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Effects of stimulus contrast and temporal delays in saccadic distraction

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ABSTRACT

In a recent study, we observed that saccadic distraction (i.e., the remote distractor effect, RDE) was reduced when target and distractor were displayed at unequal contrast [Born, S., & Kerzel, D. (2008). Influence of target and distractor contrast on the remote distractor effect. *Vision Research, 48*(28), 2805–2816]. We hypothesized that arrival times explain the RDE modulation: With equal contrast, target and distractor signals arrive simultaneously in the oculomotor system so that mutual inhibition (and therefore saccadic distraction) is largest. With unequal contrast, high-contrast signals arrive earlier than low-contrast signals, resulting in less mutual inhibition and little saccadic distraction. In the current contribution, we presented target and distractor at different stimulus onset asynchronies (SOA) to re-align arrival times with unequal contrast. Results confirmed that unequal contrast of target and distractor reduced saccadic distraction with simultaneous presentation and that strong distraction could be reestablished by introducing a SOA. However, maximal saccadic distraction also varied strongly with the specific combination of target and distractor contrast. Thus, contrast may not only modulate arrival times of target and distractor signals, but also their strength in the mutual inhibition process. Finally, we found more saccadic distraction when the distractor was presented slightly after the target. A second experiment suggests that alerting effects superimposed on the distraction contribute to this effect, but may not fully explain it. We suggest that distraction may be strongest when the rise-to-threshold of the target-related signal has already advanced.

1. Introduction

The remote distractor effect (RDE) denotes the finding that saccadic eye movements towards a visual target are delayed if a distractor stimulus is presented simultaneously with and at a certain distance from the target (Walker, Deubel, Schneider, & Findlay, 1997; Walker, Kentridge, & Findlay, 1995). In a recent study (Born & Kerzel, 2008), we looked at the impact of target and distractor contrast on the RDE. Most models suggest that the effect stems from competitive processes in the oculomotor system (Findlay & Walker, 1999; Godijn & Theeuwes, 2002; Kopecz, 1995; Leach & Carpenter, 2001; Munoz & Fecteau, 2002; Trappenberg, Dorris, Munoz, & Klein, 2001). They assume that target- and distractor-related signals mutually inhibit each other and because of the inhibitory influence of the distractor on the target, saccadic latencies are prolonged. From this notion, we inferred that stimulus properties (such as contrast) should influence the corresponding signal in some way. It is well known that high-contrast targets produce shorter saccadic latencies than low-contrast targets (Carpenter, 2004; Doma & Hallett, 1988a, 1988b; Ludwig, Gilchrist, & McSorley, 2004; White, Kerzel, & Gegenfurtner, 2006). Therefore, we hypothesized that increasing the contrast of a stimulus should somehow enhance its signal. Consequently, in the remote distractor paradigm, targets presented at high contrast should produce a stronger signal and therefore be less affected by a simultaneous distractor than low-contrast targets. Conversely, a distractor presented at high contrast should be more disruptive than a low-contrast distractor. In other words, we predicted small RDEs with high-contrast targets and large RDEs with high-contrast distractors. However, for central distractors we mostly found exactly the opposite pattern: The RDE was *greater* with high-contrast targets and *smaller* with high-contrast distractors (Born & Kerzel, 2008).

To explain these findings, we proposed a temporal explanation for the effects of contrast that is illustrated in Fig. 1. We hypothesized that the contrast of a stimulus modulates the arrival time of the corresponding signal in the oculomotor system: High-contrast stimuli provoke an earlier response in the oculomotor structures than low-contrast stimuli. Assuming competitive processes between target and distractor signals, a distractor prolongs saccadic latency most when distractor- and target-related activity show a maximal temporal overlap in the oculomotor system (Fig. 1B). Taking this idea to the extreme, one may say that inhibition by the distractor can only be effective when there is simultaneous activation from both stimuli: If there is a target-related signal

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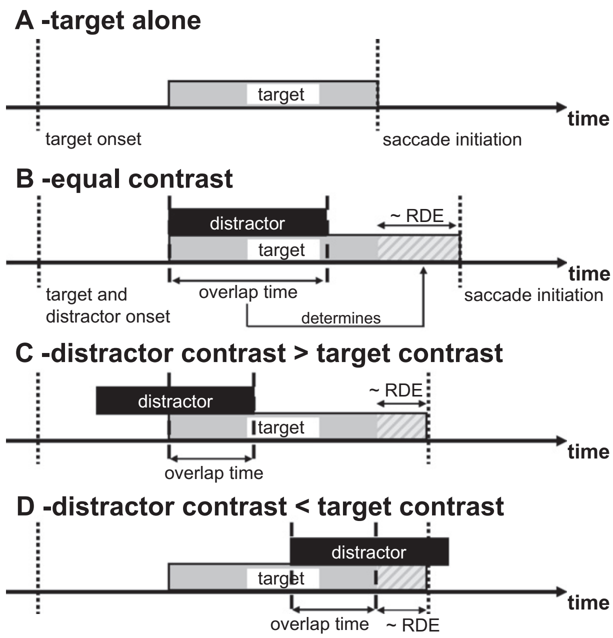

Fig. 1. Illustration of how the temporal overlap of target- and distractor-related signals in the oculomotor system may modulate the remote distractor effect. The gray box represents the presence of a target-related signal across time, the black box the corresponding distractor-related signal. For simplicity, the strength of the signals is neglected in the illustration. The more the two overlap in time, the more saccade initiation will be delayed; this additional time period is marked by the patterned area and corresponds to the remote distractor effect (RDE).

but no distractor-related signal to inhibit it, there should be no RDE. Conversely, if there is a distractor-related signal, but no target-related signal to compete with, there should be no RDE either. Critically, we further assumed that distractor-related signals are only transiently represented in the oculomotor system. Thus, distractor-related signals may miss target-related activity by either being evoked too early (Fig. 1C) or too late (Fig. 1D) to produce a strong RDE.

In sum, our temporal account suggests that varying target and distractor contrast may have the same effects as varying the stimulus onset asynchrony (SOA) between the two stimuli. The idea is in line with neurophysiological evidence showing that neurons in the superior colliculus (a midbrain structure associated with the generation of saccadic eye movements) respond earlier to stimuli of high luminance compared to stimuli of low luminance (Bell, Meredith, Van Opstal, & Munoz, 2006). Further, a similar idea has already been implemented in a computational account. Carpenter (2004) modeled the effects of contrast on saccade generation by assuming two serial rise-to-threshold mechanisms. The first one is concerned with the detection of a stimulus: the presence of a stimulus causes a signal in a detection unit to rise until a fixed activity threshold is reached. Once the stimulus has been detected (i.e., threshold has been surpassed), a second rise-to-threshold mechanism in a motor unit determines whether a saccadic response to the stimulus is required. Contrast is assumed to affect the rise-to-threshold only in the detection unit: the higher the contrast, the earlier the threshold in the detection unit is reached. If the stimulus is detected earlier, the rise-to-threshold in the motor unit can begin sooner. In accordance with the neurophysiological data (Bell et al., 2006), one may thus say that contrast affects *when* saccadic motor units start to respond.

Finally, there is also behavioral evidence that supports a temporal account for effects of contrast in the oculomotor system. In a recent study, Bompas and Sumner (2009b) varied the contrast of peripheral distractors and the stimulus onset asynchrony (SOA) between target and distractor in a remote distractor paradigm. Target contrast was fixed and always higher than distractor contrast. They showed that the SOA at which the RDE was strongest (optimal SOA) shifted according to distractor contrast: the lower the distractor contrast, the earlier it had to be presented to produce strong saccadic distraction. This fits well with our assumption that showing the target at higher contrast than the distractor gives the target-related signal a head-start in the oculomotor system (thus, reducing overlap time and in consequence the RDE). This head-start may be diminished when the low-contrast distractor is presented slightly before the high-contrast target and the optimal SOA (i.e. the SOA at which the RDE is strongest) depends on the exact contrast difference between the two stimuli.

The current study was designed to further test this arrival-time account by varying target and distractor contrast as well as the SOA between the two stimuli. Our approach complements the previous work from Bompas and Sumner (2009b) in several respects: First, we tested our predictions on a larger number of participants. Second, we randomly varied target *and* distractor contrast across trials whereas they only randomized distractor contrast but had a fixed target contrast in every experimental block. Third, we examined the effect of central distractors. Fourth, we used a different approach to predict optimal SOA for a given target and distractor contrast combination. Our results are mostly consistent with their data. However, we also observed differences that we interpret in the sense that central distractors interact with top-down processes that control the maintenance of fixation. Importantly, we propose that the RDE may in fact not be strongest when target- and distractor signal *arrive* simultaneously; rather disruption from a distractor may be strongest when the rise-to-threshold of the target-related signal has already advanced.

2. Experiment 1

Gabor patches were used as targets and distractors. The distractors were presented centrally and targets and distractors were displayed at two different contrast levels. In the low-contrast conditions, stimuli were presented at 1.5 times their contrast detection threshold (1.5× CDT), in the high-contrast condition at 16× CDT. By presenting stimuli at multiples of their CDT, we tried to equate the effects of the central distractor stimuli and the peripheral targets. Moreover, we presented the distractor at various SOAs with respect to the target. We hypothesized that when target and distractor are presented at equal contrast (i.e., both at low or both at high contrast), saccadic distraction should be maximal when they appear simultaneously. With equal contrast and simultaneous presentation, there should be no temporal bias in the arrival times of the two signals in the oculomotor system and overlap time should be maximal (Fig. 1B). When introducing a SOA between two stimuli of equal contrast, overlap time should diminish and the RDE should decrease.

With simultaneous presentation and unequal contrast, arrival times are expected to differ (see Fig. 1C and D), which may be corrected by advancing the presentation time of the low-contrast stimulus. When the target is presented at low contrast and the simultaneous distractor is presented at high contrast, the distractor signal arrives earlier in the oculomotor structures because of its higher contrast. Therefore, saccadic distraction should be weak. In order to compensate for the distractor's head-start and to have a strong RDE, the target must be presented slightly before the distractor. When the target is of high and the distractor of low contrast, we would expect a head-start for the target-related signal. We assume that this may reduce the RDE as the distractor signal arrives too late to compete with the target signal. To produce a strong RDE, we would have to present the distractor slightly before the target to compensate for the target signal's head-start. These predictions concerning the SOA range in which the peak RDE was expected are also illustrated by the gray shaded areas in the graph showing the results (Fig. 3).

2.1. Methods

2.1.1. Participants

Ten participants were tested that ranged from 18 to 28 years of age. All were students of the University of Geneva and received either course credit or 20 Swiss Francs (~18 US Dollar) per hour for their participation.

2.1.2. Stimuli

The central fixation stimulus was a horizontal black line of 3 × 1 pixels (0.10° × 0.03° of visual angle). Targets and distractors were vertically oriented stationary Gabor patches with a spatial frequency of 4 cycles per degree and a standard deviation of 0.42° for the Gaussian envelope. They had the same average luminance as the gray background on which they were displayed (66 cd/m^2). Targets were presented at an eccentricity of 10° of visual angle to the left or right on the horizontal meridian. Distractors were presented centrally. Contrast was varied in terms of multiples of detection threshold to equate the subjective contrast of the central distractor and the peripheral target. Both were presented at either 1.5× (low contrast) or 16× (high contrast) their threshold.

2.1.3. Determining contrast detection thresholds

Thresholds were determined using staircase procedures that followed a 2-down, 1-up rule (71% detection threshold; Macmillan & Creelman, 1991). Participants indicated in which of two prespecified time intervals (200 ms each) a target Gabor was presented (left button for first interval, right button for second interval). Stimulus contrast was adapted in fixed steps of 0.2% Michelson contrast: $(L_{max} - L_{min})/(L_{max} + L_{min}) \times 100\%$. Two staircases were run per stimulus location (left, right, center). Stimulus location was blocked and order was counterbalanced across subjects. The final detection thresholds for each stimulus location were calculated by averaging over reversal points of both staircases. How many reversal points were taken into account was individually determined for each participant by consulting a graphical visualization of the staircase data.

2.1.4. Equipment

Stimuli were generated using a ViSaGe Visual Stimulus Generator (Cambridge Research Systems Ltd., Rochester, UK) and displayed on a 21″ CRT monitor (Mitsubishi Diamond Pro 2070SB) running at 100 Hz. The screen's resolution was set to 1024 × 768 pixels. About 31 pixels were displayed per degree of visual angle. At a viewing distance of 67 cm, the display occupied a retinal area of 33° horizontally and 25° vertically. Eye movements were recorded using a CRS High Speed Video Eyetracker (Cambridge Research Systems Ltd., Rochester, UK) at a sample rate of 250 Hz. The subject's head was stabilized by a chin and a forehead rest.

2.1.5. Procedure

The timing of events is illustrated in Fig. 2. At the beginning of each trial observers fixated the central fixation line. After a random delay of 500–1200 ms the first stimulus was presented (the target or the distractor). Target-to-distractor SOA varied between −160 ms, −80 ms, −40 ms, 0 ms, 40 ms, 80 ms and 160 ms. Negative SOAs denote that the distractor was presented first, replacing the central fixation line. Then, after the respective SOA interval (160 ms, 80 ms, 40 ms), the peripheral target would appear. For positive SOAs the target was presented first and the central fixation line was extinguished simultaneously with target onset. In the 0 ms SOA condition, target and distractor were presented simultaneously. The observers' task was to execute a saccade to the center of the target patch as soon as it appeared. They were instructed that speed as well as accuracy was important, though the emphasis lay on speed. After saccading to the target, participants returned their gaze to the center to await the beginning of the next trial. Trials were initiated automatically after an intertrial-interval of ~1 s, no specific action (e.g. button press) of the observer was required. Note that beside distractor trials, there were also trials in which the target was presented without a distractor (20% of trials). When distractors were presented, observers were asked to ignore them. All conditions (target direction: left vs. right, distractor presence: present vs. absent, target and distractor contrast: high vs. low and the different target-distractor SOAs) were varied orthogonally and randomly interleaved across trials. Participants completed four 1-h sessions. In the first session, the detection thresholds were determined. The subsequent sessions consisted of five blocks of 140 trials each (15 blocks in total, corresponding to 2100 trails per participant). The experimental procedure was approved by the ethics committee of the Faculty of Psychology and Educational Sciences of the University of Geneva.

2.1.6. Analyses

Eye movement data were analyzed off-line. A time window of 250 ms before and 800 ms after target onset was specified for analysis in each trial. Saccade onsets were detected using a velocity criterion of 30°/s. Only the first saccade in the time window with an amplitude >1° was considered. Trials were excluded if: (1) no saccade was found within the time window, (2) saccades were executed into the wrong direction, (3) saccades were anticipatory (latency <80 ms), (4) gaze deviated by more than 1.5° from the display center at the time of saccade onset (5) saccadic landing position (horizontal gaze coordinate of the first sample with a velocity <30°) deviated more than 3° from the target's center or (6) the eye tracker lost track between the beginning of the time window and the end of the saccade (e.g. as a result of a blink). Median saccadic latencies in the various distractor and no distractor control conditions were computed for every subject. The RDEs were calculated by subtracting the median value of the no distractor control condition from the corresponding distractor condition.

2.2. Results and discussion

2.2.1. Contrast detection thresholds

The staircase procedures revealed mean contrast detection thresholds of 4.5%, 4.5% and 1.6% for left, right and central stimuli, respectively. Pairwise *t*-tests showed that the thresholds for left and right stimuli were higher than for the central stimulus, $ts(9) > 12.13$, $ps < .001$. No significant difference was found between left and right stimuli, $t(9) = 0.49$, $p = .635$.

2.2.2. Discarded trials and saccadic latencies in no distractor control trials

In total, 11.3% of trials were discarded from analysis (see Section 2.1.6 for criteria). Inspection of a graphical visualization of the discarded data on a trial-by-trial basis revealed that it was very difficult to tell whether an individual error trial was due to technical problems (e.g. loss of eye coordinates, poor calibration) or due to participants' performance. Therefore we did not analyze the rejected trials any further. In the no distractor control trials, saccadic latencies were ~120 ms shorter for high-contrast targets compared to low-contrast targets (205 vs. 324 ms), $t(9) = 20.32$, $p < .001$.

2.2.3. Optimal SOAs

Fig. 3 shows the observed saccadic latencies as a function of target and distractor contrast and target-to-distractor SOA. The no

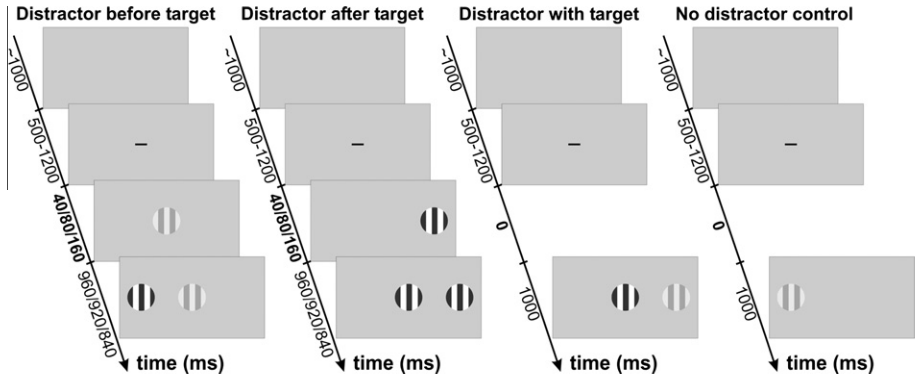

Fig. 2. Procedure in the different SOA conditions of Experiment 1. Participants were asked to saccade to the peripheral Gabor target as soon as it appeared. Stimuli are shown schematically and not drawn to scale. Central distractors could appear and were presented either slightly before the target (negative SOAs in the following graphs and descriptions), slightly after the target (positive SOAs), simultaneously with the target or the target was presented alone. Moreover, we randomly varied target and distractor contrast.

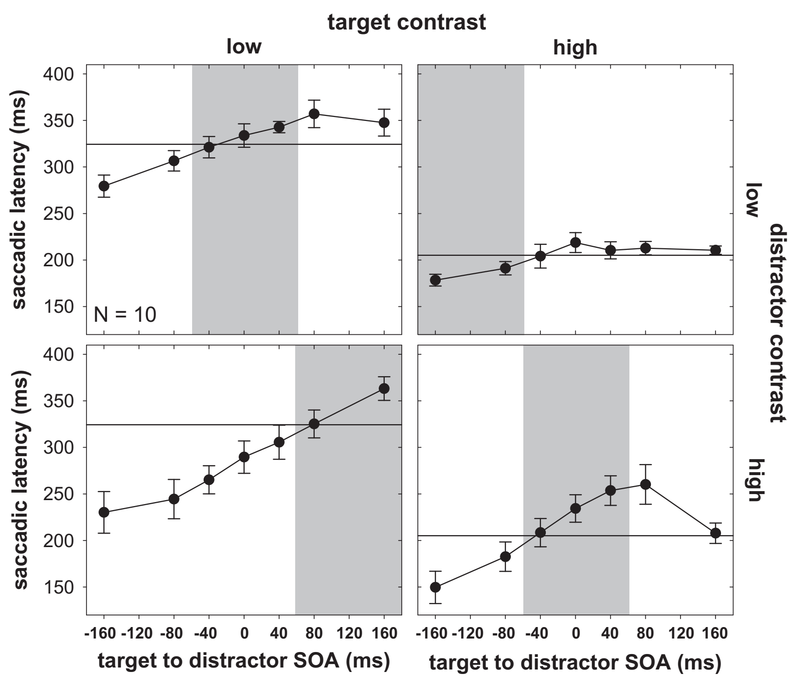

Fig. 3. Saccadic latency as a function of target and distractor contrast and target-to-distractor SOA in Experiment 1. Negative SOAs: the distractor is presented before the target; positive SOAs: the distractor is presented after the target. The horizontal line represents the latency in the no distractor control trials. Gray shaded areas illustrate the SOA range in which the peak RDE was expected, i.e., around 0 ms (equal contrast conditions), at negative (high target, low distractor contrast) or positive SOAs (low target, high distractor contrast; the illustration is only a rough approximation, e.g., the width of the area is not based on exact predictions). Error bars represent the 95% confidence interval of the difference between distractor and no distractor trials (i.e., of the RDE).

distractor baseline latency is marked by the horizontal line in each panel. The RDE is the latency difference between the distractor conditions and their corresponding no distractor baseline. Error bars represent the 95% confidence interval of this latency difference. Therefore, the RDE is significantly different from zero in a given condition when error bars do not cross the baseline.

Looking at the equal contrast conditions, it is immediately obvious that the RDE did not show a peak at an SOA of 0 ms. Rather, the strongest latency increases with respect to the no distractor baseline were found around an SOA of +80 ms. This was true for both the low (Fig. 3, upper left panel) and the high-contrast conditions (lower right panel). Thus, the two equal contrast conditions nevertheless showed a peak around the same SOA. When the target was of high contrast and the distractor of low contrast (upper right panel), the strongest RDE was found around a SOA of about 0–40 ms. Thus, the optimal SOA is shifted to the left compared to the equal contrast conditions. For low target and high distractor contrast (lower left panel), data show an RDE peak at the longest SOA tested (160 ms). Fig. 3 suggests that the true RDE peak may even be found at longer SOAs, possibly around 200 ms. Thus, the optimal SOA is shifted to the right with respect to the equal contrast conditions. In sum, the relative shifts of optimal SOA across contrast conditions are in line with predictions for peak RDEs (see shaded areas in Fig. 3): the lower the distractor contrast compared to the target contrast, the earlier the distractor has to be presented.

We also tested these differences statistically. We marked for each individual observer and contrast combination the optimal SOA (i.e., the SOA at which the RDE was strongest). Mean optimal SOAs are summarized in Fig. 4A. Note that the order of the bars reflecting the different contrast conditions does not match the order depicted in Fig. 3. Rather, Fig. 4A reflects our hypotheses about optimal SOAs with the condition in which we expected the highest bar to the left and the smallest bar (or rather a bar in the negative range) to the right. A two-way repeated-measures ANOVA revealed main effects for both target contrast, $F(1, 9) = 44.18$, $p < .001$ and distractor contrast, $F(1, 9) = 21.00$, $p = .001$, confirming that varying target as well as distractor contrast results in a shift of the optimal SOA. The interaction did not reach significance, $F(1, 9) = 0.50$, $p = .496$. Moreover, a pairwise *t*-test confirmed that there was no significant difference in optimal SOA between the two equal contrast conditions, $t(9) = 1.18$, $p = .269$. Therefore, we collapsed the data for comparison with the two conditions of unequal contrast. These tests revealed that the optimal SOA in the low target, high distractor contrast condition was more positive than in the equal contrast conditions, $t(9) = 6.04$, $p < .001$. The optimal SOA in the high target, low distractor contrast conditions tended to be smaller than in the equal contrast conditions, but this difference did not reach significance, $t(9) = 2.14$, $p = .061$. We had expected a negative SOA to produce peak RDEs in this condition (see Fig. 3, upper right panel), which was clearly not the case.

One possible reason for the failure to find a RDE peak at negative SOAs may be facilitation effects that are superimposed on the RDE. In general, faster latencies than in the no distractor control trials were found in all four contrast combinations at negative SOAs. These may be explained by warning effects: When the distractor preceded the target, it may have alerted participants to the upcoming target appearance, especially with high-contrast distractors (Findlay & Walker, 1999; Ross & Ross, 1980, 1981; Walker et al., 1995). In the low-contrast distractor conditions, facilitation may additionally occur through a fixation release component. Recall, that we extinguished the fixation stimulus upon presentation of the distractor in Experiment 1. That is, in the low-contrast distractor conditions, the small but clearly visible fixation stimulus was replaced by a barely visible distractor. This may have triggered a partial release from fixation. It is well known that the offset of the fixation stimulus prior to target onset reduces saccadic latency (Saslow, 1967) which may partly be attributed to oculomotor release from fixation (Findlay & Walker, 1999; Kingstone & Klein, 1993; Reuter-Lorenz, Hughes, & Fendrich, 1991; Rolfs & Vitu, 2007). The fixation release component may have been stronger than the distractor effect und thus, RDE at negative SOAs were precluded. Experiment 2 tried to clarify the role of a fixation release component and facilitation effects in general.

Finally, despite the fact that the relative shifts in optimal SOA across contrast conditions are in line with our predictions, it has to be mentioned that in absolute terms, the observed optimal SOA was shifted to the right (i.e. towards more positive SOAs than expected) compared to the predicted optimal SOA range in all conditions (see Fig. 3). This can best be observed in the two equal contrast conditions in which we predicted an optimal SOA of 0 ms, whereas observed optimal SOAs lay in the positive SOA range (around 80 ms). We will elaborate on this observation in the General discussion.

2.2.4. Remote distractor effects

Along with optimal SOAs, we also looked at the magnitude of the RDEs: What is the strongest RDE found for a given contrast combination (RDEmax)? To this end, we obtained the RDEs at the optimal SOA for each observer and contrast combination individually (see Fig. 4B; order of bars according to potentially decreasing RDEmax from left to right). A repeated-measures ANOVA revealed a main effect of distractor contrast, $F(1, 9) = 16.73$, $p = .003$, indicating that the RDE was stronger for high-contrast compared to low-contrast distractors. The main effect of target contrast was not significant, $F(1, 9) = 0.00$, $p = 1.00$. However, the interaction between target contrast and distractor contrast was significant, $F(1, 9) = 30.97$, $p < .001$. Fig. 4B shows that for low-contrast distractors (the two rightmost columns), the RDE was larger with low-contrast targets than with high-contrast targets. For high-contrast distractors, this pattern was reversed (the two leftmost columns). Recall, that the SOA range that we used was probably too small to measure the RDE at its maximum in the low target, high distractor contrast condition (leftmost column). A more realistic estimate of RDEmax in this condition would probably be around 65–90 ms (depending on whether one would expect the RDE to level off). This is illustrated in Fig. 4B by the gray outlines. Thus, we assume that in general, RDEmax should increase (or at least stay unaffected) with decreasing target contrast. Note, however, that in any case, the impact of distractor contrast seems to be stronger than the impact of target contrast. This is evident when comparing the two equal contrast conditions (middle columns): Despite equal contrast of target and distractor, the RDE is stronger in the high-contrast condition, $t(9) = 3.50$, $p = .007$. If varying target and distractor contrast had equally strong, but opposite effects on the RDE, then RDEmax should have been equal in the two conditions. The higher RDEmax in the high-contrast condition shows that an increase in RDE due to higher distractor contrast cannot be counteracted by increasing the contrast of the target by the same amount.

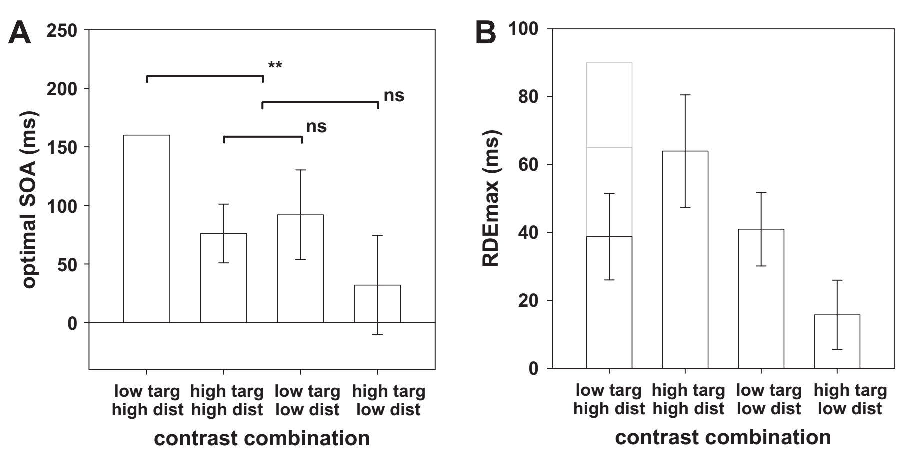

Fig. 4. Optimal SOA (panel A) and maximal remote distractor effect (RDEmax, panel B) as a function of target and distractor contrast in Experiment 1. The gray outline in panel B indicates that RDEmax for this particular contrast combination could probably not be assessed in the experiment and may be larger than observed. Error bars represent 95% confidence intervals (the missing error bar in the leftmost column of panel A is due to the fact that all participants had their optimal SOA for this condition at 160 ms).

3. Experiment 2

One interesting issue in Experiment 1 is that for all contrast combinations, saccadic latencies were shorter with a distractor than in the no distractor control condition in some SOA conditions (reversed RDE). This was mostly confined to negative SOAs, that is, to the conditions where the distractor appeared before the target (but see the low target, high distractor contrast condition for reversed RDEs up to SOAs of +40 ms, Fig. 3, lower left panel). Such reversed RDEs may be attributed to a warning issued by the distractor onset that triggers either motor preparation processes or temporal preparation processes (the onset of a distractor tells the observer that the target is certain to appear within the next 160 ms; see Rolfs & Vitu, 2007 for a discussion) and that may be exogenous (involuntary general alerting effect) or endogenous (e.g. the distractor's temporal features are voluntarily used to speed up saccades) in nature. Moreover, in the low distractor contrast conditions, partial release from fixation may have speeded up saccade initiation for negative SOAs as the fixation line is replaced by a barely visible distractor prior to target onset. Fig. 5 illustrates the idea that such facilitation effects, riding on top of the distractor effect, may on the one hand explain why no RDE was found for negative SOAs and on the other hand, more generally, why the optimal SOA in all conditions is shifted to the right compared to our predictions. We assume a facilitation effect that is triggered by distractor onset and increases over time. Therefore it should be strongest when the distractor is presented early, that is, long before the target (i.e. at negative SOAs). As the time interval between distractor and target onset decreases (negative SOA closer to zero), facilitation effects become smaller. Facilitation does not occur anymore when the distractor is presented long after the target (positive SOAs) as the time interval between distractor onset and initiation of the saccade may be too short for facilitation to take effect. Fig. 5 depicts a model in which saccadic latencies are determined by both distractor interference (which is maximal with synchronous presentation) and facilitation effects (which is maximal when the distractor appears before the target). Interference and facilitation may cancel each other out or facilitation effects may even cause shorter saccadic latencies than in the no distractor control condition. Moreover, the optimal SOA in an equal contrast condition is shifted from 0 ms towards a positive SOA. To further tap into this issue, we tested more observers in a variant of Experiment 1 that aimed at minimizing facilitation effects.

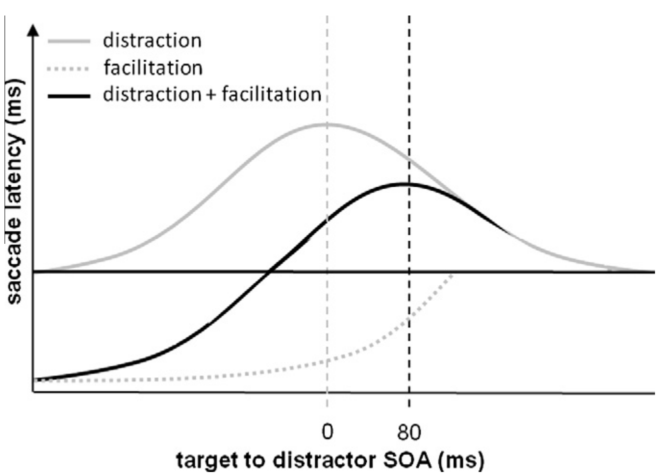

Fig. 5. Facilitation effects may explain "reversed" RDEs and the shift of the optimal SOA (vertical dashed lines) towards more positive SOAs. The horizontal black line marks the no distractor control condition. Curves above the horizontal black line indicate slowing of saccadic latency (RDE), curves below the line indicate reversed RDE. The gray curve represents the latency distribution in an equal contrast distractor condition across SOAs when no facilitation effect is assumed. Distractor interference is strongest at 0 ms SOA (maximal temporal overlap of target and distractor signal). The gray dotted curve shows the facilitation effect caused by the distractor. It increases with time from distractor onset, i.e. it is largest when the distractor is presented before the target (negative SOAs). The black curve shows the combined latency distribution with a facilitation effect superimposed on the interference effect.

3.1. Methods

Stimuli, procedure, design, equipment and analyses were identical to Experiment 1 except for the following changes. First, we presented the target for the saccadic response at a fixed time interval of 1000 ms after onset of the fixation stimulus. In this way, at least temporal uncertainty regarding target onset should be minimized. Second, the fixation stimulus was always extinguished simultaneously with target onset. This means that on trials with negative SOA, the distractor stimulus was superimposed on the fixation line until the target was presented and the fixation line extinguished. With this manipulation, we sought to counteract a fixation release effect triggered by the offset of the fixation line prior to target onset, in particular for conditions with low-contrast distractors. The experiment was run on eight new observers (five members of the cognitive psychology unit of the University of Geneva, three first year psychology students), none of whom had participated in Experiment 1. They ranged from 22 to 51 years of age. Initially, we included target direction (left, right) as a factor in the analyses of Experiment 1. As no systematic effects were observed, we did not report them in the results section and we did not include this factor in the analyses of Experiment 2. Therefore we could reduce the number of experimental trials: Experiment 2 was run in three sessions. In the first session, the detection thresholds were determined. The subsequent sessions consisted of five blocks of 140 trials each (10 blocks corresponding to 1400 trials per participant).

3.2. Results and discussion

3.2.1. Contrast detection thresholds

Contrast detection thresholds were at 6.1%, 6.0% and 1.6% for left, right and the central stimulus, respectively. As for Experiment 1, pairwise *t*-tests showed that the thresholds for left and right stimuli were higher than for the central stimulus, $ts(7) > 5.32$, $ps = .001$. No significant difference was found between left and right stimuli, $t(7) = 0.79$, $p = .457$. Thresholds seemed slightly elevated compared to the group tested in Experiment 1. However, independent samples *t*-tests comparing CDTs for left, right and central stimuli across experiments did not reveal any significant differences, $ts(16) < 1.51$, $ps > .151$.

3.2.2. Discarded trials and saccadic latencies in no distractor control trials

14.2% of trials were discarded from analysis. Saccadic latencies were ~90 ms shorter for high-contrast targets compared to low-contrast targets (183 vs. 273 ms), $t(9) = 15.48$, $p < .001$. A repeated-measures ANOVA with target contrast as within-subjects factor and experiment as between-subjects factor revealed a highly significant main effect of target contrast, $F(1, 16) = 623.30$, $p < .001$, and a marginally significant main effect of experiment, $F(1, 16) = 4.32$, $p = .054$, indicating that saccadic latencies were shorter in the present than in the previous experiment (228 vs. 265 ms). Further, the interaction between target contrast and experiment reached significance, $F(1, 16) = 12.38$, $p = .003$, indicating that latencies in the low target contrast condition were much shorter in Experiment 2 than in Experiment 1 (273 vs. 324 ms), whereas the latencies in the high target contrast condition differed less between Experiment 2 and Experiment 1 (183 vs. 205 ms). The overall shorter latencies in Experiment 2 can be easily explained by the fixed time course: The target appeared at a fixed time interval of 1000 ms after onset of the fixation stimulus. Therefore, the target appeared with less temporal uncertainty than in Experiment 1. The interaction may reflect a floor effect in the high target contrast condition: possibly, saccadic eye movements towards our Gabor stimuli could not be speeded up much further than 180 ms.

3.2.3. Optimal SOAs

Fig. 6 shows that in the low distractor contrast conditions (upper row), no reversed RDEs were observed anymore. Thus, facilitation effects found in Experiment 1 may indeed be partly attributed to fixational release. In contrast, data also shows that reducing the temporal uncertainty for target onset did not abolish the reversed RDEs produced by high-contrast distractors (lower row). At the most, facilitation is slightly attenuated compared to Experiment 1. This result may suggest that the facilitative effect of the distractor may not act through reducing temporal uncertainty about the target's onset. Rather, the facilitative effect may stem from a more exogenous alerting component. Note, however, that this conclusion must be regarded with caution as the distractor's appearance may simply be a better temporal predictor of the target's imminent appearance than the fixed time course of trials. Most importantly, the overall pattern of results is very similar to Experiment 1. Again, we find relative shifts in the optimal SOA across contrast conditions (see also Fig. 7A). Analyzing the optimal SOAs in a repeated-measures ANOVA revealed only a significant main effect of distractor contrast, $F(1, 7) = 6.27$, $p = .041$, but no significant main effect target contrast, $F(1, 7) = 2.67$, $p = .146$. However, the interaction between the two contrast factors reached significance, $F(1, 7) = 7.00$, $p = .033$. A subsequent pairwise t-tests showed that there was no significant difference in optimal SOA between the two equal contrast conditions, $t(7) = 0.48$, $p = .644$. Therefore, we again collapsed the data for comparison with the two conditions of unequal contrast. In line with our predictions, optimal SOA in the low target, high distractor contrast condition was significantly longer (i.e. shifted to more positive SOAs) than in the equal contrast conditions, $t(7) = 5.99$, $p = .001$. However, the difference in optimal SOA between the high target, low distractor contrast conditions and the equal contrast conditions failed to reach significance, $t(7) = 0.26$, $p = .803$. Fig. 6 (upper right panel) and Fig. 7A show that the high target, low distractor contrast condition again failed to show the predicted RDEs at negative SOAs (see gray regions).

Further, the same ANOVA including experiment as between-subjects factor revealed highly significant main effects of target contrast, $F(1, 16) = 20.20$, $p < .001$, as well as distractor contrast, $F(1, 16) = 21.67$, $p < .001$, and a significant interaction between the two contrast factors, $F(1, 16) = 4.99$, $p = .040$. There were no significant interactions between the between-subjects factor experiment and the contrast factors, $Fs(1, 16) < 1.65$, ps > .217. However, the main effect of experiment was significant, $F(1, 16) = 10.24$, $p = .006$, indicating that optimal SOAs were generally shorter in Experiment 2 than in Experiment 1 (48 vs. 90 ms). In other words, the optimal SOA in absolute terms was shifted less to the right in Experiment 2 than in Experiment 1. This may indicate that the shift can partly be explained by a superimposed facilitation effect (see Fig. 5) that was stronger in Experiment 1 than in Experiment 2. Still, there was a significant rightwards shift as can best be seen in the two equal contrast conditions: optimal SOAs lay again in the positive SOA range. Although Fig. 7A suggest that the shift in the low contrast condition may not be significant (error bars cross the zero line, therefore the optimal SOA is not significantly different from zero), close inspection of the data reveal that this was due to an outlier value present in one single participant who showed an optimal SOA at −160 ms. All other participants showed optimal SOAs between 0 and +80 ms that were significantly different from zero (mean 46 ms), $t(6) = 2.83$, $p = .030$. Thus, a rightwards shift occurred even in the low contrast condition (Fig. 6, upper left panel), that is, despite the fact that we did not find any evidence for a fixational release or warning component (no reversed RDEs). We therefore conclude that facilitative effects may not be entirely responsible for the observed shift towards positive SOAs. An account of the shift of the optimal SOA will be presented in the General discussion.

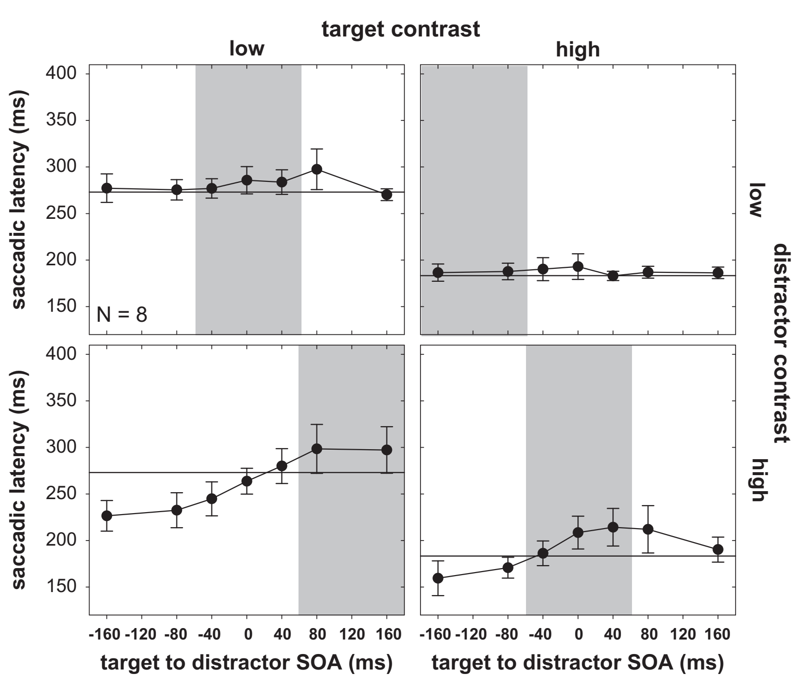

Fig. 6. Saccadic latency as a function of target and distractor contrast and target-to-distractor SOA in Experiment 2. Conventions as in Fig. 3.

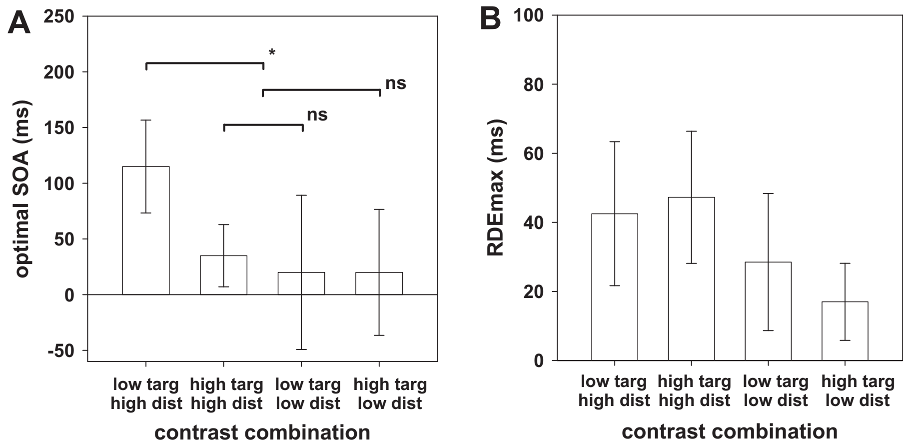

Fig. 7. Optimal SOA (panel A) and maximal remote distractor effect (RDEmax, panel B) as a function of target and distractor contrast in Experiment 2. Conventions as in Fig. 4.

3.2.4. Remote distractor effects

The repeated-measures ANOVA on the RDEmax values for Experiment 2 (see Fig. 7B) revealed a significant main effect of distractor contrast, $F(1, 7) = 15.39$, $p = .006$, indicating that the RDE was stronger for high-contrast compared to low-contrast distractors. The main effect of target contrast was not significant, $F(1, 7) = 0.20$, $p = .667$, but there was a significant interaction between target contrast and distractor contrast, $F(1, 7) = 10.72$, $p = .014$. Thus, results closely resemble those of Experiment 1. This was further confirmed in an ANOVA including experiment as between-subjects factor. This analysis likewise revealed a significant main effect of distractor contrast, $F(1, 16) = 32.30$, $p < .001$, and a significant interaction between the two contrast factors, $F(1, 16) = 36.05$, $p < .001$. Further the interaction between target and distractor contrast and experiment reached significance, $F(1, 7) = 9.47$, $p = .007$. No further effect or interaction was significant, $Fs(1, 16) < 0.84$, ps > .374. Comparing Fig. 4B with Fig. 7B suggests that the three-way interaction may be due to the low target, high distractor contrast condition. Recall that in Experiment 1, the true RDEmax for this condition was probably underestimated and numerically smaller than in the high target, high distractor condition. Fig. 7B suggests that the two conditions are similar when RDEmax is properly measured.

3.3. General discussion

The results of our experiments can be summed up in four major findings. First, optimal SOAs (i.e., the SOA at which the strongest RDE can be found) were shifted across the different target and distractor contrast combinations according to our predictions: the lower the distractor contrast with respect to the target contrast, the earlier the distractor had to be presented to produce a strong RDE. We interpret these findings as evidence for the assumption that varying target and distractor contrast modulates at which point in time the respective stimulus signal reaches the oculomotor structures. A strong RDE can only be observed when target and distractor signals show large temporal overlap in the oculomotor structures. If target and distractor are presented simultaneously but at different contrast levels, the distractor-related signal may be evoked either too early or too late to compete with the target signal. A strong RDE can only be found when introducing a compensatory SOA that realigns the arrival times of target and distractor in the oculomotor structures. Our results confirm previous findings from Bompas and Sumner (2009b) who used peripheral distractors and showed that for a target of a given contrast, the optimal SOA shifts to the right (towards more positive SOAs) with increasing distractor contrast (i.e., presentation of the distractor has to be delayed). We complement their findings by showing that the optimal SOA for a given distractor contrast also shifts with target contrast: with increasing target contrast optimal SOAs shifted to the left (i.e., Presentation of the distractor has to be advanced; something that was only alluded to in their study, see their Experiment 1b).

Second, although optimal SOAs were shifted according to predictions, the magnitude of the RDE at these optimal SOAs was also dependent on the specific target and distractor contrast combination. This suggests that contrast does not only affect when a stimulus signal arrives in the saccade map, but also the subsequent motor competition processes. In fact, when applied to RDEmax, the prediction from our first study (Born & Kerzel, 2008) also holds: RDEmax increased with increasing distractor contrast, suggesting that a stronger signal perturbed saccade programming more than a weak signal (see also Bompas & Sumner, 2009b). RDEmax was less influenced by target contrast: The slowing due to the distractor was not weaker when the target signal was strong. This may be explained by considering that distractor contrast influences the disruptive power of the distractor in the competition whereas target properties influence the ability of the target signal to resist the disruption. The two processes may not necessarily produce quantitatively equal modulations of the RDE. Alternatively, modulations of the RDE due to target properties such as contrast may be more strongly attenuated through top-down influences on the target signals (see Born & Kerzel, 2009). Note that the saccades in our experiments were not necessarily purely stimulus-driven. Observers followed the experimental instructions to saccade to the peripheral stimulus as fast as possible. Therefore, top-down influences on the target-related signal may account for the limited influence of target contrast on the RDE. For instance, at a certain point, the target may be voluntarily selected as the goal for the saccadic eye movement and consequently target-related activity may be enhanced in a top-down manner, blurring bottom-up effects of target contrast. As target locations were limited, top-down enhancement of activity at the two potential target locations may even have occurred before stimulus onset (e.g. in the wake of motor preparation processes; see Rolfs & Vitu, 2007). As this top-down enhancement occurred for low- and high-contrast targets alike, part of the target-related signal would have been independent of stimulus properties and therefore the impact of target contrast reduced.

Third, we never observed any RDEs at negative SOAs. This finding contrasts with reports from studies using peripheral distractors (Bompas & Sumner, 2009a, 2009b) where RDEs at negative SOAs could be observed. We therefore conclude that prior to target

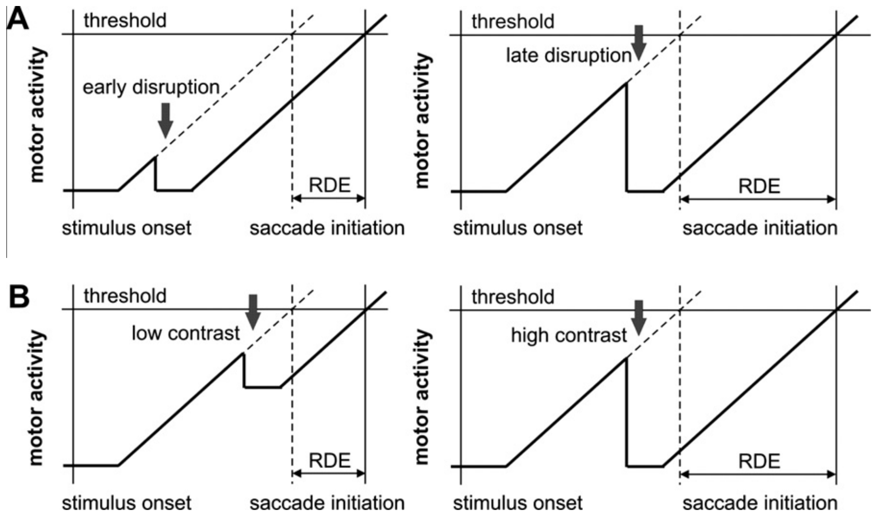

Fig. 8. Illustration of how distractor effects may be stronger when the distractor signal arrives after the target signal. Saccadic latency is determined by a rise-to-threshold mechanism in a motor unit coding for the saccade target. As soon as threshold is reached, the saccade is initiated. Dashed lines mark the rise-to-threshold in target-related activity when no distractor is presented. Panel A shows disruption (marked by the gray arrow) from high-contrast distractors either early into the rise-to-threshold of target-related activity (left) or at a later point (right). As the rise-to-threshold has not advanced as much in the former case, it will take less time to recover from disruption than in the latter case. Panel B shows modulations in the strength of disruption by distractor contrast. A low-contrast distractor (left) may not be able to suppress target-related activity as strongly as a high-contrast distractor (right).

onset, stimuli at central locations are processed differently from peripheral stimuli. One reason for the lack of RDE with central distractors may be that prior to target onset, activity is focused at the central location in a top-down manner to maintain fixation as instructed (Findlay & Walker, 1999; Kopecz, 1995; Munoz & Wurtz, 1993). The distractor stimulus may therefore not be able to increment fixational activity any further.

Fourth, although the relative shifts in optimal SOA across contrast conditions were in line with our hypotheses, we also found an absolute shift towards more positive optimal SOAs that was not predicted. Moreover, Experiment 2 showed that this shift cannot be fully explained by facilitation effects that ride on top of the distractor effect. One may assume that the finding is a peculiarity of our experiment. For instance, it may reflect irregularities in our procedure to equate the contrast of target and distractor by using multiples of detection threshold or it may simply reflect that despite equal visibility, foveal signals still reach the oculomotor structures sooner than peripheral signals. However, inspection of other RDE studies that used a SOA manipulation shows that data are surprisingly consistent with our shift. Bompas and Sumner (2009b) found a similar shift from expected optimal SOA that they derived from saccade latency differences. Further, other studies showed larger RDEs when the distractor was presented after the target. White, Gegenfurtner, and Kerzel (2005) obtained a maximum RDE for a small central distractor around SOAs of 50–100 ms. Reingold and Stampe (2002) showed that distractor effects by large flashed stimuli presented in the periphery could be maximized when the flash was presented 100 ms before saccade initiation. In all of their conditions, this meant that the flash had to be presented after the saccade target. Finally, in the classic study by Walker et al. (1995) using peripheral distractors and fixed saccade direction, although there was a peak in the RDE at 0 ms SOA, presenting the distractor slightly after the target (up to 40–80 ms) still produced distractor effects, whereas there was a sharp drop with negative SOAs (see also Buonocore & McIntosh, 2008). To this point, one may only speculate why distractors may be more disruptive when presented after the target. However, the finding may be taken to argue against a simple and smooth lateral inhibitory mechanism between the target- and the distractor-related signal. The reason is that lateral inhibition predicts that when target-related activity is build up before distractor-related activity, the onset of distractor activity would essentially be "squashed" straight away, resulting in very little, or at least less, distraction than when the two signals arrive simultaneously or when the distractor-related signal arrives first.[1] One alternative might be that distractors do not disrupt saccade motor preparation through a smooth and sustained inhibition process but through a sharp disruption in the target-related signal. Fig. 8A illustrates this idea. Following Carpenter's (2004) suggestion of a rise-to-threshold mechanism in a motor unit representing the saccade target, a disruption that occurs early on, that is, at a point when the level of target-related activity is still low, would take less time to recover from than when it occurs later. In a sense, we assume a kind of floor effect: If target-related activity has not advanced much, it cannot be disrupted as strongly. A similar general "interrupt" signal caused by the onset of a new visual event has already been proposed by Reingold & Stampe (2002; see also Buonocore & McIntosh, 2008; Kerzel, Born, & Souto, 2010; Pannasch, Dornhoefer, Unema, & Velichkovsky, 2001). The notion fits also well with neurophysiological data suggesting that distractors produce a sharp and transient drop in target-related activity (Dorris, Olivier, & Munoz, 2007). Furthermore, distractor properties such as contrast may determine the maximal strength of the disruption (see Fig. 8B). The account as illustrated in Fig. 8 is highly speculative and probably oversimplified. Still, it shows that distractor effects may not necessarily be strongest when target- and distractor-related activity *arrive* at the same time. Note, however, that this does not question the temporal account as such, as the disruption effect still depends on temporal overlap between target- and distractor-related signals.

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