What causes IOR? Attention or perception? - Manipulating cue and target luminance in either blocked or mixed condition

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What causes IOR? Attention or perception? - Manipulating cue and target luminance in either blocked or mixed condition

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Abstract

Inhibition of return (IOR) refers to the performance disadvantage when detecting a target presented at a previously cued location. The current paper contributes to the long-standing debate whether IOR is caused by attentional processing or perceptual processing. We present a series of four experiments which varied the cue luminance in mixed and blocked conditions. We hypothesized that if inhibition was initialized by an attentional process the size of IOR should not vary in the blocked condition as participants should be able to adapt to the level of cue luminance. However, if a perceptual process triggers inhibition both experimental manipulations should lead to varying levels of IOR. Indeed, we found evidence for the latter hypothesis. In addition, we also varied the target luminance in blocked and mixed condition. Both manipulations, cue luminance and target luminance, affected IOR in an additive fashion suggesting that the two stimuli affect human behaviour on different processing stages.

Keywords

Inhibition of return, cause of IOR, perception, attention

1.0 Introduction

At any given moment a person's capacity of the visual system is limited and, therefore stimuli compete to gain access to the limited resources. Attentional mechanisms play an important role to direct orienting to the most relevant stimuli and extinguish stimuli less relevant to our goal (Eriksen & Hoffman, 1973; Hawkins, Shafto, & Richardson, 1988; Jonides, 1976; Mountcastle, 1978; Posner, 1980; Remington, Johnston, & Yantis, 1992; Wurtz, Goldberg, & Robinson, 1980). Effective processing also depends on the ability to temporary inhibit orienting to previously attended locations and thus prevents orienting from returning to that location (Cheal & Chastain, 1999; Cheal, Chastain, & Lyon, 1998; Maylor, 1985; Posner & Cohen, 1984; Pratt, 1995; Rafal, Calabresi, Brennan, & Sciolto, 1989). One classical experimental design to study spatial attention is the spatial cueing paradigm by Posner and Cohen (1984). In this procedure, participants typically see a spatial cue either to the left or right side of the fixation followed by a target either at the same location as the cue or on the opposite side. Participants are asked to press a key as soon as they detect the target. At relatively short time intervals (up to 150 ms) between cue and target participants are faster in detecting the target when target and cue appear at the same location compared to when these stimuli appear on opposite sides. However, when the time interval between cue and target is increased (after about 300 ms) the facilitation effect is reversed. Participants respond faster when target and cue are on opposite sides compared to when they are on the same side. This effect was termed inhibition of return (IOR) (Posner, Rafal, Choate, & Vaughan 1985).

The early facilitation effect is thought to reflect reflexive orienting of attention towards the sudden appearance of the cue, resulting in more efficient processing of the target at that location (Posner, 1980; Posner & Cohen, 1984; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). However, the mechanisms of the IOR-effect are under major debate. In order to structure this debate in this paper, we distinguish between the ‘cause of IOR’ and the ‘effect of IOR’ as proposed by Klein (2000). This distinction emphasises that the cue can initialize the inhibition (cause) but then the responses to the target are used to examine the implementation of the inhibition (effect). An example for a cause of the IOR is the oculomotor cause where the programming of saccades can lead to an IOR-effect (e.g. Rafal, et al. 1989). An example for the effect of IOR can be a delay in the execution of eye movements (e.g. Taylor & Klein, 2000) or reaching movements (Cowper-Smith & Westwood, 2013). However, this paper focuses on the long-standing debate, whether IOR is caused by attentional or perceptual mechanisms (see Klein, 2000 and Berlucchi, 2006; for reviews). Typically this research question is explored by measuring the effect of IOR with manual responses and asking participants to maintain fixation during a trial to rule out oculomotor causes. In this paradigm it is generally assumed that the cause of IOR is the sole consequence of either attentional or perceptual processes (or both as we will suggest at the end of this paper).

According to the ‘attention hypothesis’ (Maylor, 1985), IOR is the consequence of attentional orienting to a cued location. Maylor compared double cue with single cue conditions and revealed that presenting double cues led to a reduced IOR compared to when a single cue was presented. Interestingly, this occurred even though both cues had the same luminance. Given that double cues also reduced the facilitation effect from single cue, Maylor argued that IOR and attention are linked and that IOR is a direct consequence of attending to a cued location. She presented further support for this argument by showing that IOR was eliminated when the early facilitation effect was disrupted when participants performed various demanding secondary tasks, e.g. pursuit eye tracking of a predictably or unpredictably moving dot on the screen. Further evidence for an attentional cause of IOR comes from a study by Klein, Christie and Morris (2005) who examined the spatial distribution of IOR in a multiple-cue paradigm. They found that multiple cues induced an inhibitory gradient centred in the direction of the net vector of the multiple cues. The magnitude of the inhibitory gradient was independent of the number of cues. More recently, Zhao, Humphreys, and Heinke (2012) demonstrated that in double-cue conditions (similar to Maylor, 1985) with mixed luminance pairings (bright-bright; dim-dim; bright-dim) IOR effects were found only with the bright cues but not the dim cues, despite the fact that the dim cue produced an IOR-effect when presenting on its own. Interestingly, facilitation at early stimulus onset asynchrony (SOA) showed the same pattern. In other words, the IOR-effect was predicated on the occurrence of facilitation supporting the hypothesis of an attentional cause of IOR.

On the other hand, there is also evidence supporting the alternative view that IOR is caused by perceptual processes, i.e. the detection of a change of the luminance energy at the cued location. This view was put forward as early as Posner and Cohen (1984), who reported that the reduced early benefit in the double cue condition did not lead to a reduced IOR effect. In line with the perceptual account is that IOR can occur in conditions when no facilitation effects occur (Tassinari, Aglioti, Chelazzi, Peru & Berlucchi, 1994; Tassinari & Berlucchi, 1993; Danziger, Kingstone, & Snyder, 1998; Enns & Richards, 1997). Further supporting evidence was provided by a study of Mele, Savazzi, Marzi, and Berlucchi (2008) by using cues varying in luminance. Mele et al. considered the bright cues to be operating supraliminal, whereas the dim cues were judged to be subliminal. They found only facilitation for the supraliminal cue, but not for the subliminal cue. Interestingly, both conditions produced an IOR-effect, with the effect being reduced when dim cues were presented, supporting the perceptual account of IOR.

The experiments in this paper also manipulate the cue luminance but in contrast to Mele et al. (2008), we will use supraliminal cues. We will manipulate the cue luminance in either a mixed fashion or a blocked fashion. We think this simple manipulation allows us to clarify the question whether a perceptual process or an attentional process causes the inhibitory effects on the behavioural responses. If the attentional hypothesis was true, it is conceivable that attention is able to adapt to the level of the cue luminance in a particular experiment. Such an adaption may make the reflexive orienting towards the cue and the subsequent inhibition more efficient. Therefore, we would not expect the magnitude of IOR to vary if cue luminance was blocked. Note that it is not clear how this hypothesis would play out in the mixed condition, as one could argue that the level of luminance is proportional to the level of attention elicit by the cue; or it is also plausible to see attention a binary factor which is either there or not predicting a luminance independent effect. In contrast and central to the current paper, if IOR is caused by a perceptual effect, blocking should elicit a similar effect compared to the mixed manipulation. In other words, the IOR-effect is expected to be proportional to the level of cue luminance, irrespectively whether luminance is manipulated in a blocked or mixed fashion. In addition the current study also follows up a question arisen from the previous study by Zhao et al. (2012). The experiments in Zhao et al.'s (2012) study manipulated cue luminance by varying the brief increase of the frame thickness of an open box, while in the current study we changed the true luminance of the frame of the open box. Obviously, there is a distinct possibility that this manipulation is qualitatively different from a true luminance manipulation and might explain why we found evidence for the attentional rather than for the perceptual hypothesis. At this point it is also worth noting that this dichotomy is potentially a false dichotomy as it is not inevitable that the brain uses either mechanism but potentially both mechanisms. We will return to this point in the general discussion.

Furthermore the present paper combines the manipulation of the cue luminance with the manipulation of the target luminance (blocked vs. mixed). There are several studies varying the target luminance in a mixed condition (e.g. ReuterLorenz, Jha, and Rosenquist (1996); Hunt and Kingstone, 2003; and Souto and Kerzel, 2009). They reported that dim targets in a mixed condition produced larger IOR-effects than bright targets. These findings can be explained by assuming that participants' responses are governed by the well-known Piéron's law for perceptual processes. Piéron's law states that reaction times decrease with increasing target luminance. A simple process model can explain the law by assuming that the luminance signal is accumulated until a response threshold is reached (see Stafford and Gurney, 2004; for a recent support of this assumption; see also Hunt & Kingstone, 2003; for a similar model). In contrast, Castel, Pratt, Chasteen, and Scialfa (2005) demonstrated that blocked target luminance results in delayed IOR and smaller IOR for dim targets compared to bright targets. They explained their findings with the Klein's (2000) theory on IOR. Klein (2000) argued that the observed cueing effects are the result of two signals: facilitation and inhibition. Now in tasks that require a higher attentional setting, the facilitation signal (attention to the cue) is higher leading to a delayed onset of the inhibition and lower levels of IOR. To explain their findings with this theory Castel et al. (2005) argued that the detection of the dim target required participants to set themselves into a high attentional setting whereas the bright target led to a low attentional setting. However, their explanation does not take into account Pieron's law and their study did not include a mixed baseline. Numerous methodological differences in Castel et al.'s (2005) study compared to the studies with mixed target luminance prevent a meaningful direct comparison. Such a comparison is possible through our four experiments. It is also worth noting that Castel et al. (2005) used the term "attentional control setting" (ACS) instead of "attentional setting" to theorize about their findings. ACS was originally coined by Folk, Remington, and Johnston (1992). Folk et al. (1992) showed that performance in tasks where participants search for a particular stimulus (i.e. visual search task) is typically disrupted by a cue when the cue shared a feature (e.g.

colour) with the search target. They explained their findings by postulating that the search target leads to the adoption of an ACS to guide attention in their search for the target. Consequently, this setting also allows the cue to guide attention due to the shared characteristics. Since Castel et al.'s (2005) experiment did not require search for a target the term ASC seems not suitable. Nevertheless, it is important to highlight the theoretical prediction from their findings that the task requirements instilled by the target luminance may affect the influence of the cue similarly to Folk et al.'s findings. We therefore used the term "attentional setting" in this paper.

In addition, the manipulation of target luminance in a mixed vs. blocked condition opens up the possibility to produce additional evidence for the cause of IOR. This possibility is based on examining the statistical interactions between cue luminance and target luminance. As suggested by Sternberg (1969) if there is a significant interaction between factors the respective factors may affect the same processing stage. In contrast, if the effects are additive the factors can be assumed to relate to different processing stages. In the context of our study this methodology leads to the following predictions. As stated earlier, the mixed manipulation of the target luminance is likely to play out on a perceptual processing stage. Hence, if IOR is caused by perceptual processing and the target luminance is varied in a mixed condition we would expect an interaction between target luminance and cue luminance. However, if the attentional hypothesis (cause) is true, such an effect should be additive, i.e. the cue luminance affects attentional process whereas target luminance influences the perceptual stage. In the blocked manipulation of the target luminance, the level of luminance can be assumed to affect an attentional setting as suggested by Castel et al. (2005) (and supported by our findings). Hence if the attentional hypothesis is true, cue luminance should interact with target luminance, but if perceptual hypothesis is true, the effect should be additive. Table 1 summarizes these hypotheses. However and importantly, if the theory by Klein (2000) is true and if the cause of IOR and the effect of IOR (response to target) operate on the different processing stage we should find no interactions between target luminance and cue luminance.

<table>
<tr><th rowspan="2">Ex.</th><th rowspan="2">Cue
lum.</th><th rowspan="2">Target lum.</th><th colspan="3">Perceptual cause (by cue)</th><th colspan="3">Attentional cause (by cue)</th></tr>
<tr><th>Within or combined exp.</th><th>Between exp.</th><th>Interaction</th><th>Within or combined exp.</th><th>Between exp.</th><th>Interaction</th></tr>
<tr><td>1a</td><td>Mixed</td><td>Bright</td><td rowspan="2">Bright > dim (cue)</td><td rowspan="2">No effect (target)</td><td rowspan="2">No effect</td><td rowspan="2">Bright > dim (cue) (see text)</td><td rowspan="2">No effect (target)</td><td rowspan="2">Effect</td></tr>
<tr><td>1b</td><td>Mixed</td><td>Dim</td></tr>
<tr><td>2a</td><td>Bright</td><td>Mixed</td><td rowspan="2">Bright < dim (target)</td><td rowspan="2">Bright > dim (cue)</td><td rowspan="2">Effect</td><td rowspan="2">Bright < dim (target)</td><td rowspan="2">No effect (cue)</td><td rowspan="2">No effect</td></tr>
<tr><td>2b</td><td>Dim</td><td>Mixed</td></tr>
</table>

Table 1. The table gives an overview of the four experiments and summarizes the hypotheses for the two causes of IOR, attentional and perceptual. The entries in bold font highlight the crucial predictions. Details in particular on the interaction hypotheses can be taken from the text.

In summary (see Table 1), Experiment 1a and 1b vary cue luminance in a mixed condition whereas Experiment 2a and 2b block cue luminance. Hence a comparison across these four experiments will allow us to contrast the perceptual hypothesis with the attentional hypothesis. On the other hand, Experiment 1a and 1b block two different levels of target luminance and Experiment 2a and 2b randomize target luminance allowing us to compare different attentional settings with a perceptual baseline. In addition, the four experiments can explore whether the cause of IOR and the effect of IOR are generated in the same processing stage.

2.0 Experiments

2.1 Experiment 1a: Mixed cue luminance with bright target

Experiment 1a aims to test the cause of IOR by manipulating cue luminance (bright vs. dim) while the target is always bright. If the perceptual hypothesis (cause) for IOR is correct, we expect IOR for both dim and bright cues, with the magnitude of IOR depended on the luminance level (bright > dim). On the other hand, if the attentional hypothesis for IOR is correct, IOR should be independent of the cue luminance. Moreover, Experiment 1a enabled participants to adopt a low attentional setting compared to Experiment 1b, because the target in Experiment 1a was easy to detect whereas the dim target will be more difficult to detect in Experiment 1b.

2.1.1 Method

Participants

Twenty-one volunteers (twenty females and one male, aged from 18 to 34 years) from the University of Birmingham participated. The research was conducted in accord with the Code of Ethics of the World Medical Association. They were either paid 3 British pound or they received course credits for their participation in a session of approximately 25 minutes. All participants reported normal or correct-to-normal vision and all were right handed.

Apparatus

Stimulus presentation and data collection were performed using E-Prime software (Version 1.1). The visual stimuli were presented on a 17-inch SAMSUNG monitor controlled by a personal computer. Responses were recorded using a standard keyboard.

Stimuli

The stimulus display (see Figure 1) consisted of a fixation cross (68.0 cd/ m^2) subtending 0.7˚ × 0.7˚, presented in the centre of the screen (background 4.4 cd/m^2), and two outline boxes (5.9 cd/m^2), aligned horizontally to the left and right side of the fixation cross.

The distance between the fixation and the centre of each box was 8.1˚. Each box had a 0.15˚ thick frame subtending 3.4˚ in length. The target was a hash sign (#) (56.0 cd/m^2) subtended 1.3˚ x 1.3˚, displayed in the centre of one of the two boxes. The cue comprised of a change in the frame luminance from 5.9 cd/m^2 to 68.0 cd/m^2 (bright cue) and to 8.5 cd/m^2 (dim cue), with the brightening lasting 150 ms[1].

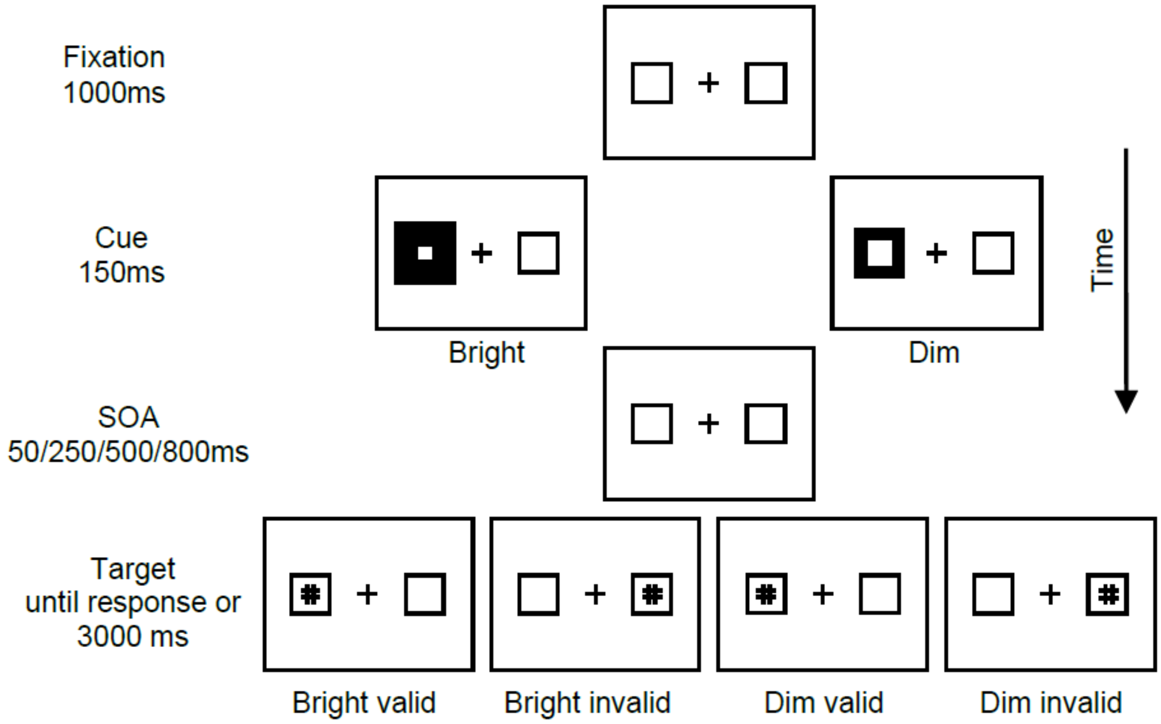

Figure 1. The trial sequence used in Experiment 1a. After the fixation period, one of the peripheral cues had a high or low luminance increase for 150 ms. After various SOAs, the target appeared randomly at either the left or right side of the fixation cross. Note that the black and white portions of this figure were reversed in the actual experiment.

Design

[1] The experimental design was similar to Experiment 1 in Zhao et al.'s study (2012) except from the cue manipulations. Instead of changing the thickness of the open box (cue), here the true luminance of the cues was manipulated. The present luminance values were chosen to match the subjectively perceived changes of the cues in Experiment 1 in Zhao et al.'s study (2012).

The experiment consisted of a 2 (cue luminance: bright/dim) × 2 (validity: valid/invalid) × 4 (SOA: 50/250/500/800 ms) repeated measures design. The experiment consisted of a total of 540 trials, 60 of these were catch trials. They were randomised with respect to trial type, and equally divided with respect to cue luminance, validity, SOA and target location. Each of the experimental conditions contained 30 trials.

Procedure

The experiment was conducted in a quiet, dimly illuminated room. Participants were tested individually sitting at a distance of approximately 57 cm from the computer screen. Prior to the experiment, participants were given both written and oral instructions. All participants received then 10 practice trials and the responses on these trials were not recorded or analysed. Participants were asked to respond to the onset of the target as quickly and accurately as possible by pressing the space bar on the keyboard with their dominant hand. Response times (RT) and errors were recorded by the computer. Participants were also told that cues were uninformative with respect to the potential locations of subsequent targets and to withhold responses on catch trials (when no target appeared). Catch trials were included to discourage anticipatory responses. Throughout the experiment the participants were instructed to maintain fixation. Eye movements were not monitored, as previous studies have showed that participants were generally successful at maintaining fixation (Castel et al., 2005; Muller & Findlay, 1987; Pratt & Abrams, 1995).

The trial sequence is shown in Figure 1. Each trial began with a display consisting of a central fixation cross and two peripheral boxes. Following a period of 1000 ms, one of the peripheral boxes was then cued by increasing the luminance of the outline of the box for 150 ms before returning it to its original luminance. This was experienced as a brief flash. The cue comprised of two levels of luminance change (see above). After various SOAs presented randomly (50 ms, 250 ms, 500 ms or 800 ms), the target was presented equally at the centre of the left or right box and remained visible until the participants responded or 3000 ms had elapsed. RT was measured from the target onset to the response emission. The experiment was divided into three blocks and participants were provided with a short break after each block.

2.1.2 Results

Trials in which RTs were less than 100 ms or greater than 1000 ms were eliminated from the analysis, as were those in which a response occurred on a catch trial or prior to the target onset. Moreover, participants were excluded from the analysis if they made either an excessive proportion of anticipatory responses or misses (greater than 10%) or of false alarms (greater than 15%). Consequently two participants' entire data sets were excluded because one had an error rate of 22.41% and another had a false alarm rate of 30%. The mean error rate for the remaining participants was 2.89%. Outliers were eliminated based on a procedure proposed by Van Selst & Jolicoeur (1994) in which trials with RTs above or below three standard deviations (SDs) from the mean of each condition were removed in an iterative way.

The mean RTs for each condition and the mean cueing effects for each combination of cue luminance and SOA are presented in Figure 2. Positive values indicate facilitation effects, negative values indicate IOR effects. A 2 × 2 × 4 within-subjects ANOVA was conducted with cue luminance (bright or dim), validity (valid or invalid) and SOA (50 ms, 250 ms, 500 ms or 800 ms) as factors. The main effect of cue luminance was significant ($F(1, 18) = 11.00$, $p < 0.01$). RTs were 5.48 ms faster in the bright relative to the dim condition. The main effect of SOA was also significant ($F(1.64, 29.55) = 43.68$, $p < 0.001$). Bonferroni-corrected multiple comparison showed that overall RTs decreased significantly from SOA 50 ms (356.76 ms) to SOA 250 ms (323.45 ms) ($p < 0.001$), stayed constant between SOA 250 ms and SOA 500 ms (314.28 ms) ($p > 0.05$), and increased significantly from SOA 500 ms to SOA 800 ms (326.55 ms) ($p < 0.001$). The validity × SOA interaction was also significant (F (3, 54) = 77.62, $p < 0.001$). Bonferroni-corrected multiple comparisons showed that a reliable 27.52 ms facilitation effect was obtained at SOA 50 ms ($p < 0.001$), a significant 29.22 ms IOR effect was obtained at SOA 500 ms ($p < 0.001$), and a 20.39 ms IOR was obtained at SOA 800 ms ($p < 0.001$). There was neither a facilitation effect nor an inhibition effect at SOA 250 ms. Furthermore, the cue luminance × validity × SOA interaction was significant (F (3, 54) = 4.08, $p < 0.05$). None of the other main effects or interactions reached significance ($p > 0.05$).

Furthermore, in order to explore the three-way interaction two-way ANOVAs were carried out separately. First the data for the bright cue conditions and the dim cue conditions were examined separately with ANOVAs with two within-subject factors: validity (valid, invalid) and SOA (50, 250, 500, 800 ms). For the bright cue condition there was a significant main effect of SOA (F (2.01, 36.26) = 27.94, $p < 0.001$) and also a significant validity × SOA interaction (F (3, 54) = 74.46, $p < 0.001$). Given this interaction, validity effects were evaluated at each SOA. The Bonferroni-corrected pairwise comparison showed that there was a significant 32.88 ms facilitation effect ($p < 0.001$) at SOA 50 ms; neither facilitation nor IOR at SOA 250 ms; a significant 30.66 ms IOR effect ($p < 0.001$) at SOA 500 ms; and a significant 25.96 ms IOR ($p < 0.001$) at SOA 800 ms. The same analyses were conducted for the dim cue conditions. The ANOVA revealed a significant main effect of SOA (F (1.88, 33.75) = 47.47, $p < 0.001$) and a validity × SOA interaction (F (3, 54) = 29.54, $p < 0.01$). The Bonferroni-corrected pairwise comparison tests showed that there was a significant 22.16 ms facilitation effect ($p < 0.001$) at SOA 50 ms; a significant 26.78 ms IOR effect ($p < 0.001$) at SOA 500 ms and a significant 14.82 ms IOR effect ($p < 0.01$) at SOA

800 ms. Secondly, in order to explore the magnitude of the cueing effects across the SOAs, three separate ANOVAs were performed on the RTs at SOA 50 ms, 500 ms and 800 ms (where the magnitudes of the cueing effects were significant), with cue luminance and validity as factors. At SOA 50 ms, there was a main effect of validity ($F(1, 18) = 72.20$, $p < 0.001$) and a marginally significant cue luminance × validity interaction ($p = 0.056$). At SOA 500 ms, there was only a main effect of validity ($F(1, 18) = 47.65$, $p < 0.001$); the cue luminance × validity interaction failed to reach significance ($p = 0.200$). At SOA 800 ms both the main effect of validity ($F(1, 18) = 37.76$, $p < 0.001$) and the cue luminance × validity interaction were significant ($F(1, 18) = 4.95$, $p < 0.05$). This indicates that bright rather than dim cues generated a stronger IOR effect (SOA 800 ms).

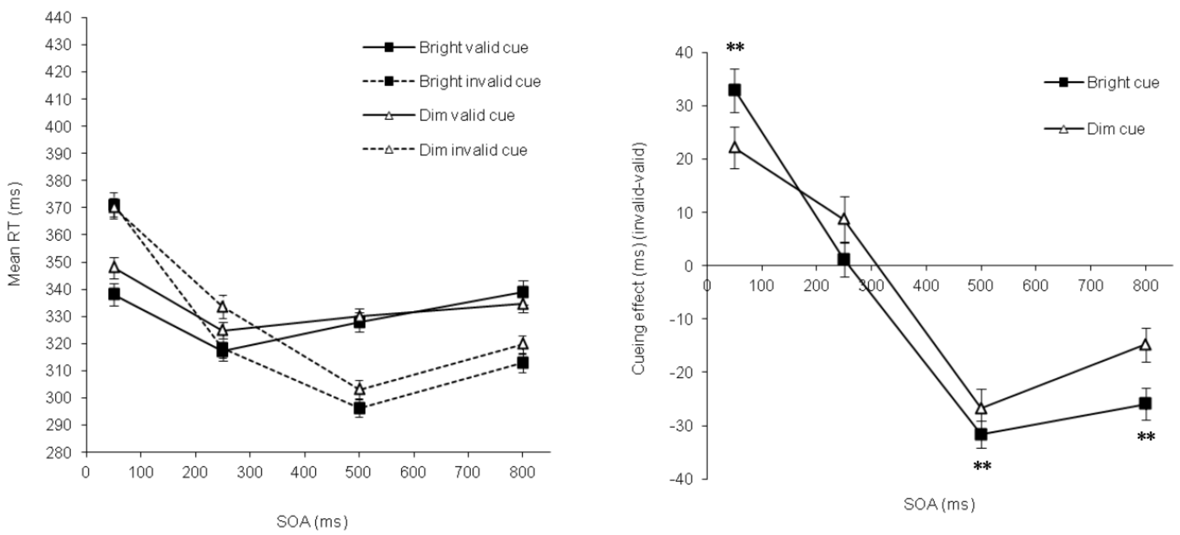

Figure 2. (Left) Mean RTs with errors bars for each condition in Experiment 1a[2]. The cue luminance was mixed (bright vs. dim) and the target was bright in contrast to Experiment 1b. (Right) Cueing effect for each condition in Experiment 1a. The cue luminance was mixed (bright vs. dim cue), whereas the target was bright in contrast to Experiment 1b where the

2 In this figure and all other figures the error bars were determined by a method proposed by Cousineau (2005). This method adjusts the standard confidence interval for the within participants design.

target was dim. * Cueing effect reaches significant level of 0.05. ** Cueing effect reaches significant level of 0.01.

2.1.3 Discussion

This experiment compared the effects of bright and dim cues on target detection. First, bright cue overall speeded RTs, suggesting that an increase in cue luminance can enhance the alerting effect of the cue (Hughes, 1984). Second, overall RTs showed the standard U-shaped function relative to SOA, which can be interpreted as a general warning signal effect of cues (Niemi & Naatanen, 1981). Third, both bright and dim cues generated roughly similar facilitation effects at the shortest SOA (50 ms), with a rapid decline in positive cueing as the SOA increased to 250 ms. At SOA 500 ms and 800 ms, there was an IOR effect, and the magnitude of IOR decreased slightly at SOA 800 ms but this held only for dim cues. This result is consistent with the perceptual account of IOR which predicts that IOR may reflect the perceptual change induced by the cue, with the effect being greater with bright cues. However, luminance effect of IOR did not appear at the intermediate SOA of 500 ms. This might be due to the small size of effect which might not be detected. Alternatively, IOR might present at a different SOA range for the bright cues compared to the dim cues.

On the other hand, this experiment cannot completely rule out the attentional hypothesis for the cause of IOR as explained in the introduction. However, the attentional hypothesis also predicts that the attentional setting should affect the size of IOR, i.e. a higher attentional setting may lead to a larger cue luminance effect. Therefore we will increase the attentional setting by decreasing the target luminance in Experiment 1b.

2.2 Experiment 1b: Mixed cue luminance with dim target

The same levels of cue luminance were applied as in Experiment 1a, however in order to realise a higher attentional setting, a low target luminance was employed compared to Experiment 1a.

2.2.1 Method

Unless otherwise mentioned, the method was the same as that used in Experiment 1a.

Participants

Nineteen volunteers (thirteen females and six males, aged from 18 to 23 years) were recruited in the same way as in experiment 1a. All except one were right-handed.

Stimuli

The cue was a change in the frame luminance from 5.9 cd/ m^2 to 68.0 cd/ m^2 (bright cue) and to 8.5 cd/ m^2 (dim cue). The target hash sign was 7.2 cd/ m^2 (dim target).

2.2.2 Results

The same error and outlier-removal procedure was carried out as in Experiment 1a. No participant was excluded. The mean error rate per participant was 2.65%. The mean RTs for each condition and the mean cueing effects for the combinations of cue luminance and SOA are presented in Figure 3. The results were analysed the same way as in Experiment 1a. The main effect of cue luminance was significant ($F(1, 18) = 6.55$, $p < 0.05$). RTs were 5.40 ms faster in the bright cue than in the dim cue condition. The main effect of SOA was also significant ($F(1.49, 26.89) = 20.39$, $p < 0.001$). Bonferroni-corrected multiple comparison tests showed that overall RTs significantly decreased from SOA 50 ms (395.40 ms) to SOA

250 ms (355.17 ms) ($p < 0.001$), they were constant between SOAs 250 ms and 500 ms (355.11 ms) ($p = 1.00$), and they significantly increased from SOA 500 ms to 800 ms (365.67 ms) ($p < 0.05$). The validity × SOA interaction was also significant ($F(3, 54) = 42.01$, $p < 0.001$). The Bonferroni multiple comparisons showed a reliable 29.89 ms facilitation effect at SOA 50 ms ($p < 0.001$), a 17.12 ms IOR effect at SOA 500 ms ($p < 0.01$), and a 24.71 ms IOR effect at SOA 800 ms ($p < 0.001$). There was neither a facilitation effect nor an inhibition effect at SOA 250 ms ($p = 0.736$). None of the other main effects or interactions reached significance ($p > 0.05$).

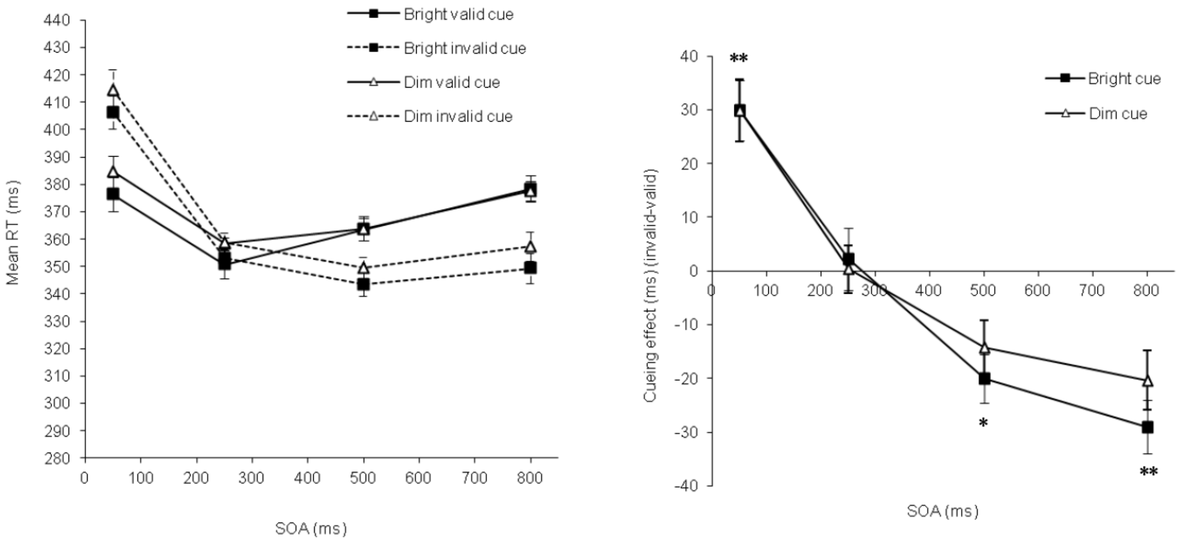

Figure 3. (Left) Mean RTs with error bars for each condition in Experiment 1b. The cue luminance was mixed (bright vs. dim cue) and the target was dim in contrast to Experiment 1a. (Right) Cueing effects for the bright and the dim cue conditions at each SOA in Experiment 1b. The cue luminance was mixed and the target was dim. * Cueing effect reaches significant level of 0.05. ** Cueing effect reaches significant level of 0.01.

Comparison between Experiments 1a and 1b

A mixed ANOVA was conducted with target luminance as between-subject factor. The main effect of target luminance (F (1, 36) = 6.41, $p < 0.05$) was significant; RTs were 37.58 ms faster with dim targets (Experiment 1b) than with bright targets (Experiment 1a). There was also a significant main effect of cue luminance (F (1, 36) = 16.47, $p < 0.001$). Participants were 5.44 ms faster with bright than with dim cues. Furthermore, there was a significant main effect of SOA (F (3, 108) = 54.32, $p < 0.001$) and a validity × SOA interaction (F (3, 108) = 108.29, $p < 0.001$).

Because the main focus of this paper is the IOR-effect we conducted a mixed ANOVA for SOAs 500 ms and 800 ms with target luminance (bright vs. dim) as a between-subject factor. The main effect of target luminance was significant (F (1, 36) = 8.14, $p < 0.01$). The detection of a dim target took 9.91 ms longer than the detection of a bright target. There was a main effect of cue luminance (F (1, 36) = 5.01, $p < 0.05$). RTs were 3.18 ms faster with a bright cue than with a dim cue. There was also a main effect of validity (F (1, 36) = 91.95, $p < 0.001$), with a reliable overall IOR effect of 22.86 ms. There was also a main effect of SOA (F (1, 36) = 29.91, $p < 0.001$). More importantly, the cue luminance × validity interaction was significant (F (1, 36) = 5.89, $p < 0.05$). Bright cues produced a larger IOR than the dim cues (effect sizes of 22.68 ms and 19.04 ms, respectively). The analysis also revealed a validity × SOA × target luminance interaction (F (1, 36) = 8.87, $p < 0.01$). When the target luminance was bright, IOR decreased from SOA 500 ms to 800 ms (effect sizes of 29.22 ms and 20.39 ms, respectively). In contrast, when the target luminance was dim, IOR increased from SOA 500 ms to 800 ms (effect sizes of 17.12 ms and 24.71 ms, respectively). None of the other interactions were significant.

2.2.3 Discussion

Given that the design was the same as in Experiment 1a except that the target luminance was dimmer relative to Experiment 1a, we were able to show that the bright cues led to faster RTs and increased the alertness effect compared to the dim cues. This corresponds to the typical pattern of early facilitation and late IOR. There was no reliable difference between the facilitation effects for bright and for dim cues.

When the two experiments were pooled together, there was a cue luminance effect on the magnitude of IOR (with a greater IOR effect for bright cues), supporting the perceptual hypothesis of IOR. Now it could be argued that higher cue luminance simply attracts more attention subsequently leading to larger IOR-effect. On the other hand, it is possible that attention is able to adapt to the level of the cue luminance in a particular experiment. Therefore, the perceptual account of IOR was tested further in Experiment 2a where the effect of blocking luminance was examined. If IOR reflects the perceptual processing of the cue, then cue luminance should influence the size of IOR regardless whether the cue luminance is blocked or mixed.

Blocked target luminance manipulation did not affect any IOR-size effect when comparing bright (Experiment 1a) and dim targets (Experiment 1b). This will be continually investigated in Experiment 2a and 2b when target luminance is randomised but all other experimental conditions will be kept the same.

2.3 Experiment 2a: Bright cue and mixed target luminance

Experiments 1a and 1b supported the idea that IOR reflects the perceptual processing of the cue as the magnitude of IOR varies with cue luminance. This perceptual interpretation also implies that if cue luminance is blocked, the size of IOR should be nevertheless affected by cue luminance as well. Alternatively, according to an attentional account of IOR, blocking cue luminance may work against finding an effect of cue luminance on IOR, if participants can adjust their orienting response to bright (Experiment 2a) and dim cues (Experiment 2b) to be equal, under blocked conditions.

2.3.1 Method

Unless otherwise mentioned, the method was the same as for Experiment 1a.

Participants

Nineteen volunteers, sixteen females and three males, 18 to 31 years of age, were recruited in the same way as for Experiment 1a. All except two were right-handed.

Stimuli

The cue luminance was 68.0 cd/ m^2 (bright cue) and the target was either 68.0 cd/ m^2 (bright target) or 8.5 cd/ m^2 (dim target). Thus, the cue luminance was the same as the bright cue in Experiment 1. The two target luminances matched the two cue luminances in Experiment 1.

2.3.2 Results

The same error and outlier-removal procedure was carried out as in Experiment 1a. One participant was excluded because of a high error rate of 14.81%. The mean error rate per participant was 3.25%. The mean RTs for each condition and the mean cueing effects for each combination of cue luminance and SOA are presented in Figure 4. The same analysis was conducted as for Experiment 1a. The main effect of target luminance was significant ($F(1, 17) = 52.42$, $p < 0.001$), showing that RTs were 20.96 ms faster for bright than for dim targets. The main effect of validity was significant ($F(1, 17) = 10.52$, $p < 0.01$). RTs were 9.54 ms faster in the invalid than in the valid condition. The main effect of SOA was also significant ($F(2.02, 34.26) = 45.06$, $p < 0.001$). Bonferroni-corrected multiple comparison tests showed that overall RTs significantly decreased from SOA 50 ms (372.46 ms) to SOA 250 ms (330.34 ms) ($p < 0.001$), stayed constant between SOA 250 ms and SOA 500 ms (333.55 ms) ($p = 1.000$) and between SOA 500 ms and SOA 800 ms (340.69 ms) ($p = 0.366$). The target luminance × validity interaction was significant ($F(1, 17) = 6.02$, $p < 0.05$) indicting that the IOR-effect depended on the target luminance with being smaller for bright targets (6.23 ms) than for the dim targets (12.85 ms). Importantly, this effect supports our prediction that the mixed target luminance taps into a perceptual stage. The validity × SOA interaction was also significant ($F(3, 51) = 37.05$, $p < 0.001$). A reliable 22.60 ms facilitation effect was obtained at SOA 50 ms ($p < 0.001$), a significant 27.58 ms IOR was obtained at SOA 500 ms ($p < 0.001$), and a 26.64 ms IOR was obtained at SOA 800 ms ($p < 0.001$). There was neither a facilitation effect nor an inhibition effect at SOA 250 ms. None of the other main effects or interactions reached significance ($p > 0.05$).

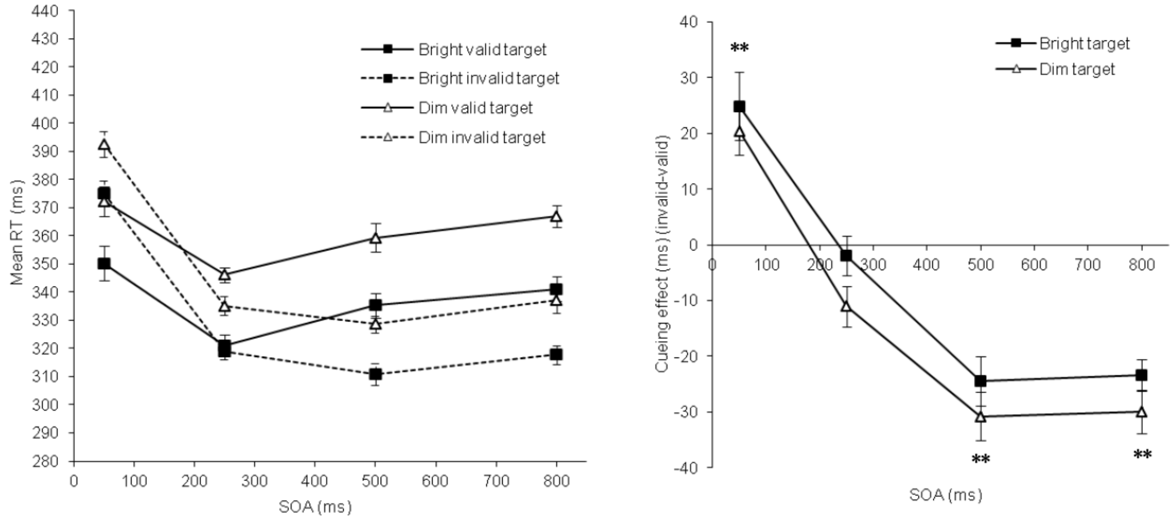

Figure 4. (Left) Mean RTs for each condition in Experiment 2a. The cue was bright and the target luminance was mixed. (Right) Cueing effects for the bright and the dim target conditions at each SOA. The cue was bright. * Cueing effect reaches significant level of 0.05. ** Cueing effect reaches significant level of 0.01.

2.3.3 Discussion

The results showed that target luminance affected overall RT (with faster RTs for bright than for dim targets), and again the cue affected overall RTs (a U-shaped RT function related to SOA). The cueing effects at SOA 50 ms (facilitation), 500 ms and 800 ms (IOR) replicated the results from Experiments 1a and 1b. However, the magnitude of IOR stayed constant at SOAs 500 ms and 800 ms. Most interestingly, at these SOAs the target luminance changed the size of the IOR effect by the same amount, with a larger IOR effect for the dim than for the bright target (at SOAs 500 and 800 ms; for more analyses and discussions see the comparison between Experiments 2a and 2b). This result replicates ReuterLorenz et al. (1996), Hunt and Kingstone (2003) and Souto and Kerzel (2009). Therefore our results present further evidence that the mixed target luminance affects a perceptual stage.

The lowering of cue luminance in the next experiment should have the following effects. If the perceptual hypothesis for the cause of IOR is correct, the IOR-effect should be smaller. Additionally, if the cue luminance influences processing at the same stage as the stage that generates the target response, there should be an interaction between target luminance, cue luminance and validity (see also Introduction; Sternberg, 1969).

2.4 Experiment 2b: Dim cue and mixed target luminance

2.4.1 Method

Unless mentioned, the same method was used as in Experiment 1a.

Participants

Nineteen volunteers, eighteen females and one male, 18 to 29 years of age, participated. All except two were right-handed.

Stimuli

The luminance of the outline boxes was 5.5 cd/m^2 slightly lower than in the previous experiments (5.9 cd/m^2). The cue luminance was 7.1 cd/m^2 (dim cue) and therefore slightly lower than in the previous experiments (8.5 cd/m^2). The target was either 68.0 cd/m^2 (bright target) or 7.1 cd/m^2 (dim target).

2.4.2 Results

The same error and outlier-removal procedure was carried out as in Experiment 1a. Two participants were excluded because of high false alarm rates of 23.33% and 16.67%. The mean error rate per participant was 2.76%. The mean RTs for each condition and the mean cueing effects for combinations of target luminance and SOA are presented in Figure 5.

The same analysis was conducted as for Experiment 1a. The same analysis was conducted as for Experiment 1a. The main effect of target luminance was significant ($F(1, 16) = 155.65$, $p < 0.001$). RTs were 19.45 ms faster for bright than for dim targets. The main effect of SOA was also significant ($F(1.76, 28.19) = 19.75$, $p < 0.001$). Bonferroni-corrected multiple comparison tests showed that overall RTs significantly decreased from SOA 50 ms (373.71 ms) to SOA 250 ms (343.09 ms) ($p < 0.001$), stayed constant between SOAs 250 ms and 500 ms (342.12 ms) ($p = 1.000$) and between SOAs 500 ms and 800 ms (345.46 ms) ($p = 1.000$). The validity × SOA interaction was also significant ($F(3, 48) = 30.88$, $p < 0.001$). A 24.49 ms facilitation effect was obtained at SOA 50 ms ($p < 0.001$), a 12.01 ms facilitation effect occurred at SOA 250 ms ($p < 0.01$), and a 11.20 ms IOR was obtained at SOA 800 ms ($p < 0.05$). There was neither a facilitation effect nor an inhibition effect at SOA 500 ms. The target luminance × validity × SOA interaction was significant ($F(3, 48) = 2.84$, $p < 0.05$). None of the other main effects or interactions reached significance ($p > 0.05$).

In order to explore the three-way interaction, separate ANOVAs were conducted for each target luminance condition with two within-subject factors: valid (valid, invalid) and SOA (50, 250, 500, 800 ms). For the bright target conditions, there was a significant main effect of SOA ($F(1.70, 27.13) = 14.90$, $p < 0.001$). In addition, there was a significant validity × SOA interaction ($F(3, 48) = 12.28$, $p < 0.001$). Bonferroni-corrected pairwise comparisons showed that there was a significant 20.43 ms facilitation effect ($p < 0.001$) at SOA 50 ms and a 18.30 ms facilitation effect ($p < 0.01$) at SOA 250 ms. Neither facilitation nor IOR was reliable at SOAs 500 ms and 800 ms. For the dim target condition, the ANOVA revealed again a significant main effect of SOA ($F(3, 48) = 15.57$, $p < 0.001$) and a validity × SOA interaction ($F(3, 48) = 22.15$, $p < 0.001$). The Bonferroni-corrected pairwise comparison showed that there was a significant 32.55 ms facilitation effect ($p < 0.001$) at SOA 50 ms and a significant 15.23 ms IOR effect ($p < 0.05$) at SOA 800 ms. Neither facilitation nor IOR reached significance at SOAs 250 ms and 500 ms. Furthermore, in order to explore the magnitude of the cueing effects on bright and dim targets across the SOAs, an ANOVA was performed on RTs at SOA 50 ms (where significant facilitation effects were found in both bright and dim conditions), with target luminance and validity as factors. This analysis revealed a significant main effect of validity ($F(1, 16) = 42.44$, $p < 0.001$) but no target luminance × validity interaction ($p = 0.118$). The magnitude of facilitation was the same for bright and dim targets at SOA 50 ms.

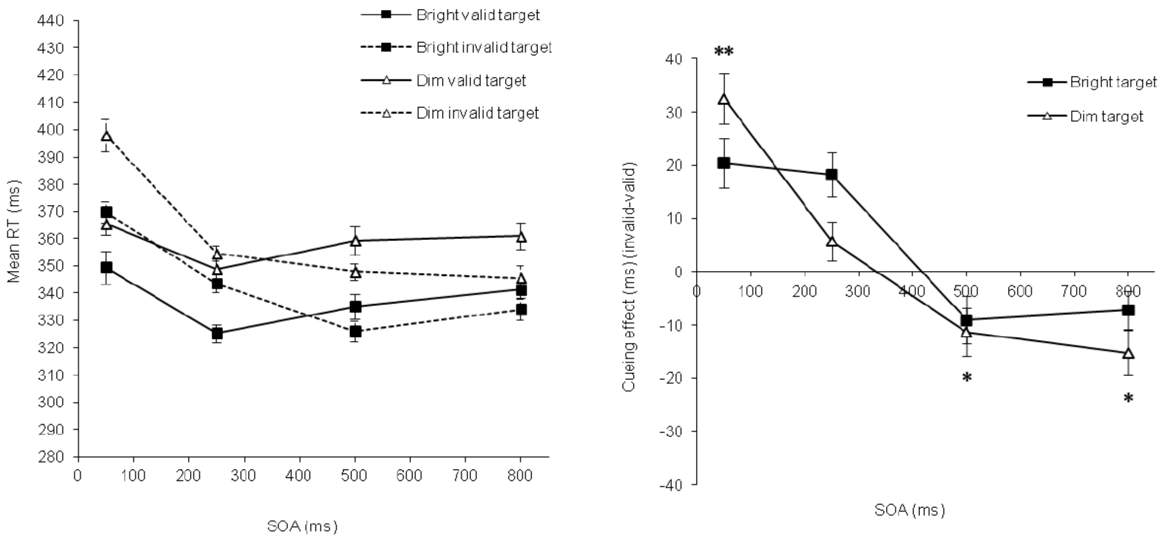

Figure 5. (Left) Mean RTs for each condition in Experiment 2b. The cue luminance was dim and the target luminance was mixed. (Right) Cueing effects for the bright and the dim target conditions at each SOA. The cue was dim. * Cueing effect reaches significant level of 0.05. ** Cueing effect reaches significant level of 0.01.

Comparison between Experiments 2a and 2b

Because the main concern of this paper is the IOR-effect a mixed-design ANOVA was employed for SOAs 500 and 800 ms, with cue luminance as a between-subject factor.

The results revealed a target luminance main effect (F (1, 33) = 198.11, p < 0.001). RTs for bright targets were 20.48 ms faster than for dim targets. There was a main effect of validity (F (1, 33) = 35.66, p < 0.001), indicating an overall IOR-effect of 18.90 ms. The main effect of SOA was also significant (F (1, 33) = 5.76, p < 0.05). More importantly, the validity × target luminance interaction was significant (F (1, 33) = 4.81, p < 0.05). There was a smaller IOR-effect for bright targets than for dim targets (effect sizes of 16.00 ms and 21.80 ms, both p < 0.001). The cue luminance × validity interaction was significant (F (1, 33) = 6.73, p < 0.05). Bright cues produced a larger IOR effect than dim cues (effect sizes of 27.11 ms and 10.69 ms). None of the other cue luminance interactions were significant.

Comparing the same conditions from different experiments

Four ANOVAs compared the same conditions in different experiments (e.g. bright cue and bright target in Experiment 1a vs. bright cue and bright target in Experiment 2a). Neither main effect of experiment nor interactions involving experiment were found.

Power analysis

The finding of a significant interaction between target luminance and validity for SOA 500 and 800 ms in Experiment 2a/b raises the prospect that we may not have had enough power in the Experiment 1a/b to find a similar effect. We therefore conducted an a-priori power analysis using “ANOVA: repeated measures, within-between interaction” in *G*Power 3.1* (Faul, Erdfelder, Buchner, & Lang; 2009). This way we were able to determine the required sample size that would have been necessary to detect the same effect in Experiment 1a/b as in Experiment 2a/b. The effect size of the relevant interaction in experiment 2a/b was 0.381. The lowest correlation among the repeated measures was 0.614 and the nonspericity correction was 1. The required statistical power was set to a highly conservative 0.9. Nevertheless, the power analysis indicated that the required sample size would have been 8 while the real sample size was 38. Therefore, the failure of finding a significant interaction in Experiment 1a/b was not due to the lack of statistical power.

2.4.3 Discussion

Results showed again that overall RTs were affected by target luminance (bright target < dim target) and cue (U-shaped RT pattern related to SOA). The bright and dim target conditions produced the same magnitude of facilitation at SOA 50 ms. Facilitation was then continually present for bright target up to an SOA of 250 ms, while facilitation disappeared at 250ms for the dim target condition. For longer SOAs, the bright target condition did not show any significant IOR-effect, whereas the dim target condition revealed an IOR-effect at SOA 800 ms.

When data were pooled across Experiment 2a and 2b, bright targets produced a smaller IOR than dim targets, replicating the results of ReuterLorenz et al. (1996) and Hunt and Kingstone (2003) and Souto and Kerzel (2009). Most importantly, when the cue luminance was blocked bright cues produced a larger IOR-effect relative to dim cues (between Experiment 2a and 2b), supporting the perceptual account of IOR.

A summary of main results from all experiments

Exp.	cue	target	within or combined experiments	between experiments
1a	mixed	bright	**bright > dim (cue)**	no effect (target)
1b	mixed	dim		
2a	bright	mixed	**bright < dim (target)**	**bright > dim (cue)**
2b	dim	mixed	**IOR only for dim targets**	

Table 2. A summary of main results from all experiments. Bold font indicates significant results ($p < 0.05$).

3.0 General Discussion

This paper investigated the cause and the implementation of IOR in four experiments by manipulating cue and target luminance in either mixed or blocked conditions. We aimed to investigate whether IOR is due to an attentional or a perceptual mechanism and whether the effect of IOR is generated in the same processing stage.

In all experiments, there were overall effects of luminance, regardless whether it was a cue or a target, and of SOA. RTs were faster for bright relative to dim stimuli irrespective of target or cue luminance was manipulated. Moreover, RTs exhibited a U-shape dependency on SOA. These results can be explained in terms of varying the alertness of participants (Hughes, 1984; Niemi & Naatanen, 1981). In addition, the experiments indicated that the magnitude of facilitation did not depend on cue luminance. There was also no effect of target luminance on facilitatory cueing across all four experiments.

However, the most important findings of this paper concern the size of IOR (see Table 2; for a summary of all results). Bright cues produced larger IOR than dim cues. This effect occurred both when cue luminance was mixed and when it was blocked, indicating that participants were not able to adapt themselves to the cue luminance as it would expect if the cue causes IOR via attentional processing. This finding strongly supports the perceptual account on the cause of IOR and is consistent with previous evidence in the literature (e.g. Posner & Cohen, 1984; Tassinari et al., 1994). This conclusion receives further support by the fact that IOR was modulated despite no modulation of facilitation due to the variation of cue luminance (at SOA 50 ms). However, according to the attentional hypothesis the facilitation effects and IOR should be strongly linked.

The experiments also demonstrated an influence of target luminance on the size of IOR in the mixed condition replicating results by ReuterLorenz, et al.'s (1996), Hunt and

Kingstone's (2003), and Souto and Kerzel (2009). To explain these findings we can draw on the process model of the Pieron's law introduced in the introduction (see e.g. Stafford and Gurney, 2004). The model of the Pieron's law assumes that the sensory evidence for a stimulus is accumulated until a response threshold is passed. The time it takes to pass the threshold corresponds to the detection time of the stimuli. The speed of the accumulation is modulated by the luminance level of the signal, i.e. high luminance leads to fast responses whereas low luminance leads to slow responses. To adapt this model to the IOR-effect we can first assume that a similar accumulation process occurs during the detection of the target. However rather than determining the reaction times directly, the accumulation process modulates the inhibitory effect of the cue. To be more specific, the IOR-effect in the model is the result of adding the duration of the target accumulation process to the inhibitory effect from the cue. Hence a dim target leads to a slow accumulation and subsequently a greater IOR-effect compared to a bright target which leads to a faster accumulation and subsequently to a diminished IOR-effect. Thus the model replicates our findings on the influence of target luminance. Furthermore the fact that we found no IOR-effect when the cue was dim and the target was bright (mixed) suggests that the accumulation process can also overwrite the inhibitory effect and not only add to the IOR-effect. This occurs when the speeded accumulation due to the bright target is sufficient to override the weaker inhibitory effect of the dim cue. Consequently and interestingly, the accumulation model predicts that a very brighter target can even turn an IOR-effect into response facilitation. This prediction goes beyond the scope of our paper and will need to be explored in future studies. Nevertheless, the prediction that characteristics of targets can switch between IOR and facilitation receives some support from a study by Lupianez, Ruz, Funes, and Milliken (2007) where they showed that high frequent targets (letters) can lead to IOR while low frequent targets can result in facilitation. A more stringent and detailed modelling effort, e.g. fitting a mathematical model to the data, goes beyond the scope of this paper. Nevertheless, this qualitative treatment of the model illustrates its usefulness.

In the mixed target luminance conditions we found reduced IOR with bright than with dim targets whereas with blocked target luminance this effect was not observed. The power analysis demonstrated that we had enough power to find an effect similar to the mixed condition. Hence this result supports the idea that participants are able to adjust their attentional setting according to the target's luminance. Within the accumulation model this finding can be explained by linking the response threshold with the level of target luminance. This linkage can nullify the effect of the target luminance on the accumulation process. To be more specific, in the high target luminance condition responses are associated with a high threshold cancelling out the speed up of the accumulation due to the higher target luminance. In contrast, the low target luminance condition is connected with a low threshold countering the slow accumulation in this condition. As a result the IOR-effect is not affected by the target luminance in the blocked condition. In other words, a change in the attentional setting can be interpreted as a simple change in response threshold in the framework of our model. It is also worth noting that our results don't replicate Castel et al.'s (2005) findings that the onset of IOR was affected by the blocked target luminance conditions. However, the choice of SOAs is crucial for the detection of IOR onsets, as well as for determining the magnitude of IOR. For instance, the failure to detect a change in IOR-onset could be due to the choice of 'wrong' SOAs, sampling too coarsely the time course of cueing effects. As to the magnitude of IOR, it is possible that IOR may be delayed so that longer SOAs are needed to determine the magnitude of IOR correctly. Further research is needed to clarify this issue by collecting more data on finely sampled SOAs over a long time period.

The evidence for a perceptual cause of IOR in this paper contradicts evidence from an earlier study by Zhao et al. (2012). The discrepancy is interesting as the only major difference between the two studies is the way of manipulating cue luminance, size change and luminance change. However, whether this difference is the reason for this discrepancy will have to be verified by comparing these manipulations directly. Nevertheless, these contradictory findings also point towards the possibility that IOR is not necessarily caused by either an attentional process or a perceptual process alone. Instead, it seems that the two processes conjointly influence IOR. Such a combination makes intuitive sense as the brain may operate more efficiently by using both mechanisms. Future research is needed to explore this hypothesis.

The finding of a perceptual cause of IOR also predicts that the target luminance should also interact with cue luminance, if the two factors influence the same processing stage (see introduction). However, there was no such interaction. On the other hand, there was also no interaction between cue luminance and target luminance in the blocked condition which would have been expected if the attentional hypothesis for the cause of IOR would have been true. Hence, our findings suggest that the cause of IOR (initialization of IOR) and effect of IOR (responses to target) operate at different processing stages (at least as manipulated by variations in luminance) which is in line with Klein's (2000) theory. This lack of interaction between these factors may be due to the experimental design which contrasted performance across different sets of participants. Nevertheless, the results provide some indication that the cause and effect of IOR (the cue and target effects, respectively) may not occur at the same processing stage. Future research will need to explore this finding in a more direct test.

To summarize, the manipulation of target luminance in a mixed vs. blocked condition suggests that participants adopt an attentional setting related to the level of the target luminance. A bright target leads to a low attentional setting while a dim target leads to a high attentional setting. Varying cue luminance in either mixed or blocked condition provides strong evidence that the cause of IOR is initialized on a perceptual stage. There was no interaction between the target luminance conditions and the cue luminance conditions indicating that the cause of IOR and the effect of IOR (response to target) operate at different processing stages.

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