



## The role of response in spatial attention: direct versus indirect stimulus–response mappings

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### Abstract

Recent research has suggested that inhibition of return (IOR) develops more quickly when subjects must respond with an eye movement than when they make a manual response to the target (*Perception and Psychophysics* 62 (2000) 1512–1524). Four spatial cueing experiments were conducted where subjects had to indicate the location of visual targets. Within each of the oculomotor and manual modalities, responses could be either directed towards the target (saccade or pointing) or had a more complex stimulus–response (S–R) mapping. For both saccadic and manual responses, IOR onset was delayed as the required S–R mapping became more indirect. This finding further emphasizes the role of response-related processes in spatial attention. Possible explanations for this pattern of results are considered, including the notion that activity in prefrontal cortex, needed for execution of such abstract S–R mappings, may influence the time course of reflexive spatial cueing effects.

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The spatial cueing task (Posner, 1980; Posner & Cohen, 1984) represents one of the most commonly used paradigms to study spatial attention. In a recent study Briand, Larrison, and Sereno (2000) used exogenous, non-predictive spatial cues to reflexively orient covert spatial attention, and asked a deceptively simple question. When all stimulus factors and task demands are equated in a spatial cueing paradigm, should it matter *how* the subject is required to generate a particular response? More specifically, if the task required of subjects is to indicate the location of a visual target, should it matter how they are asked to indicate target location? Briand et al. (2000) required their subjects to indicate target location either by making a speeded saccade to the target, or via one of two speeded manual responses (using a mouse to control a cursor on the stimulus display screen or pressing one of two response keys).

The data reported by Briand et al. (2000, Experiments 3 & 4) are presented in Fig. 1. The most important

finding was that while all responses were initially facilitated at the cued position and inhibited at the longest cue–target SOA (inhibition of return or IOR; Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985), the point of transition from facilitation to IOR differed, depending on the response. Specifically, whereas both types of manual response were still significantly facilitated at a 200 ms SOA, saccadic responses had already switched to significant IOR at a 200 ms SOA. Thus there was a range of cue–target SOAs where manual localization responses were facilitated, while saccadic localization responses were inhibited.

Briand et al. (2000) proposed one possible explanation for this pattern, based on premotor theory (Rizzolatti, Riggio, Dascola, & Umiltà, 1988, 1994). Posterior parietal cortex has different spatial maps that represent saccadic and manual or reaching responses (Rizzolatti et al., 1994; see also Snyder, Batista, & Anderson, 1997). The operations of these maps and the pathways into and out of these maps may differ, since eye movements are in many ways simpler than movements of other parts of the body. For one thing, the physiological demands and constraints differ significantly (i.e., number of muscles, joints, presence of a

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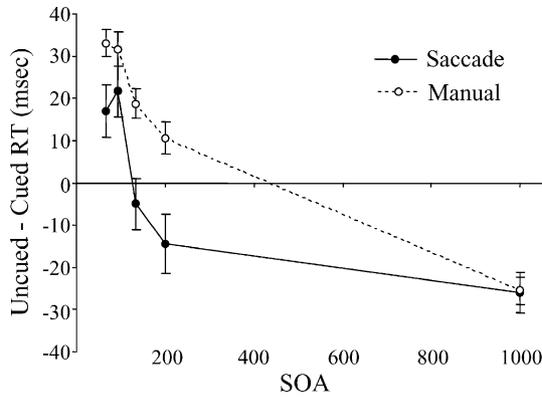


Fig. 1. Spatial cueing effects obtained in two versions of a target localization task by Briand et al. (2000). Note that saccadic responses switch to IOR before manual responses.

fixed load), thus making it unlikely in principle that a simple one-to-one mapping between control of saccadic and manual responses is to be expected. It is also well known that the pattern and distribution of neural activity governing saccadic and manual responses to visual targets differs as well (e.g., see Glimcher, 1999; Schieber, 1999).

Briand et al. (2000) proposed that spatial attention may have to work within different spatial maps when different response modalities are called for. Given the possibility that control of actions via these maps have different output demands, they suggested that attentional effects could also vary. Specifically, the variable onset of IOR Briand et al. (2000) reported for saccadic and manual responses may have arisen because IOR is generated more quickly in some maps (i.e., those coding for eye movements to locations) than others (those coding for manual responses to locations).

The present study is a further investigation of how response factors affect IOR. Specifically, we address the earlier findings of Briand et al. (2000) by considering an alternative explanation of their data. Briand et al. (2000) attributed their time course differences to the modality of the response per se, i.e., whether oculomotor or manual responses were required. However there are significant differences in the stimulus–response (S–R) mappings between a saccadic localization response and the two manual responses Briand et al. (2000) employed. Indicating a target's location via a stimulus-directed saccade is a direct S–R orienting mechanism, and can be considered a natural, perhaps even hard-wired, response. On the other hand, indicating target location by pressing a key or using a mouse involves an arguably more indirect and arbitrary S–R mapping than a simple target-directed saccade.

In the experiments reported here, non-predictive exogenous spatial cues were used to orient spatial attention, and subjects had to indicate the location of the

target. Both manual and saccadic responses were used, but within each modality, the direct versus indirect nature of the S–R mapping was varied. Subjects had to indicate the target location either by making a response directly to the target, or by performing an indirect response involving a more arbitrary S–R mapping.

## 1. Experiment 1

### 1.1. Method

Eighteen undergraduates at Rutgers–Newark received either partial course credit or monetary compensation for participating. All had normal or corrected vision, and informed consent was obtained prior to testing.

The testing procedure was similar to that used by Briand et al. (2000). The stimulus display consisted of a gray fixation spot ( $0.2^\circ \times 0.2^\circ$ ) on a black background, flanked by two gray boxes ( $1.0^\circ \times 1.0^\circ$ ) positioned such that their centers were  $5.8^\circ$  to the left and right of fixation. The target stimulus was a green square measuring  $0.6^\circ \times 0.6^\circ$  which appeared in the center of one of the two flanking boxes. Fig. 2 shows examples of the stimulus display and the sequence of events on each trial.

After the subject had oriented to the central fixation point, the trial sequence started. Following a fixation period (1000 ms), there was a 27 ms brightening of one of the two peripheral boxes, which acted as a cue. After an additional 13 ms period elapsed, the fixation point itself then brightened for 27 ms. The entire duration of the cue sequence, from initial brightening of the box to termination of the fixation brightening, was 67 ms. Following this cue sequence, the fixation screen was displayed for either 0, 27, 67, 133 or 933 ms. This re-

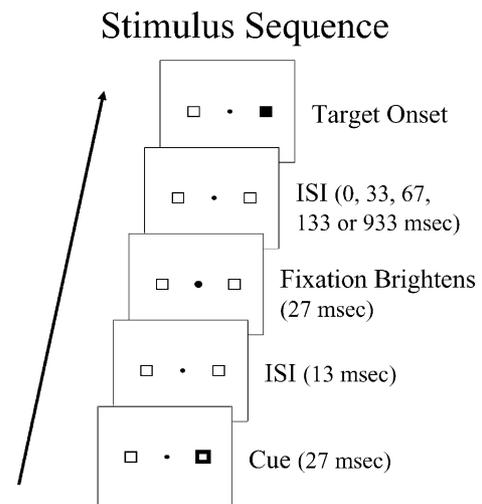


Fig. 2. Illustration of the sequence of events occurring during a trial, starting at the lower panel. The subject's task in all cases was to make a speeded response indicating the location of target.

sulted in SOAs between the initial cue (i.e., box brightening) and the target of 67, 93, 133, 200 and 1000 ms. Subjects had to make a speeded response to the target following its appearance, and the target remained in view until subjects had completed a response to one of the two boxes. Brightening of the cue displays was accomplished by switching the color of the box and fixation point from gray to white. Luminance of stimuli was as follows: fixation spot and peripheral boxes, 5.6 cd/m<sup>2</sup>; cue brightening, 41.1 cd/m<sup>2</sup>; target, 12.5 cd/m<sup>2</sup>.

There were two types of trials, defined by what preceded target onset. On Cued trials, the target was shown within the peripheral box that had brightened. On Uncued trials, the target was shown within the box that had not brightened. The probability of the target appearing within the brightened box was 50:50; hence cues were unpredictable of target location.

Each subject was tested in three blocks of 120 trials, one each for the three response modes used. The order was counterbalanced between subjects. Each combination of cue position (Cued or Uncued) and SOA was represented by 12 trials. A practice block of 16 trials was completed before starting each task.

**Saccade:** In the saccade task, subjects had to make a speeded eye movement to the target. Eye movements were recorded using an ISCAN RK-426 eye-tracking system, interfaced with an infrared sensitive camera. After target onset a saccade was assumed to have started when eye velocity exceeded 100 deg/s, and the end of the saccade was indicated when velocity fell below 12 deg/s.<sup>1</sup> The terminal point of the saccade had to be within 2.9° of the target position to be scored as correct. Saccades that terminated in any other position on the screen were coded as errors. If a successful saccade was not initiated within 1000 ms of target onset, a tone was sounded to indicate non-response, and that trial was replaced in the pool of unfinished trials to be completed later. The target remained in view until the saccade was completed.

**Mouse:** Subjects controlled a mouse that moved a cursor on the display screen, and were required to move the cursor to the left or right to indicate target location. Instead of using point-of-gaze to determine when a response started and ended, the mouse version of the task kept track of where the cursor was positioned. A velocity criterion was also used to detect mouse move-

ments, with the cutoff velocities for the start and end of mouse responses being 24 and 12 deg/s, respectively.

**Pointing:** Subjects were required to touch the fixation point on the display screen with a stylus, and then move it to the target as soon as it appeared. Following target appearance, a response was assumed to have occurred when the stylus was lifted from the touch screen, and this latency was recorded. Since the pointing response required subjects to be within comfortable reaching distance of the display screen, stimuli for the pointing version of the manual response were scaled down so that they would cover the same retinal area as they did when viewed at a greater distance (45% of normal size). A touch screen (Keytek MagicTouch) was overlaid on the display screen, and subjects sat approximately 30 cm from the screen. The stylus had to be placed within 4.4° of the center of the target in order to be counted as a correct response.<sup>2</sup>

## 1.2. Results

Trials with latencies longer than 750 ms or faster than 120 ms were excluded from analysis, as were trials in the saccade task where blinks occurred after target onset (2.2%, 0.3% and 3.1% excluded for saccadic, pointing and mouse respectively). We used a value of 120 ms because this corresponded approximately to the shortest saccade latencies in an unpracticed subject in an overlap paradigm (see Fig. 9, Fischer, 1987). Each subject's mean correct response latency for cued and uncued trials at the five SOAs was calculated separately for each response (see Table 1). Error rates (responses to non-target locations) were similarly calculated.

**RT:** Cueing effects ( $RT_{\text{Uncued}} - RT_{\text{Cued}}$ ) followed the expected trend across the three tasks, with initial facilitation followed at longer SOAs by IOR. An ANOVA with factors of Response, Cue and SOA was run. All main effects were significant: Cue ( $F_{1,17} = 11.33, p < 0.004$ ), SOA ( $F_{4,68} = 39.26, p < 0.001$ ), and Response ( $F_{2,34} = 87.77, p < 0.001$ ). For the latter effect, saccades (295 ms) had the fastest RT, followed by pointing (349 ms) and mouse (412 ms). In addition, three interactions were significant: Response  $\times$  SOA ( $F_{8,136} = 5.09, p < 0.001$ ), Response  $\times$  Cue ( $F_{2,34} = 31.58, p < 0.001$ ),

<sup>1</sup> The criterion used for detection of saccades was higher than that typically found in the literature (usually in the range of 30 deg/s). However, we found our chosen values to be optimal given our relatively slow sampling rate (180 Hz) and noise inherent in the ISCAN system which causes apparent eye position to vary randomly from sample to sample by about 0.1–0.4°. That is, a 30 deg/s criterion would correspond to an eye position shift of approximately 0.17° between two consecutive samples at 180 Hz.

<sup>2</sup> A slightly more liberal criterion was used for the pointing response than for the saccade and mouse responses. This was largely because the touch screen overlaid on the display monitor was not flush to its surface. This led to a slight disparity between the location the subject believed they were pointing to on the image and the actual screen coordinate on the touch screen. Furthermore, since no chin rest was used for the pointing task this disparity could itself vary as viewing position changed slightly. Despite this, responses were generally accurate, with saccades on average falling within 1.2° of the center of the target (see Appendix A). Pointing responses, despite having a more liberal criterion, were actually more accurate, falling within 0.5° of the target center on average.

Table 1  
Mean RTs and Cue position effects (Uncued–Cued) in Experiment 1, as a function of Response type and SOA

Response	SOA (ms)	Cued	Uncued	Uncued–Cued	$F_{1,136}$
Saccade	67	285 (8.9)	303 (8.0)	18	14.26, $p < 0.001$
	94	279 (8.4)	294 (6.8)	15	10.12, $p < 0.002$
	133	280 (9.4)	278 (8.3)	-2	<1, $p > 0.61$
	200	294 (8.3)	279 (7.0)	-15	8.71, $p < 0.004$
	1000	348 (9.2)	312 (9.7)	-36	52.50, $p < 0.001$
Pointing	67	339 (8.6)	367 (9.9)	28	32.94, $p < 0.001$
	94	330 (7.3)	357 (9.7)	27	29.55, $p < 0.001$
	133	334 (8.3)	335 (10.2)	1	<1, $p > 0.84$
	200	346 (7.9)	336 (8.9)	-10	4.08, $p < 0.05$
	1000	387 (6.0)	357 (6.9)	-30	36.29, $p < 0.001$
Mouse	67	396 (8.3)	443 (9.4)	47	90.58, $p < 0.001$
	94	390 (8.8)	434 (9.8)	43	78.17, $p < 0.001$
	133	386 (9.6)	425 (9.6)	39	62.52, $p < 0.001$
	200	393 (11.3)	414 (10.4)	21	16.90, $p < 0.001$
	1000	432 (8.1)	413 (7.9)	-19	14.70, $p < 0.001$

Standard errors are given in parentheses. Also included are the  $F$ -test values for planned contrasts used to assess cueing effects, and the probability levels associated with those particular contrasts.

and  $SOA \times Cue$  ( $F_{4,68} = 44.74$ ,  $p < 0.001$ ). The Response  $\times$  Cue  $\times$  SOA interaction failed to reach significance ( $F_{8,136} = 1.49$ ,  $p > 0.16$ ).

Planned contrasts were used to assess the significance of cueing effects at each SOA for the three different responses, and these results are also included in Table 1. Fig. 3 shows the cueing effects for the three response modes as a function of cue–target SOA. As is apparent from these data, the mouse task showed facilitation up to an SOA of 200 ms, and IOR only at the 1000 ms SOA. In contrast, both of the tasks requiring a direct response to the target (saccade and pointing) showed facilitation only up to a 93 ms SOA. At the 200 ms SOA, mouse responses were still facilitated whereas both the saccade and pointing responses showed IOR. While only a modest -10 ms inhibition effect was observed with pointing at this SOA, still 14 of 18 subjects showed IOR in this condition, a trend significant with a Wilcoxon

sign-rank test ( $p < 0.05$ ), and even with a more conservative sign-test ( $p < 0.02$ ).

**Errors:** Error data are shown in Appendix B. ANOVA of these revealed a significant effect of Response ( $F_{2,34} = 9.99$ ,  $p < 0.0005$ ) with fewer errors for the saccade and mouse tasks (1.0% for each) than for the pointing task (3.6%). Also significant were an effect of Cue ( $F_{1,17} = 19.81$ ,  $p < 0.0005$ ) (fewer errors on cued trials). SOA was not significant ( $F < 1$ ,  $p > 0.96$ ). There were two significant interactions, first between Response and SOA ( $F_{8,136} = 4.77$ ,  $p < 0.0002$ ) and finally a Cue by SOA interaction ( $F_{4,68} = 3.08$ ,  $p < 0.03$ ) (facilitation at the four shortest SOAs, no cueing effect at 1000 ms). Response  $\times$  Cue was not significant ( $F < 1$ ,  $p > 0.71$ ), and the Response  $\times$  Cue  $\times$  SOA interaction failed to reach significance ( $F_{8,136} = 1.76$ ,  $p < 0.10$ ). Finally, planned contrasts on cueing effects for errors did not reveal any trends that conflicted with the RT results.

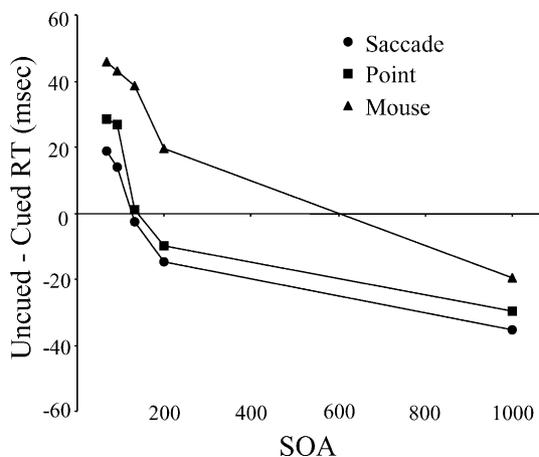


Fig. 3. Cueing effects (Uncued–Cued RT) in Experiment 1, as a function of response (Saccade, Pointing, or using a Mouse) and SOA.

## 2. Experiment 2

Experiment 1 showed that the type of response made by the subject affected the time course of spatial cueing. When subjects had to indicate the location of a target by responding directly to it with a saccade or pointing response, facilitation was eliminated relatively quickly, and IOR developed by 200 ms after the appearance of the cue. However when a mouse was used to indicate target location, facilitation persisted at least until 200 ms following the cue. Thus the present findings, as well as those reported recently by Briand et al. (2000), indicate that exogenous spatial cues have very different consequences, depending on the exact nature of the response. However the present findings differ from those of Briand et al., in that the difference in time course can be ex-

plained solely by the direct versus indirect nature of the S–R mapping.

Experiment 1 varied the direct versus indirect S–R mapping of the localization response within the manual modality. In Experiment 2 we varied the directness of the S–R mappings within the oculomotor modality. Three tasks were given to subjects, each requiring subjects to indicate the location of the target. All responses required subjects to make an eye movement.

### 2.1. Method

Twelve students from Rutgers–Newark were tested, and all had normal or corrected vision. Each subject performed three versions of the spatial cueing task with order counterbalanced between subjects. There were 120 trials in each block of trials, and subjects were asked to indicate the location of the target. The procedure was the same as that used for the saccade task of Experiment 1.

*Saccade:* This task was identical to the saccade task from Experiment 1, i.e., subjects had to make a speeded saccade to the target when it appeared.

*Antisaccade:* This task used the same stimulus sequence and display as the saccade task, but subjects had to indicate the target location by making an eye movement in the direction opposite to where it appeared.

*Indirect:* The stimuli for this task differed slightly from the other two tasks. Besides the two boxes positioned to the left and right of fixation, two additional boxes, equivalent in size and eccentricity to these, were located above and below the fixation point. These boxes simply served as location markers, i.e., no cue or target ever appeared at these locations. The subject's task was to indicate the target location by making a vertical eye movement. For example, a target appearing on the left

would require a saccade to the upper location, while a target appearing on the right would require a downward saccade (this mapping was counterbalanced between subjects). In all other respects (e.g., criteria for detecting saccades) all three tasks were identical.

### 2.2. Results

After excluding fast and slow trials and those where blinks occurred after target onset (3.8%, 1.2% and 3.2% for saccade, AS, and indirect, respectively), each subject's mean correct response latency (and error rate) for cued and uncued trials at the five SOAs was calculated separately for each response (see Table 2).

*RT:* An ANOVA with factors of Response, Cue and SOA was conducted. All main effects were significant: SOA ( $F_{4,44} = 5.38$ ,  $p < 0.002$ ), Cue ( $F_{1,11} = 16.62$ ,  $p < 0.002$ ), and finally Response ( $F_{2,22} = 112.24$ ,  $p < 0.0001$ ), with prosaccades being fastest (300 ms), followed by antisaccades (393 ms) and then indirect responses (488 ms). All interactions were also significant: Response  $\times$  SOA ( $F_{8,88} = 2.88$ ,  $p < 0.007$ ), Response  $\times$  Cue ( $F_{2,22} = 7.79$ ,  $p < 0.003$ ), SOA  $\times$  Cue ( $F_{4,44} = 9.65$ ,  $p < 0.0001$ ), and finally Response  $\times$  Cue  $\times$  SOA ( $F_{8,88} = 3.68$ ,  $p < 0.002$ ).

Planned contrasts were used to assess the significance of cueing effects at each SOA for the three different responses, and these results are also included in Table 2. Fig. 4 shows the cueing effects for the three responses as a function of cue–target SOA. As expected, the saccade task switched to IOR by a 200 ms SOA. However, the AS task was still significantly facilitated at this SOA, only showing IOR at 1000 ms. Finally, the indirect task never did reveal IOR, or at least did not show IOR by the longest SOA we tested (1000 ms).

Table 2  
Mean RTs and Cue position effects (Uncued–Cued) in Experiment 2, as a function of Response type and SOA

Response	SOA (ms)	Cued	Uncued	Uncued–Cued	$F_{1,88}$
Saccade	67	289 (7.7)	322 (9.9)	33	16.32, $p < 0.001$
	94	267 (7.9)	309 (9.2)	42	25.31, $p < 0.001$
	133	277 (4.2)	295 (12.5)	18	4.71, $p < 0.04$
	200	323 (12.1)	282 (9.9)	–41	24.38, $p < 0.001$
	1000	334 (11.5)	303 (10.6)	–31	14.10, $p < 0.001$
Antisaccade	67	385 (12.9)	417 (11.2)	32	14.47, $p < 0.001$
	94	381 (11.9)	422 (14.6)	41	24.73, $p < 0.001$
	133	385 (11.2)	402 (17.4)	17	4.24, $p < 0.05$
	200	363 (11.1)	380 (11.6)	17	4.44, $p < 0.04$
	1000	407 (16.1)	391 (11.6)	–16	4.09, $p < 0.05$
Indirect	67	468 (17.4)	524 (17.2)	56	47.29, $p < 0.001$
	94	462 (19.2)	515 (13.1)	53	42.18, $p < 0.001$
	133	460 (18.0)	495 (11.4)	35	18.46, $p < 0.001$
	200	458 (19.9)	499 (13.3)	41	25.09, $p < 0.001$
	1000	496 (11.8)	507 (10.5)	11	1.69, $p > 0.20$

Standard errors are given in parentheses. Also included are the  $F$ -test values for planned contrast used to assess cueing effects, and the probability levels associated with those particular contrasts.

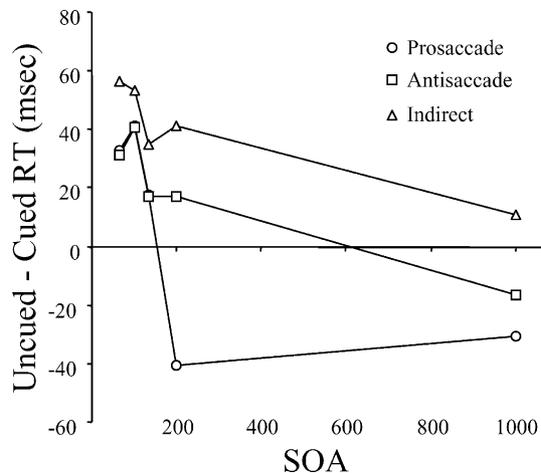


Fig. 4. Cueing effects (Uncued–Cued RT) in Experiment 2, as a function of response (Saccade, Antisaccade, or Indirect) and SOA.

*Non-parametric tests:* Where cueing effects were significant but small ( $p = 0.01$  or greater), Wilcoxon sign-rank tests were also used to provide converging evidence regarding the reliability of the cueing effects reported (there were only four such instances). First, in the saccade task, the 18 ms facilitation effect seen at  $SOA = 133$  ms was only marginally significant (7/12 subjects, Wilcoxon test,  $p < 0.07$ ). In the case of the antisaccade task, the cueing effects seen at the SOAs 133–1000 ms were as follows: 133 ms, facilitation, observed in 7/12 subjects (Wilcoxon test  $p > 0.17$ ); 200 ms, facilitation in 9/12 subjects (Wilcoxon  $p < 0.04$ ); 1000 ms, inhibition in 8/12 subjects (Wilcoxon,  $p < 0.04$ ).

*Errors:* An ANOVA of error rates revealed a main effect of Response ( $F_{2,22} = 15.31$ ,  $p < 0.0002$ ), mostly due to a high error rate for the indirect task (12.8%) compared to the saccade and AS tasks (2.0% and 5.2% respectively). There was also a main effect of Cue ( $F_{1,11} = 31.70$ ,  $p < 0.0003$ ). SOA was not significant ( $F < 1$ ,  $p > 0.46$ ). In addition, there were significant interactions between Response and SOA ( $F_{8,88} = 2.05$ ,  $p < 0.05$ ) and between Cue and SOA ( $F_{4,44} = 3.18$ ,  $p < 0.03$ ). Task  $\times$  Cue was not significant ( $F_{2,22} = 1.88$ ,  $p > 0.17$ ), nor was the three-way interaction of Response, Cue and SOA ( $F_{8,88} = 1.22$ ,  $p > 0.29$ ). Planned contrasts on errors were consistent with the overall pattern observed with RT, namely that the AS and indirect tasks were each facilitated until the 200 ms SOA while the prosaccade task was not (see Appendix B).

### 3. Experiment 3

The results of the first two experiments are consistent with the idea that direct versus indirect S–R mappings can alter the time course of IOR. However, the saccadic and manual data are not strictly comparable due to the

different versions of the target localization tasks used in Experiments 1 and 2. In the third experiment, all subjects were tested in comparable versions of direct and indirect target localization tasks, using both saccadic and manual responses. In addition, the time course was altered to allow more sampling of intervals between SOAs of 200 and 1000 s.

#### 3.1. Method

Twenty-four subjects from Rice University were tested, and all had normal or corrected vision. Each subject performed four versions of the spatial cueing task. Two tasks required subjects to make saccades in response to visual targets; the Saccade-Direct and Saccade-Indirect tasks were exactly the same as the prosaccade and indirect tasks used in Experiment 2. In addition, all subjects were tested in two tasks requiring them to make manual pointing responses rather than saccades; Point-Direct (exactly the same as the pointing task from Experiment 1, i.e., subjects pointed towards the targets) and Point-Indirect (comparable to the Saccade-Indirect task but subjects had to point instead of make eye movements). The order in which these four tasks were given was counterbalanced across subjects. There were 120 trials in each block of trials, and all criteria concerning detection of response onset and accuracy were as described previously for the saccadic and manual versions of the tasks.

#### 3.2. Results

After excluding fast and slow trials and those where blinks occurred after target onset (2.0% and 2.1% for saccade and pointing responses respectively), each subject's mean correct response latency (and error rate) for cued and uncued trials at the five SOAs was calculated separately for each of the four conditions (see Table 3).

*RT:* An ANOVA with factors of Response Mode (Saccade/Point), Mapping, Cue and SOA was run. SOA was significant ( $F_{4,92} = 32.93$ ,  $p < 0.001$ ), Cue was not ( $F_{1,23} < 1$ ,  $p > 0.82$ ), but the interaction between these was significant ( $F_{4,92} = 15.11$ ,  $p < 0.001$ ), indicating early facilitation and a transition to IOR at longer SOAs. An interesting set of comparisons involved the effects of Response Mode and Mapping. Each of these main effects and their interaction were significant. While as expected direct mappings resulted in faster latencies than indirect mappings (339 and 447 ms respectively,  $F_{1,23} = 400.42$ ,  $p < 0.001$ ) saccades had an overall slower latency than did pointing responses (406 and 381 ms respectively,  $F_{1,23} = 17.42$ ,  $p < 0.001$ ). A detailed look at the Response  $\times$  Mapping interaction ( $F_{1,23} = 155.65$ ,  $p < 0.001$ ) revealed that this was due to the fact that saccades were faster than pointing responses when direct mappings were used (329 and 350 ms respectively), but

Table 3  
Mean RTs and Cue position effects in Experiment 3, as a function of Task and SOA (std. errors, *F*- and *p*-values as in Tables 1 and 2)

Response	SOA (ms)	Cued	Uncued	Uncued–Cued	<i>F</i> <sub>1,92</sub>
Saccade-Direct	94	336 (7.0)	347 (9.9)	11	3.59, <i>p</i> < 0.07
	200	317 (7.2)	311 (9.0)	-6	<1, <i>p</i> > 0.34
	300	334 (8.2)	315 (8.6)	-19	11.05, <i>p</i> < 0.002
	400	338 (7.0)	317 (7.6)	-21	13.18, <i>p</i> < 0.001
	1000	344 (9.3)	329 (9.5)	-15	7.01, <i>p</i> < 0.01
Saccade-Indirect	94	500 (10.9)	514 (11.8)	14	5.59, <i>p</i> < 0.03
	200	481 (10.5)	481 (11.5)	0	<1, <i>p</i> > 0.96
	300	476 (11.6)	471 (13.0)	-5	<1, <i>p</i> > 0.38
	400	481 (11.5)	469 (11.4)	-12	4.45, <i>p</i> < 0.04
	1000	486 (11.9)	471 (10.9)	-15	5.98, <i>p</i> < 0.02
Point-Direct	94	355 (9.0)	378 (8.8)	23	14.55, <i>p</i> < 0.001
	200	342 (8.1)	347 (9.0)	5	<1, <i>p</i> > 0.38
	300	345 (6.8)	333 (7.7)	-12	4.16, <i>p</i> < 0.05
	400	352 (6.3)	342 (6.8)	-10	3.16, <i>p</i> < 0.08
	1000	358 (7.8)	343 (7.9)	-15	7.18, <i>p</i> < 0.01
Point-Indirect	94	422 (10.2)	446 (10.2)	24	17.53, <i>p</i> < 0.001
	200	398 (10.2)	422 (12.9)	24	16.45, <i>p</i> < 0.001
	300	384 (10.3)	414 (13.5)	30	27.07, <i>p</i> < 0.001
	400	394 (11.5)	409 (10.9)	15	6.43, <i>p</i> < 0.02
	1000	416 (9.4)	412 (10.6)	-4	<1, <i>p</i> > 0.56

were slower than pointing responses when indirect mappings were used (483 and 412 ms respectively). Thus indirect S–R mappings slow both saccadic and pointing responses, but are more disruptive for eye movements. The full results of the four-factor ANOVA are provided in Appendix C.

Planned contrasts were used to assess the significance of cueing effects at each SOA for the three different responses, and these results are also included in Table 3. Fig. 5 shows the cueing effects for the four tasks as a

function of cue–target SOA. The data show that for both saccadic and pointing responses, direct mapping leads to significant IOR at shorter SOAs than is the case for the indirect S–R mappings.

*Non-parametric tests:* Saccade-Direct: Cueing effects at the 94 and 1000 ms SOAs were analyzed: 94 ms, facilitation in 16/24 subjects (Wilcoxon *p* < 0.03); 1000 ms, inhibition in 16/24 subjects (Wilcoxon *p* < 0.01). Saccade-Indirect: Cueing effects at 94, 400 and 1000 ms were analyzed: 94 ms, facilitation in 16/24 subjects

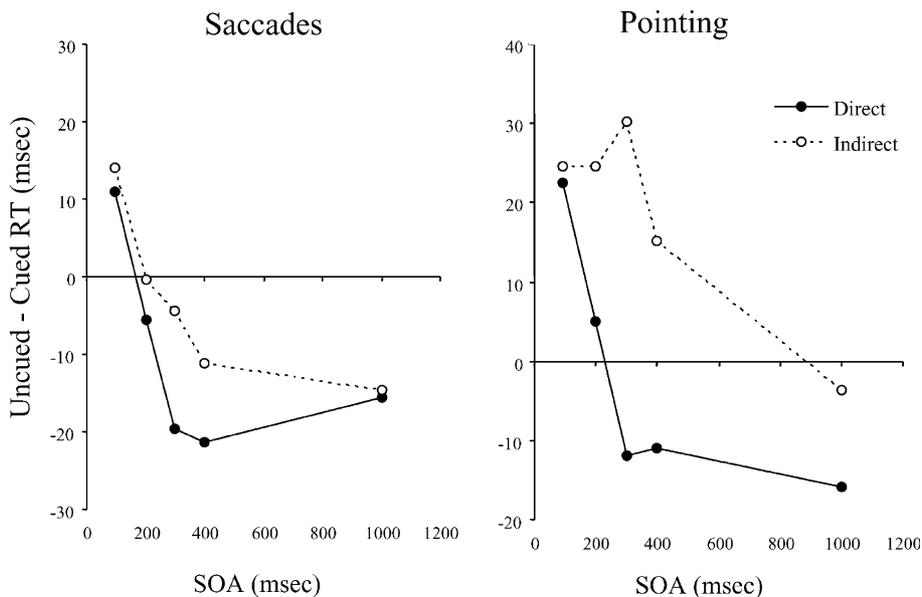


Fig. 5. Cueing effects (Uncued–Cued RT) in Experiment 3, as a function of response (Saccade or Pointing), S–R mapping, and SOA.

(Wilcoxon  $p < 0.04$ ); 400 ms, inhibition in 18/24 subjects (Wilcoxon  $p < 0.02$ ); 1000 ms, inhibition in 17/24 subjects (Wilcoxon  $p < 0.03$ ). Point-Direct: Cueing effects at 300–1000 ms were analyzed: 300 ms, inhibition in 14/24 subjects (Wilcoxon  $p < 0.05$ ); 400 ms, inhibition in 17/24 subjects (Wilcoxon  $p < 0.01$ ); 1000 ms, inhibition in 19/24 subjects (Wilcoxon  $p < 0.001$ ). Point-Indirect: Cueing effects at only the 400 ms SOA were analyzed: facilitation in 19/24 subjects (Wilcoxon  $p < 0.02$ ).

*Errors:* Error data are presented in Appendix D. ANOVA revealed a significant effect of Response ( $F_{1,23} = 57.59$ ,  $p < 0.001$ ), with fewer errors for pointing (0.6%) than for saccades (2.6%). There was also a significant effect of Mapping ( $F_{1,23} = 52.42$ ,  $p < 0.001$ , with more errors for indirect mappings), and an interaction between Response and Mapping ( $F_{1,23} = 29.88$ ,  $p < 0.001$ ). As was the case with the RT data, this interaction indicated that performance deteriorated under indirect mappings, and this was greater for saccades. Finally, planned contrasts on cueing effects for errors did not reveal any trends that conflicted with the RT results (see Appendix C for full ANOVA results).

#### 4. Experiment 4

The results of the first three experiments suggest that indirect S–R mappings lead to a delay in the onset of IOR effects. While there is some variability across the results of all the tasks reported, this overall trend is fairly striking. For instance, the size of the facilitatory and inhibitory effects observed in Experiment 3 are of smaller magnitude and the particular SOAs that show facilitation or inhibition differ slightly from those observed in earlier experiments. This may be due to a sample effect, or it is possible that the selection of SOAs itself may affect the attentional set, altering the size and time course of cueing effects. What is consistent across experiments, however, is that direct S–R mappings switch to IOR sooner than indirect mappings.

However, we did not monitor subjects' eye movements when they were being tested in manual versions of these tasks. Thus, it is conceivable that subjects were executing eye movements to either the visual targets or to the location they were pointing to, either before or in conjunction with any manual response that they executed. Further, it is possible that they were making different eye movements in the direct and indirect manual tasks, and it is this difference that was resulting in the shift in time course. Although, this possibility could not account for the shift in time course for the saccade tasks, it is an important variable that could affect the pointing and mouse findings. Hence, in a final experiment, we compared direct and indirect manual responses under two conditions: one condition in which

the subjects' eyes remain at fixation throughout the trial while they respond manually to the target (FIXATE), and one in which the subjects make saccades in addition to their manual response (MOVE).

##### 4.1. Method

Four volunteers from the University of Texas—Houston were tested, and all had normal or corrected vision. Each subject was tested in multiple testing sessions on separate days. All subjects did the following versions of the spatial attention tasks:

*Fixate-Direct:* Subjects performed both the Mouse and Pointing versions of the target localization task described in Experiment 1. Cue–target SOAs of 94, 200, 300, 400 and 1000 ms were used. Each task was performed four times, with each block consisting of 60 trials (i.e., a total of 24 trials per cell). While performing the task, the subject's eyes were watched by two observers via a monitor, and the subject was instructed to perform the entire task while keeping their eyes at the central fixation point. Subjects were warned when they did not maintain fixation, and trials where they did not follow this instruction were excluded from data analysis.

*Fixate-Indirect:* This was identical to the previous task, except that now subjects had to use an indirect S–R mapping identical to the Indirect task of Experiment 2 (except that the response was either a pointing or mouse movement). Specifically, if a target appeared on the right they were instructed to point to (or move the cursor towards) a box appearing at the top of the screen, and if the target appeared on the left, to point to (or move the cursor towards) a box at the bottom of the screen (this mapping was counterbalanced between subjects). In addition, they had to do this while maintaining fixation.

*Move-Direct:* This was identical to the Fixate-Direct task, except that subjects were instructed that while making the manual response, they were also to make an eye movement to the location they were responding to (i.e., to the left or the right). Eyes were monitored by two observers. Subjects were warned if they did not make a saccade to the target location. Such trials were excluded from data analysis. To monitor eye movements, the image of the left eye was displayed on a 9 in. monitor with a cross hair through the center of the pupil. The diameter of the pupil image was approximately 3 in., and observers were positioned directly in front of the monitors. Under these conditions it was quite easy to detect whether subjects maintained fixation or moved their eyes.

*Move-Indirect:* This was identical to the Fixate-Indirect task, except now subjects also had to make saccades to the upper and lower positions that they were responding to manually.

The four subjects tested performed these various tasks in a number of testing sessions spaced across a few days. Order of the various tasks was counterbalanced within and between subjects.

#### 4.2. Results

Fewer than 1% of trials had to be excluded because of failure to follow instructions regarding eye movements. While subjects performed both Mouse and Pointing versions of each of the described tasks, we collapsed across this factor to decrease the variability caused by the small  $n$  tested. Because of this variability we also decided that median rather than mean RT would be a more appropriate measure of RT, and used a cutoff of 1000 ms to exclude extremely slow trials (<1% excluded including both fast and slow responses).

An ANOVA with factors of Instruction (Fixate/Move), Mapping (Direct/Indirect), SOA, and Cueing (Cued/Uncued) was carried out on these median RTs (see Table 4). Instruction was not significant ( $F_{1,3} = 1.08$ ,  $p > 0.37$ ) but Mapping was ( $F_{1,3} = 122.27$ ,  $p < 0.002$ ) (RTs of 417 and 489 for direct and indirect mappings, respectively). Cueing was also significant ( $F_{1,3} = 48.36$ ,  $p < 0.01$ ) with net facilitation overall. Cueing in turn interacted with SOA ( $F_{4,12} = 5.26$ ,  $p < 0.02$ ) with facilitation effects declining at longer SOAs. Cueing also interacted with Mapping ( $F_{1,3} = 22.59$ ,  $p < 0.02$ ) with

more net facilitation with indirect (25 ms) than with direct S–R mapping (10 ms). Critically, there was no interaction of Cueing  $\times$  Mapping  $\times$  SOA, Cueing  $\times$  Mapping  $\times$  Instruction, nor of Cueing  $\times$  Mapping  $\times$  SOA  $\times$  Instruction (all  $F_s < 1$ ). This latter interaction is displayed in Fig. 6, where it can be seen that besides the declining facilitation effect at longer SOAs, the only significant trend is for indirect S–R mappings to show more persistent facilitation than direct mappings. Furthermore, this was true for both the Move and Fixate conditions (see Appendix E for a full list of ANOVA results).<sup>3</sup>

Error rates were <1%, likely due to the extensive practice all subjects received. Analysis of errors revealed only one significant effect, Instruction  $\times$  Response  $\times$  Mapping  $\times$  SOA ( $F_{4,12} = 6.75$ ,  $p < 0.005$ ; see Appendix F).

#### 5. General discussion

The results of these experiments show that IOR can be systematically delayed in onset simply by varying the nature of the response that subjects are required to make. In the experiments reported here subjects merely had to indicate the location of the target with a speeded response. When the task required a simple S–R mapping or target-directed response, such as making a visually guided saccade or pointing to the target, IOR occurred by around 200 ms. However, when the localization response required some more arbitrary or indirect S–R mapping, onset of IOR was delayed to varying degrees. This was true for both manual and saccadic versions of the same tasks. Furthermore, when manual responses were involved, the effect of the directness of the S–R mapping occurred whether or not subjects made eye movements in conjunction with their hand movements. Thus the effects of S–R mapping generalized across response modality, and cannot be explained by a failure to control for the effects of eye movements on manual trials. Whereas Briand et al. (2000) proposed that a

Table 4  
Mean RTs and Cue position effects in Experiment 4, as a function of instruction (Fixate versus Move), Task and SOA

Task	SOA (ms)	Fixate		Move	
		Cued	Uncued	Cued	Uncued
Point-Direct	94	410	433	422	445
	200	401	413	407	411
	300	393	410	384	424
	400	403	409	413	416
	1000	413	410	435	432
Point-Indirect	94	499	518	514	542
	200	481	512	471	525
	300	465	485	469	507
	400	464	480	476	509
	1000	512	514	506	517
Mouse-Direct	94	427	452	419	446
	200	410	422	413	412
	300	398	411	409	411
	400	403	406	414	422
	1000	433	422	431	424
Mouse-Indirect	94	473	525	483	521
	200	471	497	458	482
	300	450	461	458	481
	400	452	474	452	476
	1000	497	502	479	499

<sup>3</sup> The four subjects in Experiment 4, while naive, became highly practiced, performing almost 2000 experimental trials across several sessions. In order to compare several different conditions within subjects (Fixate/Move, Mouse/Point, Direct/Indirect), a much larger number of trials were needed than are typically used in IOR experiments. While not aware of any published studies examining the effects of practice on IOR, unpublished data from our own lab suggests that practice may well alter this function. Thus, the results from highly practiced subjects tested for thousands of trials may not necessarily match with those from subjects tested on 100–200 trials, which could account for some of the differences in time course in the data from Experiment 4 (e.g., compare the time course for Point-Direct in Experiments 3 and 4).

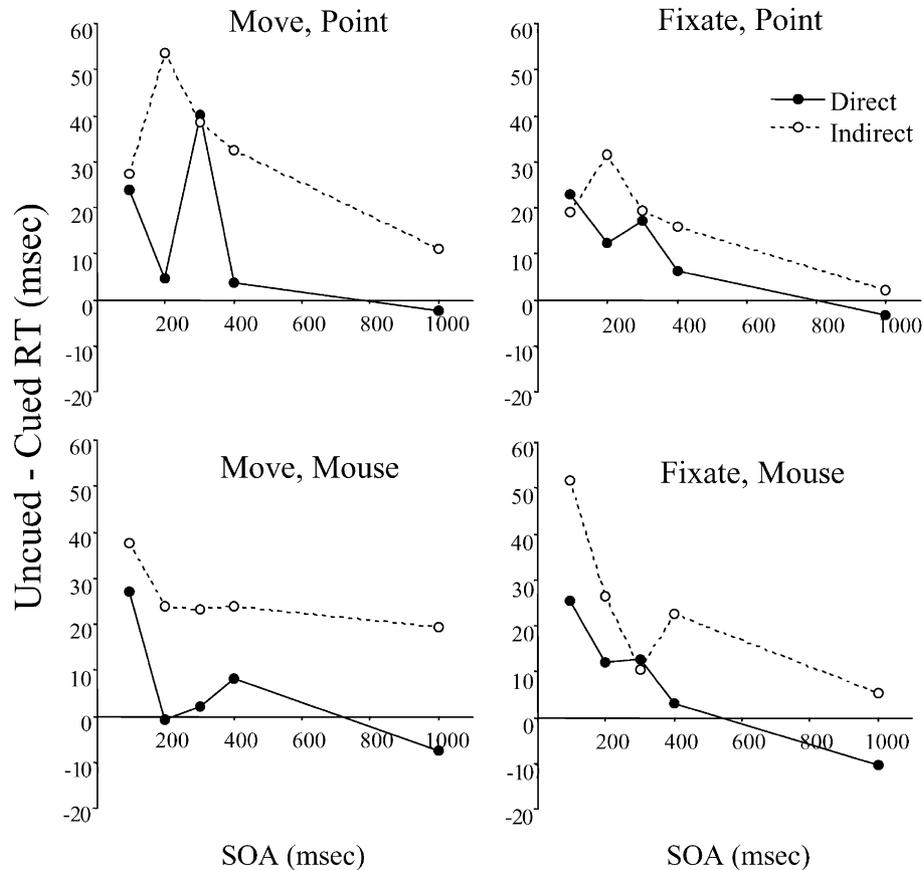


Fig. 6. Cueing effects (Uncued–Cued RT) in Experiment 4, as a function of instruction (Fixate or Move), S–R mapping, and SOA.

distinction between saccadic and manual responses was critical for the different time courses they obtained, we find that the direct-indirect nature of the S–R mapping may account for most of the differences in time course that they reported.

Given that response-related components have a systematic influence on the pattern of spatial cueing effects, it seems clear that the act of orienting covert attention in space must do more than simply facilitate stimulus input. Rather, spatial attention involves something akin to “selection for action” (Allport, 1987; see also Tipper, Lortie, & Baylis, 1992; cf. Rizzolatti et al., 1994). Posner’s original conception of how spatial attention operated in fact assumed that one of its functions consisted of linking up stimuli with arbitrary responses (Posner, Snyder, & Davidson, 1980). Some previous work has attributed IOR to a motor bias against responding to targets at inhibited locations (Berlucchi, Tassinari, Marzi, & DiStefano, 1989; Klein & Taylor, 1994; Maylor, 1985; Taylor & Klein, 1998; see also Ivanoff & Klein, 2001). The present findings extend and elaborate this view by showing that the nature of the S–R mapping itself can determine the motor bias.

### 5.1. Delayed onset of IOR

Other lines of research have also reported a delayed onset of IOR. For instance, several studies have now shown a delay in the onset of IOR (or enhanced facilitation) in schizophrenic patients compared to control subjects (Huey & Wexler, 1994; Larrison-Faucher, Briand, & Sereno, 2002; Sapir, Henik, Dobrusin, & Hochman, 2001). In addition, other studies in normals have reported that onset of IOR can vary (Lupianez, Milan, Tornay, Madrid, & Tudela, 1997, 2001; Lupianez & Milliken, 1999). We now briefly consider three potential explanations for time course effects in IOR.

#### 5.1.1. Increasing facilitation

Tipper et al. (1997) suggested that exogenous spatial cues lead to separate facilitatory and inhibitory effects, each with an independent time course. They propose that it is the additive effect of a declining facilitation component and an increasing inhibitory component that we observe empirically as the onset of IOR. Changes in the apparent onset point of IOR could logically be due to either an enhancement of the *facilitatory* effects

following exogenous cues, or a delay in the buildup of automatically generated *inhibition* at cued locations. Strictly speaking, the data do not allow any way of distinguishing these two possibilities. One explanation for the present data, thus, might be that inhibitory processes do not differ for the different S–R mappings but that facilitation does vary. Thus, more indirect S–R mappings may reveal IOR at longer SOAs because a prolonged or enhanced facilitation effect obscures the point at which inhibition begins to build up. A separate and variable facilitation component could thus account for variable onset IOR.

In fact, such an explanation need not depend on reflexive processes per se. Voluntary attention to cued locations could also vary in intensity, thus leading to changes in facilitation effects at cued locations. When added with reflexive effects (both facilitatory and inhibitory) having a constant time course, the net result would be the same; the transition point from facilitation to IOR would vary across task and experiment. However, regardless of whether one assumes that reflexive or voluntary facilitation effects are the basis of variable onset IOR, there should be specific details regarding the mechanisms underlying the variation in facilitation across tasks, so that one can make clear or unambiguous predictions as to which conditions should have greater facilitation effects and why.

### 5.1.2. Attentional control settings

Another potential explanation for varying onsets of IOR is that of task difficulty. Specifically, it has been proposed that more difficult tasks will show a later onset of IOR than easier tasks (Lupianez & Milliken, 1999; Lupianez et al., 1997; see Klein, 2000 for a review). Klein (2000) discusses how attentional control settings (ACS; Folk, Remington, & Johnston, 1992) might be able to explain this effect. The notion of an ACS reflects the belief that sudden-onset (i.e., exogenous) cues can attract attention to varying degrees. More difficult tasks (e.g., stimulus discrimination as opposed to localization or detection) may require higher degrees of attentional allocation. Furthermore, because ACS cannot be switched very rapidly, this might mean that attention is allocated to the cue (or the cued location) in direct proportion to its required degree of involvement in processing stimuli occurring there (Klein, 2000). More difficult tasks thus would result in more attention being allocated to the cue. Attention would persist and facilitate processing at cued locations, thus delaying the appearance of IOR.

It is important to note that in our experiments the required degree of stimulus analysis was held constant. In all of our experiments simple localization was required. That is, “difficulty” in our experiments arose not

from varying the difficulty of stimulus analysis, but because *the response the subject had to make* varied in the directness of its S–R mapping. If the ACS explanation is to apply to the present results, it must be modified to allow “task difficulty” to apply to the response selection and execution end of the stimulus processing sequence. While it can be argued that reformulating the ACS argument to encompass difficulty caused by response factors represents a considerable departure from its original form (where only factors related to initial stimulus analysis are relevant; Folk et al., 1992), attempts to do so have been made. Klein (2000) has suggested that the ACS account can include factors other than target discrimination difficulty. It is thus plausible that factors related to response difficulty may affect ACS. This being the case, it is conceivable that when indirect responses are required, more attention is allocated in varying degrees to the tasks of response selection, planning, and even execution. Hence, one would expect more persistent facilitation and a delayed onset of IOR, just as we have reported.

Lupianez et al. (2001) have gone even further, proposing an account in which task difficulty per se is not even the relevant factor. Lupianez et al. (2001) included a manipulation where subjects had to discriminate two possible targets, either alone or in the presence of a distracting stimulus (an asterisk) which appeared together with the target in the location opposite the target. Logically, one would expect that the presence of distracters would make the task more difficult. According to the ACS account just described, this would entail a greater allocation of attention to the cued location and a subsequent delay in the onset of IOR. In fact the results were just the opposite; IOR onset occurred *sooner* when visual distracters were present.

This result demonstrates that task difficulty, however one defines it, may not account for all the variability in time course in spatial cueing paradigms. Lupianez et al. (2001) propose an explanation for such effects that is closely related to the ACS account, in that it assumes that visual attention is flexibly allocated to spatial cues in response to varying task demands. However while previous formulations relied on task difficulty as a central factor affecting the allocation of attention to spatial cues, they suggest another factor. Specifically, the proposal is that attentional set is controlled by two contrasting needs. One is the need to integrate newly processed visual information with currently represented visual information. The second need is to accurately detect and encode visual information representing new events. At this point it is difficult to see how this latest explanation of time course effects in IOR relates to the present data, where the degree or type of stimulus analysis required should not vary for different response mappings.

### 5.1.3. Tonic inhibition of reflexive attention

We would like to propose a third alternative that is consistent with the present data, and is based on current knowledge about the neurophysiology of attention and orienting systems. First, we distinguish between voluntary attention processes (controlled by prefrontal or frontal cortical systems) and more reflexive attention mechanisms (involving subcortical orienting systems). The prefrontal cortex (PFC) is believed to play a central role in inhibiting reflexive orienting processes via the basal ganglia (for review, see Hikosaka & Wurtz, 1989). In addition, patients with lesions of the PFC have great difficulty with the antisaccade task, making instead, prosaccades to the target (Guitton, Buchtel, & Douglas, 1985). Sereno (1992) has proposed a model of voluntary and reflexive spatial attention which suggests that voluntary systems, localized in PFC, exert tonic inhibition on more reflexive orienting mechanisms, and evidence from a number of subject populations supports the model (Briand, Hening, Poizner, & Sereno, 2001; Briand, Strallow, Hening, Poizner, & Sereno, 1999a,b; Larrison, Ferrante, Briand, & Sereno, 2000; Sereno, 1996; Sereno & Holzman, 1996). A prediction of this model is that deficits in prefrontal activity should result in hyper-reflexive orienting and increased prefrontal activity should result in increased inhibition of reflexive orienting.

To account for the data reported from our experiments, we propose that (a) prefrontal systems become more active when indirect S–R mappings are used. This (b) perhaps engenders a voluntary facilitation (similar to explanation in Section 5.1.1 above) and causes increased tonic inhibition to be exerted on the subcortical systems governing reflexive orienting, specifically those responsible for automatically maintaining IOR. These two effects in turn lead to (c) a delay in the apparent onset of IOR as S–R complexity increases. The first assumption in our proposal should be non-controversial, since one of the most distinctive disorders following prefrontal damage is the inability to plan and execute tasks that are guided by internal cues (Fuster, 1989; Perecman, 1987). The prefrontal patient often has trouble when forced to develop a new form of behavior or novel sequence of acts. Thus, the increasing complexity or “internalization” of the S–R mappings used in the present experiments would be likely to require increased involvement of prefrontal systems during performance of the task (for recent review, see Murray, Bussey, & Wise, 2000). Inhibition of reflexive orienting mechanisms, and subsequent delay of IOR, would follow based on much neurophysiological and neuropsychological work that suggests that PFC plays an inhibitory role with respect to the colliculus (e.g., Everling, Dorris, & Munoz, 1998; Everling, Dorris, Klein, & Munoz, 1999; Everling & Munoz, 2000;

Guitton et al., 1985; Hikosaka & Wurtz, 1989). Inhibition of reflexive orienting mechanisms by voluntary orienting mechanisms is also consistent with experimental work that shows that when exogenous cues are predictive of target location, facilitation persists at the cued location and IOR is absent (Wright & Richard, 2000). Our finding that varying S–R directness affects IOR onset therefore may suggest a role for prefrontal systems in modulating these effects.

This tonic inhibition account includes the assumption that IOR is mediated by primarily subcortical mechanisms. Several lines of research have provided much of the evidence for a collicular role in IOR in humans (see Briand, Szapiel, & Sereno, submitted for publication, for review). First, Posner and colleagues found that both initial covert orienting (Posner, Cohen, & Rafal, 1982; Rafal, Posner, Friedman, Inhoff, & Bernstein, 1988) and later occurring IOR (Posner et al., 1985) were reduced in the vertical direction in progressive supranuclear palsy patients with damage to the midbrain and superior colliculus. Also, Rafal, Calabresi, Brennan, and Sciolto (1989) demonstrated a visual field asymmetry in spatial cueing that they argued was due to the unequal visual field representation that occurs in the innervation of the SC. In addition, two recent studies found that patients with collicular lesions failed to show IOR (Briand et al., 1999a,b; Sapir, Soroker, Berger, & Henik, 1999). Finally, Dorris, Klein, Everling, and Munoz (in press); Dorris, Everling, Klein, and Munoz (1998) have demonstrated that neurons in the superficial and intermediate layers of the superior colliculus show an attenuated visual response to the target if it has been preceded by a peripheral non-informative cue, demonstrating for the first time a potential physiological manifestation of IOR in the superior colliculus.

Dorris et al. (in press) also demonstrate that these neurons with attenuated visual responses do not seem to be inhibited at the time of target onset, because baseline activity is actually elevated. This could be interpreted as suggesting that other cortical regions may also play a role in generation of IOR. For instance, some work has suggested there may be more than one kind of IOR and that other cortical areas may be involved. Tipper, Weaver, Jerreat, and Burak (1994, 1997) have argued for the presence of two forms of IOR: one based on locations, and the other on object representations. Further, they proposed that location-based IOR utilizes subcortical structures, whereas object-based IOR requires cortical circuitry. The procedures we used to study spatial attention do not assess object-based IOR, and therefore it is unclear whether time course effects analogous to the ones we report here would even be observed when object-based, not location-based IOR, was studied.

We have laid out a number of alternative explanations for the present findings. Future research will be necessary to determine which of these alternatives provides a more adequate account for the results we have presented here. In conclusion, the present study makes three important contributions to the spatial attention literature. First, we have demonstrated systematic delays in onset of IOR as a function of the directness of the S–R mapping in tasks requiring target localization. Second, the influence of response demands on IOR suggests that spatial attention does not merely operate on the input end of stimulus processing. In our studies, the act of attending to a location in space is perhaps better conceived of as facilitating (or in the case of IOR, inhibiting) responses. Finally, we suggest a testable neurophysiologically based theory (increasing prefrontal demands) for the differences in time course observed here.

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**Appendix A. Percentage gain and standard errors for correct responses in each task reported in Experiments 1–3**

Experiment × Task	% Gain (std. err.)
<i>Experiment 1</i>	
Saccade	78.9 (1.1)
Mouse	77.3 (3.3)
Point	93.6 (1.9)
<i>Experiment 2</i>	
Saccade	77.8 (1.2)
Antisaccade	77.3 (1.4)
Indirect	76.0 (2.4)
<i>Experiment 3</i>	
Saccade-Direct	82.0 (1.1)
Saccade-Indirect	81.9 (1.9)
Point-Direct	89.4 (1.4)
Point-Indirect	94.1 (2.3)

**Appendix B. Error rates for Experiments 1 and 2, as a function of Response type, Cue and SOA (standard errors are given in parentheses)**

Experiment	Cue	67	94	133	200	1000
<i>Experiment 1:</i>						
Saccade	Cued	0.2 (0.2)	0.0 (0.0)	0.2 (0.2)	0.7 (0.4)	0.4 (0.3)
	Uncued	2.6 (0.8)	1.3 (0.6)	2.2 (0.7)	1.7 (0.6)	0.7 (0.7)
Pointing	Cued	1.1 (0.6)	3.0 (0.8)	3.8 (0.9)	2.5 (1.3)	4.8 (1.4)
	Uncued	4.7 (1.9)	5.9 (1.2)	3.5 (0.8)	1.7 (0.6)	4.9 (1.3)
Mouse	Cued	0.2 (0.2)	0.2 (0.2)	0.0 (0.0)	0.2 (0.2)	0.2 (0.2)
	Uncued	1.9 (0.9)	1.4 (0.9)	2.3 (0.8)	3.7 (0.9)	0.0 (0.0)
<i>Experiment 2:</i>						
Saccade	Cued	0.0 (0.0)	0.0 (0.0)	2.8 (1.2)	0.8 (0.8)	0.0 (0.0)
	Uncued	4.3 (1.3)	3.5 (1.6)	4.0 (1.8)	3.9 (1.8)	0.9 (0.9)
Antisaccade	Cued	3.7 (1.7)	2.9 (1.2)	2.2 (1.1)	3.5 (1.6)	4.9 (1.9)
	Uncued	5.6 (1.9)	5.6 (1.9)	10.7 (3.3)	9.6 (3.3)	3.8 (1.4)
Indirect	Cued	10.8 (2.7)	9.4 (2.5)	4.3 (1.7)	7.6 (2.8)	17.2 (4.2)
	Uncued	16.4 (3.7)	12.1 (3.1)	14.6 (3.6)	18.4 (3.7)	17.0 (3.8)

## Appendix C

Source	df	F-value	p-value
<i>Analysis of RTs, Experiment 3:</i>			
Response (R)	1, 23	17.42	0.0004
Mapping (M)	1, 23	400.42	0.0001
SOA (S)	4, 92	32.93	0.0001
Cue (C)	1, 23	0.05	0.8255
R × M	1, 23	155.65	0.0001
R × S	4, 92	0.79	0.5334
M × S	4, 92	4.46	0.0024
R × C	1, 23	17.07	0.0004
M × C	1, 23	33.90	0.0001
S × C	4, 92	15.11	0.0001
R × M × S	4, 92	1.72	0.1524
R × M × C	1, 23	4.89	0.0373
R × S × C	4, 92	1.04	0.3907
M × S × C	4, 92	2.06	0.0920
R × M × S × C	4, 92	0.77	0.5449
<i>Analysis of percent errors, Experiment 3:</i>			
Response (R)	1, 23	57.60	0.0001
Mapping (M)	1, 23	52.42	0.0001
SOA (S)	4, 92	1.34	0.2624
Cue (C)	1, 23	3.34	0.0804
R × M	1, 23	29.88	0.0001
R × S	4, 92	71.34	0.2606
M × S	4, 92	1.22	0.3090
R × C	1, 23	0.96	0.3374
M × C	1, 23	0.25	0.6228
S × C	4, 92	1.94	0.1102
R × M × S	4, 92	0.92	0.4552
R × M × C	1, 23	0.54	0.4688
R × S × C	4, 92	0.83	0.5100
M × S × C	4, 92	1.00	0.4119
R × M × S × C	4, 92	0.64	0.6375

## Appendix D. Error rates for Experiments 3 and 4, as a function of Response type, Cue and SOA

Experiment	Cue	94	200	300	400	1000
<i>Experiment 3:</i>						
Saccade-Direct	Cued	0.0 (0.0)	0.0 (0.0)	0.3 (0.3)	0.7 (0.5)	0.3 (0.3)
	Uncued	1.4 (0.7)	1.7 (0.7)	0.7 (0.5)	0.0 (0.0)	0.0 (0.0)
Saccade-Indirect	Cued	5.3 (1.4)	4.2 (1.1)	4.6 (1.1)	3.8 (1.1)	4.2 (0.9)
	Uncued	7.0 (1.6)	5.5 (1.1)	3.1 (1.3)	5.8 (1.4)	3.2 (1.3)
Point-Direct	Cued	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.3 (0.3)
	Uncued	0.3 (0.3)	0.7 (0.5)	0.3 (0.3)	0.0 (0.0)	0.7 (0.5)
Point-Indirect	Cued	0.8 (0.5)	1.0 (0.6)	1.0 (0.6)	1.5 (0.7)	1.1 (0.6)
	Uncued	0.7 (0.5)	1.7 (0.9)	1.1 (0.6)	1.4 (0.7)	0.0 (0.0)
<i>Experiment 4:</i>						
Fixate-Direct	Cued	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Uncued	0.5 (0.5)	0.5 (0.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Fixate-Indirect	Cued	1.1 (1.1)	0.5 (0.5)	1.6 (1.0)	1.1 (1.1)	2.1 (0.8)
	Uncued	2.1 (0.9)	1.6 (1.0)	0.5 (0.5)	0.5 (0.5)	1.0 (1.0)
Move-Direct	Cued	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.5 (0.5)	1.1 (0.6)
	Uncued	1.1 (0.6)	0.5 (0.5)	0.0 (0.0)	1.1 (0.6)	0.5 (0.5)
Move-Indirect	Cued	1.1 (1.1)	1.6 (0.5)	0.5 (0.5)	1.6 (0.5)	1.0 (1.0)
	Uncued	0.5 (0.5)	2.1 (0.8)	0.0 (0.0)	0.5 (0.5)	0.5 (0.5)

## Appendix E. Analysis of RTs, Experiment 4

Source	df	F-value	p-value
Eyes (E)	1, 3	1.08	0.3761
Response (R)	1, 3	0.10	0.7691
Mapping (M)	1, 3	122.27	0.0016
SOA (S)	4, 12	10.09	0.0008
Cue (C)	1, 3	48.36	0.0061
E × R	1, 3	1.68	0.2859
E × M	1, 3	0.07	0.8069
R × M	1, 3	2.90	0.1871
E × S	4, 12	2.53	0.0955
R × S	4, 12	0.11	0.9769
M × S	4, 12	2.24	0.1259
E × C	1, 3	2.28	0.2283
R × C	1, 3	0.21	0.6806
M × C	1, 3	22.59	0.0177
S × C	4, 12	5.26	0.0111
E × R × M	1, 3	0.25	0.6519
E × R × S	4, 12	1.10	0.4023
E × M × S	4, 12	1.66	0.2240
R × M × S	4, 12	0.05	0.9942
E × R × C	1, 3	2.91	0.1864
E × M × C	1, 3	0.62	0.4890
R × M × C	1, 3	2.53	0.2101
E × S × C	4, 12	0.39	0.8108
R × S × C	4, 12	1.89	0.1773
M × S × C	4, 12	0.72	0.5947
E × R × M × S	4, 12	1.32	0.3192
E × R × M × C	1, 12	0.22	0.6704
E × R × S × C	4, 12	0.24	0.9081
E × M × S × C	4, 12	0.20	0.9327
R × M × S × C	4, 12	1.15	0.3808
E × R × M × S × C	4, 12	0.65	0.6406

## Appendix F. Analysis of percent errors, Experiment 4

Source	df	F-value	p-value
Eyes (E)	1, 3	0.08	0.7982
Response (R)	1, 3	1.19	0.3555
Mapping (M)	1, 3	2.94	0.1852
SOA (S)	4, 12	2.13	0.1398
Cueing (C)	1, 3	0.00	1.0000
E × R	1, 3	0.04	0.8625
E × M	1, 3	3.21	0.1711
R × M	1, 3	0.29	0.6285
E × S	4, 12	1.72	0.2100
R × S	4, 12	0.55	0.7056
M × S	4, 12	0.66	0.6310
E × C	1, 3	0.34	0.6034
R × C	1, 3	0.64	0.4834

Source	df	F-value	p-value
M × C	1, 3	1.24	0.3466
S × C	4, 12	2.11	0.1419
E × R × M	1, 3	0.77	0.4441
E × R × S	4, 12	1.30	0.3239
E × M × S	4, 12	2.06	0.1500
R × M × S	4, 12	0.57	0.6879
E × R × C	1, 3	2.85	0.1897
E × M × C	1, 3	0.69	0.4660
R × M × C	1, 3	1.40	0.3224
E × S × C	4, 12	0.10	0.9802
R × S × C	4, 12	0.28	0.8867
M × S × C	4, 12	0.31	0.8651
E × R × M × S	4, 12	6.75	0.0044
E × R × M × C	1, 3	0.36	0.5911
E × R × S × C	4, 12	0.52	0.7255
E × M × S × C	4, 12	0.43	0.7826
R × M × S × C	4, 12	0.55	0.7032
E × R × M × S × C	4, 12	1.15	0.3811

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