the "IOR effect size"). For target absent trials there was a 14ms difference. While 14ms is a modest effect, it is fairly consistent with IOR effects found in the literature (typical IOR effects range from 20-30ms according to Law et al., 1995). A t-test revealed the 14ms difference in probe-dot RT for target absent trials to be significant, $t(10) = 2.33$, $p < .05$. This suggests that there was a moderate inhibitory effect when detecting a probe-dot on a D2 (relative to a D1) location for target absent trials. This is consistent with the negative prioritisation hypothesis (e.g. visual marking of some initial distractors). The effect for target present trials was not significant. In light of this result, however, we must consider that fact that RT to the probe-dot on either a D1 or a D2 for target present trials was approximately equal to RT to the probe-dot on a D2 for target absent trials (see Figure 9). One would expect faster probe RT for target present trials since less items ought to be visited, on average, before target detection (therefore, less items ought to have inhibition associated with them).

In terms of the 2 X 2 ANOVA, it is possible that the lack of a more powerful effect was the result of our search task being too easy resulting in fewer eye movements during serial search. Müller and von Mühlenen (2000; see Footnote 2) made this same suggestion for failures to replicate Klein (1988), although the results of Müller and von Mühlenen's (2000) study did not provide a definitive answer to this question. Nonetheless, IOR is suggested to be intrinsically linked to eye movements (Rafal et al., 1989). So it is possible in our experiment that target detection may have occurred without observers making many eye movements, and scanning each item in detail. If this is true, we ought to see a weaker IOR effect for those with faster RTs to the target (i.e., those who found the difficult search task too easy).

To test this possibility, we correlated observers' individual average target RTs with their IOR effect size, for target present and target absent trials separately. The correlation was not significant for target absent trials, $r = .13$, $p = .35$ (one tailed). However, the correlation approached significance for target present trials, $r = .46$, $p = .08$ (one tailed). This suggests that, for target present trials, individuals with smaller target RTs (i.e., faster RT) tended to show a smaller effect of IOR. This might explain the overall lack of an IOR effect for target present trials. As was mentioned, Klein (1988) analysed only target absent trials because of the fact that individuals would often find the target before inspecting every item on target present trials. This provides support for the moderate effect we found when analysing target absent trials separately. An important note about analysing target-absent trials is that search may be very different from target-present trials (see Chun & Wolfe, 1996). There are several possible differences between search on target present trials, versus target absent trials, and we do not wish to generalize from one to the other.

One alternative to the possible problem of having a difficult search display that is too easy is to simply make search more difficult by decreasing all observers' distractor colour distances. This might compel observers to inspect the items in greater detail. However, theoretically, target detection still ought to occur before visiting all the items on target present trials. As well, other variations using this same paradigm showed negligible results (see Footnote 1). In fact, since full marking requires 400ms (Watson & Humphreys, 1997), we might expect to see a greater effect using a longer SOA than was used here (80ms); that is, if partial marking is indeed possible. However, previous tests (see Footnote 1) using a longer SOA (160ms) did not appear to support this. Therefore, at this point, the results probably do not warrant repeating the experiment using more difficult (similar) distractor colours. As an alternative, Experiment 2 attempted to test the hypotheses regarding the nature of search assistance by using a different dependent measure from RT, the perception of the temporal order of two simultaneous events.

Using Temporal-Order Judgements to Determine the Locus of Attention

Attention is believed to speed the transfer of visual information. This is known as the doctrine of prior entry—that attended events are perceived as occurring prior to unattended events (see Shore, Spence & Klein, 2001). When judging the perceived temporal order of two simultaneous events, the one that receives the bulk of attentional resources tends to be perceived as occurring first (Stelmach & Herdman, 1991). This makes it possible to use temporal-order judgements (TOJs) as a means of determining the locus of attention. Therefore, it should also be possible to use TOJs to test the hypotheses regarding the nature of search assistance.

Temporal Order Judgements and Directed Attention

Stelmach and Herdman (1991) examined the effect of directed attention on the perceived temporal order of two events. Following the theoretical framework of the general threshold model of temporal-order judgements (Ulrich, 1987, as cited in Stelmach & Herdman, 1991), attention is assumed to affect the speed at which information is transmitted from the retina to the "temporal comparator". In essence, attended events are processed faster than unattended events.

As such, Stelmach and Herdman (1991) had observers judge the temporal onset of two stimuli. On a trial, observers' attention was first directed towards a location marker either to the left or right of fixation (with eyes fixated at center). Following this, two target dots were presented from 0ms to 100 ms apart temporally. Observers had to indicate which dot appeared first. Meanwhile, over numerous trials the computer adjusted the SOA until observers could no longer reliably judge which dot appeared first (i.e., the point of greatest temporal uncertainty). The results showed that the point of greatest temporal uncertainty occurred when the unattended dot preceded the attended dot by approximately 40ms. In essence, observers judged the onset of the dot at the attended location as occurring first.

Abrams and Law (2000) used the same theoretical framework to determine if directed attention can access object-based representations. Observers viewed a display consisting of a fixation dot flanked by three grey disks equidistant from fixation such that they formed an equilateral triangle (see Figure 11). However, two of the disks were connected by a thick line making them appear as a single object (a barbell). On a trial there was a 1500msec onset of the display, after which the display remained on, and a cue directed attention (either exogenously or endogenously) to one of the disks. The exogenous cue was a black ring presented in one of the disks for 200msec. The endogenous cue was an arrow pointing to one of the disks from the central fixation position for 300msec. Following one or the other cue there was a short delay (500msec for the exogenous cue, 400msec for the endogenous cue). Finally, two simultaneous white dots appeared at the center of two of the disks, and observers had to indicate which dot was perceived first.

The interesting condition occurred when the object (i.e., one of the disks that formed a barbell) was cued, and the target dots were presented on the two remaining disks. Abrams and Law (2000) found that observers tended to judge the dot presented on the uncued side of the cued object (i.e., the barbell) as occurring first. That is, although neither of the dots appeared at previously cued locations, the dot that appeared on the cued object tended to be perceived first.

Response Bias in Making Judgements of Temporal Order

Shore et al. (2001) pointed out a major problem with TOJs: In a typical experiment, attention is first directed either to the left or right of fixation. Observers have to determine which of two subsequent stimuli (one to the left and one to the right of fixation) was perceived first. Often the interval between the two events varies, and the point of subjective simultaneity (PSS; the time interval between the two events that results in the greatest uncertainty) is measured. Thus, the PSS occurs when the proportion of "left first" and "right first" responses is approximately equal. The problem is that observers may simply be reporting the side to which they were instructed to attend. That is, the doctrine of prior entry—that attended events are perceived earlier than unattended events—may not reflect a true perceptual effect, but rather a response bias.

Some researchers have used a "simultaneous" option in an attempt to reduce this potential response bias (see Stelmach & Herdman, 1991). As such, we would expect to see a greater proportion of "simultaneous" responses at the PSS since this is the point of greatest uncertainty. However, using a "simultaneous" option was found to be unreliable given the mixed results from different studies (e.g., observers chose the "simultaneous" option on less than 5% of trials at the PSS in Stelmach & Herdman, 1991, but observers chose the "simultaneous" option for most trials in Jaskowski, 1993, as cited in Shore et al., 2001).

Shore et al. (2001) used a method that enabled them to control the effect of response bias in TOJs. They first directed the observer's attention to one side of fixation (either by an exogenous or endogenous cue). Then, some observers had to indicate which of two subsequent line segments (a horizontal and a vertical to either side of fixation) had been presented first ("which first?" condition), while others observers had to indicate which line segment had been presented second ("which second?" condition). Note that there was an interval between the two stimuli from 15msec to 240msec. In addition, there was no "simultaneous" option. Instead, RT to make the TOJ was measured. Note that observers were explicitly told not to make a speeded response. The notion here is that observers should, nonetheless, respond slowest when they are most uncertain (i.e., at the PSS), and respond more quickly when a true temporal difference between the two events is perceived.

The logic behind this approach is that if observers simply report the side to which attention is directed (i.e., make a response bias), then the PSS should shift in opposite directions for the "which first?" and "which second?" conditions.

The results showed that while some response bias was still present, there was still a significant effect of prior entry (attended events were perceived first). As well, RTs to make the judgements tended to be slowest at the greatest PSS (when observers were most uncertain of their response). This is consistent with the doctrine of visual prior entry.

<u>Rationale Behind Using TOJs to Determine the Locus of Attention</u>

Our goal was to use TOJs of two simultaneous events to test the hypotheses regarding the nature of search assistance. The main assumption underlying this approach is that TOJs are affected by IOR in visual search. Note that unlike Experiment 1, using TOJs relies on IOR as a real attentional phenomenon (because the perception of temporal order is assumed to be affected by attention). TOJs have been used to measure the effect of IOR, though some studies have failed to show inhibition (see Gibson & Egeth, 1994). However, Gibson and Egeth have demonstrated that IOR can affect TOJs (note that RT latency was used as the dependent measure in their study). Therefore, like IOR in the previously proposed paradigm, TOJs ought to provide an index of the locus of attention during the difficult search portion of the display in experiments such as those reported by Olds et al. (2000). This is because IOR should inhibit attention from revisiting previously searched locations. Therefore, in a visual search array, if one of two simultaneous stimuli appears at a recently searched location, it ought to be perceived as occurring later than the stimulus that appears at a location not recently searched. This is because the bulk of attentional resources ought to be directed away from recently attended locations, and towards locations not yet inspected.

In Experiment 2, following target response, two physically simultaneous lines (one vertical and one horizontal) appeared on two of the coloured disks (see Figure 12). One line appeared at a D1 location while the other appeared at a D2 location. Observers had to indicate, by pressing the appropriate key, which of the two lines appeared first (note, however, that observers were told that the lines were never simultaneous). If IOR operates in visual search, and if IOR is indeed an attentional phenomenon, then inhibited locations (i.e., locations recently visited) ought to be perceived second. As such, locations not previously visited ought to be perceived first.

One potential problem is that if a line appears at a currently attended location following target response (e.g., target location on target-present trials, or a distractor location on target-absent trials), it should be perceived first regardless of inhibition at other locations. This could dampen the predicted effect. However, the probability of a line landing exactly where attention is immediately following target response is relatively small (note that a line will never appear on the target, so this potential problem is only possible for target absent trials).

Experiment 2

Method

The method was the same as Experiment 1 except for the following changes:

Observers. Ten students (7 females and 3 males) attending Wilfrid Laurier University took part in Experiment 2. All participants were naive as to the nature of the experiment.

Stimuli. All the search stimuli (coloured disks) were the same as in Experiment 1. The line stimuli used for the temporal order judgement task were black lines 1 pixel in diameter. One line was horizontal, and the other vertical. The length of the lines was the same as the diameter of a coloured disk (8mm). The lines were centered over the coloured disks (which remained on the screen) during the TOJ task.

Procedure. The procedure was identical to that of Experiment 1 except that immediately following target response, two physically simultaneous lines (one vertical and one horizontal) appeared on two of the coloured disks on all trials (see Figure 12). While the lines were presented at the same time, observers were told that the lines always occurred slightly out of time with one another with the horizontal line first 50% of the time, and vertical line first the other 50% of the time.

The two lines were presented randomly on the disks with the constraint that one line landed on a D1 location, and the other line landed on a D2 location, but no line fell on a target location (as such, the two lines never appeared on the same disk). In addition, all stimuli remained visible until a response was made. Responses to the TOJ task were made using the same keys that were assigned for "yes/no" responses in the search task. Observers had to determine which line appeared first by pressing the "no" key for "horizontal first", and the "yes" key for "vertical first". A note was placed at the top of the keyboard indicating which line corresponded to which key, and observers were advised to use this as a reminder. Note that this type of discrimination task is similar to the method employed by Shore et al. (2001) which is believed to reduce potential response bias (even though such a bias may not be as significant a problem in visual search because attention is not explicitly directed in any systematic way). Therefore, unlike Shore et al. (2001) we saw no need for a "which second?" condition. In addition, there was no "simultaneous" option. Recall that use of the "simultaneous" option was found to be unreliable (e.g., observers chose the "simultaneous" option on less than 5% of trials at the PSS in Stelmach &

Herdman, 1991, but observers chose the "simultaneous" option for most trials in Jaskowski, 1993, as cited in Shore et al., 2001). Instead, RT to make the TOJ was measured. This was intended to provide an indication of when both events are perceived as simultaneous because observers ought to be slower at making a decision in such cases (Shore et al., 2001). However, while observers were told that RT would be measured for the TOJ task, they were informed that it was not a speeded task (i.e., observers were told to take as much time as needed to make a reasonable decision). Observers were also told to make their best guess if they were unsure as to which of the two lines appeared first.

All observers ran in all 3 conditions (2 experimental conditions intended to produce search assistance, and a control condition): Yellow distractors first, pink distractors first, or both distractors simultaneously in a pure difficult search control condition. Each observer completed approximately 1300 trials over three sessions. The computer recorded RTs and the decision on each trial of the search task (the proportion correct was later calculated from this). For the TOJ task, the computer recorded the decision made on each trial (the proportion of trials in which each observer indicated that the line on the D1 appeared first, versus the line on the D2 appeared first, was later calculated from this). As well, RT to make the TOJ was recorded.

Results and Discussion

The same outlier screening procedure used in Experiment 1 was used here. As well, average search errors were below 10%. RT to the orange target for both target absent trials (M = 2123ms, SE = 188) and target present trials (M = 1385ms, SE = 120) showed a pattern indicative of difficult search (i.e., RTs were well above the normal range of that which is typically indicative of pop-out search). Thus, like Experiment 1, the search task did not appear to be too easy.

Figure 13 shows the mean proportion of trials in which observers indicated that the line event on a D1 (relative to D2) location appeared first, as a function of target (present/absent) and condition. A 2 X 3 repeated measures analysis of variance was conducted with target (present/absent), and condition (yellow distractors first, pink distractors first, difficult search control) as independent factors. The dependent measure was the mean proportion of trials in which observers indicated that a line on a D1 (relative to D2) location appeared first. Of interest was the main effect of condition, and the target by condition interaction. The target by condition interaction was not significant, $F(2, 18) = 1.16$, $p > .05$. As well, the main effect of condition was not significant, $F(2, 18) = 2.59$, $p > .05$. Thus, there was no difference between the experimental conditions, and the control condition. In short, observers were no more likely to choose a line event as appearing first on D1 location than a D2 location for all conditions.

A 2 X 3 repeated measures analysis of variance was also conducted on the line RT data, with target (present/absent), and condition (yellow distractors first, pink distractors first, difficult search control) as independent factors. The dependent measure was RT to make the line decision. Figure 14 shows observers' mean RTs (plus standard errors) to the line task. Again, the target by condition interaction was not significant ($F < 1$). As well, the main effect of condition was not significant, F (2, 18), $p > .05$. Recall that the purpose of this data was to provide an indication of when both events were perceived as simultaneous because observers ought to be slower at making a decision in such cases (Shore et al., 2001). However, given the non-significant results of the TOJ task itself, it is not surprising that the RT to make the TOJ was also not significantly different across conditions.

Experiment 2 was based on the premise that attended events are perceived faster than unattended events (the doctrine of prior entry). Thus, it was predicted that the lines would be perceived as simultaneous in the control condition (at least for most trials) because attention was presumably not systematically deployed to one set of distractors more than the other during search for the target. Since the experimental conditions were assumed to produce search assistance, it was argued that attention would be deployed to one set of distractors over the other (as described earlier by the hypotheses regarding the nature of search assistance). As such, attention ought to have been inhibited from one set of distractors following the search task (according to predictions based on IOR). Thus, upon the presentation of the two line segments, a line that appeared at a location where inhibition exists ought to have been perceived as occurring later than a line at a different location (e.g., other set of distractor locations). However, the results of Experiment 2 did not support either of the hypotheses regarding search assistance.

One possible reason Experiment 2 did not show significant results is that it was partially built on the same premise as Experiment 1, which also showed negligible results. Recall that the TOJ task in this experiment was assumed to be affected by inhibition at previously visited locations. While Experiment 1 (using IOR) tentatively supported the negative prioritisation hypothesis, the effect was relatively weak (estimated power for the main effect of probe in Experiment 1 was .34). Therefore, our lack of an effect in Experiment 2 may simply have been an issue of power with respect to amount of noise in the data. If this is the case, further research employing either of the previous paradigms ought to focus on reducing some of the error variance, and perhaps increasing the number of observers.

Alternatively, it is possible that IOR in visual search is not possible using isoluminant stimuli such as was used in Experiments 1 and 2. However, IOR has been demonstrated using isoluminant texture changes (Oonk & Abrams, 1998). These texture changes apparently produced the IOR effect by exogenously capturing attention. However, Oonk & Abrams (1998) employed a traditional IOR paradigm with only 2 possible target locations on either side of fixation. To the best of my knowledge, studies have not yet used isoluminant stimuli to test IOR in a dual task visual search paradigm such as was employed by Klein (1988), Müller and von Mühlenen (2000), and Takeda and Yagi (2000). In addition, I would argue that the traditional IOR paradigm has some significant differences from IOR as measured in dual task visual search paradigms. One important difference is that in traditional IOR attention is experimentally directed (either exogenously or endogenously), whereas no such manipulation occurs in visual search.

Nonetheless, for Experiment 3, we decided to use a different approach from Experiments 1 and 2, by attempting to test just one of the hypotheses of search assistance in isolation. This experiment was aimed at testing the effect of positive prioritisation while attempting to eliminate any effects of negative prioritisation. This was accomplished by employing a spatial cuing paradigm.

Measuring the Effect of Initial Placeholders on Difficult Search

If search assistance involves somehow prioritising initial item locations, this might occur because the initial items simply act as location cues to the relevant search-set. If this is the case, then simple placeholders that provide the observer with location information ought to facilitate difficult search in much the same manner as was found in the research that first demonstrated search assistance (Olds et al., 2000). While this approach may not prove whether or not the negative prioritisation hypothesis is possible, it should provide a controlled method of measuring potential positive prioritisation effects minus potential negative prioritisation effects.

Placeholders as Cues to the Relevant Search-Set

As was mentioned earlier, Palmer (1995) presented evidence that difficult search can be facilitated by using spatial cues to potential target locations. Recall that observers were presented with search displays preceded by spatial cues (crosses). Some of these cues (black crosses) indicated potential locations where a subsequent target, when present, could appear ("relevant set"), whereas the other cues (white crosses) did not indicate a potential target location ("irrelevant set"). By holding constant the total set-size while varying the number of cues that indicated potential target locations, the effect of this "relevant set-size" could be measured. Palmer found that the effect of the relevant set-size was nearly identical to the actual display set-size effects that did not employ cues. In short, spatial cues enabled observers to confine their search to a smaller portion of the total search array where the target would appear (when present). This makes spatial cuing a particularly useful method to shed light on the nature of search assistance. Search assistance might be made possible because the initial items act as cues to a smaller search set that contains the target (when present). This would be consistent with a positive prioritisation hypothesis.

Therefore, for Experiment 3, we used placeholders (homogeneous circular rings the same colour as the D1s) in place of the initial items typically seen in the experiments demonstrating search assistance (see Olds et al., 2000). These placeholders simply acted as spatial cues to potential target locations (see Figure 15). This method was used as a means of eliminating the possibility of marking (negative prioritisation hypothesis), while measuring the effect of encoding initial item locations (positive prioritisation hypothesis). If partial pop-out facilitates difficult search by encoding initial item location information, then simple placeholders indicating potential target locations ought to facilitate difficult search as well. These spatial cues would not contain the target, but would only indicate *potential* target locations. Therefore, any effect of the spatial cues on difficult search cannot be the result of visual marking because marking any portion of the initial display (i.e., placeholders) would have a potentially negative effect on search (e.g., marking the target location). In short, faster target response in the placeholders condition (relative to the difficult search control condition) would provide support for the positive prioritisation hypothesis. This method will also allow us to measure the size of any positive prioritisation effects irrespective of negative prioritisation effects.

Experiment 3

Method

The method was identical to Experiment 1 except for the following:

Observers. Ten students (7 females and 3 males) attending Wilfrid Laurier University took part in Experiment 3. Eight of the ten participants were naive as to the nature of the experiment.

Stimuli. All stimulus colours were chosen the same way as was described in Experiment 1. In addition, placeholders were circular rings with a slightly larger diameter than the coloured disks. The placeholders were the same colour as the D1 distractors (note that in this experiment D1s and placeholders were always yellow, and the D2s were always pink). In addition, the number of search items for both the experimental and control conditions varied (the display contained 8, 18, or 32 items).

Procedure. The procedure was similar to that of Experiments 1 and 2 except that nothing followed the visual search task. Instead there were 2 conditions: In the experimental condition, placeholders (circular rings) preceded a difficult search display, and the control condition consisted of a difficult search display without placeholders.

In the experimental condition (see Figure 15), each trial began with the 400ms fixation stimulus, followed by a 400ms blank screen, after which the yellow placeholders appeared. The proportion of D1s (and placeholders) to D2s was equal (except on target present trials in which one D1 distractor was replaced by the target). Placeholders remained on the screen for 200ms after which time they became yellow D1 distractors plus an orange target (on 50% of trials). At the same time the same number of pink distractors filled in previously empty locations. In short, a difficult search display followed the placeholder display with the placeholders indicating potential target locations (that is, the placeholders acted as spatial cues to potential target locations). Note that observers were told that the target would only be present after the placeholders were transformed into search items, and that the target (when present) would appear within this subset of locations. The control condition was a pure difficult search array with no placeholders.

Both the experimental and control condition were run separately, and all observers completed both conditions (the order of the conditions was counterbalanced). Observers completed a total of 1200 trials over four sessions. The computer recorded RTs and the decision on each trial for target responses (the proportion correct was later calculated from the decision data).

Results and Discussion

The same outlier screening procedure used in Experiments 1 and 2 was used here. As well, average search errors were below 10%. Figure 16 shows the average RTs (and standard errors) to target response for the experimental and control conditions, for both target present and target absent trials. A 2 X 2 X 3 repeated measures analysis of variance was conducted with target (present/absent), condition (placeholders/no placeholders), and set-size (8, 18 and 32 items) as factors. The dependent measure was response time to the target. Of interest was the main effect of placeholders as well as interactions with the placeholders variable. The main effect of placeholders was significant showing overall faster target RT for the placeholder condition (M = 1430ms, SE = 102ms) than the control condition (M = 1551ms, SE = 102ms), $F(1, 9) = 18.63$, $p < .005$. The placeholder by target interaction was also significant, $F(1, 9) = 7.75$, $p < .05$ (no other interactions with placeholders were significant).

Figure 17 shows the size of the placeholder effect for target absent and target present trials. These effect sizes were calculated by subtracting the target RT in the control condition from target RT in the placeholder condition for target present and target absent trials. With regard to the significant placeholder by target interaction. Figure 17 clearly shows that the placeholder effect was greater for target absent trials (166ms effect) than for target present trials (73ms effect). Nonetheless, the graph is suggestive of, at least, a moderate effect for target present trials as well. Therefore, we ran Tukey post hoc tests on the placeholder effect sizes for target absent and target present trials. The placeholder effect was found to be significantly greater than 0ms only for target absent trials. Nonetheless, this supports the positive prioritisation hypothesis of search assistance.

The greater overall effect for target absent trials makes intuitive sense when we consider the relative advantage placeholders provided on target absent versus target present trials. Consider, for example, target absent trials at the intermediate set size (18 items). For the difficult search control condition, we would expect, on average, that all 18 items would be visited before a response was made. For the placeholder condition, this ought to be about half that (i.e., 9 items visited, since there were half as many placeholders as there were items). Therefore, the placeholder condition should have a 9-item advantage so to speak. If we consider the same thing for target present trials at the intermediate set size (18 items), we would expect, on average, 9 items to be visited in the control condition, and, on average, 4.5 items to be visited in the placeholder condition. Therefore, the placeholder condition should only have a 4.5-item advantage in this case. Thus, the overall placeholder effect for target absent trials ought to be about twice that of target present trials. This is, in fact, approximately what we found (166ms effect for target absent trials as compared to 73ms for target present trials; see Figure 17).

However, one might also expect to see a larger effect of placeholders as set size increases. Consider the relative advantage placeholders ought to provide, in comparison to controls, between set size. For the 8-item set size (target absent trials), placeholders ought to have provided a 4-item advantage. However, the placeholder advantage ought to be approximately double that for the 18-item set size (approximately a 9-item advantage), and approximately four times that for the 32-item set size (approximately an 18-item advantage). However, the interaction between placeholders and set size was not significant, $\underline{F}$ (2, 18) = 1.49, $\underline{p} > .05$.

It is possible, at least for target absent trials, that some D2 locations were visited, even when using placeholders. That is, even though placeholders indicated potential target locations, if a target was not found after visiting these item locations, the visual system may still have begun to search a proportion of D2 locations before making a decision. If, indeed, a *proportion* of D2 locations were visited (besides D1 locations) this would mean that a greater number of D2 locations were visited at larger, relative to smaller, set sizes (note that the suggestion here is that a *proportion* of D2 locations may have been visited rather than simply a certain number of D2 locations). This could explain the lack of an increasing placeholder effect as set size increased. Why might more D2 locations be visited at larger set sizes? At larger set sizes (at least for target absent trials), observers may simply be less confident that the target is indeed absent after visiting the locations previously occupied by placeholders. In other words, with more items in the display, observers may feel they are at a greater risk of missing a target that is present. Observers might, therefore, visit a greater proportion of D2 locations before making a decision in such a case. Further research could be aimed at testing this possibility.

The results of Experiment 3 are also consistent with Palmer's (1995) study demonstrating how spatial cues to the relevant search set can enable the observer to confine search to only those cued locations. We know that this effect cannot be the result of negative prioritisation (e.g. visual marking). Visual marking was simply not possible because there were no initial items to mark (only placeholders). The observer could not eliminate any of the placeholder locations from consideration because there was no way of knowing which of these locations would contain the target in the second portion of the display. Instead, difficult search was more likely facilitated in this experiment because the initial placeholders acted as spatial cues to a smaller subset of the search array where the target might appear. In addition, this experiment extends the finding of Palmer's (1995) spatial cuing experiment to isoluminant search stimuli, which was not a controlled factor in Palmer's study.

Note that while search assistance has been shown at an SOA of approximately 200ms (see Olds et al., 2000), we realize that the results of Experiment 3 cannot be generalized to search assistance at other SOAs. It is entirely possible that different things are going on at different SOAs. In addition, negative prioritisation is still a viable explanation for search assistance that requires further exploration.

General Discussion

This study attempted to determine the nature of the information that partial pop-out provides difficult search in visual displays that produce search assistance. To recap, the first two experiments used an intricate approach of trying to determine where the bulk of attentional resources are allocated during the difficult search portion of a display assumed to produce search assistance. In Experiment 1, a detection task was used in which observers had to determine the presence or absence of a small probe-dot, appearing at either a D1 or a D2 location. The results of this experiment did provide some evidence that search assistance might involve some form of negative prioritisation at a fairly short SOA (80ms). However, variations of Experiment 1 using longer SOAs showed negligible results (see Footnote 1). Experiment 2 was similar to Experiment 1, with the exception that, following target response, a discrimination task was used instead of a detection task. The results here did not support either of the hypotheses regarding the nature of search assistance. Finally, Experiment 3 employed a different approach aimed at testing the potential effect of positive prioritisation while eliminating any effects of negative prioritisation. This was accomplished by comparing the effect of spatial cues (placeholders) on difficult search, with a pure difficult search control condition. Consistent with positive prioritisation, a short (200ms) initial display of placeholders facilitated difficult search an average of 166ms for target absent trials (the effect for target present trials is so far inconclusive).

It must be noted that for Experiments 1 and 2 there was no way of being sure that all the trials produced search assistance (i.e., we had no way of knowing which trials showed successful pop-out, and which trials showed partial pop-out). It is entirely possible that pop-out processes were able to find the target before the onset of the D2 distractors on several trials. This could have had a negative impact on the effects we were trying to measure. We had no way of controlling this factor, but we did seek to minimize it. This is partially why we chose a fairly short SOA (80ms) that has been shown to produce search assistance (see Olds et al., 2000). Therefore, for most of the trials, it was assumed that target response occurred after the second set of distractors appeared simply because pop-out typically takes longer than this. This was not an issue for Experiment 3 because the initial set of placeholders only provided location information as to potential target locations (i.e., pop-out was not possible). Target response could not reliably occur before the onset of the complete array of search items because no target was present until that time.

While consistent with the positive prioritisation hypothesis, the results of Experiment 3 might appear to be inconsistent with the tentative findings of Experiment 1. Recall that for target absent trials, probe-dot RT appeared to be slower when on a D2, relative to a D1, location (14ms impairment), suggesting some form of negative prioritisation of initial distractors. One might expect a greater effect of marking at longer SOAs given that complete marking takes much longer than 80ms (e.g., >400ms according to Watson & Humphreys, 1997). However, additional variations of Experiment 1 did not support this (see Footnote 1). Nonetheless, as was mentioned, there may be different things going on at different SOAs (i.e., both positive and negative prioritisation could occur).

To make sense of the seemingly contradictory results of Experiment 1 and Experiment 3, one could make the argument that at fairly short SOAs a very limited form of visual marking occurs, and that positive prioritisation effects (e.g., spatial cuing) only occur at later SOAs. However, this argument would not be convincing given that visual marking is believed to take significantly longer than 80ms (400ms according to Watson & Humphreys, 1997), and this is also considerably longer than the 250ms SOA employed by Palmer (1995) to demonstrate the effects of spatial cuing on search RTs. Currently it is unknown whether the placeholder effect found in Experiment 3 is possible at shorter SOAs, or whether some form of partial marking can occur at less than 400ms. The literature tells us that, if anything, spatial cuing ought to occur earlier than marking.

Alternatively, it is possible that the tentative findings of Experiment 1 were the result of positive prioritisation (as opposed to negative prioritisation). For example, on target absent trials, it is possible that observers did indeed search D1s first, but when a target was not found observers may have switched and searched some D2s before making a response (note that this same idea was proposed for the lack of a placeholder by set size interaction in Experiment 3). In other words, in Experiment 1, initial items may have been prioritised, but most inhibition was associated with those last few D2s to be searched before making a response (since they were the most recently searched items). This might account for the slower response to a probe-dot at a D2 location in Experiment 1. If correct, this suggests that both Experiments 1 and 3 were consistent with positive prioritisation. Further research could test this possibility.

While the results of Experiment 3 do not prove definitively that search assistance is the direct result of positive prioritisation of initial items, they do provide convincing evidence that positive prioritisation is one particularly plausible method of search assistance. In addition, the method employed in Experiment 3 does not rule out potential negative prioritisation effects at other SOAs. Continued research employing the method used in Experiment 3 (i.e., using spatial cues) ought to be aimed at examining effects at shorter SOAs. Note that we used a relatively long SOA (200ms) to be fairly consistent with Palmer's (1995) spatial cuing experiment (250ms). As was mentioned, it is possible that search assistance involves different types of processing at different SOAs. In fact, one weakness with using a spatial cuing paradigm is that it is impossible to directly test possible negative prioritisation effects of search assistance.

New variations of Experiment 3 could also include both the experimental and control trials intermixed. Recall that in this experiment, observers completed each condition separately. Observers were aware that the target (when present) would appear within the initial set of placeholder locations. Therefore, observers could have biased the results to produce the effects the experimenter was interested in. For instance, while it may not have been possible to speed up search in the experimental condition, it may have been possible to slow RT in the control condition if observers were aware of what the experiment was testing. This potential bias ought to be more difficult with intermixed trials because observers would have little time to prepare a mind set for such a bias (because observers could not predict which type of trial would occur next, experimental or control). Further testing ought to be aimed at reducing this potential bias.

Future research could also be directed towards increasing the power of the methods used in Experiments 1 and 2 (since spatial cuing can only answer part of the question regarding search assistance). This can be done by increasing the number of observers, and reducing possible sources of unexplained error. It is common to use few observers in psychophysical experiments because each observer often completes a large numbers of trials. However, given the large amount of noise in the data for experiments 1 and 2, using more observers might prove beneficial in these cases. Part of the reason we did not run more observers is because of the time factor in training each observer before any actual experiment can be run (approximately 5 hours of testing prior to any actual experiment). Interestingly, the power of Experiment 3 did not appear to be a problem. However, IOR is a very subtle effect (typical IOR effects range from 20-30ms according to Law, Pratt & Abrams, 1995). Since both Experiments 1 and 2 relied on an effect of IOR in visual search, this might explain the lack of power (relative to Experiment 3).

As well, it is entirely possible that IOR in visual search is not possible using isoluminant stimuli such as was used in Experiments 1 and 2. However, as was mentioned earlier, traditional IOR has been demonstrated using isoluminant texture changes (Oonk & Abrams, 1998). These texture changes apparently produced the IOR effect by exogenously capturing attention. However, the traditional IOR paradigm appears to have some differences from IOR in visual search paradigms. In particular, traditional IOR involves an exogenous orientation of attention towards a cue. There does not appear to be an exogenous cue pulling attention towards the search items in visual search. Therefore, it would be useful to test IOR in a dual task visual search paradigm in the same way others (Klein, 1988; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000) have tested it, while using isoluminant search stimuli (i.e., to test the difference between so called "ON-probes" and "OFF-probes", rather than "onto a D1 versus onto a D2). Of course, this would require an isoluminant probe-dot of a different colour from the background in order to be seen against the background (recall that the probe-dot in Experiment 1 had the same luminance and chromaticity values as the background).

Another option is to test IOR for isoluminant stimuli using a sequential search paradigm similar to that of Danziger et al. (1998). While such a paradigm may not be identical to visual search, it can provide a controlled method of investigating IOR for isoluminant stimuli. In particular, the sequential search paradigm (Danziger et al., 1998) does appear to facilitate scanning each and every item in search for the target. This makes it particularly useful for testing both the number of inhibited items/locations, and the decay of IOR for two reasons: 1) It forces observers to attend to every item in a controlled sequence, and 2) it allows us to make comparisons of the relative amount of inhibition associated with each location. Furthermore, the research surrounding this paradigm provides fairly convincing evidence that IOR operates in visual search. It would be useful to employ this method as a means of testing IOR for isoluminant stimuli.

Finally, future research might also consider reasons why search assistance might be an adaptive quality of the visual system. Evolutionarily speaking, one can imagine how search assistance might be adaptive. Consider, for example, the predator-prey relationship between wolves and deer. Deer feed off of green vegetation in an environment with many textures and colours (a forest; this is essentially a difficult search background). While feeding, the deer must remain acute to its most dangerous enemy, wolves. In many cases, the movement of a bush from a wolf will pop-out of a background of green vegetation, and allow the deer to detect the presence of its predator and respond accordingly. However, in some cases, the movement of a bush will only partially pop-out of the complex background, but this may assist difficult search by enabling the deer to consider only potential predator-target locations. Further research might also consider how real world situations of humans also utilize such a quality.

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Footnotes

1. Three additional experiments using this same paradigm were run with slight variations in either the SOA, or the set-size. The first of these was identical to Experiment 1 of this paper (using IOR), but with a shorter SOA of 53ms. We chose an SOA of 53ms for that experiment because RT to a target that moved mid-trial was found to be faster when it moved onto a D1 location (Olds et al., 2001) using an SOA of 53ms, supporting the encoding of initial items hypothesis. The second variation used fewer items (10 versus 18 in Experiment 1) based on the assumption that IOR can be attached to a limited number of items, and previous experiments demonstrating IOR in visual search typically used a maximum of 10 items (see Klein, 1988; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). Finally, for the third variation we chose a longer SOA of 160ms (with an 18 item set size). This was motivated by the fact that the results of Experiment 1 showed the strongest effect and had the longest SOA thus far. However, these variations produced negligible results, and were therefore not pursued any further.

2. Müller and von Mühlenen (2000) proposed three possible reasons for Wolfe and Pokorny's (1990) failure to replicate Klein (1988). 1) The serial search task may have been too easy. Thus, target detection may have occurred in parallel before subjects scanned each stimulus in detail. 2) There is also evidence that IOR is intrinsically linked to eye movements (Rafal et al., 1989), and if the serial search task was too easy, it may not have required eye movements. 3) There is evidence

that IOR in serial visual search is object based (rather than space based). Therefore, extinguishing the search display before the probe appeared may have also extinguished any inhibition that was associated with the search stimuli.

Müller and von Mühlenen (2000) used the same dual task paradigm as in Klein's (1988) study with a few changes. Müller and von Mühlenen's stimuli consisted of "L" shapes formed by segmenting out one of four quadrants of a square. The "L" shaped stimuli were at four possible orientations (0°, 90°, 180° or 270°). The parallel search condition had a target "L" (orientation of 0°), but only one set of the three other possible distractor shapes, whereas the serial search condition had all the remaining possible "L" orientations. This design apparently made the serial condition much more difficult than in the experiments of Klein (1988) or Wolfe and Pokorny (1990), which Müller and von Mühlenen (2000) claimed forced observers to make eye movements and scrutinize the items in greater detail.

Müller and von Mühlenen (2000) found an inhibitory effect similar to Klein's only when the search array remained visible during the subsequent probe task. In addition, IOR was eliminated when the stimuli were changed immediately following target response lending support for object-based IOR. However, on-probes were detected slower than off-probes in all the experiments reported by Müller and von Mühlenen (even in parallel-search target-absent trials, which Klein, 1988, would argue is inconsistent assuming the purported role of IOR as a mechanism to facilitate search of complex scenes). These authors argue that this residual effect can be best explained in terms of visual marking (see Watson & Humphreys, 1997) of search items. In addition, Müller and von Mühlenen pointed out a problem with Experiments 1 to 3: Since on-probes and off-probes were equally likely, there may have been a bias to expect probes at occupied locations because there were fewer of these than unoccupied locations (e.g., these authors used 2, 6 or 10 item display sizes in a possible 6 X 6 matrix which left 34, 28 or 24 unoccupied locations respectively). Experiment 4 of Müller and von Mühlenen addressed this problem such that each location (whether occupied by a visual search display stimulus or not) was equally likely to be probed. These results showed that on-probe costs (while still detected slower than off-probes in both serial and parallel conditions) were significantly larger following serial search than following parallel search. This is consistent with IOR in serial visual search.

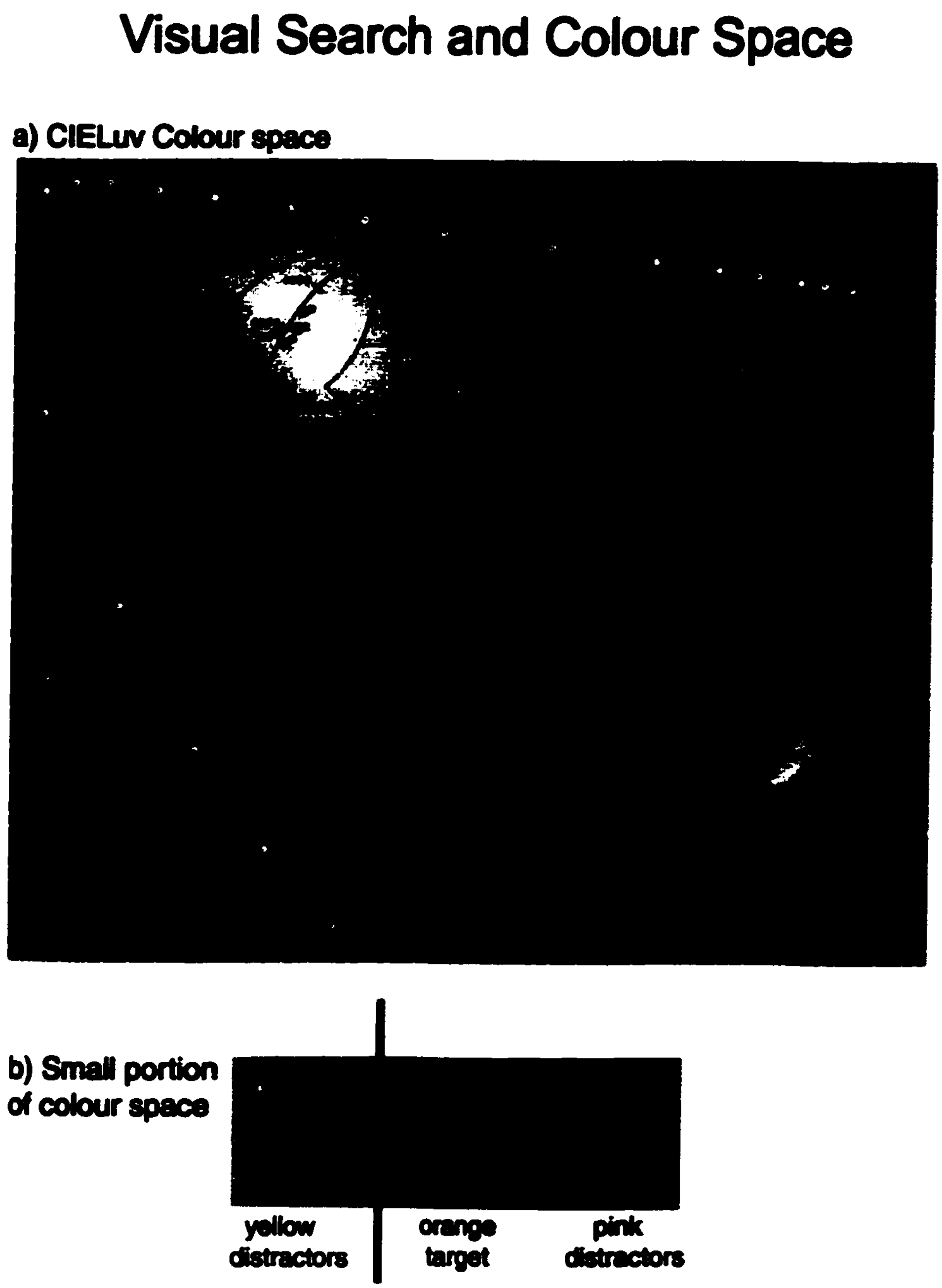

Figure 1. Visual search and colour space. Figure a) shows a complete map of CIELuv colour space, and figure b) is a magnified portion of this space. For colour stimuli, distractor colours can be chosen to fall on a line with a target in CIELuv space such that the distractor colours fall an equal distance on either side of the target colour. In this case, no single line can be drawn that will separate both distractors from the target in colour space (i.e., the target is not linearly separable from the distractors; see D'Zmura, 1991; Bauer, Jolicoeur & Cowan, 1996).The result is a difficult search array. Pop-out search is only possible for targets that are linearly separable from the distractors.

Search Assistance (Olds et al., 2000)

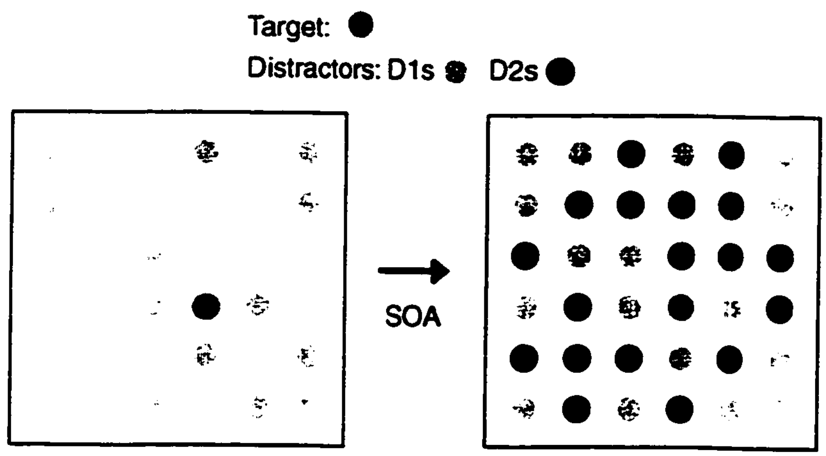

Figure 2. Search Assistance. Pop-out display (left portion of figure) interrupted at various SOAs by additional distractors. The second portion is a difficult search display. Note that the disks are grey-scaled here, but the actual experiment used isoluminant coloured disks (yellow and pink distractors and an orange target).

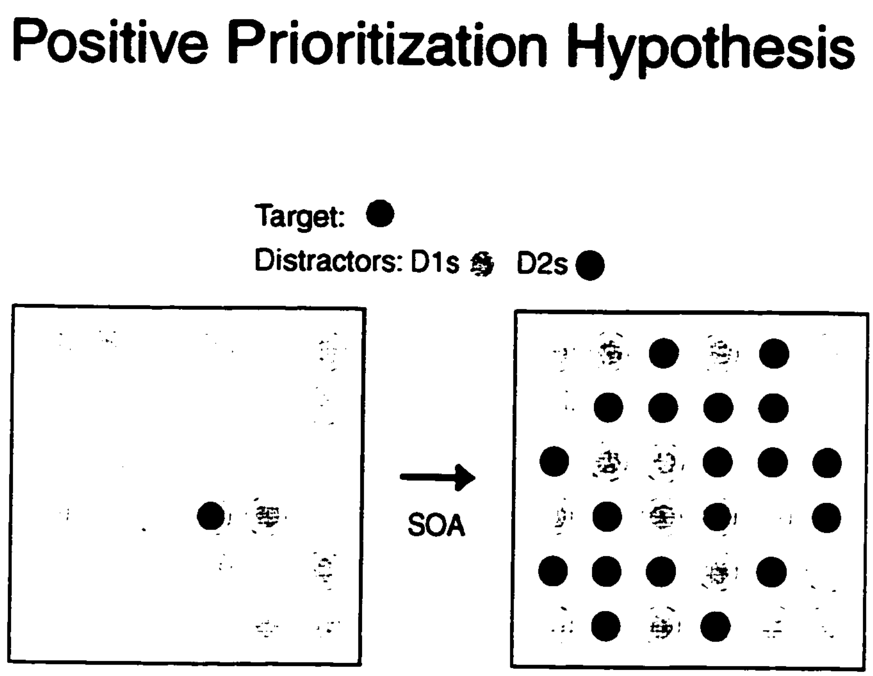

Figure 3. Positive prioritization hypothesis: Pop-out encodes initial item location information before the onset of the D2 distractors. Search is facilitated during the second portion by visiting only previously encoded locations which consist of D1 distractors, plus the target when present. Note: The dotted circles represent prioritized locations.

Negative Prioritization Hypothesis

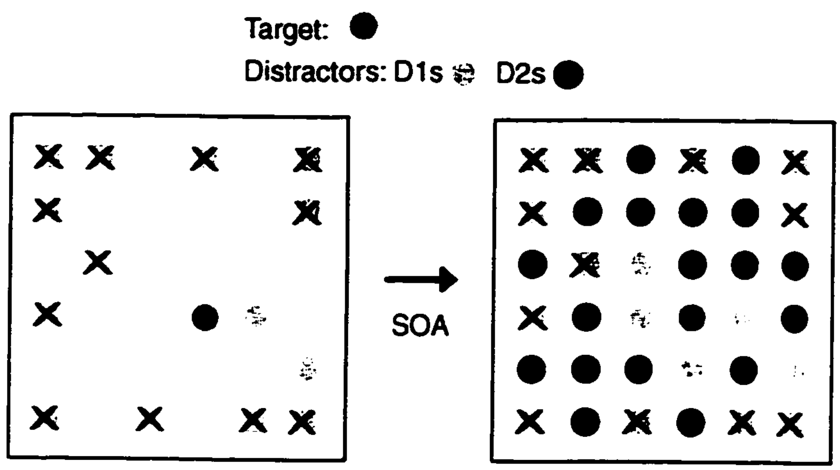

Figure 4. Negative prioritization hypothesis: Some initial distractors are eliminated from consideration (possibly by Visual Marking, Watson & Humphreys, 1997). Search is facilitated during the second portion by visiting only the unmarked locations which consist of, mainly, D2 distractors. Note: the "X"s indicate "marked" locations.

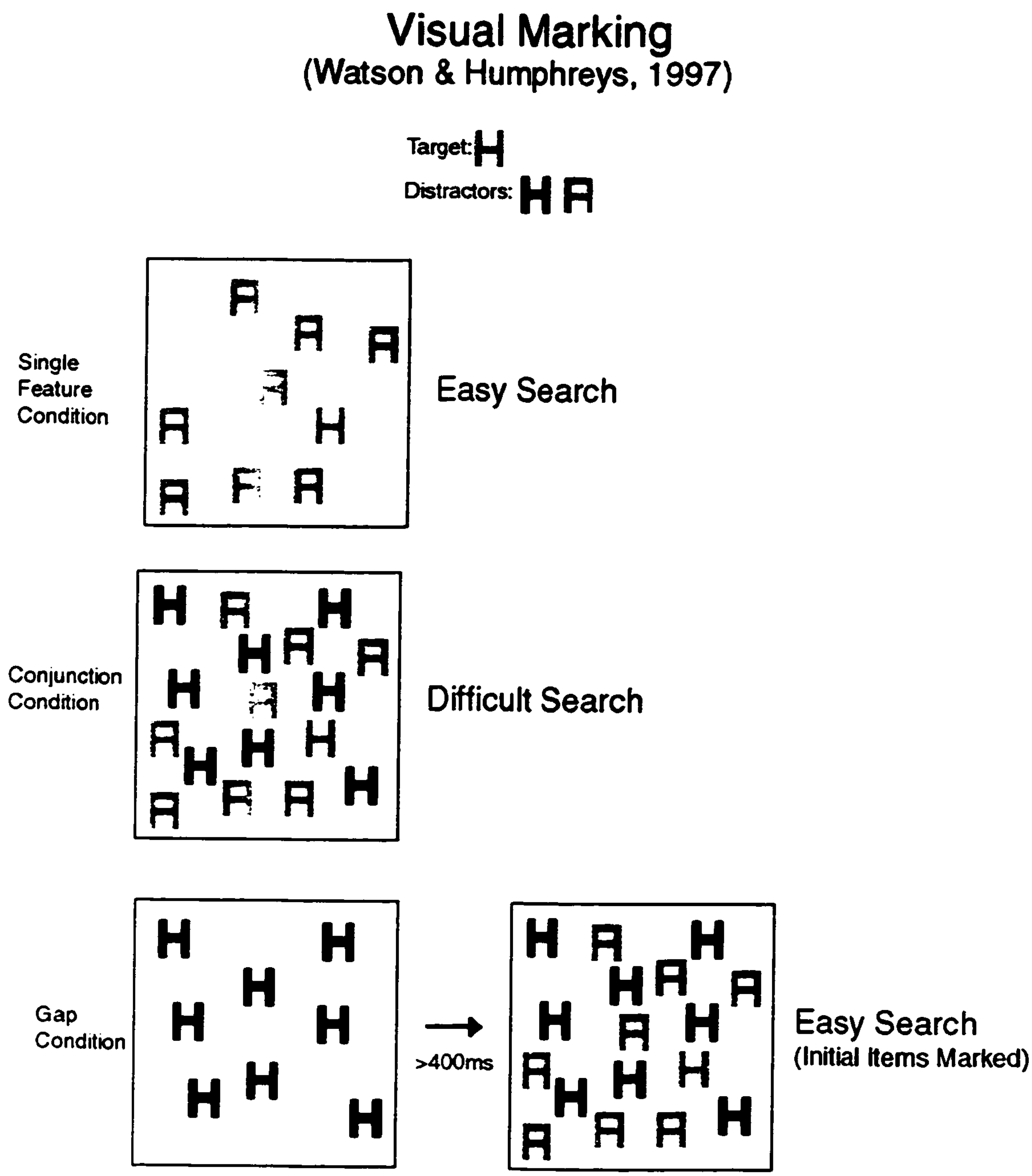

Figure 5. Visual marking (Watson & Humphreys, 1997). Note that the stimuli are greyscaled here. In the actual experiment, the target was a blue "H", and the distractors were green "H"s and blue "A"s. The important finding was that search was as efficient in the gap condition as in the single feature condition.

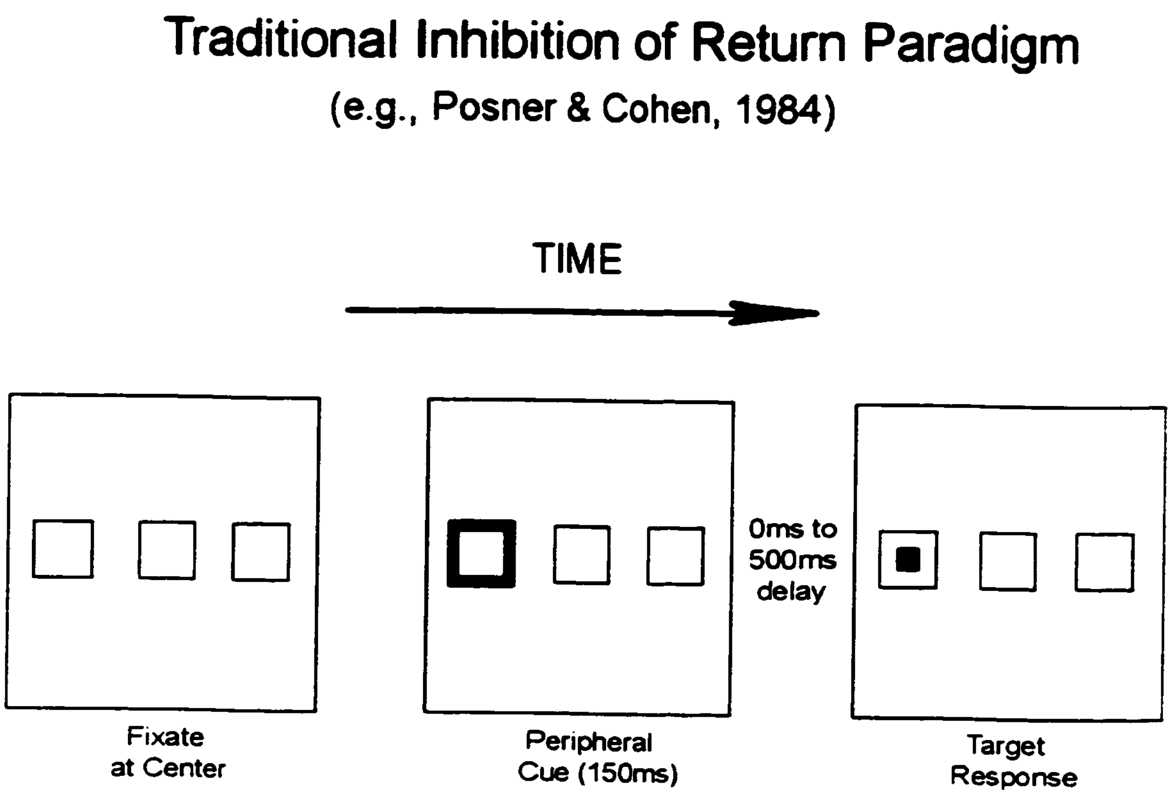

Figure 6. Traditional Inhibition of return paradigm. A trial started with observers fixating at the central box. Following this, one of the peripheral boxes would brighten (150ms), acting as an exogenous attentional cue. After a delay, the target would then appear in one of the boxes. with the greatest probability of appearing in the center ($p = 0.6$ for center, $p = 0.1$ for each peripheral box, and $p = 0.2$ for catch trials). At delays > 300ms, observers are inhibited from responding to targets in cued locations relative to the uncued side.

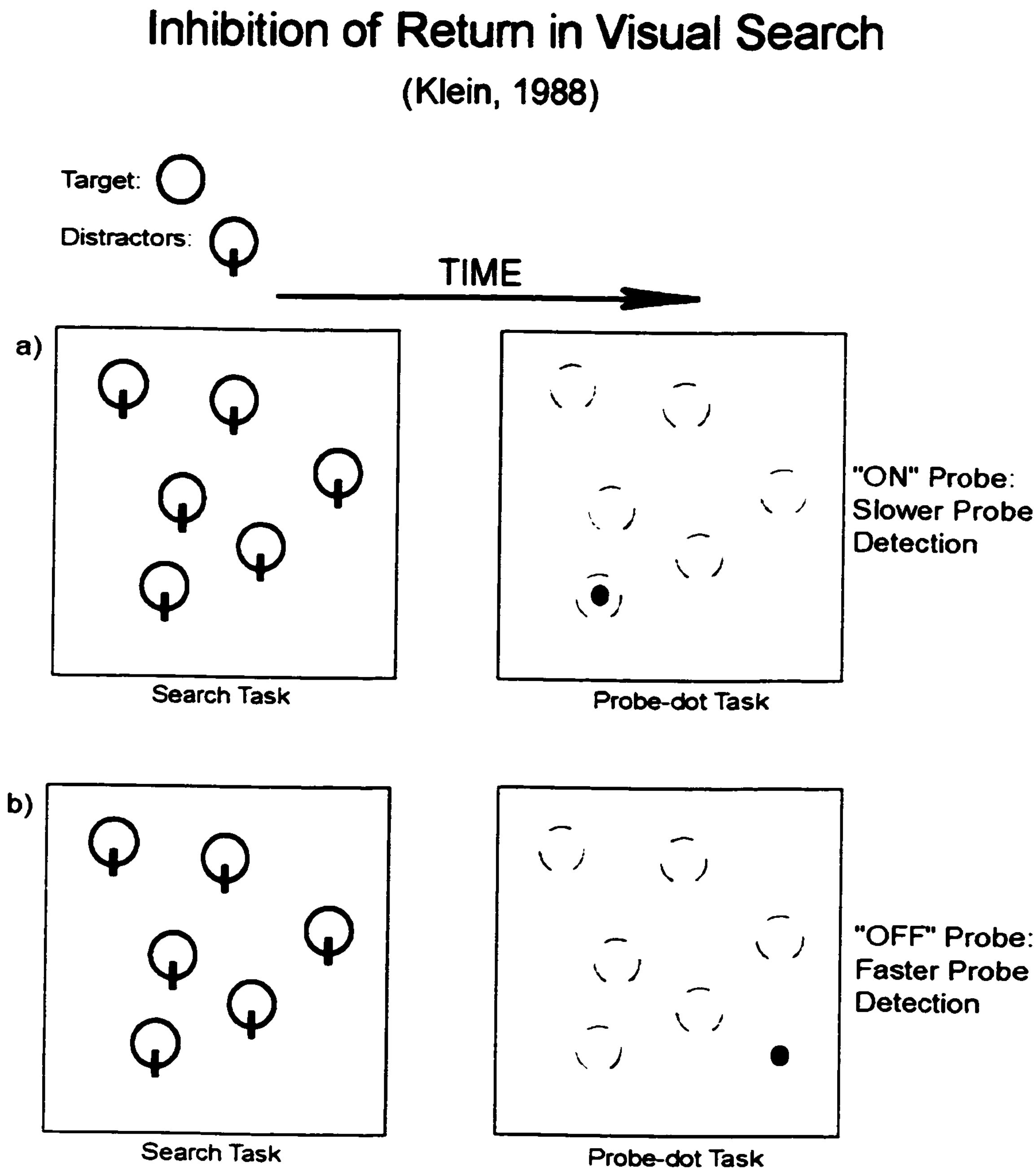

Figure 7. Inhibition of return in visual search (Klein, 1988). Target absent (serial search) trial shown here. The actual experiment had target present trials as well. The dotted circles represent visited locations, but in the actual experiments, only the probe was present at this point of the trial. The important finding was that probe-dots that appeared where a search item had been (figure 7a, "ON" probes) were detected slower than probe-dots that appeared where no search item had been (figure 7b, "OFF" probes), presumably because of inhibition at recently visited locations.

Using IOR to Determine the Locus of Attention

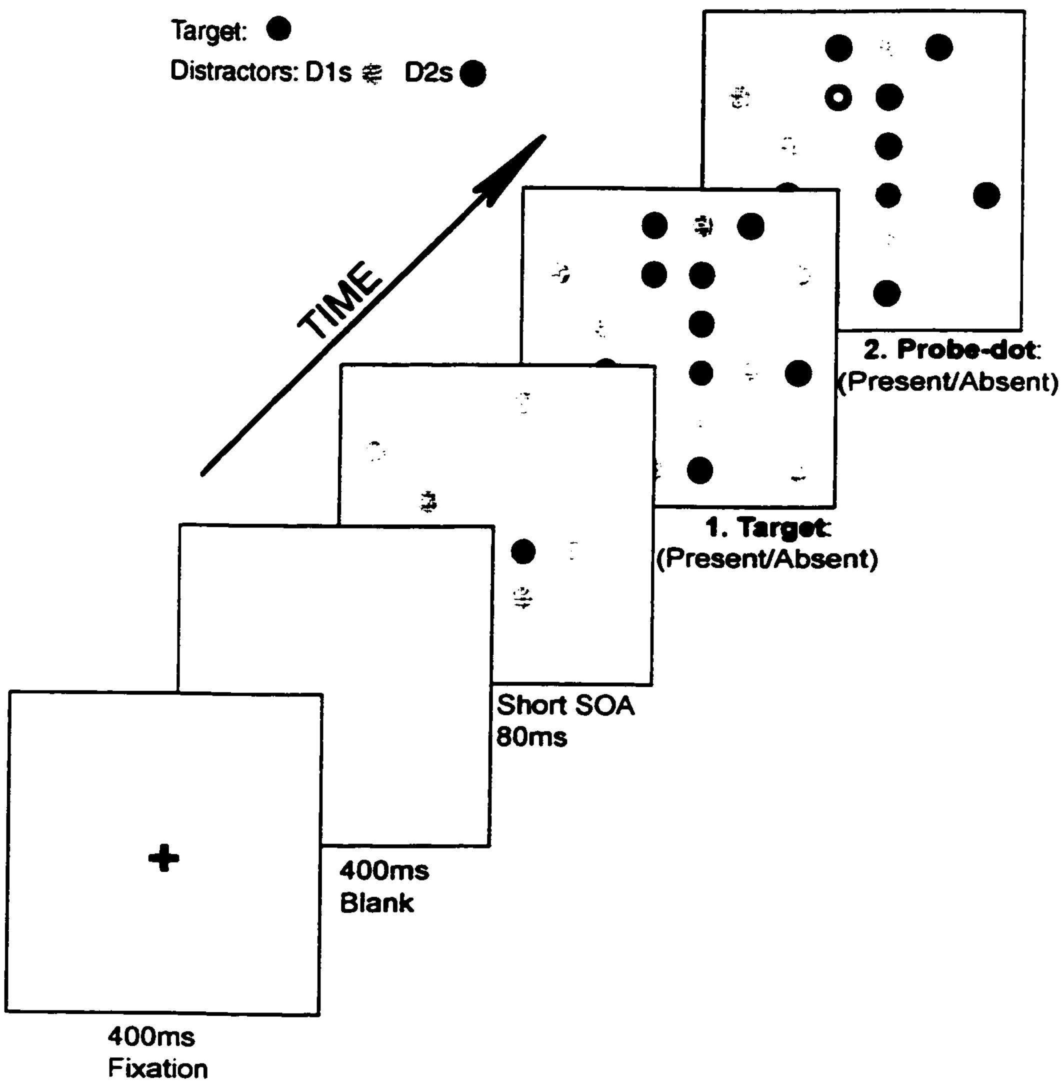

Figure 8. General sequence of events in a trial of Experiment 1 (target present/probe present trial shown here with probe onto a D2 distractor). Note that, for illustration purposes, the disk stimuli are grey-scaled here (although they were isoluminant colours in the actual experiment), and the size of the probe-dot is exaggerated as well.

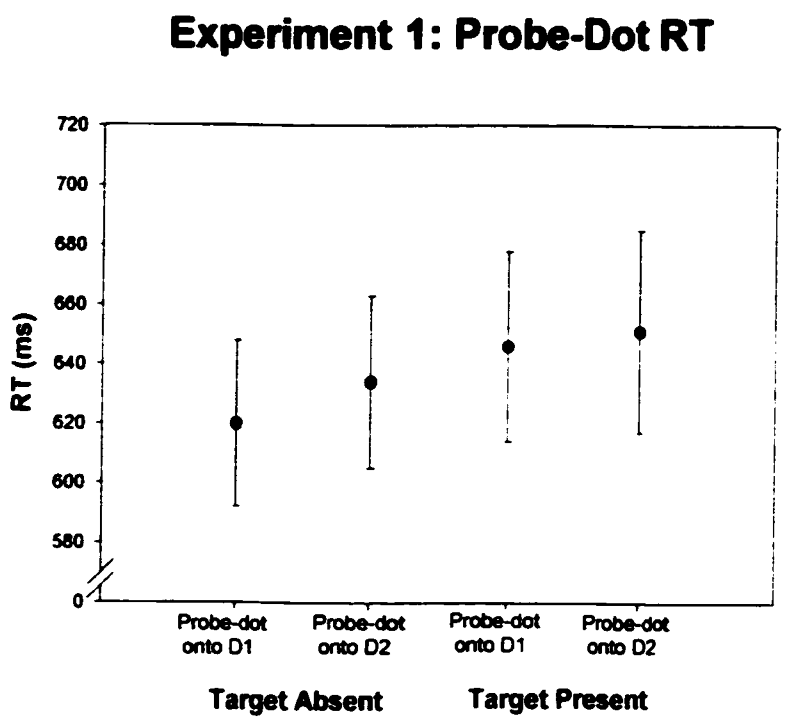

Figure 9. RT (plus SE) to a probe-dot on a D1 versus a D2 location for target absent and target present trials separately.

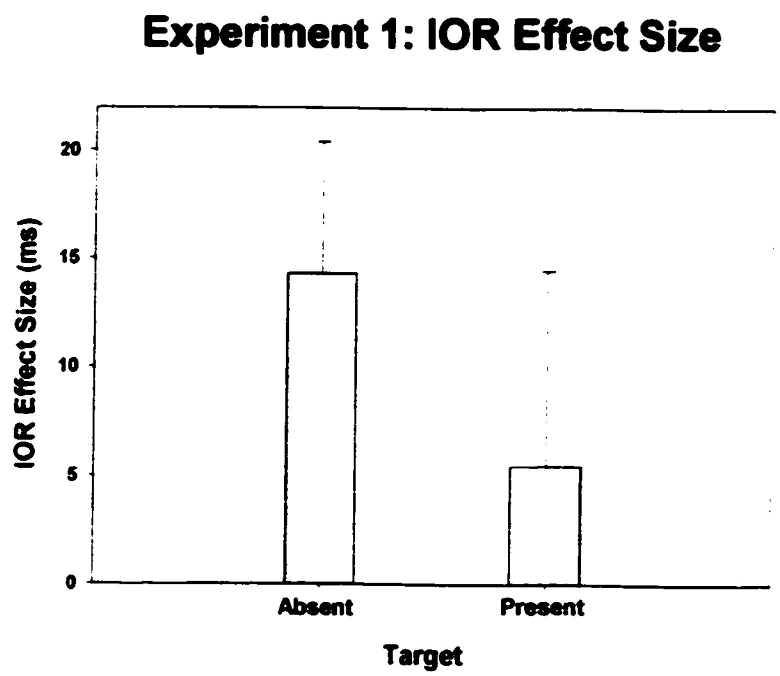

Figure 10. IOR effect size (defined as RT to a probe-dot on a D2 location minus RT to a probe-dot on a D1 location): RT to a probe-dot was, on average, 14ms slower when on a D2 location, relative to a D1 location, for target absent trials ($p < .05$). The effect for target present trials was not significant. This provided tentative support for the negative prioritization hypothesis at an SOA of 80ms

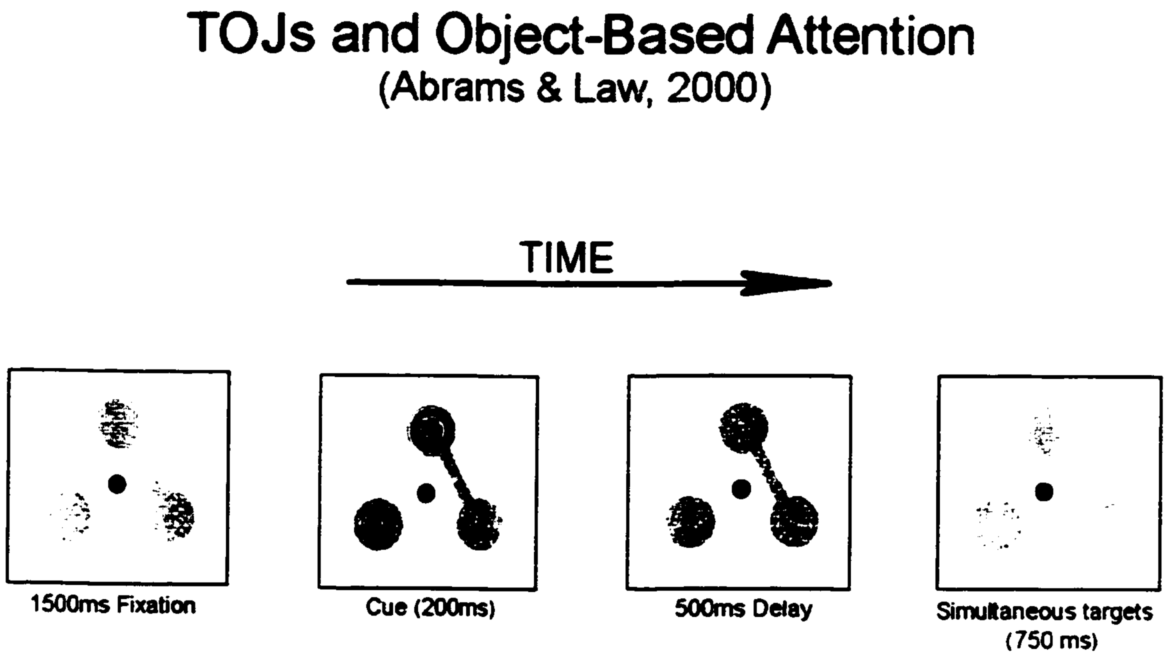

Figure 11. Sequence of events in Experiment 3 of Abrams and Law (2000). Shown here is an exogenous cue trial (the actual experiment also used an endogenous cue). Note that each of the 3 disks was equally likely to be cued, and the cue was not predictive of the target. The important finding was that the target that appeared on the cued object was perceived as occuring first, even though neither target disk was actually cued.

Using TOJs to Determine the Locus of Attention

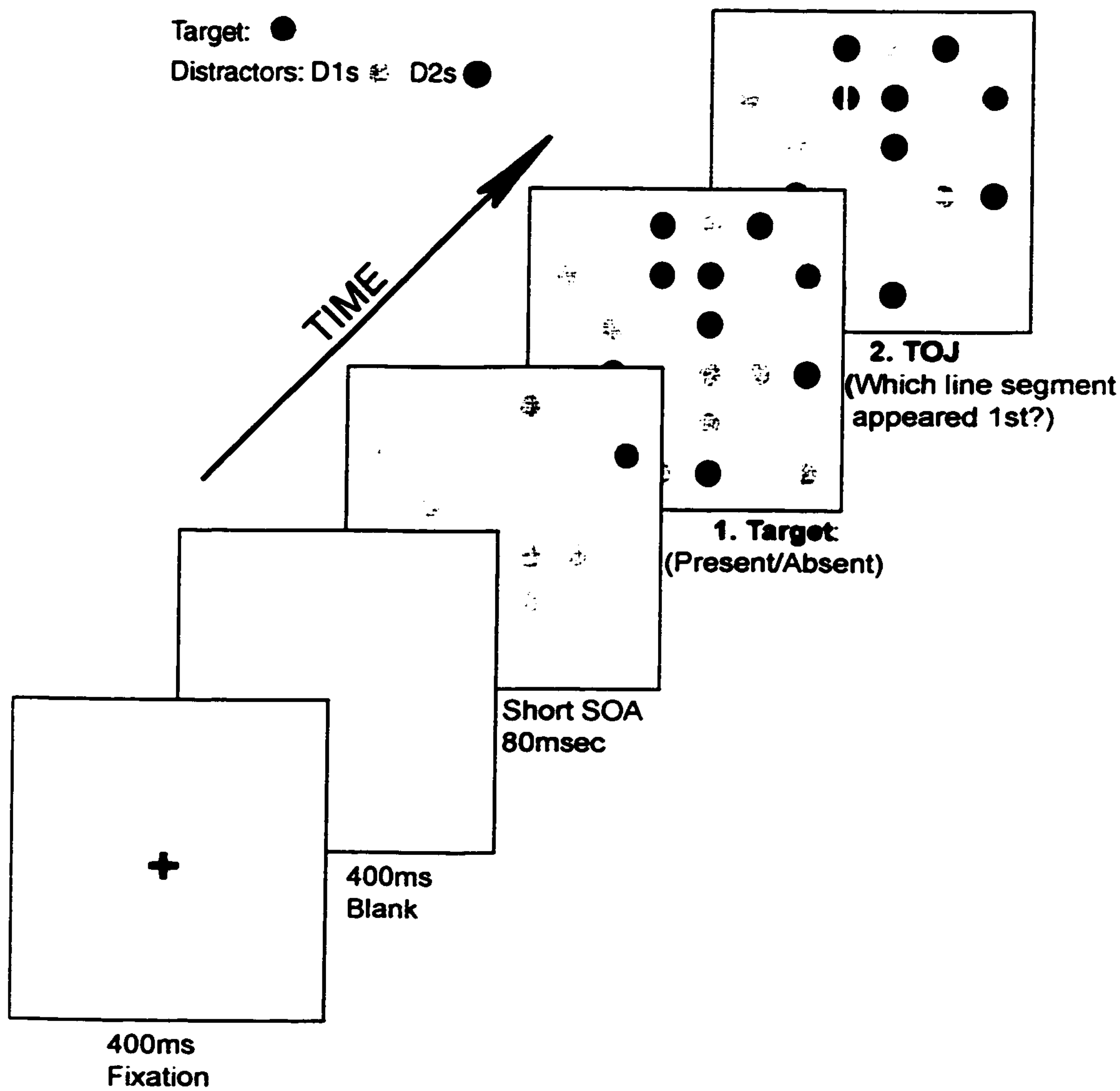

Figure 12. General sequence of events on a trial of Experiment 2 (target-present trial shown here). Following target response, two physically simultaneous black line segments appeared on two of the coloured disks (note that the lines are necessarily white here in order to be seen against the greyscaled disks for demonstration purpose only). Observers had to decide which line appeared first (the vertical or the horizontal).

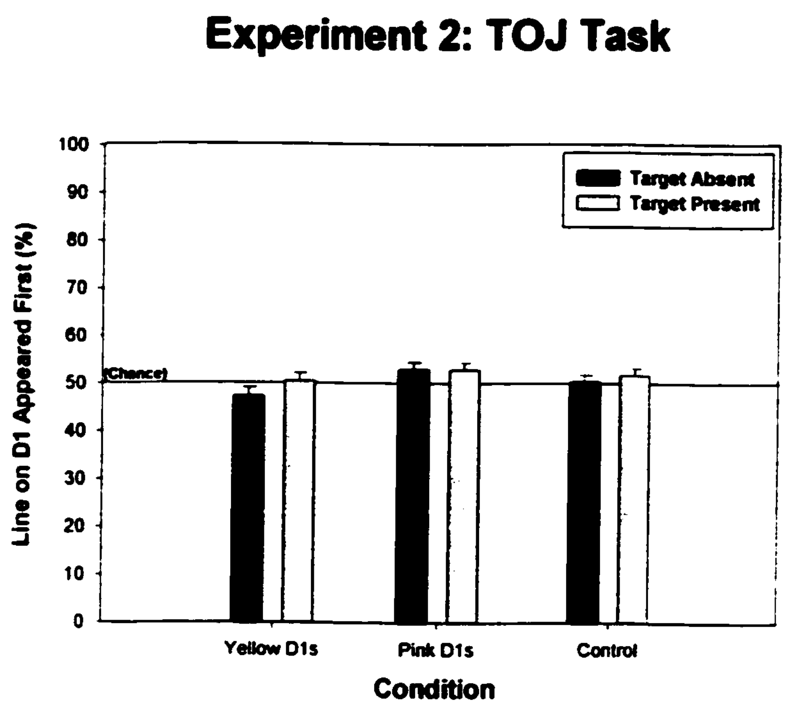

Figure 13. Mean proportion of trials (plus SE) observers reported that a line event on a D1 appeared first. The 50% line represents a chance effect.

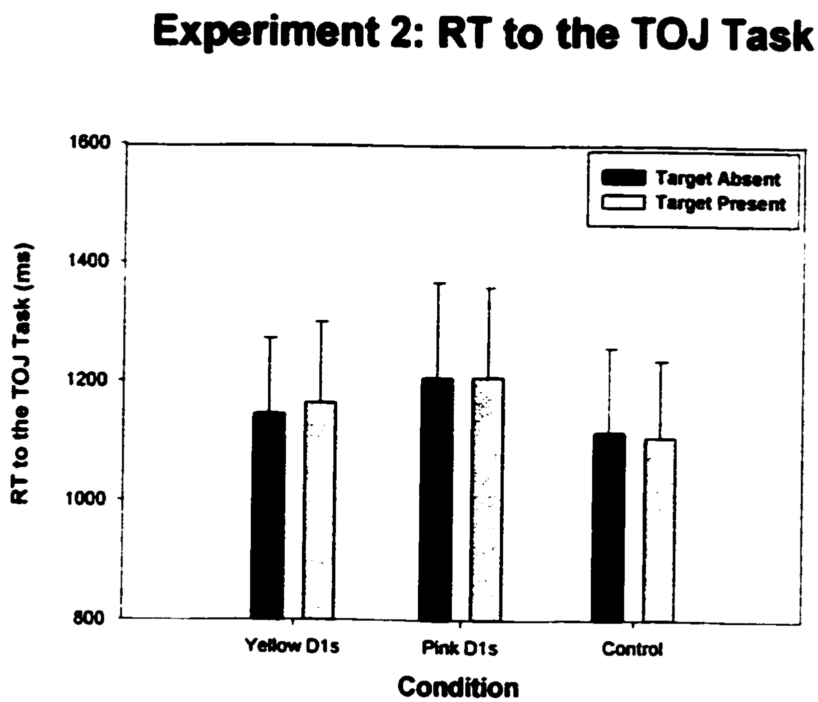

Figure 14. Mean RT (plus SE) to make the line judgement as a function of target, and condition.

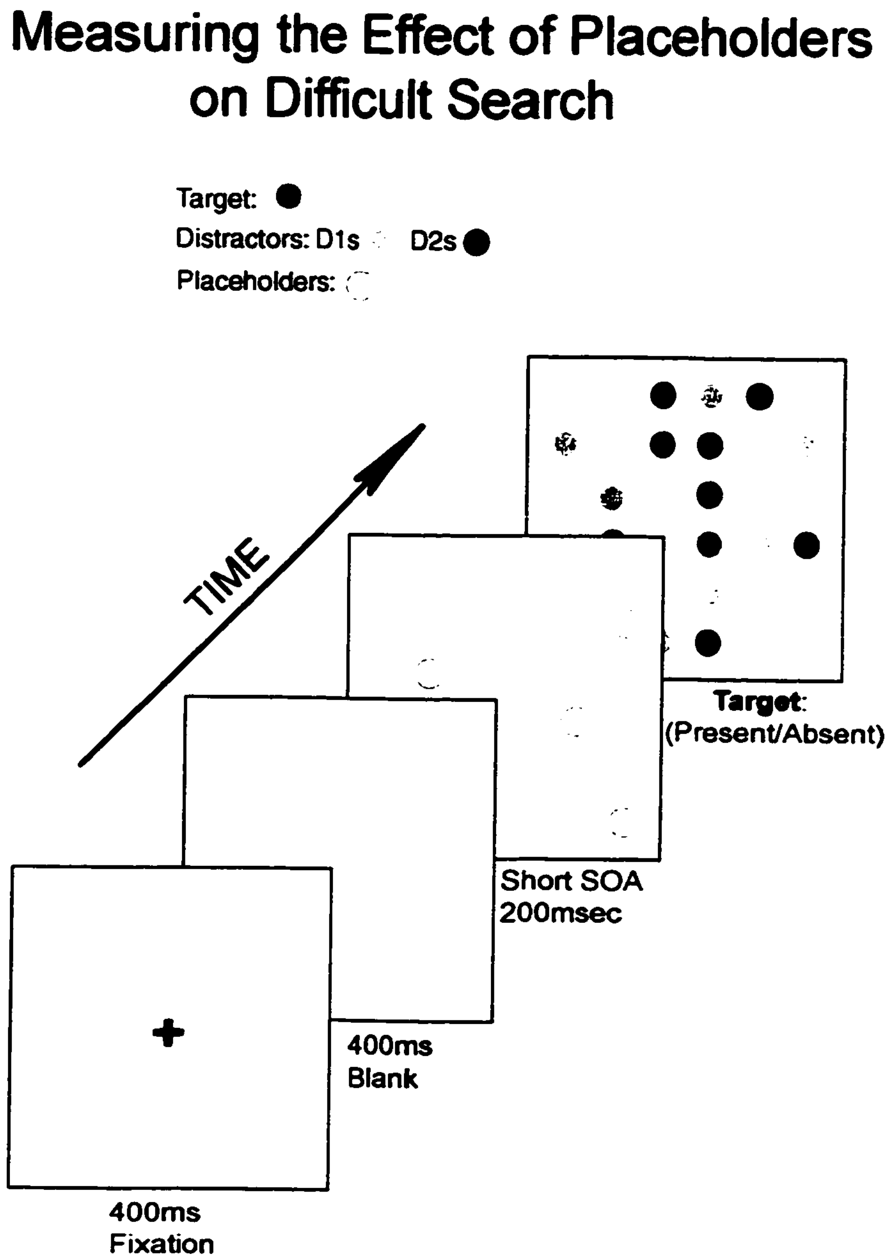

Figure 15. General sequence of events on a trial of Experiment 3 (target present trial shown here). A "pure" difficult search condition (without placeholders) was the control measure. Note that the disks and placeholders are grey-scaled here for demonstration purpose only.

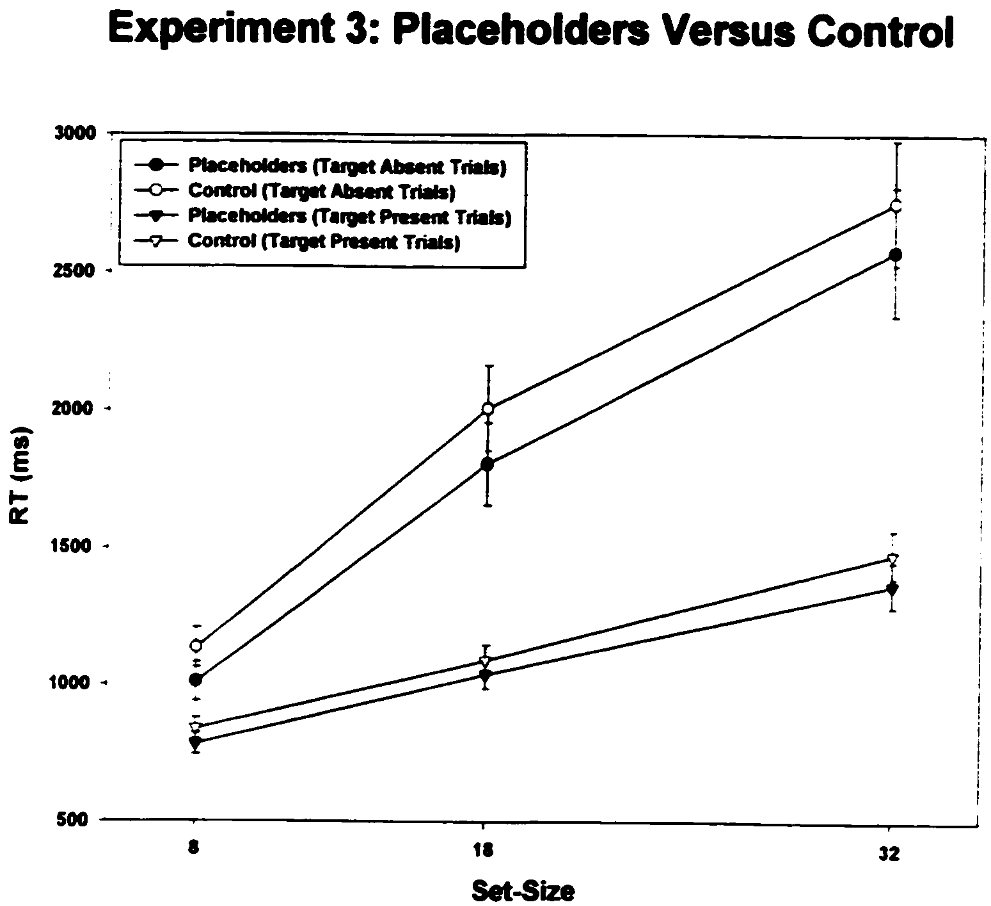

Figure 16. The graph shows target RT (plus SE) for the placeholder and difficult search control conditions. There was a significant decrease in target RT for the placeholder condition relative to the difficult search control condition ($p < .05$). This effect was greater for target absent trials.

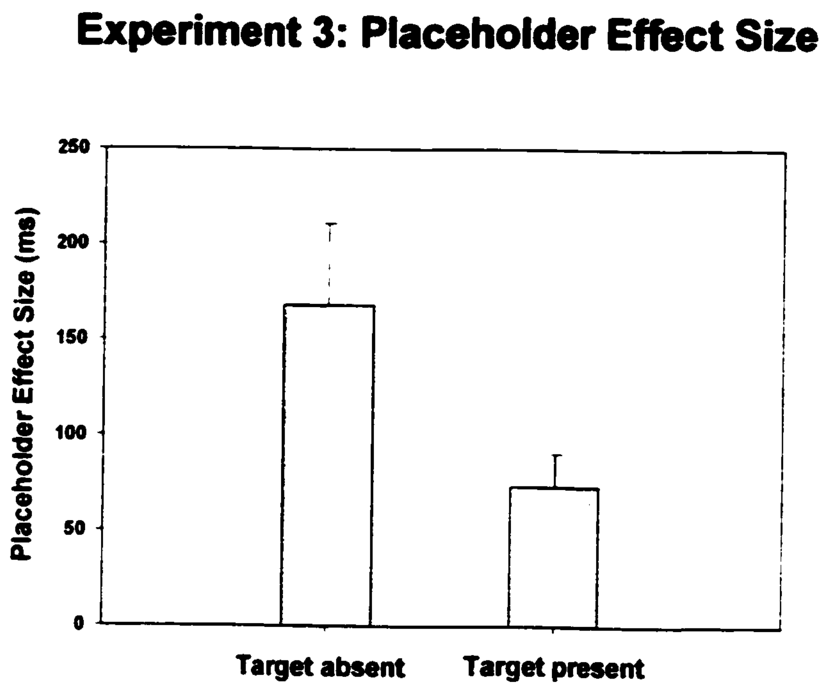

Figure 17. The graph shows the size of the placeholder effect (ms) for target present and target absent trials separately. The placeholder effect size was significantly greater than 0ms for target absent trials only.