Attention delays perceived stimulus offset ☆

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Abstract

Yeshurun and Levy (2003) [Transient spatial attention degrades temporal resolution. *Psychological Science*, *14*, 225 –231.] have suggested that visual attention enhances the activation of the parvocellular system and thus delays the perceived offset of a stimulus. We tested this assumption in a spatial cueing paradigm in which participants responded to stimulus offset. Consistent with this assumption, offset reaction time (RT) was prolonged for attended compared to unattended stimuli. For onset RT, however, we confirmed the well-known spatial cueing effect that attention speeds up the detection of stimulus onset. The results provide direct evidence for the proposal made by Yeshurun and Levy.
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1. Introduction

The functional role of visual attention is often compared to a filter mechanism which selects relevant information from the bulk of all environmental stimuli (Broadbent, 1958), and which may enhance the processing of selected stimuli (cf. Pashler, 1998). This view about attention is supported by numerous studies. For example, participants respond faster to attended than to unattended stimuli (e.g., Henderson, 1991; Jonides, 1980; Posner, Snyder, & Davidson, 1980). In addition, discrimination of line length (Bonnel, Possamaï, & Schmitt, 1987), line orientation (e.g., Cheal, Lyon, & Hubbard, 1991; Downing, 1988), orientation of Gabor patches (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lu & Dosher, 1998; Yeshurun & Carrasco, 2000), vernier stimuli (Yeshurun & Carrasco, 1999), Landolt-squares (Yeshurun & Carrasco, 1999), and letters (e.g., Henderson, 1991, 1996) is enhanced if attention is

allocated to these stimuli. All these studies support the hypothesis that visual attention facilitates perceptual processing. There are, however, two exceptions to this rule. First, Yeshurun and Carrasco (1998) found that visual attention improves the detection of texture segregation at the periphery, but hampers this detection at central locations by enhancing spatial resolution.

Second, Yeshurun and Levy (2003) reported another even more dramatic impairment by showing that attention can actually lower the temporal processing of the visual system. Their participants performed a temporal discrimination task. In some trials, two successive light flashes, separated by a brief temporal interval, were presented to the same location in the display. In the remaining trials, a single continuous flash was presented. Participants were asked to discriminate between both types of trials. Furthermore, a spatial cue appeared shortly before the presentation of the target stimulus. In the valid condition, this cue shifted visual attention to the location at which the stimulus was presented. In the neutral condition, however, the cue did not restrict attention to a particular location. Surprisingly, the detection of the temporal gap was impaired in the valid condition.

Recently, Rolke, Dinkelbach, Hein, and Ulrich (2006) replicated this effect with an alternative arrangement of

cues. These authors replaced the neutral cue employed in the study of Yeshurun and Levy (2003) by an invalid cue, which was physically identical to the valid one. In line with the results of Yeshurun and Levy, temporal gap detection was impaired when attention was oriented toward the stimulus location. In addition, Hein, Rolke, and Ulrich (2006) have successfully generalized this effect to another temporal task in which participants were asked to discriminate the temporal order of two spatially adjacent dots. In a series of three experiments and in accordance with Yeshurun and Levy's result, they have shown that automatically oriented visual attention impairs discrimination performance.

Yeshurun and Levy (2003) also ruled out the possibility that the decrement of performance in the valid condition merely reflects a non-attentional interference effect. In a control experiment, participants were required to detect a spatial gap in a Landolt-circle instead of a temporal gap. Consistent with the bulk of studies on visual attention (e.g., Yeshurun & Carrasco, 1999), the detection of the spatial gap was improved in the valid condition. In sum, then, the results of Yeshurun and Levy (2003) show that visual attention enhances the performance of spatial discrimination but impairs temporal discrimination. In other words, attention enhances the spatial yet lowers the temporal resolution of the visual system.

To account for this trade-off between the temporal and the spatial resolution, Yeshurun and Levy (2003) have proposed a *neurophysiological hypothesis* of attention. Accordingly, attention selectively influences the parvo- and the magnocellular pathways of the visual system. More specifically, the authors have assumed that visual attention facilitates the activity of parvocellular neurons at the attended location, which in turn is assumed to inhibit the activity of magnocellular neurons at the same location. Thus, attention should highlight the attributes of the parvocellular system compared to those of the magnocellular system. Neurophysiological studies have shown that parvocellular neurons not only exhibit smaller receptive fields but also longer response durations than magnocellular neurons (e.g., Maunsell & Gibson, 1992). Thus, Yeshurun and Levy (2003) have argued that the increased activity of parvocellular neurons at the attended location enhances the spatial resolution due to their smaller receptive fields. Crucially, however, the associated prolonged neuronal response minimizes the possibility of detecting the temporal gap in the target stimulus at the attended location, since stimulus input at the attended location is integrated over a longer period within the parvocellular system.

To further test the assumed inhibitory interaction between the parvocellular and the magnocellular channels, Yeshurun (2004) minimized the contribution of the magnocellular system on stimulus processing and predicted that this should eliminate the differential effect of attention on temporal discrimination performance. As predicted, the cueing effect was reduced when isoluminant stimuli (Experiment 2) or a red background (Experiment 3) were employed, which are known to primarily activate the par-

vocellular system. This pattern of results strengthens the notion that the negative effect of attention involves an inhibition of the magnocellular system; otherwise no reduction of this effect should have occurred.

The neurophysiological hypothesis of Yeshurun and Levy (2003) also implies that attention should influence the perceived duration of a visual stimulus. Since the hypothesis assumes that attention facilitates the activity of parvocellular neurons and since parvocellular neurons have longer response latencies than magnocellular ones, the hypothesis implies that attention delays the perceived termination of a stimulus.

Consequently, attended stimuli should be perceived to last longer than unattended ones. In fact, psychophysical studies by Mattes and Ulrich (1998) and Enns, Brehaut, and Shore (1999) clearly support this prediction. These authors employed a spatial cueing paradigm (Posner et al., 1980) to assess the effect of spatial attention on perceived duration. For example, Mattes and Ulrich used exogenous and endogenous precues to direct spatial attention and found that stimuli at the precued location appear generally longer than stimuli at the uncued location. Enns et al. additionally examined the relationship between this effect on stimulus duration and the cueing effect of attention on perceived stimulus onset. An endogenous cue oriented attention. One group of participants performed a duration judgment. Consistent with the study of Mattes and Ulrich, the perceived duration of the attended stimulus was prolonged. A second group of participants performed a temporal order task, i.e., they were required to indicate which one of two dots appeared first on the screen. The results of this task showed that the perceived onset of the attended dot speeds up. On the basis of the results of the two groups, Enns et al. have reasoned that the effect of attention on perceived duration does not reflect changes of perceived stimulus onset. Accordingly, the attentional effect on perceived stimulus duration should result from an attentional influence on perceived stimulus offset. We are not aware, however, of any study providing direct evidence for the hypothesis that attention prolongs the perceived termination of a stimulus.

The finding by Yeshurun and Levy (2003) that attention impairs temporal gap detection might be due to two (not necessarily exclusive) reasons. First, as proposed by the neurophysiological hypothesis, the perceived gap might be shortened because of a prolonged persistence of the first disc due to longer response latencies of parvocellular neurons. Second, and contrary to their hypothesis but in agreement with the prior entry effect (Carrasco & McElree, 2001; Shore, Spence, & Klein, 2001; Titchener, 1908), the perceived gap might be shortened because attention exclusively accelerates the perceived onset of the post-gap disc. Available data do not allow to distinguish which of the two accounts might have been contributed to the impaired gap detection performance in the study of Yeshurun and Levy (2003).

Therefore, the present study aimed to disentangle these two accounts. We used the experimental setup of Yeshurun

and Levy (2003) and presented target stimuli either at an attended or unattended position. Instead of the gap-detection task, a simple reaction time (RT) task was employed to assess the effect of attention on perceived stimulus offset (e.g., Baro, Brzezicki, Lehmkuhle, & Hughes, 1992). According to the neurophysiological hypothesis, we expected that offset RT should be prolonged in the attended condition compared to the unattended one. In an additional condition, we asked the participants to respond to stimulus onset. According to the prior entry effect (Schneider & Bavelier, 2003; Shore et al., 2001), we expected that attentive stimulus processing should result in shorter onset RT.

2. Experiment 1

The first experiment assessed the influence of visual attention on the perception of stimulus onset and offset. Stimulus presentation was similar to Experiment 1 of the study of Yeshurun and Levy (2003). Either a neutral or a valid cue preceded the target stimulus. Participants responded in one condition to the onset and in the other condition to the offset of the target stimulus by pressing a response button. This approach for assessing the perceived on- and offset of a stimulus has been employed by studies on signal detection, visual persistence, and for investigating the perceived duration of a stimulus (Baro et al., 1992; Briggs & Kinsbourne, 1972; Di Lollo, Enns, Yantis, & Dechief, 2000; Parker, 1980; Tolhurst, 1975). To control for non-attentional persistence effects associated with stimulus duration (e.g., Efron, 1970), three different target durations were used. Therefore, the factorial combination of stimulus duration, cueing condition, and task resulted in twelve experimental conditions.

2.1. Method

2.1.1. Participants
Twenty participants were recruited.

2.1.2. Stimuli and apparatus
Stimulus presentation is illustrated in Fig. 1. As in the study of Yeshurun and Levy (2003), all stimuli but the cue (green, 44 cd/m^2) were presented in white (38 cd/m^2) on a black (<0.01 cd/m^2) background of a standard VGA computer screen (60 Hz). A disk of 3° diameter visual angle served as target stimulus and appeared with an eccentricity of 4° either to the left or to the right of a white fixation cross (0.5 × 0.5°) which remained at the center of the screen during the whole course of a trial. As in Yeshurun and Levy's study, the cue in the validly cued trials was a horizontal bar, which subtended a visual angle of 1 × 0.3° and appeared 0.5° above the target's location. The neutral cue—which stretched almost the entire display—consisted of two 14 × 0.3° horizontal lines appearing 0.5° above and 0.5° below the target's location.

Participants viewed the screen from a distance of 50 cm. A chin rest was adjusted to place the fixation cross in the center of the participant's horizontal straight-ahead line of sight. Participants responded with their right index finger on an external response button.

2.1.3. Procedure and design
A trial began with the presentation of the fixation cross. After an interval of 1000 ms, the cue appeared. Then, after a stimulus onset asynchrony (SOA) of 100 ms the target was presented for 33, 50, or 100 ms. Participants responded as fast as possible to the onset or to the offset of the target. To minimize anticipatory behavior, no-go catch trials, in which the participants had to withhold their response, were included in one forth of all trials. As in the study of Baro et al. (1992), we employed different catch trials for the onset and for the offset conditions. Specifically, in onset catch trials, no target stimulus appeared, whereas in the offset condition, the target remained on the screen for an especially long period (1000 ms) and disappeared together with the cue at the end of the trial.
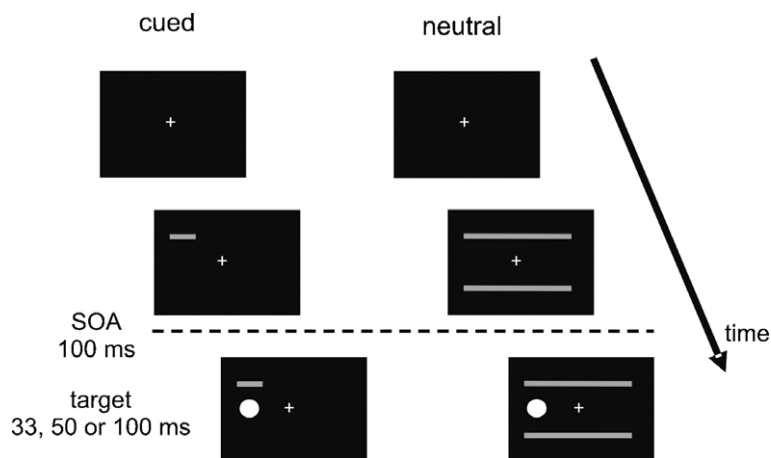

Fig. 1. Time course of a single trial in Experiment 1. Following the fixation cross, the cue orients attention to one location in the display (cued condition) or to no specific location (neutral condition). After a fixed stimulus onset asynchrony (SOA) of 100 ms the target appeared for 33, 50 or 100 ms. The task of the participant was either to react to the onset (onset condition) or the offset (offset condition) of the target. No-go catch trials in which participants must not respond were included in one forth of all trials.

To avoid a possible interference by the termination of the cue or the fixation cross (e.g., Pratt & Hirshhorn, 2003), both the cue and the cross stayed on the screen for 1000 ms after target onset. Only in the catch trials of the onset condition, fixation cross and cue disappeared 1000 ms after cue onset. The next trial was initiated after 2000 ms. At the end of each experimental block, feedback about the overall percentage of correct responses was provided on the screen. The participants initiated the next block by pressing a key.

Each participant was tested in two conditions. In the onset condition, participants had to respond as fast as possible to the onset of the target. In the offset condition, however, participants responded to the offset of the target. Auditory feedback was presented when they responded in no-go trials or when RT was shorter than 150 ms after target presentation (onset condition) or target disappearance (offset condition), or when RT exceeded 500 ms after target onset (onset condition) or after target disappearance (offset condition). Participants were asked to respond correctly and quickly and to keep their eyes on the fixation cross as long as the cross was visible. The maximal interval (200 ms) between the onset of the cue and the offset of the target was too brief to allow an eye movement towards the target (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Mayfrank, Kimming, & Fischer, 1987).

Each participant worked on each task condition (onset and offset), and the sequence of both conditions was balanced across participants. Each task condition consisted of 12 blocks of 32 trials each. The first two blocks were considered practice and excluded from data analysis. Each factorial combination of Cue (cued or neutral), Target Duration (33, 50, 100 ms, or catch trials), and Target Position (left or right) occurred equally often within a block. In 50% of all trials the valid cue was presented and the target stimulus appeared at the cued location (cued condition). In the remaining 50% of all trials, the neutral cue was presented and the target was equally probable presented at one of the two target locations (neutral condition).

2.2. Results and discussion

All trials with false alarms (too early reaction or reaction within no-go trials; 2.7%) or trials with misses (too late or no reaction in go trials; 1.4%) were discarded from RT data analysis. An analysis of variance (ANOVA) was performed on go-trial RT of correct responses with factors Task Condition (onset vs. offset), Cue (cued vs. neutral), and Target Duration (33, 50, and 100 ms). *p*-values were, whenever appropriate, adjusted for violations of the sphericity assumption using the Greenhouse-Geisser correction.

Fig. 2 depicts mean RT of correct responses as a function of Task Condition, Cue, and Target Duration. Consistent with previous studies (Baro et al., 1992; Briggs & Kinsbourne, 1972), shorter RTs were obtained for the onset than for the offset condition, $F(1,19) = 43.1$, $p < .001$, mean RT = 273 vs. 312 ms. The interaction between Task Condition and Target Duration,
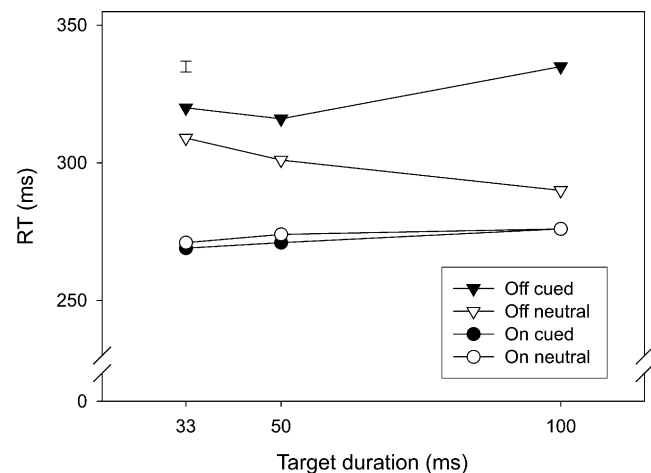

Fig. 2. Results of Experiment 1. Reaction times (RT) of correct responses as a function of task condition (onset vs. offset), cueing condition (cued vs. neutral), and target duration (33, 50, and 100 ms). The standard error was computed from the pooled error-terms of the corresponding ANOVA according to a suggestion made by Loftus (2002).

$F(2,38) = 4.2$, $p < .05$, reflects somewhat prolonged RT for the 100 ms compared to the other target durations in the onset condition. Most important, however, Cue affected RT, $F(1,19) = 14.7$, $p < .01$, and this effect differed between the onset and offset condition, $F(1,19) = 54.7$, $p < .001$. Whereas there was no significant effect of Cue on onset RT, offset RTs were prolonged for cued trials, $F(1,19) = 43.4$, $p < .001$, mean RT = 323 vs. 300 ms. This cueing effect even increased with target duration, $F(2,38) = 21.3$, $p < .001$.[1] An additional analysis of d' with the factors Task Condition and Cue indicated that the RT effects were not caused by a tradeoff between speed and accuracy. Participants performed better in the onset ($d' = 5.2$) than in the offset condition ($d' = 3.7$), $F(1,19) = 4.5$, $p < .05$, and were also better in the neutral ($d' = 4.7$) than in the cued trials ($d' = 4.2$), $F(1,19) = 34.1$, $p < .001$. Task condition and Cue did not interact significantly on d', $F(1,19) = 1.9$, $p > .18$.

Although the obtained offset cueing effect is consistent with the notion that attention prolongs the perceived offset, one might attribute this outcome to an alternative account.[2] Accordingly, participants respond to the onset of the stimulus in a certain percentage of trials, even if they were instructed to respond to the offset. If one assumes that this happens primarily in the neutral condition, this account might explain why mean offset RT was shorter in the neutral than in the cued condition. An additional analysis of the observed RT distributions revealed, however, that this alternative account must be ruled out (Appendix A).

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[1] In a further ANOVA, order of task condition (onset–offset vs. offset–onset) was included as an additional factor. This factor, however, did not modulate the cueing effect, $F < 1$, and hence this effect cannot be attributed to task order.

[2] We thank Adam Reeves for suggesting this alternative.

The present experiment shows that attention prolongs the perceived offset of a visual stimulus and this supports Yeshurun and Levy's (2003) neurophysiological hypothesis. However, the result that onset RTs were unaffected by the cueing manipulation is inconsistent with studies which show earlier onset detection RT in cued compared to uncued conditions (e.g., Shore et al., 2001). This lack of an effect may be due to low temporal stimulus uncertainty. More specifically, since SOA was kept constant at 100 ms, temporal uncertainty (e.g., Niemi & Näätänen, 1981) was especially low in the onset condition and so temporal preparation could have masked potential cueing effects on RT. For example, participants may have temporally anticipated stimulus onset rather than based their response on perceived stimulus onset. Experiment 2 addresses whether this possibility might account for the missing influence of attention on onset RT.

3. Experiment 2

In Experiment 1, we obtained a reliable spatial cueing effect on offset RT. Contrary to the literature (e.g., Shore et al., 2001), however, there was no cueing effect on onset RT. Because we hypothesized that the missing effect might be due to low temporal uncertainty, Experiment 2 enhances this uncertainty.

3.1. Method

3.1.1. Participants
A fresh sample of 20 participants was recruited.

3.1.2. Stimuli, apparatus, design, and procedure
These were identical to the previous experiment except for the following modifications. First, the offset condition was eliminated, i.e., participants responded only to the onset of the target and the target terminated with response onset (e.g., Di Lollo et al., 2000). No target appeared in catch trials. Second, SOA between the cue and the onset of the target was varied and prolonged. In order to enable a comparison of the onset and the offset condition in Experiment 1, we used SOAs of 133, 150, or 200 ms to mirror the cue-offset intervals of Experiment 1. Third, block duration was shortened and an experimental session consisted of 44 blocks of 16 trials each. The first four blocks were considered practice and excluded from data analysis. Each factorial combination of Cue (cued or neutral), SOA (133, 150, 200 ms, or catch trials), and Target Position (left or right) occurred equally often in each block.

3.2. Results and discussion

Participants produced an overall false alarm rate of 1.4% and 0.7% misses. Analogous to Experiment 1, an ANOVA was performed on go-trial RT of correct responses with factors Cue (cued vs. neutral) and SOA (133, 150, and 200 ms). Fig. 3 depicts mean RT of correct responses
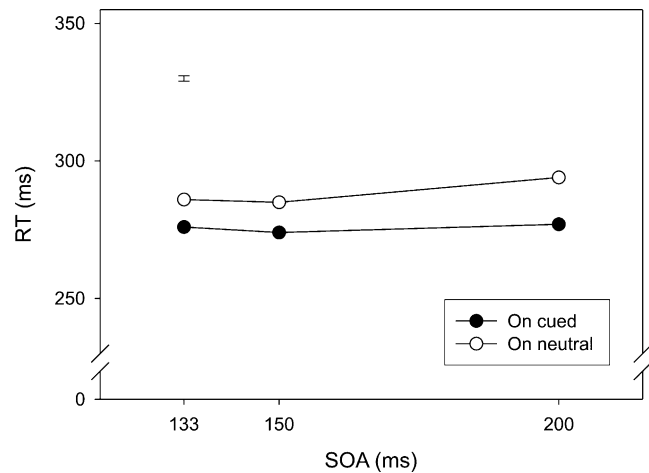

Fig. 3. Results of Experiment 2. Reaction times (RT) of correct responses as a function of cueing condition (cued vs. neutral) and SOA (133, 150, and 200 ms). The standard error was computed from the pooled error-terms of the corresponding ANOVA according to a suggestion made by Loftus (2002).

as a function of Cue and SOA. Theoretically most important, RTs in cued trials were shorter than RTs in neutral trials $F_{(1, 19)} = 18.9$, $p < .001$. Although this cueing effect is small, it is comparable in size with other results (Shore et al., 2001). The effect tended to vary with SOA, $F_{(2, 38)} = 3.3$, $p = .051$, and was most pronounced at the longest SOA. In addition, RTs were generally prolonged in the 200 ms SOA condition, $F_{(2, 38)} = 8.5$, $p < .01$. Discrimination performance (d') was marginally lower here than in the onset condition of Experiment 1 and did not differ between cued and neutral trials (both $d' = 4.9$), $F < 1$. The results of Experiment 2 reveal that attention shortens onset RT. More important, however, the results show that the lack of any cueing effect on onset RT in Experiment 1 can be attributed to low temporal uncertainty.

4. General discussion

Based on psychophysical results, Yeshurun and Levy (2003) proposed that visual attention prolongs the perceived offset of a visual stimulus. The present study employed a chronometric approach to provide convergent evidence for this proposal. Specifically, our participants were asked to conduct a speeded response to the offset of a visual stimulus whereas the stimulus appeared either at an attended or unattended location. The results of the first experiment clearly revealed longer offset RT for attended than for unattended stimuli and thus provide further independent evidence for Yeshurun and Levy's proposal. Experiment 2 served as a control experiment and confirmed a possible explanation (temporal advance preparation) why an attentional effect on onset RT was absent in Experiment 1.

The neurophysiological hypothesis of Yeshurun and Levy (2003) provides an explanation for the finding that

attention prolongs the perceived stimulus offset. As outlined in Section 1, the primary premise of their hypothesis asserts that attention facilitates parvocellular over magnocellular processing. As a result of the longer response duration of parvocellular neurons relative to magnocellular neurons, the neuronal signal of attended stimuli should persist longer within the visual system than that of unattended stimuli. Accordingly, the offset of an attended stimulus should be perceived relatively late.

As discussed in Section 1, this hypothesis is also consistent with previous psychophysical studies demonstrating that visual attention prolongs perceived stimulus duration (Enns et al., 1999; Mattes & Ulrich, 1998). Furthermore, it agrees with other studies that have shown that the amount of attention allotted to a stimulus influences its perceived duration. For example, infrequent, attention-catching "oddball" stimuli are judged to last longer than frequently encountered and thus less attended stimuli (Tse, Intriligator, Rivest, & Cavanagh, 2004; Ulrich, Nitschke, & Rammsayer, in press). In addition, allocation of attention to a nontemporal second task shortens the perceived duration of a simultaneously occurring event (e.g., Brown, 1995, 1997). Although, each of these phenomena can be addressed by a different account, the neurophysiological hypothesis by Yeshurun and Levy (2003) provides a unitary framework on how attention modulates the temporal representation of stimulus input within the visual system.

None of these studies just mentioned separated the influence of attention on perceived stimulus onset and offset. Thus, it remained unclear whether the prolonged perceived duration of an attended stimulus resulted exclusively from a prior entry effect, i.e., an earlier perception of an attended stimulus (Carrasco & McElree, 2001; Schneider & Bavelier, 2003; Shore et al., 2001) or an additional effect of attention on the perception of stimulus offset. The present results show that attention not only accelerates onset perception but also delays offset perception. Therefore, the present results reveal new insights into the influence of attention on visual stimulus processing. To our knowledge, this is the first experimental demonstration that visual attention shortens the perceived stimulus onset but delays its perceived offset.

Appendix A

This appendix briefly outlines the assumptions and the main prediction of the alternative account that we have mentioned in the main text. This prediction will be compared to the observed results.

Consider a single trial in the offset RT condition with a stimulus of duration d. According to this alternative account, the participant responds incorrectly with probability p to the onset of the stimulus and correctly with $1 - p$ to the offset of the stimulus. Let $A(t)$ be the cumulative distribution function (CDF) of RTs, when the response is triggered by stimulus onset. Likewise let $B(t)$ be the CDF

of RTs when the participant correctly responds to the termination of the stimulus. For example, function $B(t)$ might be identical to $A(t)$ but shifted by d milliseconds to the right along the t-axis, i.e., $B(t) = A(t - d)$. Therefore, the predicted overall CDF of RTs in the offset condition represents a probabilistic mixture distribution, that is

$$CDF(t) = p \cdot A(t) + (1 - p) \cdot B(t).$$

According to this mixture model, if p is larger in the neutral than in the cued condition, mean RT should be shorter in the neutral condition than in the cued condition, because the mean associated with $A(t)$ is smaller than the mean
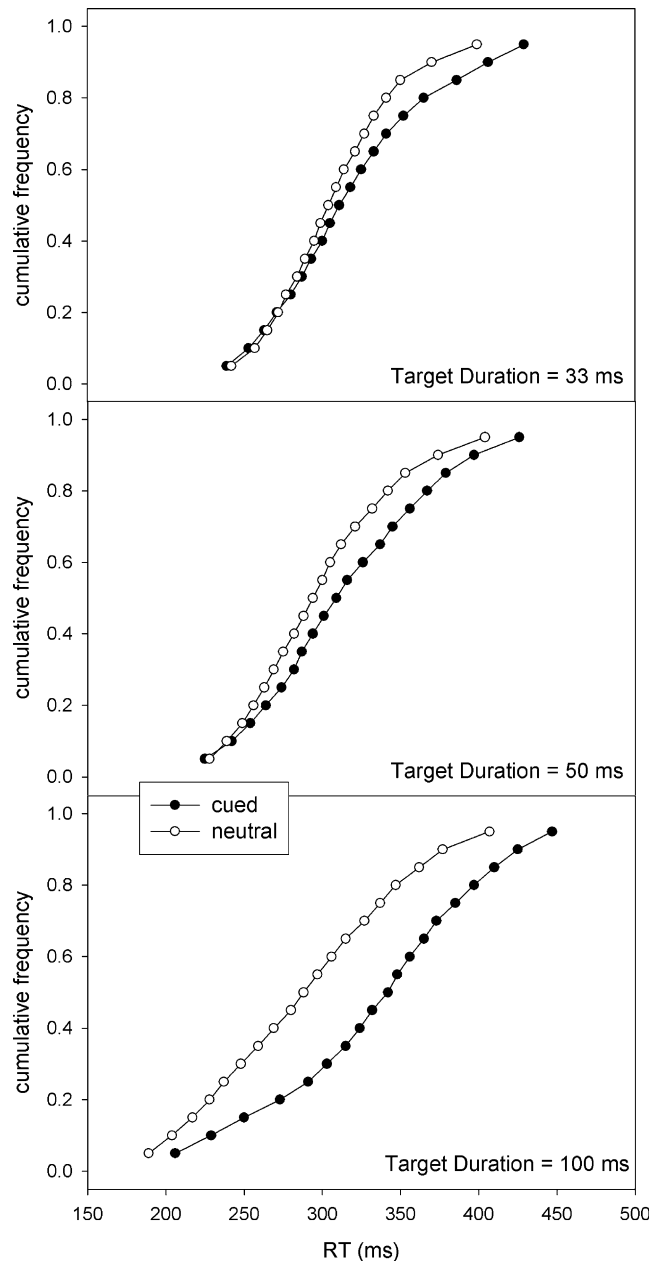

Fig. 4. Vincentized cumulative reaction time distributions for the cued and neutral condition. Each panel depicts the results for a different target duration.

associated with $B(t)$. In addition, however, this simple model predicts a testable relationship between the observed CDFs in the neutral and cued condition. Specifically, this model implies that these two observed CDFs should diverge at short RTs but converge at long RTs. To illustrate, in the specific case when d is long, $A(t)$ and $B(t)$ would not overlap, and thus the overall CDF of the neutral condition should reveal a plateau after an initial increase due to the responses triggered by stimulus onset. After this plateau the CDF should rise again, since RTs triggered by the offset will then contribute to the RT distribution.

Fig. 4 depicts the observed offset RT distributions of Experiment 1 for the neutral and cued condition. Each panel displays the result for a single target duration. The distributions shown in these panels are Vincentized cumulative RT distributions (Vincent, 1912) and estimated with the routine developed by Ulrich, Miller, and Schröter (in press).

The observed CDFs are clearly at variance with the CDF prediction of the above mixture model. As one can see, these observed CDFs do not obey the prediction of the mixture model, that is, a divergence at short RTs and a convergence at long RTs. In contrast, the empirical CDFs revealed rather the reversed relationship from that predicted by the mixture model. For example, for the two shortest stimulus durations, the observed CDF of the neutral and the cued condition converge for short RTs while they diverge for long ones. Even for the longest target duration, the observed CDFs do not agree with those predicted by the mixture model. Therefore this CDF analysis rules out the possibility that the obtained results can be attributed to this mixture model.

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