THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2013
http://dx.doi.org/10.1080/17470218.2013.859282

Routledge
Taylor & Francis Group

Inhibition of return affects contrast sensitivity

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Inhibition of return (IOR)—a slow response to targets at recently attended locations, is believed to play an important role in guiding behaviour. In the attention literature it has been shown that attentional capture by an exogenous cue affects contrast sensitivity so that it alters the appearance of low-contrast stimuli. Despite a significant amount of work over the last quarter century on IOR, it is not yet clear whether IOR operates in the same way. In the current study we examined the effect of IOR on contrast sensitivity—a very early, low-level perceptual process. We found in both a detection task and an orientation discrimination task that lower contrast was needed to detect the stimulus (Experiment 1) and determine its orientation (Experiment 2) at the cued location than at the uncued location, at short cue–target delays, while higher contrast was needed at long delays—reflecting IOR. These results clearly demonstrate that IOR affects contrast sensitivity in a similar way as attentional capture does and suggest that IOR increases perceived contrast of an object in the uncued location.

Keywords: Attention; Inhibition; Inhibition of return; Perception; Contrast sensitivity.

The visual system is a limited-capacity processor despite its massively parallel architecture. It has long been proposed that attention is the mechanism by which we select those aspects of the visual scene that are most relevant to our current goals. This selection process allows limited resources to be allocated where they would be most beneficial.

One way in which selection takes place is in a bottom-up fashion, as when our attention is drawn to a salient stimulus such as an object that suddenly appears or changes its motion. Initially, responses to stimuli at the location of the salient event are facilitated, reflecting the allocation of limited visual resources there. However, the facilitation is typically short-lived, and after a brief period of time people are actually slower to respond to events at the previously enhanced location. This latter process is called *inhibition of return* (IOR; Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985), a term that reflects the belief that people are inhibited in returning their attention to the recently attended location after they have moved their attention elsewhere (but see, for example, Martin-Arevalo, Kingstone, & Lupianez, 2013, suggesting that IOR occurs without moving attention away from the cue). IOR is thought to play a key role in visual search by driving the visual system to sample from fresh sources of input (Itti & Koch, 2001; Klein, 1988; Klein & MacInnes, 1999; Mirpour, Arcizet, Ong, & Bisley, 2009; Wang & Klein, 2010).

There is wide agreement in the literature that IOR can affect both motoric and perceptual processes (see, for example, Taylor & Klein, 2000, and recently Zhao, Heinke, Ivanoff, Klein, &

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We thank Giovanni d'Avossa for technical assistance.

Humphreys, 2011). There is considerable evidence that IOR biases performance against responding to stimuli from the cued location (Abrams & Dobkin, 1994; Ivanoff & Klein, 2001, 2004, 2006; Ivanoff, Klein, & Lupiáñez, 2002; Schmidt, 1996; Taylor, 2007; Taylor & Ivanoff, 2003), which suggests a late influence of IOR on performance. For example, Ivanoff and Klein (2001) tested the effect of response competition on IOR. The authors compared IOR in a condition where a simple reaction time (RT) was used with that in a condition where the nonresponding hand was placed on an irrelevant response key. Because there is a natural tendency to respond with the hand corresponding to the location of the target, even when the location is irrelevant (Simon & Rudell, 1967), placing the nonresponding hand on a key would induce a response competition. The authors found that IOR was larger when response competition was introduced, and they took it as evidence for a response (motoric) inhibition component in IOR.

On the other hand, IOR was also found to operate at a relatively early stage of processing. For example, IOR influences the amplitude of P1, an early electrophysiological wave that evokes from activity in extrastriate visual areas (McDonald, Ward, & Kiehl, 1999). Klein and Dick (2002) found that IOR can even affect accuracy in a paradigm that does not require rapid responses and concluded that IOR can influence perception and therefore affects performance at early stages of the visual process (see also Cheal & Chastain, 1999; Theeuwes & Chen, 2005). Finally, Handy, Jha, and Mangun (1999) suggested that IOR affects perception by showing that it is reflected in reduced sensitivity (d') at the cued location at long cue–target delays compared to that at the uncued location (see also Ivanoff & Klein, 2006).

Despite great interest in the question of the stage of processing that is influenced by IOR, no study has yet looked at the effect of IOR on contrast sensitivity, one of the most basic perceptual processes affecting activation of early visual areas (Liu, Pestilli, & Carrasco, 2005; Martinez-Trujillo & Treue, 2002; McAdams & Maunsell, 1999; Reynolds, Pasternak, & Desimone, 2000). Studies on the effect of attentional capture on visual processing revealed that orienting of attention affects early perceptual processes such as contrast sensitivity (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lu & Dosher, 1998, 2000) and spatial resolution (Carrasco & Yeshurun, 2009; Yeshurun & Carrasco, 1998), suggesting that shifting attention to a location enhances perception (but see, for example, Kerzel, Zarian, & Souto, 2009; Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, & Garrett, 2005, contrasting this finding). No similar study has been conducted with IOR. Studying IOR using the same tasks as those used to study shifts of attention would allow better comparison between the mechanisms of attention and IOR.

In the present study, we test whether IOR affects contrast sensitivity in detection (Experiment 1) and orientation discrimination (Experiment 2) tasks. We used Gabor stimuli in different contrasts and measured the effects of IOR on contrast sensitivity—a basic, very early visual process.

EXPERIMENT 1

Unlike most studies of IOR, our main dependent measure was accuracy, not reaction time (RT). Accuracy measures, in contrast to response latencies, are unlikely to be affected by the motoric component in IOR and thus would be more likely to reveal purely perceptual IOR.

Method

Participants

Fourteen (7 females) naive undergraduate students, age between 18 and 21 years ($M = 19.8$), from Bangor University, participated in the experiment and received course credit for their participation. All had normal or corrected-to-normal vision. All participants gave a written consent, and the experiments were approved by the Bangor University, School of Psychology ethics board.

Apparatus and stimuli

Participants sat in a dark room facing a computer screen 57 cm in front of them at eye level. The target stimulus was a sinusoidally modulated luminance circular patch, oriented either vertically or horizontally. The luminance profile $L(x, y)$ of the vertically oriented grating, with a Michelson contrast C_M, was computed using the following formula:

$$L(x, y) = L_0 \cdot \left[1 + C_M \sin\left(\frac{2\pi \cdot x}{\lambda}\right) \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right)\right]$$

The grating's spatial period, λ, was 0.42° and was windowed by a circularly symmetric Gaussian envelope with a spatial constant, σ, of 0.3°. Stimuli were presented on a gamma corrected monitor whose background luminance L_0 was 31 cd m^{-2}.

The experiment was programmed using E-Prime 1.2 (Psychology Software Tools, Pittsburgh, PA). The participant's index fingers rested on the "M" and "Z" keys of a keyboard located on the table between the participant and the screen, and their heads were steadied with a chinrest. A constant display consisted of three boxes (white squares, on a grey background), each 2° on a side. One box was in the centre of the screen, and the other two were displayed with their centres 8° to the right and to the left of the centre box (see Figure 1). The target stimulus was a Gabor stimulus, which could appear in one of six different contrasts (3, 6, 9, 12, 15, and 18%) inside either one of the peripheral boxes with equal probability. Half of the trials contained no target. When the target appeared it could be either horizontal or vertical. Cues were presented by surrounding a box with a 0.5° black border in a flashing manner (on–off–on–off) and were not predictive for the location of the target.

Procedure

Each trial began with a blank screen for 500 ms, followed by three white boxes presented for 1000 ms. The cue was then presented for 200 ms (50 ms for each on and off phase). The target followed the cue offset after 100 or 750 ms, corresponding to two stimulus onset asynchronies (SOAs), 300 or 950 ms, and remained visible for 50 ms. In the long SOA condition, following the cue and a blank screen of 250 ms, a central cue was presented (a thick outline around the central box) for 250 ms to reorient attention back to the central box (see Figure 1). The target could appear in the right or the left box in with equal probability. Participants were asked to determine whether the target was present or absent (regardless of whether it was horizontal or vertical) by pressing one of the two response keys. They were told that this was not a speeded task so there was no need to hurry, but to be as accurate as possible. Feedback was provided by distinct tones after correct and incorrect trials. Participants were also instructed to fixate their eyes in the centre and to refrain from making eye movements. Eye movements were not recorded but the experimenter was seated in front of the participants and encouraged them to keep their eyes fixed if it was needed.

Design

Each participant was presented with 12 practice trials and 768 experimental trials. The three independent variables were contrast (3, 6, 9, 12, 15, 18%), SOA (300, 950 ms), and cueing (cued, uncued). The dependent variable was percentage correct in the target-present trials. We analysed only target-present trials because it is not possible to sort the target-absent trials into the different conditions.

Results

Two participants failed to complete the experiment, and thus the analysis is based on 12 participants only. Percentage correct in the target-present trials was calculated for each experimental condition, normalized with the arcsine of the square root of the probability in order to transform them to a normally distributed variable, and entered into a three-way repeated measures analysis of variance (ANOVA; with factors of contrast, SOA, and cueing). Note that normalized data were used

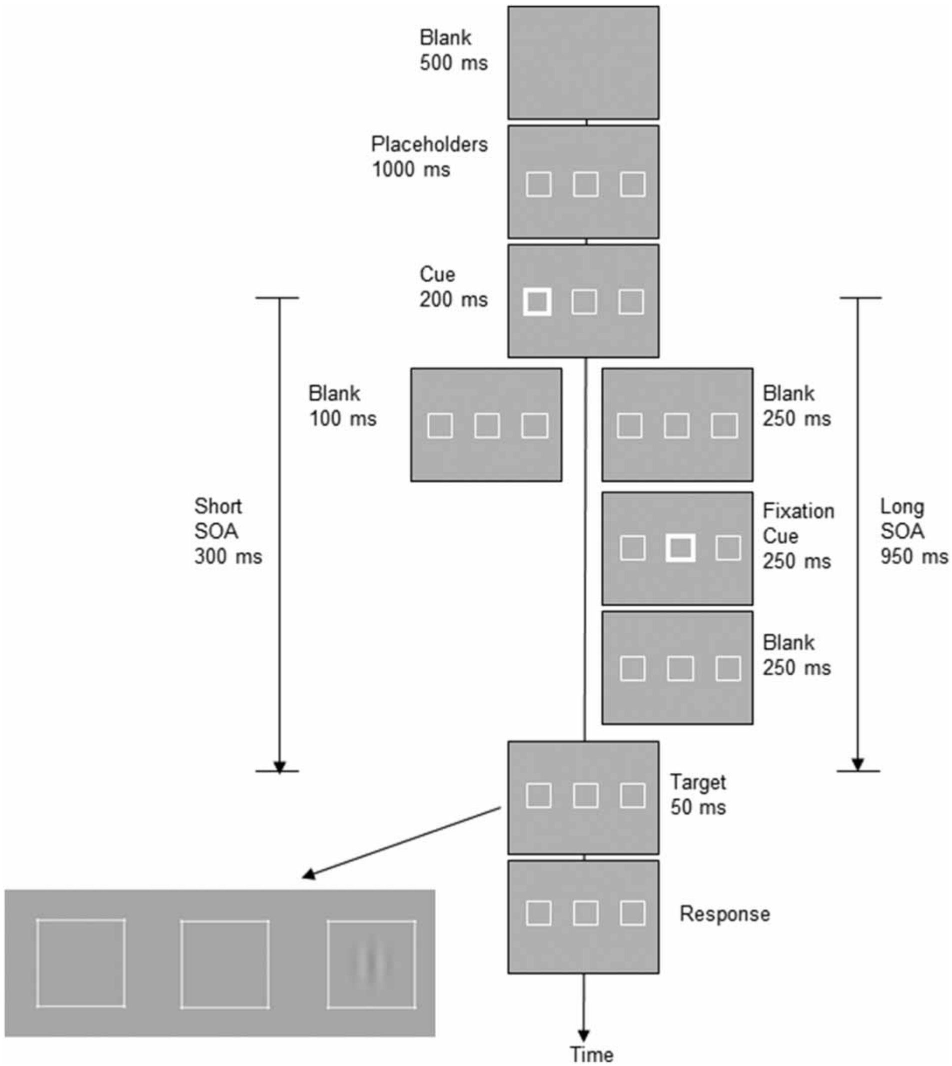

Figure 1. *Experimental procedure. Each trial consisted of the following events: a blank screen presented for 500 ms; three boxes (placeholders) presented for 1000 ms; a cue (brightening of one of the boxes) presented for 200 ms; placeholders for either 100 ms (short stimulus onset asynchrony, SOA) or 250 ms (long SOA); then, either the target appeared in one of the peripheral boxes for 50 ms (short SOA) or a fixation cue was presented for 250 ms, followed by another 250-ms presentation of the placeholders before the target appearance. The target was a Gabor stimulus. The two SOAs were 300 ms and 950 ms.*

for the analysis only. All figures and tables show raw data. Although this was not a speeded task, RTs of less than 100 ms were treated as guesses and were removed from subsequent analyses. This procedure excluded less than 1% of the data and did not interact with trial condition. No upper limit for RT was applied.

Figure 2 shows the mean psychometric functions for accuracy in target-present trials (percentage of pressing yes given that the target was present) as a function of contrast, in cued and uncued conditions from all participants, in the short (left panel) and the long (right panel) SOAs. As expected, accuracy increased as a

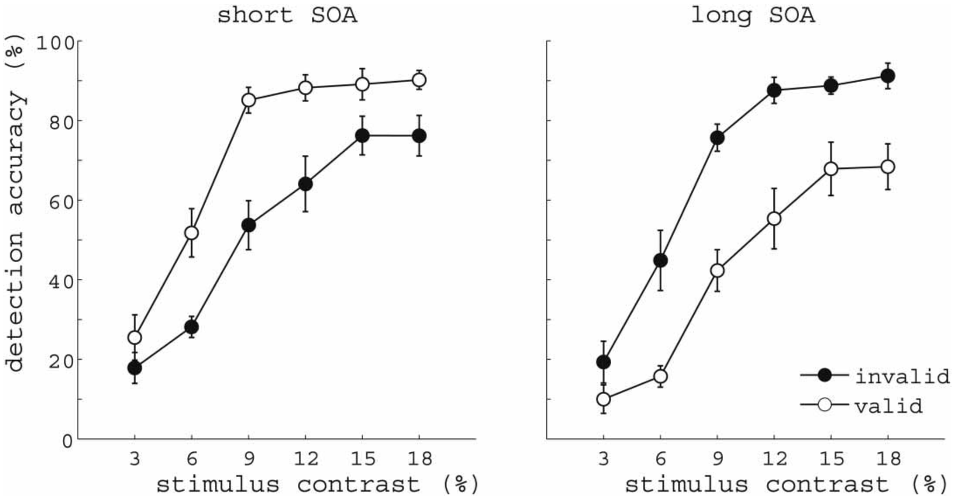

Figure 2. *Results from Experiment 1: detection task. Percentage of hits (percentage of pressing "yes" given that the target is present) for cued (white circles) and uncued (black circles) trials in short (left panel) and long (right panel) stimulus onset asynchrony (SOA), as a function of percentage contrast. Error bars represent standard error of the mean.*

function of target contrast in both cued and uncued conditions for the two SOAs, resulting in a main effect of contrast, $F(5, 55) = 43.08$, $p < .0001$. There was also a main effect of SOA, $F(1, 11) = 6.563$, $p < .05$, showing greater accuracy in the short SOA than in the long SOA. Most importantly, the interaction between SOA and cueing was significant, $F(1, 11) = 44.628$, $p < .0001$, indicating that accuracy was higher on cued trials than on uncued trials at the short SOA, but was lower on cued than on uncued trials when the SOA was long (i.e., IOR was found). Thus, while the cue enhanced contrast sensitivity at the short SOA, it reduced contrast sensitivity at the long SOA. In addition, the three-way interaction between SOA, cueing, and contrast was significant, $F(5, 55) = 8.016$, $p < .0001$. A paired t-test confirmed that this reflects the fact that the difference between cued and uncued was significant in all contrast levels [all $t(11) > 2.68$, $p < .05$], apart from contrast 3% in the short SOA, $t(11) = 1.22$, $p = .24$.

In this design, it is not possible to calculate false alarms separately for the cued and uncued conditions, as absent trials cannot be allocated to the two cueing conditions. However, we calculated the overall false-alarm rates in the short and the long SOAs, and they were 13% (*SD* 0.079) and 11% (*SD* 0.049), respectively.

Although participants were instructed to prefer accuracy over speed, in order to determine whether there was a speed–accuracy trade-off, we also analysed the RT data. In an ANOVA with SOA, cueing, and contrast as variables, significant

Table 1. *Mean RTs from Experiment 1*

SOA	*Contrast*	*Cued*	*Uncued*
Short SOA	1	1051.2 (116.88)	1234.82 (186.09)
	2	829.1 (57.22)	955.92 (61.72)
	3	774.01 (45.36)	937.62 (115.73)
	4	736.03 (40.25)	938.06 (98.95)
	5	767.28 (61.47)	830.55 (54.26)
	6	739.3 (58.28)	843.68 (64.64)
	All	816.15 (55.5)	956.77 (80.01)
Long SOA	1	941.79 (93.62)	771.98 (84.22)
	2	838.57 (65.17)	910.04 (118.72)
	3	805.60 (46.83)	780.88 (54.43)
	4	822.02 (71.95)	735.65 (78.68)
	5	800.69 (61.19)	709.68 (48.87)
	6	820.99 (68.9)	706.18 (45.8)
	All	838.27 (48.58)	769.06 (61.96)

Note: RT = reaction time, in ms; SOA = stimulus onset asynchrony. Standard errors are in parentheses.

effects were found for SOA, $F(1, 11) = 9.537$, $p < .01$, reflecting the fact that trials with long SOA had shorter RTs than trials with long SOA (803.67 vs. 886.46 ms); contrast, $F(5, 55) = 12.497$, $p < .001$, showing that higher contrast stimuli resulted in shorter RTs (999.9, 883.4, 824.5, 807.9, 777.1, 777.5 ms for contrast levels 3, 6, 9, 12, 15, 18%, respectively); and the interaction between SOA and cueing, $F(1, 11) = 16.1$, $p < .002$, reflecting IOR (see Table 1). No other main effect or interaction was significant.

Discussion

In the first experiment, we showed that accuracy in detecting the presence of a low-contrast Gabor stimulus depends on whether attention is allocated to the stimulus's location and on the occurrence of IOR. Attention was drawn to one location on the screen by a flash of one of the place-holders. If the target then appeared shortly after the cue (300 ms), less contrast was required to detect the stimulus in the cued location than in the uncued location. In contrast, if the target appeared 950 ms after cue onset, the opposite pattern was observed, with lower contrast needed to detect the stimulus in the uncued location than in the cued location. The result that orienting attention to a location lowers a perceptual threshold is consistent with a growing psychophysical and neurophysiological literature on the effects of attention on early visual processing (e.g., Cameron et al., 2002; Carrasco et al., 2000; Reynolds et al., 2000; Treue & Martinez-Trujillo, 1999), including contrast sensitivity. However, to our knowledge, this is the first study that shows that IOR affects contrast sensitivity as well.

Several studies so far have used signal detection theory to show that IOR affects d' and inferred that it influences perceptual sensitivity (Handy et al., 1999; Ivanoff & Klein, 2006; Theeuwes & Chen, 2005). In our detection task we could not separately calculate false alarms for the cued and uncued conditions, and as a result it is not possible to determine definitively whether any effect is due to sensitivity or response bias. Therefore, in the next experiment participants performed a two-choice discrimination task where they were asked to determine whether a low-contrast Gabor stimulus was oriented horizontally or vertically.

EXPERIMENT 2

Experiment 2 was similar to Experiment 1 with one major difference. Instead of detecting the appearance of the Gabor stimulus, participants were asked to discriminate its orientation.

Method

Participants

Fourteen (12 females) naive undergraduate students, age between 20 and 29 years ($M = 24.02$), from Bangor University participated in the experiment to receive course credit, or monetary compensation for their participation. All the participants had normal or corrected-to-normal vision.

Apparatus and stimuli

Apparatus were the same as those in Experiment 1. Participants sat in a dark room facing a computer screen 57 cm in front of them at eye level with their heads steadied by a chinrest. The participant's index fingers rested on the "M" and "Z" keys of a keyboard located on the table between the participant and the screen. The display was the same as that in Experiment 1, with two exceptions: (a) The target appeared in all trials, and (b) the Gabor patch could be one of six contrasts, different from those used in Experiment 1 (2, 6, 10, 14, 18, 22%). These contrasts were chosen to allow a full range of accuracies, as a pilot experiment with a discrimination task (not reported here), using the same contrast levels as in Experiment 1, showed that the average accuracies ranged between 50 and 80% .

Procedure

Each trial began with a blank screen for 500 ms followed by the appearance of three grey boxes. One thousand ms later, one of the peripheral boxes was cued by flashing it for 200 ms. On short SOA trials, after a 100-ms delay the target was presented, resulting in an SOA of 300 ms. On long

SOA trials, after a 250-ms delay the centre box was cued by presenting a border around it for 250 ms. An additional 250-ms blank interval elapsed before the target was presented, resulting in an SOA of 950 ms. The target remained visible for 50 ms. Participants were asked to determine the orientation of the grating in the Gabor stimulus (either horizontal or vertical) as accurately as possible, by pressing one of two keys. Again it was emphasized that this was not a speeded task, and participants should not hurry, but instead try to be as accurate as possible. Participants were also instructed to refrain from making eye movements, though eye movements were not recorded. As in Experiment 1, the experimenter was seated in front of the participants and encouraged them to keep their eyes in the centre if it was needed.

Design

After 12 practice trials, participants received five blocks, which each contained the 96 unique trial types for a total of 480 trials: The right and left sides were equally likely to be cued at both the short and long SOA; and for each of the four cue types, the target was equally likely to be on the right or left, to be one of the six contrasts, and to be horizontally or vertically oriented. The three independent variables were contrast (2, 6, 10, 14, 18, 22%), SOA (300, 950 ms), and cueing (cued, uncued). The dependent variable was the accuracy of response (correct or incorrect).

Results and discussion

Accuracy was calculated for each experimental condition, normalized with the arcsine of the square root of the probability, and entered into a three-way repeated measures ANOVA (with factors of contrast, SOA, and cueing). Trials with RT less than 100 ms were excluded from the analysis. This procedure excluded less than 1.5% of the data and did not differ by trial condition.

Figure 3 shows the mean psychometric functions (percentage correct as a function of contrast) on cued and uncued trials from all participants, in the short (left panel) and the long (right panel) SOAs. There was one significant main effect of contrast, $F(5, 65) = 84.79$, $p < .0001$, showing that targets of higher contrast were discriminated more accurately. Most importantly, the interaction of SOA and cueing was significant, $F(1, 13) = 11.298$, $p < .005$, indicating that accuracy was higher on cued trials than on uncued trials when SOA was short but the opposite pattern was found with long SOAs—that is, accuracy was lower on cued than on uncued trials. This pattern indicates the presence of IOR. No other main effects or interactions were significant.

Sensitivity calculation

Next, we calculated sensitivity based on signal detection theory. To do so, we assumed that one orientation (say horizontal) was the correct one. Accordingly, hits were calculated as the number of pressing responses of "horizontal" when the Gabor was presented horizontally, false alarms as the number of "horizontal" responses when the vertical Gabor was presented, misses as the number of "vertical" responses when the Gabor was oriented horizontally, and correct rejections as the number of "vertical" responses when the Gabor was indeed vertical. The d' measure was calculated as a measure of sensitivity to target orientation (see Table 2) and was entered into a two-way repeated measures ANOVA with SOA (long, short) and cueing (cued, uncued) as factors. A significant interaction was found between SOA and cueing, $F(1, 13) = 13.05$, $p < .005$. The interaction reflects a larger d' for cued (compared to uncued) trials at the short SOA, and a smaller d' for cued (compared to uncued) trials at the long SOA. This pattern is exactly what would be expected if IOR affected perceptual sensitivity to orientation. Due to low rate of false alarms in high contrasts, we could not calculate d' for each contrast level. Instead, we calculated A', a nonparametric measure of sensitivity, similar to d' (Snodgrass, Levy-Berger, & Haydon, 1985). A' varies from 0 to 1, where .5 indicates chance performance, and the higher the number the better the discriminability is. In a three-way repeated measures ANOVA with SOA (long, short), cueing (cued, uncued), and contrast (2, 6, 10, 14, 18, 22%) as factors, there was a significant effect of contrast, $F(5, 65) = 66.95$, $p < .0001$, reflecting

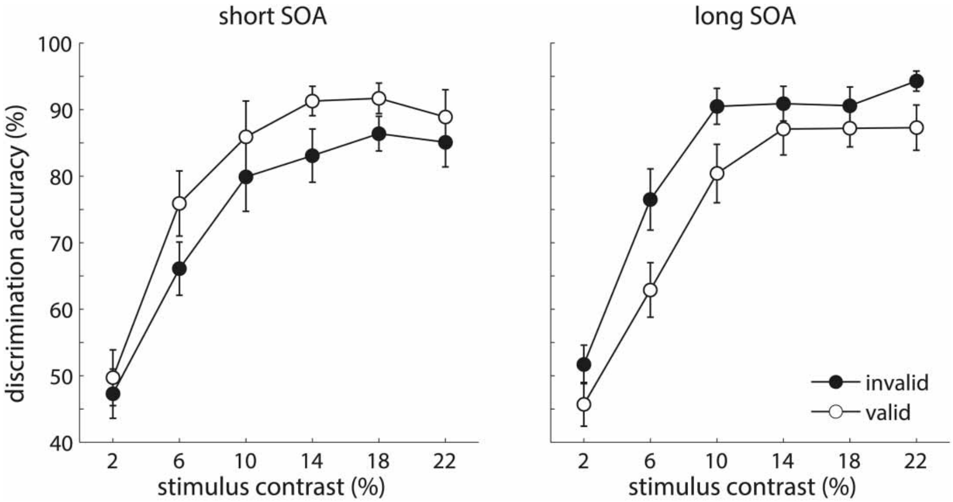

Figure 3. *Results from Experiment 2: orientation discrimination task. Accuracy (percentage correct) for cued (white circles) and uncued (black circles) trials in short (left panel) and long (right panel) stimulus onset asynchrony (SOA), as a function of percentage contrast. Error bars represent standard error of the mean.*

Table 2. *Mean* d′ *for SOA and cueing conditions, and* A′, *hit rate, and false-alarm rate for each contrast level, from Experiment 2*

Condition	d′	*Contrast*	A′	*% Hits*	*% False alarms*
Short SOA—cued	2.01 (0.694)	1	.49 (.24)	47.32 (22.56)	50.00 (25.48)
		2	.83 (.18)	75.00 (29.80)	19.64 (22.85)
		3	.93 (.09)	86.61 (14.26)	7.14 (11.72)
		4	.96 (.05)	86.61 (15.08)	2.68 (5.32)
		5	.95 (.06)	91.07 (12.43)	5.36 (8.08)
		6	.95 (.06)	91.07 (12.43)	7.14 (16.05)
Short SOA—uncued	1.49 (0.586)	1	.46 (.25)	48.21 (24.93)	60.71 (21.29)
		2	.69 (.23)	60.71 (21.85)	32.14 (20.64)
		3	.82 (.21)	75.00 (29.01)	18.75 (20.66)
		4	.90 (.10)	79.46 (19.37)	8.93 (9.08)
		5	.92 (.07)	85.71 (10.81)	11.61 (11.46)
		6	.91 (.11)	83.04 (15.20)	9.82 (13.14)
Long SOA—cued	1.56 (0.687)	1	.44 (.20)	45.54 (24.32)	54.46 (17.41)
		2	.67 (.20)	57.14 (21.77)	32.14 (22.31)
		3	.87 (.15)	78.57 (21.61)	14.29 (15.39)
		4	.92 (.10)	86.61 (21.07)	8.04 (9.31)
		5	.93 (.07)	81.25 (20.07)	6.25 (6.49)
		6	.93 (.08)	86.61 (17.99)	8.93 (13.36)
Long SOA—uncued	2.09 (0.589)	1	.53 (.19)	50.89 (14.26)	48.21 (24.44)
		2	.86 (.12)	74.11 (20.49)	16.07 (17.97)
		3	.96 (.04)	90.18 (12.19)	6.26 (6.49)
		4	.95 (.07)	91.96 (11.61)	9.82 (13.14)
		5	.96 (.05)	92.86 (11.72)	8.04 (7.92)
		6	.97 (.03)	91.96 (11.61)	3.57 (7.64)

Note: SOA = stimulus onset asynchrony. Standard deviations are in parentheses.

the increase in sensitivity (A') with the increase in contrast (see Table 2). Importantly, the interaction of SOA and cueing was significant, $F(1, 13) = 15.3$, $p = .002$, suggesting that sensitivity was higher in cued trials (compared to uncued trials) in short SOA but lower in long SOA (i.e., IOR). No other main effect or interaction was significant. Table 2 presents the mean d's for each of the cueing and SOA conditions, and A', hit rate, and false-alarm rate for each of the contrast levels (standard deviations in parentheses).

Threshold calculation

Table 3 shows the mean thresholds associated with each of the four conditions (short SOA cued trials, short SOA uncued trials, long SOA cued trials, long SOA uncued trials). The thresholds were estimated by fitting a cumulative Gaussian distribution to the discrimination data by a maximum likelihood procedure and correspond to the contrast level associated with an 84% rate of correct responses. The thresholds were then entered to a 2 × 2 ANOVA with SOA and cueing as factors. The interaction of SOA and cueing was found to be significant, $F(1, 13) = 8.34$, $p = .013$. No other effect was significant.

Again, despite the fact that this was not a speeded task, we analysed RT data as well. As can be seen in Table 4, IOR was found in RT despite the instruction to participants not to speed up their response. In an ANOVA with SOA, cueing, and contrast as variables, four significant effects were found: SOA, $F(1,13) = 21.03$, $p < .001$, reflecting the fact that trials with a long SOA had faster responses than trials with a short SOA (865 ms and 990.5 ms, respectively); contrast, $F(5, 65) = 21.34$, $p < .0001$, suggesting that increasing the contrast results in a decrease in RT (1203.9, 1021.1, 876.4, 836.9, 804.4, 824.3, for contrast levels 2, 6, 10, 14, 18 22%, respectively); the interaction between cueing and SOA, $F(1, 13) = 8.43$, $p = .012$, reflecting IOR; and, finally, the interaction between SOA and contrast, $F(5, 65) = 7.22$, $p = .001$, showing that the difference in RTs between stimuli in different contrasts was larger in the short SOA than in the long SOA.

Table 3. *Mean thresholds in percentage contrast, from Experiment 2*

SOA	*Cued*	*Uncued*
Short SOA	9.4 (1.7)	15.8 (2.6)
Long SOA	15.4 (3)	9.2 (1.3)

Note: SOA = stimulus onset asynchrony. Standard deviations are in parentheses.

Table 4. *Mean RTs from Experiment 2*

SOA	*Contrast*	*Cued*	*Uncued*
Short SOA	1	1328.239 (106.98)	1392.72 (129.07)
	2	1058.433 (54.74)	1153.786 (67.6)
	3	842.863 (61.4)	989.951 (81.62)
	4	855.099 (49.82)	927.831 (69.5)
	5	805.584 (45.3)	844.263 (54.44)
	6	797.881 (59.22)	890.241 (84.61)
	All	948.02 (50)	1033.1 (66.9)
Long SOA	1	1032.211 (69.48)	1062.391 (91.68)
	2	931.681 (52.58)	940.406 (73.43)
	3	890.609 (50.94)	782.194 (55.91)
	4	814.007 (49.3)	750.876 (40.98)
	5	800.954 (42.14)	766.861 (53.58)
	6	870.181 (56.83)	739.199 (46.35)
	All	889.9 (44.7)	840.32 (52.5)

Note: RT = reaction time; SOA = stimulus onset asynchrony. Standard errors are in parentheses.

The results of this experiment are clear-cut. Accuracy of discrimination of the orientation of low-contrast stimuli was improved at short SOAs at the cued location and impaired at long SOAs, revealing an effect of IOR on early perceptual processes. Analyses of sensitivity confirmed that the changes in accuracy were caused by changes in sensitivity. Importantly, analysis of contrast thresholds indicated that the threshold was lower for uncued than for cued trials at the long SOA, suggesting that IOR affects contrast sensitivity.

GENERAL DISCUSSION

Despite a large number of studies on IOR, there is still uncertainty regarding details of the underlying mechanisms. The purpose of this study was to examine the effect of IOR on contrast sensitivity, a low-level, early perceptual process, which has been shown to be affected by shifts of attention. We have clearly demonstrated in two experiments that IOR decreases contrast sensitivity, which suggests that it affects early perceptual processing. Specifically, we have shown that at short SOA conditions, shifting attention increased perceptual sensitivity, as participants were more accurate in detecting and making decisions about the orientation of a target on cued trials than on uncued trials. Moreover, discrimination threshold was lower on cued than on uncued trials. This result is in line with other studies showing that attention affects low-level, early perceptual processes (e.g., Cameron et al., 2002; Carrasco, Ling, & Read, 2004). However, the present study is the first to show that IOR does the same, using contrast sensitivity task. We have shown that at long SOAs, attention, through the mechanism of IOR, decreased perceptual sensitivity so participants were more accurate to respond to targets at the uncued location than to targets at cued locations. This was supported by the effect of IOR on *d′* and on discrimination threshold in the second experiment. Our results are in line with recent suggestions that attention changes the subjective appearance of the stimulus (e.g., Carrasco, Fuller, & Ling, 2008; Carrasco et al., 2004; Ling & Carrasco, 2007; Liu, Abrams, & Carrasco, 2009). But our study is the first that implies that IOR increases perceived contrast of an object in the uncued location. Showing that IOR affects contrast sensitivity suggests that the mechanisms affected by IOR are indeed the same as those that are affected by attentional shifts in general.

The effect on detection and discrimination accuracy found here is unlikely to be attributed to any effect other than a change in perceptual sensitivity. It cannot be a motor effect, as the only dependent measure that was emphasized to the participants was accuracy—not RT as in most previous studies. Measures of RT can reveal perceptual effects, but unlike measures of accuracy they may also be contaminated with motor response biases. This is not to claim that there are no motor effects in IOR, but to say that this is not what contributed to the effect we observed.

Ivanoff and Klein (2006) suggest that removing the target shortly after its onset (as is done in the current study) limits the conclusions that are possible regarding effects of IOR on accuracy. This is because responses may be based on decaying information instead of on accumulating information, and therefore low accuracy may be a result of slow responses. The fact that IOR was found in the RT pattern as well as in accuracy in our experiments does not allow us to rule out this explanation completely. However, we believe that this is unlikely to be a concern for several reasons. First, it has been shown by Ivanoff and Klein (2006) that IOR affects the *d′* in a choice RT experiment, also under conditions where the target was on throughout the trial. This finding is similar to what was found in other studies using a short target presentation (e.g., Handy et al., 1999) suggesting that perceptual processes influenced by IOR can be detected under short or long target presentation. Secondly, examining the data indicates that long RTs are found in low-contrast targets. This, of course, is not surprising, as people take more time when they are not sure about the target, but it suggests that slow RT is a result of the uncertainty regarding the target, and the low accuracy is an outcome of the same uncertainty (e.g., Usher & McClelland, 2001). Thus we feel confident in attributing the changes that we observed to true changes in perceptual sensitivity caused by IOR.

In conclusion, our data show that perceptual sensitivity is reduced at the cued location on long SOA trials, which provides the clearest evidence to date for the influence of IOR on early perceptual processing.

Original manuscript received 14 April 2013
Accepted revision received 7 October 2013
First published online 10 December 2013

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