Temporal ambiguity of onsets in a cueing task prevents facilitation but not inhibition of return

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Abstract Cueing effects, i.e., early facilitation of reaction time and inhibition of return (IOR), are well-established and robust phenomena characterizing exogenous orienting and are widely observed in experiments with a traditional Posner cueing paradigm. Krüger, MacInnes, and Hunt (2014) proposed that facilitatory effects of peripheral cues are the result of a cue-target perceptual merging due to re-entrant visual processing. To test the role and timing of these feedback mechanisms in peripheral cueing effects, we modified the traditional cueing task in Experiments 1–3 by interleaving pre- and post-cue trials at the valid and invalid location and random cue-target onset asynchrony (CTOA) ranging from –300 to +1,000 ms. Analysis of the manual reaction time distribution over CTOA showed well-pronounced IOR in the valid pre-cue condition and a small cost of perceptual merging in the post-cue condition, but no early facilitation of reaction time was observed in the pre-cue condition. In Experiment 4, we tested directly whether temporal ambiguity eliminated facilitation by restricting CTOAs to only the pre-cue time range and including a between-subject manipulation of a) random, b) mixed discrete, and c) blocked discrete CTOAs. Results obtained in the *continuous* and *binned* conditions showed no facilitation but robust IOR. We found both early facilitation and IOR in the *blocked* condition. Overall, the present findings show a small perceptual merging result without accompanying facilitation, suggesting different underlying

mechanisms. Second, they demonstrate that early facilitation is likely to be affected by the presence or absence of temporal expectations and that the early onset of IOR might be masked by stronger facilitation in traditional cueing experiments.

Keywords Attention · Facilitation · Attentional set · Inhibition of Return

Introduction

Attention is a selective process due to limitations of our processing capacity, resulting in asymmetrical resource allocation to the attended and unattended regions of the visual field. Presumably, this ability to focus selectively on particular, potentially relevant features of our environment has been of great evolutionary value and still is crucial to our successful survival: it allows us to interact effectively with the world around us and react to new stimuli rapidly and in an efficient way (see Carrasco, 2011). Attention may be influenced by a combination of external (exogenous) factors, such as sudden onsets, or internal (endogenous) factors, such as a preference for visual stimuli of a certain colour.

Exogenous orienting of attention is typically described as reflexive and automatic (Nakayama & Mackeben, 1989; Posner, 1980; Posner, Snyder, & Davidson, 1980; Yeshurun & Rashal, 2010). A typical experiment uses the traditional Posner cueing paradigm (Posner, 1980) with a noninformative peripheral cue followed by response to a probe at the same (valid) or opposite (invalid) location with a short or long intervening cue-target onset asynchrony (CTOA). The major outcomes of peripheral cueing seem to be two transient phenomena for responses at the valid location: early facilitation and later slowing of reaction time. These were described by Posner (1980) as benefits and costs of exogenous cueing,

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respectively, and widely observed during classic experiments with cue-target spatial overlap (Downing, 1988; Nakayama & Mackeben, 1989; Posner, 1980; Posner & Cohen, 1984; Posner et al., 1980). Subjects respond faster when the target appears at the valid location than at the invalid location at short CTOAs, but the opposite effect, i.e. an increase in the reaction time to the target at the valid location, is observed at long CTOAs (>250 ms). This longer lasting slowed reaction time has been termed Inhibition of Return (IOR) (Klein, 2000).

These facilitatory and inhibitory effects of peripheral cues are usually interpreted as automatic processes (Nakayama & Mackeben, 1989; Posner & Cohen, 1984), with IOR also playing an important role in visual search (Bays & Husain, 2012; Klein & MacInnes, 1999; Wang & Klein, 2010; but see Smith & Henderson, 2011). However, there is a debate about the degree to which cueing is an attentional phenomenon *per se* (Berlucchi, Chelazzi, & Tassinari, 2000; Maruff, Yucel, Danckert, Stuart, & Currie, 1999; Posner & Cohen, 1984) and whether it always results in a biphasic facilitation-inhibition response pattern (Danziger & Kingstone, 1999; Maruff et al., 1999; Collie, Maruff, Yucel, Danckert, & Currie, 2000; Taylor, Chan, Bennet, & Pratt, 2015).

In the traditional attention account, information progresses in a feedforward direction modulated by later or top-down processes. Under this account, facilitation is likely caused by spatial attention speeding the processing of future stimuli at the cued location and bringing them to conscious awareness faster (Spence & Parise, 2010). Recent views on the flow of visual information allow the coexistence of feedforward projections from low-level visual areas to the higher hierarchical levels and feedback projections from the higher hierarchical levels to the lower ones (Enns & Di Lollo, 2000; Lamme & Roelfsema, 2000). From this perspective, upon completion of the first feedforward stage, a signal goes from the target area in the extrastriate cortex back to the source area in the primary visual cortex, triggering a loop of iterative comparisons between the current perceptual hypothesis and an ongoing neural activity in the low-level cortical regions (Enns & Di Lollo, 2000). Behaviourally, this reentrant processing could produce a *perceptual merging* effect of two sequential items, such as a cue and a target, therefore producing early facilitation.

To test the *perceptual merging* hypothesis, Krüger, MacInnes, and Hunt (2014) used a modified cueing task in which the order of the stimuli presentation was manipulated to allow for a “cue” to appear pre or post target. In addition, they used two different dependent variables: either speeded manual reaction times (MRT-task) or a non-speeded perceived onset time (POT-) was recorded in separate blocks. Regardless of response, participants were instructed to fixate a spinning clock at the centre of the screen throughout each trial, which included two events at two possible peripheral locations. The cue could be displayed before the target onset (pre-cue

condition), after the target onset (post-cue condition), or the target could be presented without a cue (no-cue condition). Spatially, targets could be presented at the valid or invalid location. More explicitly, during the clock judgment task (Carlson, Hogendoorn, & Verstraten, 2006), the participants viewed a clock with the hand spinning and, on completion of the trial, reported the time of the target onset by adjusting the hand on the clock to its corresponding position. The MRT-task results showed a typical facilitation for valid cues in the pre-cue condition but a reverse effect under the post-cue condition. Reaction times were slower when the target was followed by a cue. Results for the POT-task demonstrated a tendency for the target to be perceived earlier than its actual onset time under the pre-cue condition, but no significant cueing effects were observed in case of the post-cue and no-cue conditions (for details see Krüger et al., 2014). These findings seem to be in line with predictions from the perceptual merging account, which (at least partially) explains the cueing effects observed in the traditional MRT experiments.

Manipulating temporal context and, therefore, temporal expectancy might modulate perceptual merging. Facilitation and IOR, for example, are influenced by temporal expectancy in discrimination tasks (Doherty, Rao, Mesulam, & Nobre, 2005; Rohenkohl, Coull, & Nobre, 2011), but they usually do not change the time course of spatial cueing effects in detection tasks (Milliken, Lupiañez, Roberts, & Stevanovski, 2003; Gabay & Henik, 2008, 2010). Milliken et al. (2003) manipulated temporal expectations by varying the proportion of trials presented at three different levels of the stimulus onset asynchrony (SOA) resulted in the short-, long-bias, and unbiased conditions. They found main effects of spatial and temporal orienting in both detection and discrimination tasks but an interaction between spatial and temporal orienting was observed only in the discrimination task.

Manipulations with either the length SOA or the duration of the interstimulus interval (ISI), however, do show a foreperiod effect (Wagener & Hoffmann, 2012; Weinbach & Henik, 2012; Correa, 2012) with faster RTs for shorter foreperiods than for longer ones. This pattern is reversed when short and long foreperiods are mixed within a block, possibly due to changing expectancy from the increased probability of the target being presented after longer foreperiods (Rolke & Hofmann, 2007; Correa & Nobre, 2008; Lawrence & Klein, 2013). Aging manipulations do not, however, impact cuing results in a detection-task (Gabay & Henik, 2008). With aging manipulations and four levels of SOA (100, 400, 700, 1,000 ms), temporal expectations affected RTs but did not modulate cueing effects as such. In contrast, when analogous aging manipulations were introduced in a discrimination task (Gabay & Henik, 2010), reduced temporal expectations eliminated IOR and higher temporal expectancy accelerated the transition from early facilitation to IOR. Wang, Satel, Hilchey & Klein (2012) found no early facilitation for

saccadic responses at short CTOA in the blocked condition and early IOR when short CTOAs were mixed with long CTOA trials. MacInnes (2017), likewise, found that facilitation was absent for manual and saccadic responses when CTOA was randomly sampled from a continuous distribution on each trial.

Proposal

Krüger et al. (2014) tested short (110 ms) CTOAs for pre-cue and post-cue for MRT and POT responses but did not test the transition or timing of other CTOAs, nor did they test these measures at longer CTOAs where we typically measure IOR. If the perceptual merging hypothesis is correct, we suggest that the transition between post-cue costs and pre-cue facilitation should occur at very short, positive CTOAs. Furthermore, we suggest that if IOR is based on the inhibition of attention, we should see a transition from facilitation to inhibition at roughly +250 ms for MRT responses but no transition to IOR with POT responses.

In the first three experiments, we included pre- and post-cue trials at the valid and invalid location but extended the CTOA to be selected from a random continuous interval between −300 ms (target appears before the cue) to +1,000 ms (target appears after the cue). Continuous variables provide more power than their discretized counterparts (Altman & Royston, 2006) and allow interpretation of transition effects without interpolation. To test directly the possibility that temporal uncertainty of the CTOA could reduce or remove observed facilitation, Experiment 4 included a between subject manipulation of a) random CTOAs, b) mixed trials of three discrete CTOAs, and c) blocked discrete CTOAs. For Experiments 4a, b, and c, we also restricted the time range to only pre-cue (+50 ms or greater) and returned the fixation to a tradition, nonmoving cross.

Experiment 1: Random CTOA

Methods

To determine our needed sample size, we used the power calculation for linear-mixed effects models available with the G*Power software (Mayr, Erdfelder, Buchner, & Faul, 2007). Prior effect size was based on Krüger et al. (2014) for expected facilitation (Cohen's $d = 0.36$) and MacInnes, Krüger, and Hunt (2015) for IOR with manual responses (Cohen's $d = 0.42$). With alpha set to 0.05 and power set to 0.70, we calculated sample size of 17 for IOR and 19 for facilitation and chose to exceed the larger of those numbers for this experiment.

Twenty-one adult volunteers were recruited for each of the experiments (Experiment 3 had three participants). All participants were naïve to the study and provided informed consent according to the Higher School of Economics ethical guidelines. Participation was voluntary, and each participant was given either a monetary reward or a credit depending on their preferences. The experiment was programmed using Psychtoolbox 3 (Brainard, 1997; Pelli, 1997) and displayed on an Asus VG248QE LCD monitor at 1,920 x 1,080 resolution and set to 100 Hz.

At the beginning of each trial a clock of 2° diameter with 60 small ticks was presented in the center of the screen (Figure 1). At the same time two grey boxes 5° diameter were displayed to the right and to the left from the clock on the horizontal midline. The background colour was black, location markers and clock were grey, and the response target was red. The trial initiated with the participant pressing the spacebar on keyboard. A “second” hand then appeared at a random clock location and began rotating clockwise. The cue was a white flash outlining of one of the peripheral boxes and always appeared after a random interval of 800–900 ms and remained visible for 50 ms. The response target could appear before or after the cue, however, giving us two order conditions: *pre-cue* with cue prior to the target and *post-cue* with cue appearing after the target. The target appeared as a red disk 1° in diameter in the center of one of the two peripheral boxes in a random interval of up to 1,300 ms with the first 300 ms of that range placing the target *before* the cue. The target also was presented for 50 ms. The procedure was consistent with previous experiments by Krüger et al. (2014), except for the timing of the stimuli onsets. The clock fixation was included to be compatible with Krüger et al. (2014), but this paper focuses on the reaction time data as opposed to the perceived onset time of that study. In a final experiment, the clock was replaced with a static fixation cross measuring 1° visual degree. All participants were tested for POT in Experiments 1–3 to follow Krüger et al. (2014); however, the results were not significant in that task, likely due to the lack of overall facilitation, and will not be discussed further.

MRT Task Participants were instructed to fixate on the clock and then press the spacebar on seeing the red disk. Participants were instructed to ignore the clock hand and were told that the cue was noninformative. Response to the target meant the end of the trial, but for catch trials and missed targets the display remained visible for a total of 4,000 ms. The target location target was *valid* if it appeared in the same box as the cue or *invalid* if it appeared in the alternate location. Among all trials, 10% were catch trials where no target was presented but only the cue. For the initial two experiments, there were 176 trials

Fig. 1 Experimental design. Fixation point for the first three experiments was an analogue clock face with a single hand spinning at one rotation per second to match the design of Krüger et al., 2014. Target onset was randomly generated across a continuous possible range to allow for its

presentation to happen before the cue or after the cue in ranges where we would expect to see facilitation or IOR at the valid location. The final three experiments used only traditional pre-cue CTOAs and with a simple cross at fixation

in the MRT task, split into blocks of 48 trials and participants were offered a rest in between.

Results

Experiment 1: random CTOA, pre-cue/post-cue

Data were analyzed using a linear mixed effect model with Validity (valid, invalid) and CTOA (−300 ... +1,000 ms) as fixed effects and participant as a random effect. Base levels were set as invalid for Validity and 0ms for CTOA. Variables and their slopes were added to the model one at a time and only kept in the final model if the addition improved the model as observed by a Chi-squared (χ^2) test. By-participant random slopes for CTOA were a significant improvement to the model ($\chi^2(2) = 105, p < 0.001$), with the remaining effects listed being intercepts. Mean reaction time for the base model was 367 ms with a standard error of 8.4 ms. The main effect of Validity was significant ($\chi^2(1) = 51.0, p < 0.001$); valid locations had slower (5.5 ms, SE 3.1 ms) reaction times than invalid locations. CTOA also was significant ($\chi^2(1) = 20.6, p < 0.001$) with faster (−5 ms MRT/100 ms CTOA, SE 6.5 ms) responses to later CTOAs. There also was a significant interaction ($\chi^2(1) = 28.0, p < 0.001$) showing the classic IOR effect of larger cost of validity (3.2 ms/100 ms CTOA, SE 6.2) for later CTOAs. As shown in Figure 2, however, this IOR develops somewhat early at 220 ms and is not preceded by the usual facilitation or the perceptual merging during post-cue CTOAs.

To more closely compare to previous research, we followed this mixed effects analysis with an Analysis of Variance (ANOVA) using median RTs with CTOA binned in the expected ranges of post-cue (−300 to 0 ms) short-cue (+1 ms to 300 ms) and long-cue (>301 ms). These ranges align with where we would expect to find perceptual merging, facilitation, and IOR results

respectively. There was a main effect of validity ($F(1,20) = 20.9; p < 0.001; \eta^2 = 0.02$) with slower responses at the valid location, a main effect of cue order ($F(2,20) = 37.4; p < 0.001; \eta^2 = 0.13$) with slowest responses for the post-cue condition. Finally, the interaction ($F(2,40) = 12.7; p < 0.001; \eta^2 = 0.03$) showed +33 ms of IOR (valid – invalid) for the long-cue ($t(20) = 6.8; p < 0.001; d = 0.8$) condition but no difference for the post-cue (−0.2 ms) ($t < 1$) or short-cue (−7 ms) ($t(20) = 1.3; p = 0.19$).

Although Experiment 1 showed robust IOR at long CTOAs, we did not observe well-established facilitation effects at short CTOA and also failed to replicate the post-cue results from Krüger et al. (2014). Given that our continuous CTOA had a flat probability distribution across the full variable range, it also made the much longer IOR range (300–1,000 ms) more likely than the other two ranges. To test whether this was a factor in our pattern of results, we followed with additional experiments that manipulate this probability distribution.

Experiment 2: Random CTOA Gamma distribution

Methods

Experiment 2 matched the design of Experiment 1 with the exception that a Gamma distribution was used to determine random CTOA to weight the likelihood that the range would fall within the range typical of facilitation. Gamma with $\alpha = 4.3$ and $\beta = 0.8$ generates a range of CTOA between 0 and 1,000 ms, subtracting 200 ms for the post cue range leaves a final CTOA range of −200 to +800 ms. The distribution results in approximately 20% post-cue trials, 50% of trials between 0 and 210 ms, and the remaining 30% trials with

Fig. 2 MRT results in Experiment 1. LOESS plot of observed results shows IOR at around 225 ms but without evidence of facilitation or perceptual merging. Grey bars represent 95% confidence intervals. Although we see robust IOR throughout later CTOAs, we see no

evidence of early facilitation or perceptual merging. Three direct comparison points at -100 , $+100$, and $+500$ ms represent binned trials (± 75 ms) at ranges where we would expect to see perceptual merging, facilitation, and IOR, respectively

longer CTOAs in the typical IOR range. Twenty-one volunteers participated in Experiment 2.

Results

Experiment 2: random CTOA, Gamma distribution, pre-cue/post-cue

Data were subjected to a linear mixed effects model in a manner similar to Experiment 1. The model intercept was 328 ms for invalid at 0 CTOA. Random slopes for CTOA improved the fit of the model ($\chi^2(2) = 90.6$, $p < 0.001$), with all other effects being intercepts. The main effect of CTOA was not significant ($\chi^2(1) = 2.6$, $p = 0.115$), although the trend of faster reaction times for later CTOAs was the same as E1 (-4.8 ms/100 ms CTOA, SE 0.7). The main effect of validity was small but significant ($\chi^2(1) = 5.0$, $p = 0.023$) with slightly faster responses at the valid location (-3.6 ms, SE 2.4). In addition, the validity by CTOA interaction was significant ($\chi^2(1) = 34.6$, $p < 0.001$) with larger validity effects at late CTOAs, primarily caused by faster responses at the valid location (-5.1 ms/100 ms CTOA, SE 1.6).

Again, we followed this with a median analysis of 3 (cue order) $\times$ 2 (validity) ANOVA with CTOA binned along lines described for Experiment 1. There was a main effect of validity ($F(1,20) = 8.7$; $p = 0.008$; $\eta^2 = 0.01$) with slower responses at the valid location, a main effect of cue order ($F(2,20) = 21.4$; $p < 0.001$; $\eta^2 = 0.13$) with slowest responses for the post-cue condition. Finally, the interaction ($F(2,40) = 9.7$; $p < 0.001$; $\eta^2 = 0.02$) showed $+34$ ms of IOR (valid – invalid) for the long-cue ($t(16) = 4.5$; $p < 0.001$; $d = 0.9$) condition but no difference for the post-cue ($+2$ ms) ($t(16) = 1.1$; $p = 0.26$) or short-cue ($+4$ ms) ($t < 1$).

Despite the probability manipulation to produce half of the CTOAs in the range for which we typically observe facilitation, we only observe validity effects in the form of IOR at late CTOAs (Figure 3).

Experiment 3: three participants Gamma distribution

Methods

We wanted to ensure that we had a sufficient number of trials throughout the CTOA range and replicate Experiment 2 with three participants across multiple experimental sessions. Experiment 3 was identical to Experiment 2, except that three female participants took part in five sessions totaling 880 trials. The average participant age was 26.3, and all participants had normal or corrected-to-normal vision and were naïve to the study. The sessions were spread over 2 days to prevent strain, and a minimum of 30 minute break was provided between sessions.

Results

Experiment 3: three participants, Gamma distribution, pre-cue/post-cue

Results were subjected to a linear mixed effects model with subject and session as nested random variables. We included by-participant random intercepts and slopes for the effect of CTOA ($\chi^2(4) = 28.9$, $p < 0.001$). There were once again main effects of validity ($\chi^2(1) = 46.7$, $p < 0.001$) and the validity by CTOA interaction CTOA

Fig. 3 MRT results with increased likelihood of targets in typical facilitation range. Manual reaction times are slowed at the valid location as compared to invalid for late CTOAs, but we observe no effect of validity for post-cues or short CTOAs. Three direct comparison points

at -100 , $+100$, and $+500$ ms represent binned trials (± 75 ms) at ranges where we would expect to see perceptual merging, facilitation, and IOR, respectively

($\chi^2(1) = 6.5$, $p = 0.011$). Valid trials were on average 9.9 ms slower than invalid trials (SE 2.8), and this cost increased at later CTOAs (3.5 ms/100 ms CTOA, SE 1.3). Individual participants (Figure 4) were consistent in showing IOR, although the onset and magnitude did differ. None of the three participants showed evidence of early facilitation or perceptual merging at during the post-cue time range.

combined in a Linear Mixed Effects as above, but with experiment as an addition random effect and subject nested within experiment.

Results

The model intercept was 319 ms for invalid trials at 0 ms CTOA. The slope for CTOA was significant ($\chi^2(2) = 133.5$, $p < 0.001$), and all other effects are intercepts. There were no main effects, but the validity by CTOA interaction was significant ($\chi^2(2) = 41.4$, $p < 0.001$). Valid trials were on average 0.3 ms slower than invalid trials (SE 1.6), and this increased at later CTOAs primarily due to a speeding of invalid trials (3.4

Meta-analysis and Summary

Given the similarities of the three experiments that included post-cue CTOAs, data from all subjects were

Fig. 4 Three participants across five experiment sessions using the gamma distribution for CTOA. All three participants show IOR but no perceptual merging or facilitation. IOR was seen at different magnitude and depicted different temporal characteristics across participants, but

was observable for all three. Three direct comparison points at -100 , $+100$, and $+500$ ms represent binned trials (± 75 ms) at ranges where we would expect to see perceptual merging, facilitation, and IOR, respectively

ms/100 ms CTOA, SE 1.2). Reaction times once again were faster at later CTOAs (4.5 ms/100 ms, SE .3). A median analysis of the combined data for the three binned cue orders showed a significant effect of validity for long CTOAs ($t(44) = 8.7$; $p < 0.001$; $d = 0.8$) with 32 ms of IOR. There was no evidence of facilitation at short pre-cues ($t < 1.0$), but we did observe a small but significant cost (-6.8 ms) of validity in post-cue trials ($t(44) = 2.2$; $p = 0.025$; $d = 0.2$) as suggested by the perceptual merging hypothesis.

Summary

We were able to replicate the post-cue cost in MRT as suggested by the perceptual merging account but not the accompanying facilitation in the pre-cue condition. Krüger et al. (2014) suggested the two as stemming from a similar mechanism, but the current results suggest that both post-cue merging costs and IOR can be observed without facilitation. With

this question resolved, the remaining experiment will focus on the reason for the lack of facilitation itself.

Experiment 4: binning and blocking

Methods

To test directly the idea that temporal ambiguity impacts early facilitation, we conducted an additional experiment with three levels of ambiguity as a between-subject manipulation. Twenty-one subjects each were tested using CTOA as a *continuous* variable, *binned* variable, or *blocked* variable. Furthermore, the experiment removed the spinning clock in favour of a traditional fixation cross and removed the post-cue condition to align more closely with tradition cuing tasks. The number of trials was increased to 396, including 10% catch trials. All other experiment settings remained the same. For the *continuous* condition, three CTOAs of 50 ms, 400 ms, and

Fig. 5 MRT results in Experiments 4a, b, c. (A) LOESS plot of observed results in Experiment 4a (the continuous design) shows IOR but no evidence of facilitation. Grey bars represent 95% confidence intervals. (B) The same results from Experiment 4a with CTOA in three bins. (C) MRT results in Experiment 4b (the binned design) show IOR without

early facilitation. (D) MRT results obtained in Experiment 4c (the blocked design) show both facilitation at the short CTOA and IOR at mid and long CTOAs. For Figures 5B–D, error bars represent the 95% confidence intervals

750 ms were used as the basis of three separate gamma functions resulting in a continuous distribution with a mean of 450 ms and CTOAs ranging from 50 ms to 900 ms. In the *binned* condition, these discrete three times were chosen randomly across all trials. In the *blocked* condition, these three CTOAs were run as separate blocks with block order randomized. Base level for LME remained as invalid trials for validity but was set at 50 ms for CTOA. This made comparison across experiments easier and also had the advantage of testing the main effect of Validity directly at 50 ms for signs of facilitation.

Results 4: Full

LME for Experiment 4 included nested random factors with the subject's number nested within the CTOA binning group (4a, b or c). Random slopes for CTOA improved the fit of the model ($\chi^2(4) = 1,300, p < 0.001$) with other fixed effects being intercepts. After accounting the nested random factors and slope, only the validity by CTOA interaction ($\chi^2(2) = 705, p < 0.001$) was a significant improvement of the model. The model mean RT was 353 ms ($SE = 4.6$); invalid trials were faster (21.3 ms, $SE = 6.3$) and valid trials were slower (21.1 ms, $SE = 6.3$) for each of medium and long CTOAs. We then looked at the three binning groups separately to determine the effect of binning on the validity/CTOA interaction.

Results 4a: continuous

LME for Experiment 4a was run with CTOA as its original continuous variable for direct comparison with earlier experiments and also as a binned variable (short < 150 ms, medium < 500 ms, long) for comparison with 4b and 4c. Mean RT for the model was 365 ms ($SE 7.3$). The slope of CTOA improved the fit of the model ($\chi^2(2) = 246.5, p < 0.001$) with all remaining effects being intercepts. Main effects of CTOA ($\chi^2(2) = 7.0, p = 0.008$) and Validity ($\chi^2(1) = 136.5, p < 0.001$) improved the fit of the model: later CTOAs were faster (3.9 ms/100 ms CTOA, $SE 8.8$) and valid trials were slower at baseline of 50-ms CTOA (+3.8 ms, $SE 2.3$). As with other experiments, the interaction was significant and invalid trials became faster at later CTOAs (3.1 ms/100 ms CTOA, $SE 0.49$). The results with CTOA in three bins were similar: Validity ($\chi^2(1) = 143, p < 0.001$), CTOA ($\chi^2(2) = 16.5, p < 0.001$), and the interaction ($\chi^2(2) = 56.8, p < 0.001$). The main effect of Validity did change its sign to be faster than invalid trials at baseline (−1.3 ms, $SE 2.7$), although this was not significant ($t < 1.0$).

Results 4b: binned

The CTOA for Experiment 4b was set to one of 50, 400, or 750 ms, randomly assigned over all trials. The mean RT for

the model was 372 ms ($SE 7.1$). The slope of CTOA improved the fit of the model ($\chi^2(5) = 340, p < 0.001$); all remaining effects were intercepts. Main effects of CTOA ($\chi^2(2) = 22.5, p < 0.001$) and Validity ($\chi^2(1) = 216, p < 0.001$) improved the fit of the model: later CTOAs were faster (−30 ms, $SE 5.1$ at mid CTOA and −40 ms, $SE 4.9$ at long CTOA), and valid trials were slower at the 50-ms CTOA baseline (1.2 ms, $SE 3.3$). Again, the interaction was significant: invalid trials became faster at later CTOAs (3.1 ms/100 ms CTOA, $SE 0.49$). The effect of validity was not significant at short CTOAs ($t < 1$).

Results 4c: blocked

The CTOA for 4c was 50, 400, or 750 ms, presented within blocks, and the blocks ordered randomly. The mean RT at baseline was 329 ms, $SE 6.3$. The slope of CTOA improved the fit of the model ($\chi^2(5) = 1,049, p < 0.001$) with all remaining effects being intercepts. Main effects of CTOA ($\chi^2(2) = 11.6, p = 0.003$) and Validity ($\chi^2(1) = 129, p < 0.001$) improved the fit of the model, but later CTOAs were *slower* (12 ms, $SE 7.6$ at mid CTOA and 6 ms, $SE 7.4$ at long CTOA) and valid trials were *faster* at the 50-ms CTOA baseline (−8.1 ms, $SE 2.0$). Again, the interaction was significant: invalid trials became faster at later CTOAs. The effect of validity was significant when considering the results of the LME (8.1 ms of facilitation at 50-ms CTOA, $t = -4.09$), although not using only the median value for each participant ($t(20) = 1.66, p = 0.11$).

Discussion

The first three experiments presented targets to cued and uncued locations and resulted in manual reaction times, which exhibited robust IOR at late CTOAs but no evidence of early facilitation or perceptual merging. Random, continuous CTOAs were used with a traditional cueing paradigm to test the impact of temporal onset expectations on facilitation, IOR, and perceptual merging and the transition between them, but we found no differences between responses at valid and invalid locations during post-cue (−300 to 0 ms CTOA) or short-cue (0 to 250 ms) conditions. The lack of significant differences between valid and invalid conditions for two of our three time frames prevented direct testing of these expected transitions, although we did observe relatively early onset of IOR. To examine the role of CTOA probability in generating facilitation and post-cue effects, we conducted two more experiments where we increased the number of post-cue and short-cue trials relative to long-cue trials. These experiments also showed no effect of validity at post-cue and short-cue ranges despite increasing the likelihood of these CTOAs at the expense of longer (250 ms or greater) CTOAs. We did observe robust and long-lasting IOR with relatively early

onsets (200-ms CTOA) across all three experiments. Finally, we replicated perceptual merging cost at post-cues as observed in Krüger et al. (2014), but the effect size was small and only emerged for the meta analysis of all three experiments.

Experiment 4 was designed to test directly whether temporal ambiguity affects cueing effects. Results obtained in the *mixed trial* condition did not differ from those of the first three experiments regardless of whether the CTOA was treated as a continuous variable or a binned one. There was no evidence for early facilitation at short CTOAs (<150 ms), although robust IOR emerged by at least the 400-ms bin. Restriction of temporal expectations only to three levels of CTOAs (50, 400, or 750 ms) in Experiment 4b did not change this pattern, and we observed IOR at moderate and long CTOAs but no effect of validity at the 50-ms CTOAs. We only observed the classic biphasic pattern of both early facilitation and IOR in Experiment 4c, i.e., in the *blocked* condition.

Our data suggest that early facilitation could be modulated by temporal expectations, with temporal ambiguity eliminating spatial advantages of the valid location at short CTOAs. This finding seems differ from observations from previous studies (Milliken et al., 2003; Gabay & Henik, 2008, 2010) in which spatial cueing effects have been shown to be resistant to manipulations with temporal expectancy in detection tasks.

Although exogenous cues are considered “automatic,” other results have observed a similar lack of early facilitation under various conditions. Hayward and Ristic (2013) manipulated probability of targets being presented across trials and within trial and found facilitation only when across-trial probability was lower and within-trial probability was increasing. Jaffard, Benraiss, Longcamp, Velay, and Boulinguez (2007) observed no facilitation at short CTOAs when cued and uncued trials were mixed within one experimental session, which was treated by Jaffard and colleagues as evidence for their response inhibition hypothesis. Likewise, Wang et al. (2012) only observed facilitation at early CTOAs (50 ms) with saccadic responses when that CTOA was binned, which they interpreted as the top-down influence of attentional control settings. MacInnes (2017) suggested a similar interpretation for lack of facilitation with continuous CTOAs in both manual and saccadic responses. In an experiment with informative peripheral cues aimed to establish the relationship between exogenous and endogenous orienting, Danziger and Kingstone (1999) found no reaction time advantage of the exogenously cued location compared with both noncued predicted location and noncued unpredicted location at a short CTOA (50 ms). This result was interpreted by Danziger and Kingstone as a parallel and autonomous form of attentional orienting causing early IOR to be unmasked due to interference from the endogenous cue. Maruff et al. (1999) also did not observe early facilitation but in conditions when there was a temporal gap between the cue offset and the target

onset or when the target was visible for a limited duration. They did observe facilitation in conditions with the cue-target overlap and when the target was visible until the response was given. Likewise, Taylor et al. (2015) found a typical biphasic facilitation-inhibition pattern when spatial markers were visible at the four possible target locations. Without these placeholders, however, they did not see an early facilitation component but an early IOR. Taylor et al. (2015) proposed that placeholder stimuli themselves might play the role in the formation of cueing effects, probably because of their perceptual properties. MacInnes (2017) observed robust IOR but no facilitatory effect in for manual and saccadic responses when the target was presented at random CTOAs and Euclidean distances from the cue. Because his design shared the lack of placeholders at four cued locations, he argued that the lack of facilitation was due either to the attentional set caused by the continuous design, the absence of the placeholders or the lack of cue-target spatial overlap. Finally, Van Der Lubbe, Vogel, and Postma (2005) found strong IOR but no facilitation in an experiment with five different CTOAs (144, 188, 236, 588, and 940 ms) and stimuli displayed in lower and upper hemifields, although they did not provide a specific explanation for this phenomenon. Because our current data shares temporal manipulations analogous to those of MacInnes (2017) and Van Der Lubbe et al. (2005), but not the manipulations of the other experiments, we concluded that the ambiguous temporal nature of the random or multiple binned CTOA is creating an attentional set that causes an early withdraw of attention from the cued location leading to reduced facilitation that is allowing the early onset IOR. Fixed CTOAs in traditional cueing studies create an expectation in participants and an attentional set that encourages increased attention at the cued location despite its noninformative nature.

Our CTOA in Experiment 1 used a flat, random distribution, so the likelihood of targets appearing at short CTOAs (0–250 ms) was less than at longer CTOAs (250–1,000 ms). In Experiment 2, we weighted the CTOA likelihood to prefer shorter CTOAs with a Gamma distribution but still found no evidence of early facilitation. Because this manipulation also would increase the number of cues that overlapped with the target, we suspected that neither Maruff’s (1999) nor Danziger’s (1999) explanation were the reason for our lack of facilitation. Additionally, unlike Taylor et al. (2015) and MacInnes (2017), we used marked placeholders at the two potential cue/target locations in all four experiments, so this alone cannot explain the lack of facilitation at early CTOAs in experiments with continuous and binned design. We believe that these studies have a common underlying basis for facilitation or its lack, and that is an expectation or willingness among the participants to attend the cue. Experiment manipulations in all of these examples could influence attentional control settings, which could determine the amount of

attentional engagement to the cue and how early it leaves the cued location (Klein, 2000). Pratt, Sekuler, and McAuliffe (2001), for example, also showed that participants were able to reduce the impact of cues that did not share a critical feature with the target resulting in a lack of facilitation. Similar to our findings, they observed later IOR at the valid location despite the lack of early facilitation. They interpreted these results as participants establishing an attentional control setting that changes the impact of an exogenous cue. Likewise, the lack of facilitation and the early appearance of IOR observed in our continuous and binned experiments could be a result of attentional control settings that allocate minimal attention to a cue seen as both spatially and temporally uninformative and a speedy withdraw of attention from that location. This would suggest that attention to exogenous peripheral cues is less reflexive than often described. Lupiáñez and Milliken (1999) also suggested an IOR account that might be mediated by attentional control settings, such as those caused by task difficulty. Although we manipulated the temporal uncertainty of the target with our paradigm, the simple responses do not change the task difficulty per se, so we believe our results are consistent with that account of IOR.

Reduced attentional engagement could explain the mixed results of perceptual merging in the post-cue time frames of our experiments. As with Krüger et al. (2014), we find a small cost for reaction times when data from the target precedes the cue, but only when the first three experiments were combined. We observed an overall slowing of post-cue responses at both locations. Krüger suggested a perceptual merging account for slowing in a post cue condition, possibly caused by feedback mechanisms triggered by the cue even though it followed the temporal onset of the target (see also Spratling & Johnson, 2004). Given that our pre-cue data suggest an account of minimal attentional resources to the cue, we support Krüger's interpretation that this merging cost is perceptual in nature. The perceptual merging account also predicts facilitation in the pre-cue condition, which we do not observe in the first three experiments. Because attention to the cue is supposed to be a prerequisite for reentrant processing, this result might be caused by the lack of such attention due to our temporal manipulations. However, it is possible that the cue was attended but not sufficiently or long enough to produce behavioural facilitation. For example, Bhatnagar and MacInnes (2017) have shown recently that effects of attention could be expressed in saccadic curvatures even when facilitation is not observed.

Finally, the robust IOR we measure with the lack of early facilitation reinforces the idea that IOR and facilitation are separate processes. Although typical facilitation is seen with uninformative peripheral cues at CTOAs under 200 ms, we still cannot say that facilitation is replaced by later inhibition. The data presented in this study as well as others (Danziger & Kingstone, 1999; Pratt et al., 2001; Van Der Lubbe et al., 2005) that show no facilitation might suggest that IOR begins

immediately at the onset of the cue but is initially countered by stronger facilitation. As the facilitation fades, only IOR remains as an influence on reaction time. This view is strengthened by recent diffusion model (MacInnes, 2017), which suggests IOR in simple manual and saccadic reaction time tasks is best modelled as an increase in threshold needed to respond at the cued location compared with alternate locations. This could be interpreted as a bias toward uncued locations or as a delay in the onset of evidence accumulation at or near the cued location. With either interpretation, it suggests that the mechanism responsible for IOR can be described as being in place at the time of the cue.

Conclusions

The present findings demonstrated that early facilitation with an exogenous cue is not necessarily automatic or reflexive. The absence or presence of facilitatory effect of noninformative peripheral cues at short CTOAs is likely influenced by a specific attentional set that depends in part on the temporal nature of the experiment. Also, the data give further evidence for the early onset of IOR that is usually masked by stronger facilitation in traditional experiments with mixed CTOAs. In general, these findings support other studies showing that exogenous orienting is mediated by attentional control settings and the relationship between exogenous and endogenous shifts of attention is not straightforward and simple.

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