# Contingent Capture Effects in Temporal Order Judgments

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The contingent attentional capture hypothesis proposes that visual stimuli that do not possess characteristics relevant for the current task will not capture attention, irrespective of their bottom-up saliency. Typically, contingent capture is tested in a spatial cuing paradigm, comparing manual reaction times (RTs) across different conditions. However, attention may act through several mechanisms and RTs may not be ideal to disentangle those different components. In 3 experiments, we examined whether color singleton cues provoke cuing effects in temporal order judgments (TOJs) and whether they would be contingent on attentional control sets. Experiment 1 showed that color singleton cues indeed produce cuing effects in TOJs, even in a cluttered and dynamic target display containing multiple heterogeneous distractors. In Experiment 2, consistent with contingent capture, we observed reliable cuing effects only when the singleton cue matched participants' current attentional control set. Experiment 3 suggests that a sensory interaction account of the differences found in Experiment 2 is unlikely. Our results help to discern the attentional components that may play a role in contingent capture. Further, we discuss a number of other effects (e.g., reversed cuing effects) that are found in RTs, but so far have not been reported in TOJs. Those differences suggest that RTs are influenced by a multitude of mechanisms; however, not all of these mechanisms may affect TOJs. We conclude by highlighting how the study of attentional capture in TOJs provides valuable insights for the attention literature, but also for studies concerned with the perceived timing between stimuli.

*Keywords:* visual spatial attention, contingent capture, prior entry, temporal order judgments

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While concentrating on a given task, sometimes we are distracted and our attention is involuntarily captured by salient visual events that are irrelevant to our current goals. Whether such attentional capture is purely governed by the bottom-up saliency of the event or modulated by task demands has been a longstanding debate in the attention literature (see Theeuwes, 2010 for review). One prominent theory, the contingent involuntary orienting hypothesis (Folk, Remington, & Johnston, 1992), proposes that attentional capture is contingent on attentional control sets. These sets are templates composed of visual features or stimulus characteristics that are relevant to the task at hand. Stimuli that don't possess at least some of the features or characteristics included in the current attentional set will not capture attention, irrespective of their bottom-up saliency. Only items that at least partially match the set may capture attention, for instance, a distractor item that has the same color as the searched-for target. How the attentional control set is specified in a given situation is highly task-dependent. For instance, the set can be very narrowly defined, including only a very specific feature value (e.g., a specific orange; Irons, Folk, & Remington, 2012), encompass broader categories (e.g., reddish; Anderson & Folk, 2010; Ansorge & Heumann, 2003, 2004), or contain more than one feature (e.g., two colors or a conjunction of a color and a spatial location; Adamo, Pun, Pratt, & Ferber, 2008; Grubert & Eimer, 2013; Irons et al., 2012). They can be defined in relation to distractor items (e.g., redder; Becker, 2010), or may even be established without relying on specific feature values (e.g., a set for color singletons; Bacon & Egeth, 1994; or for static vs. dynamic stimuli: Burnham, 2007; Folk, Remington, & Wright, 1994).

Typically, contingent attentional capture is tested in a spatial cuing paradigm. Participants have to discriminate the identity of a visual target, for example a green "=" or "×" presented among

gray distractors (e.g., Folk & Remington, 1998). Prior to the target display, a color singleton cue is shown, marking one of the possible target locations. However, the cue is uninformative of the location of the upcoming target. Further, the cue can be of the same color as the target (e.g., green) or of a different color (e.g., red). Despite being irrelevant for the task, the cue captures attention when its color is matching the target color: manual RTs are faster when the cue is incidentally presented at the same location as the upcoming target (valid trial), compared to trials in which cue and target are presented at different locations (invalid trials). For cues of a different color than the target, no RT difference between valid and invalid trials is observed, which is interpreted as a lack of attentional capture for nonmatching color singletons. Note that color singleton cuing benefits are spatially restricted to the location of the cue. They do not act across broad spatial categories like "left" or "right." Targets at nearby locations, only a few degrees away from the cued location, do not benefit from the cue (e.g., Ansorge & Horstmann, 2007; Turatto & Galfano, 2001; White, Lunau, & Carrasco, 2014). Also, color singleton cues may not necessarily have the same effects as abrupt onset cues (Gibson & Amelio, 2000; Pratt, Sekuler, & McAuliffe, 2001; White et al., 2014).

Although numerous studies have been conducted to confirm, oppose or refine the contingent involuntary orienting hypothesis (see Theeuwes, 2010 and related commentary in the same issue), few have tried to verify its assumptions using attentional markers other than spatial cuing effects in RTs. Attention, of course, may act through several mechanisms. For instance, attention may improve the sensory signal of a visual target or it may weaken the influence of distractors (see Carrasco, 2011 for a review). It may bias observers' decisions on which item to respond to when the target's location is uncertain or simply where to start their search for the target (Prinzmetal, McCool, & Park, 2005; Prinzmetal, Taylor, Myers, & Nguyen-Espino, 2011). As Prinzmetal et al. note, manual RTs may not be ideal to disentangle those different components as they may reflect multiple mechanisms. Thus, using different measures is important to reveal whether contingent capture is a phenomenon influencing different aspects of human perception and performance or only a single attentional mechanism. In this vein, there is now a growing number of electroencephalogram (EEG) studies using the N2pc component of the event-related brain potential as a marker for attention capture (e.g., Burra & Kerzel, 2013; Eimer & Kiss, 2008; Hickey, McDonald, & Theeuwes, 2006; Lien, Ruthruff, Goodin, & Remington, 2008; Priess et al., 2014; Wykowska & Schubö, 2010). Results are, however, typically validated by comparing them to the simultaneously observed RT differences. Similar to pure manual RT studies, EEG evidence for and against contingent capture has been reported. Other than that, rapid serial visual presentation tasks (RSVP; Folk, Leber, & Egeth, 2002; Lamy, Leber, & Egeth, 2004) report results in line with the contingent involuntary orienting hypothesis: peripheral distractors that matched the search target color attracted attention away from the central visual stimulus stream, decreasing the percentage of correctly identified targets, whereas nonmatching distractors did not. In contrast, in a spatial cuing paradigm using perceptual sensitivity ($d'$) instead of manual RTs, Theeuwes and Chen (2005) found higher sensitivity at the location of a shape target when preceded by a nonmatching color singleton cue, speaking against the notion that perceptual sensitiv-

ity benefits from visual cues are contingent on attentional control settings (see also White et al., 2014). Prinzmetal and colleagues (Prinzmetal et al., 2011) have shown that contingent cuing effects increase with the number of distractors in the target display, arguing for a search bias.

In the current study, we use cuing effects in TOJs to test for contingent capture. These cuing effects have been linked to yet another aspect of attentional functioning: the idea of prior entry for attended stimuli. According to this hypothesis, attended stimuli may benefit from accelerated processing (see Scharlau, 2007; Schneider & Bavelier, 2003; Spence & Parise, 2010 for reviews). Such an effect would directly affect RTs, but may not necessarily influence, for instance, the quality of the perceptual representation of an attended item. Thus, TOJs can help disentangle the attentional components involved in contingent capture. In a typical TOJ task, two targets are presented in rapid succession and participants are asked to tell which of the two came first. The target onset asynchrony (TOA) at which participants are equally likely to respond that one or the other stimulus appeared first is traditionally called the point of subjective simultaneity (PSS). Although careful studies demonstrated that the stimuli are not necessarily perceived as simultaneous on a given trial (Stelmach & Herdman, 1991; Weiß & Scharlau, 2011), we will keep with this nomenclature in the current study. Without further events, the PSS should lie at a TOA of 0 ms, that is, when stimuli are presented simultaneously. However, if one of the two target locations is cued, a characteristic shift away from a 0 ms TOA emerges in the PSS: participants respond equally likely to have seen the cued or uncued target first when the uncued target is presented slightly before the cued target (e.g., Hikosaka, Miyauchi, & Shimojo, 1993; Schneider & Bavelier, 2003; Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991). According to the prior entry hypothesis, drawing attention to a location by a cue accelerates processing of the upcoming stimulus at that location. When two targets are presented simultaneously, the cued target reaches the threshold for conscious perception earlier than the uncued target. Presenting the uncued target slightly before the cued target compensates for this attentional "head start" of the cued target and, on a given trial, participants are equally likely to respond in favor of the cued or uncued target.

One particular aspect of TOJ cuing effects that make them especially well-suited to investigate contingent capture is that they have been shown to be spatially specific: cues that are presented at the same location as a subsequent target induce large shifts in the PSS. However, the cuing effect rapidly declines when cues are presented only nearby (e.g., 1.3° away), and are already absent for cues at 5° from a target (Scharlau, 2004). Two previous studies have already looked into some aspects of contingent capture in TOJ tasks. Vingilis-Jaremko, Ferber, and Pratt (2008) have paired onset or offset cues with onset or offset targets. They found that for onset targets, onset and offset cues produced shifts in the PSS of similar magnitude. However, for offset targets, larger cuing effects were found for offset than onset cues. Thus, at first glance a pattern consistent with contingent capture was only found for offset targets, but onset and offset stimuli can be considered two opposite sides of the same basic coin. Previously, Scharlau and Ansorge (2003) reported that abrupt onset cues that matched either the shape or color of one of the TOJ targets provoked the PSS to shift away from a 0 ms TOA, whereas cues that did not match one of the targets did not. However, in agreement with previous work by the

authors, they used cues that were not consciously perceived due to metacontrast masking and discussed their findings rather narrowly in the context of a specific theory of sensorimotor control (direct parameter specification; Neumann, 1990). Given that both of these earlier studies used rather specific stimuli, in the present study we examined the effects of consciously perceived color singletons in a TOJ task, one of the most widely used cue type in the contingent capture literature. Thus, our main aim is to provide another valuable piece of evidence on how the interplay between attention and task demands influence human perception and performance. Moreover, we will also demonstrate, for the first time, prior entry effects with multiple, heterogeneous distractors in the target display.

## Experiment 1

Experiment 1 was designed to test whether color singleton cues, similar to the ones used in contingent capture studies, can produce shifts in the PSS in TOJs when multiple distractors are present. Previous TOJ studies have mostly used single onset cues that were not embedded in other display elements (but see Scharlau & Ansorge, 2003; Schneider & Bavelier, 2003), unlike color singletons, which by definition stand out from surrounding stimuli of a different color. Further, we aimed at clarifying whether reliable TOJ cuing effects can be observed with multiple distracting stimuli appearing shortly before or after the TOJ targets. The TOJ task display in our experiments consisted of several color-defined target and distractor items appearing at different time intervals. Classic TOJ paradigms usually only use one single target pair to be judged, without any additional distractors (e.g., Schneider & Bavelier, 2003; Shore et al., 2001; Vingilis-Jaremko et al., 2008). Scharlau and Ansorge (2003) had homogeneous distractors (all of the same shape or color), whereas we show distractors of two different colors on each trial. A recent study (Cass & Van der Burg, 2014) has demonstrated that dynamic heterogeneous visual events before and after the TOJ targets may decrease performance in the task. Thus, it is unclear if and how dynamic heterogeneous distractors affect the attentional cuing effects. In other words, if we are to test the contingent capture hypothesis with TOJs (which we do in Experiments 2 and 3), we first need to validate our new TOJ methodology. This is the goal of the present experiment.

### Method

**Participants.** Eleven students (four women) from the University of Toronto aged between 17 and 21 years participated in Experiment 1 for course credit. All reported normal or corrected to normal vision and gave informed consent prior to the experiment. Experiment 1 and all following experiments were carried out according to the principles laid down in the declaration of Helsinki.

**Apparatus.** Experiments were programmed in Matlab (The MathWorks Inc., Natick, MA) using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Participants were seated in one of three dimly lit experimental booths, at 45 cm from a CRT monitor. All three monitors were running at 85 Hz with a resolution of 1,024 × 768 pixels. The participant's head was stabilized by a chin rest. Responses were given on a standard PC keyboard placed in front of the participant: they pressed the "z" key for a "left" response, and the "m" key for a "right" response.

**Stimuli.** The fixation cross was positioned at the screen center, spanning approximately 0.2°. Placeholders were outline circles (penstroke 1 pixel), 1° in diameter, placed on the circumference of an imaginary circle at a distance of 5° from fixation at the 1, 3, 5, 7, 9, and 11 o'clock positions. The four dots surrounding each placeholder in the cue display were approximately 0.3° in diameter and presented 0.9° away from the placeholders (center-to-center). Photometer measurements were taken before the experiment, separately for each of the monitors in the three experimental booths. All stimuli were shown on a dark gray background (7 cd/m²). Stimuli presented in gray (fixation cross, placeholders, nonsingleton cue dots) were brighter than the background (11 cd/m²). All colored stimuli were brighter than this gray, and the colors were approximately the same in luminance (35 cd/m²). In Experiment 1, we used three different colors: red ($x = 0.29$, $y = 0.18$), green ($x = 0.30$, $y = 0.60$), and blue ($x = 0.21$, $y = 0.29$).

**Design and procedure.** The sequence of events is illustrated in Figure 1. Each trial started with a fixation display consisting of the central fixation cross and six placeholder circles. After a variable fixation period (500–800 ms), a cue display was flashed for 47 ms. In the cue display, four small dots were placed around each placeholder. The dots around five of the six placeholders were the same gray as the placeholders, but one of the placeholders was surrounded by colored dots. This color singleton cue could be red, blue, or green (fixed for each participant, but counterbalanced across participants). After the cue display, the placeholders alone were shown for another 94 ms. Then, one by one, in random order and in rapid succession (every 12 ms or 24 ms, i.e., every or every other refresh cycle), the placeholders were filled with large colored disks. There were always three color pairs: one blue pair, one green, and one red pair. For each pair of disks, one disk always came up in one of the three placeholders to the left of fixation and the other to the right. Other than that, the exact locations (upper, middle, or lower placeholder) were random for left and right. Further, the order in which the disks appeared was varied such that each pair was assigned one of four possible stimulus onset asynchronies (SOAs) between the first and second disk: Pairs could appear 24 ms, 47 ms, 94 ms, or 141 ms apart centered on 212 ms after cue onset. That is, the time after cue onset until the onset of the first stimulus of a pair was 141 ms for the 141 ms pair, 165 ms for the 94 ms pair, 188 ms for the 47 ms pair, and 200 ms for the 24 ms pair. The last stimulus on a trial (second stimulus of the 141 ms pair) could appear 294 ms after cue onset (see Figure 1 for illustration). Whether the left or right disk in each pair appeared first was randomized. Participants monitored one target disk pair of a designated color and indicated which of the two disks appeared first, left or right of fixation, with an unspeeded key press. The SOA between the first and second target is subsequently referred to as the target onset asynchrony (TOA).

In this first experiment the cue color was always identical to the target color. However, the cue was not predictive of the locations of the subsequent target disks: it could appear at any of the six locations with equal probability. That is, in one third of trials it was presented on one of the two target locations, either the first or the second target. But in two-thirds of trials it cued a distractor location, either a distractor on the same side of the first target, or opposite, that is on the same side as the second target. Recall that color singleton cuing effects as well as cuing effects in TOJs have been found to be spatially specific, not operating in broad catego-
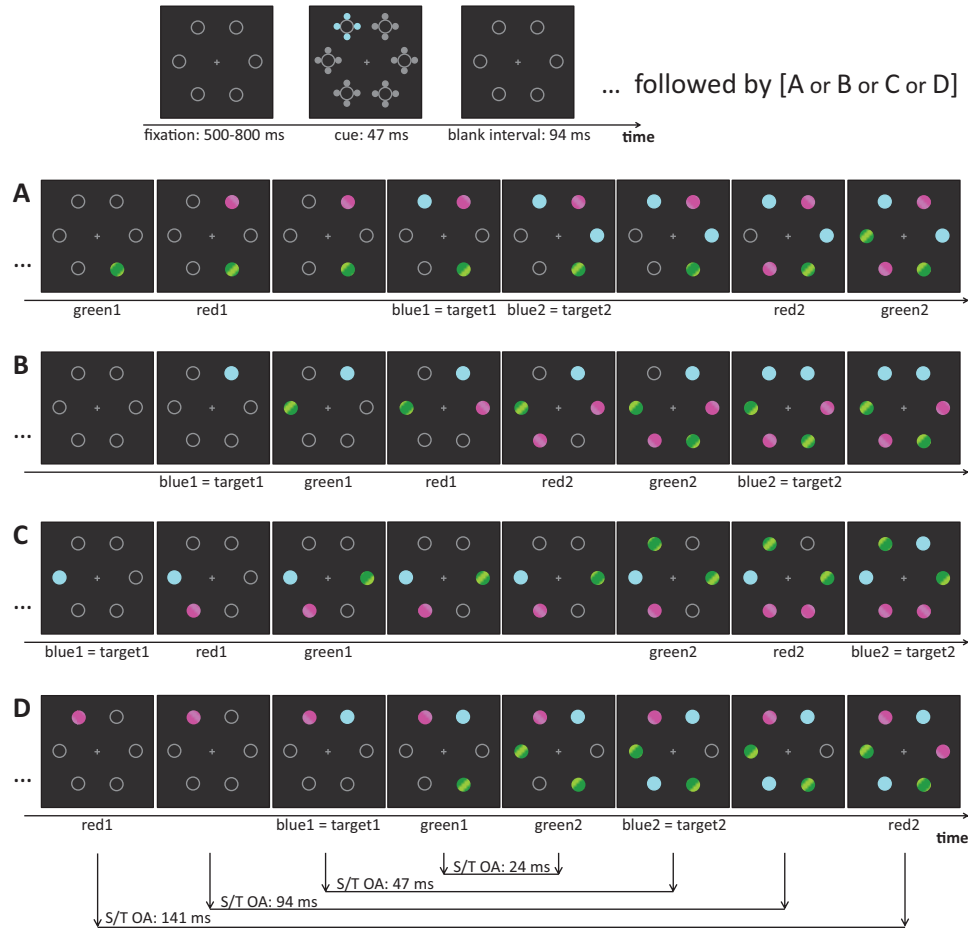
*Figure 1.* Sequence of events in Experiment 1. Rows A–D give examples of different trial types. After an initial fixation and cue display (first row), the six placeholder circles, one by one, filled up with three pairs of colored disks (red, blue, and green). Participants had to monitor a fixed color (blue in the examples above) and to indicate which of the two (blue) target disks appeared first (A: left, B: right, C: left, D: right). For each color pair, one of four possible SOAs was randomly assigned in each trial. The critical SOA between the pair of target disks is referred to as the TOA (A: +24 ms, B: −94 ms, C: +141 ms, D: −47 ms; see text for explanation). Cues were always of the same color as the disks participants were monitoring. However, the cue was not predictive of the target disks' location: it could cue one of the targets (A, B) or a distractor location (C, D). The last display with all placeholders filled remained on screen until response. See the online article for the color version of this figure.

ries (such as "left" vs. "right"; see the introduction). Thus, the trials in which a distractor was cued may help disentangle attentional cuing effects from the simplest response biases (see below). In a single 1-hr session, participants completed between five and eight blocks of 120 trials (depending on the individual pace of the participant).

Participants responded whether they had seen the left or right target disk first. However, responses were subsequently recoded such that we calculated for every TOA and condition the proportion of trials in which participants indicated to have seen the first target on the cued side, thus collapsing across trials in which the first target appeared left or right. TOAs were split up accordingly: TOAs were marked as negative when the first target appeared on the uncued side; TOAs were given a positive sign when the first target appeared on the cued side. Thus, when a target was cued, a *cued side first* response corresponds to participants indicating that

the cued target disk was the first to have appeared. When a distractor was cued, a *cued side first* response corresponds to participants indicating that the target disk presented on the same *side* as the cued distractor appeared first.

Figure 1 gives four examples of trials and their coding: The example sequence given in Figure 1A would have been coded as a *target cued* trial with a positive TOA of +24 ms (i.e., *cued side first*), as the cue was presented to the left, and the first target (blue1) at its location. Figure 1B shows a *target cued* trial with a negative TOA of −94 ms (i.e., *uncued side first*), as the cue was presented to the left, but at the location of the second target (blue2) whereas the first target (blue1) appeared to the right.

Figure 1C represents a *distractor cued* trial with a positive TOA of +141 ms (i.e., *cued side first*), as the cue was presented to the left, and the first target appeared to the left, but not at the cued location. Figure 1D is a *distractor cued* trial with a negative TOA

of −47 ms (i.e., *uncued side first*), as the cue was presented to the left, but the first target appeared to the right.

## Results and Discussion

Data of one participant was excluded from analysis as *cued side first* responses never rose above 20% for any TOA or condition, making it impossible to fit the psychometric functions (see Figure S1 in the supplementary material). For the remaining 10 participants, our recoding procedure ensured that we could collect a minimum of 15 trials per data point and participant, with an average of 31 trials per data point for trials in which one of the targets was cued, and 61 trials in which a distractor was cued.

Figure 2A shows the mean proportion of *cued side first* responses at each of the TOAs tested, separate for the two cuing conditions (one of the target disks was cued: pale red vs. one of the distractor disks was cued: dark blue) averaged across our 10 participants. For both cases, we expect few *cued side first* responses with negative TOAs, that is, when the first target was actually presented on the opposite side of the cue. With increasingly positive TOAs, the proportion of *cued side first* responses should increase, as is indeed the case. Figure 2A also shows that *cued side first* responses occurred more often when one of the target disks was cued, especially for short TOAs between the two target disks, shifting the red pale curve to the left compared to the dark blue curve. To illustrate how we quantified this shift, Figure 2B shows the proportion of *cued side first* of one representative participant (P8). For each participant, we fit two logistic functions (least squares estimate) to determine the PSS in the two conditions. Recall that cuing effects in TOJs are spatially specific (Scharlau, 2004); that is, they should only occur when the cue is in close proximity to the target. Thus, we only expect a cuing effect when a target is cued. When a distractor is cued, we expect the psychometric function to reach a proportion of 50% *cued side first* responses at a TOA of 0 ms. In other words, the PSS, that is, the TOA for which the participants are equally likely to respond with

a *cued side first* or an *uncued side first* response, should be reached when the stimuli are presented simultaneously. However, we expect a shift in the PSS when a target was cued. Figure 2B demonstrates that the PSS of P8 for trials in which one of the targets was cued was indeed shifted to the left compared to trials in which a distractor disk was cued (see dashed and dotted lines in Figure 2A for illustration). For participant P8, the PSS for trials in which a target was cued falls onto a negative TOA (−23 ms), whereas the PSS for trials in which a distractor was cued was reached at a positive TOA (+15 ms). Individual fits of all participants as well as goodness-of-fit estimates can be found in Figure S1 in the supplementary material.

Figure 2C illustrates the average PSS values across our 10 participants for *cued target* and *cued distractor* trials. The average PSS for *cued target* trials was negative, and recall that negative TOAs denote that the uncued target was presented first. Thus, the negative PSS corresponds to the classic cuing effect in TOJs found for other visual cues in previous work: because the cued target disk benefits from prior entry, the uncued disk has to be presented slightly earlier (mean PSS at a TOA of −24 ms) to produce equally likely responses on the temporal order of the targets. In contrast, cuing a distractor did not result in any reliable shift in the PSS (mean PSS at a TOA of 3 ms, not significantly different from zero; see error bars in Figure 2C). A paired-samples *t* test confirmed that there was a significant difference between the PSSs in the two conditions, $t(9) = 4.16$, $p = .002$. That is, similar to previous studies on the effect of color singletons using other response measures (e.g., Ansorge & Horstmann, 2007; Turatto & Galfano, 2001; White et al., 2014) and a TOJ study with masked abrupt onset cues (Scharlau, 2004), cuing effects were spatially specific. This further corroborates that the larger shift we found when cuing one of the targets did not result from a simple response bias: When unsure of the temporal order, participants may have chosen the target on the cued side. However, they could have used the same strategy when a distractor was cued, which was not the
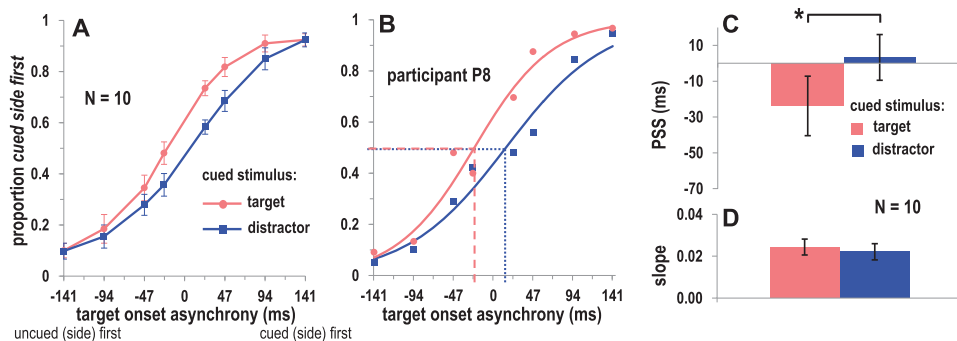


*Figure 2.* Results of Experiment 1. (A) Proportion of *cued side first* responses as a function of TOA, separate for trials in which one of the target disks was cued (pale red, circles) and trials in which one of the distractors was cued (dark blue, squares), averaged across the 10 participants. Error bars represent standard errors of the means. (B) Proportion of *cued side first* responses of one representative participant (P8). The curves show the logistic functions fit to the data. Dashed and dotted lines illustrate the PSS; i.e., the TOA that produces 50% *cued side first* responses) calculated from the fits. (C) Average PSS values for the two conditions across the 10 participants. Error bars represent 95%-confidence intervals: if error bars do not cross the zero-line, the PSS is significantly different from zero. (D) Average slope values of the logistic functions, across the 10 participants. Higher values denote steeper slopes, corresponding to better temporal order discrimination performance. Error bars represent standard errors of the means. See the online article for the color version of this figure.

case. Finally, shallower slopes (i.e., lower values) of the psychometric functions in one condition would indicate a higher difficulty in discriminating the temporal order of stimuli. However, comparing the average slopes revealed that the difference in the PSS was not accompanied by a reliable difference in the difficulty of the two conditions, $t(9) = 1.43$, $p = .186$. In sum, apart from demonstrating cuing effects in TOJs induced by color singletons, Experiment 1 also showed that cuing effects in TOJs can be observed despite using a cluttered and dynamic target display containing multiple distractors. Scharlau and Ansorge (2003) have already demonstrated that distractor items may not interfere with TOJs. However, their distractors were either single items, or multiple but homogeneous items (i.e., all of the same shape or color). In contrast, dynamic heterogeneous distractor items have recently been found to decrease general performance in a TOJ task (Cass & Van der Burg, 2014). However, our Experiment 1 shows that it is possible to generate a robust prior entry effect despite multiple heterogenous distractors.

## Experiment 2

The finding of a typical prior entry effect with color singleton cues and multiple distractors alongside the targets in the first experiment allows us to move forward and address our main experimental question: will TOJs be subject to contingent attentional capture? To answer this question, we tested whether the PSS shift we observed in Experiment 1 is sensitive to task demands. Thus, in Experiment 2, we used the same basic design but added an additional cue, such that on some trials the cue color would match the target color while on other trials the cue color would match a distractor color. If PSS shifts are contingent on top-down attentional control, only the cue matching the target color should produce a negative shift in the PSS.

### Method

**Participants.** Fourteen students (three men) from the University of Toronto aged between 18 and 46 years participated in

Experiment 2 for course credit. All reported normal or corrected to normal vision and gave informed consent prior to the experiment.

**Apparatus, stimuli, design, and procedure.** Apparatus, stimulus characteristics, and procedure were identical to Experiment 1. However, the cue could appear in one of two colors: the target color or one of the distractor colors (fixed for each participant, counterbalanced across participants). Trials with target color matching and nonmatching cues were randomly interleaved. Since the addition of a second cue color doubles the number of conditions, participants completed Experiment 2 in two 1-hr sessions. Between 13 and 16 blocks of 120 trials were completed per participant.

### Results and Discussion

Data of three subjects was collected accidentally using a different monitor refresh rate (75 Hz) which slightly changed the SOA and TOA intervals to 27 ms, 53 ms, 107 ms, and 160 ms (see Figure 3A). PSSs were calculated accordingly using those values for the fits. A minimum of 19 trials per data point and participant was collected, with an average of 37 trials in which the target was cued, and 72 trials in which a distractor was cued.

Figure 3A again shows the mean proportion of *cued side first* responses averaged across participants; Figure 3B illustrates example data and fits of one representative participant (P7). The fits for all participants are shown in Figure S2 in the supplementary material. In addition to comparing trials in which a target was cued and trials in which a distractor was cued, we now also distinguish between trials in which the cue was matching the color of the target disks or was presented in a distractor color (nonmatch).

Figure 3C illustrates the average PSS values across the 14 participants. A 2 (cued stimulus: target vs. distractor) × 2 (cue-target color: match vs. nonmatch) repeated-measures analysis of variance (ANOVA) revealed significant main effects of both factors (cued stimulus: $F(1, 13) = 20.19$, $p = .001$; cue-target color: $F(1, 13) = 10.12$, $p = .007$), but critically also a highly significant interaction: $F(1, 13) = 36.98$, $p < .001$. Subsequent pairwise $t$ tests revealed that the PSS in the *target cued*, color matching
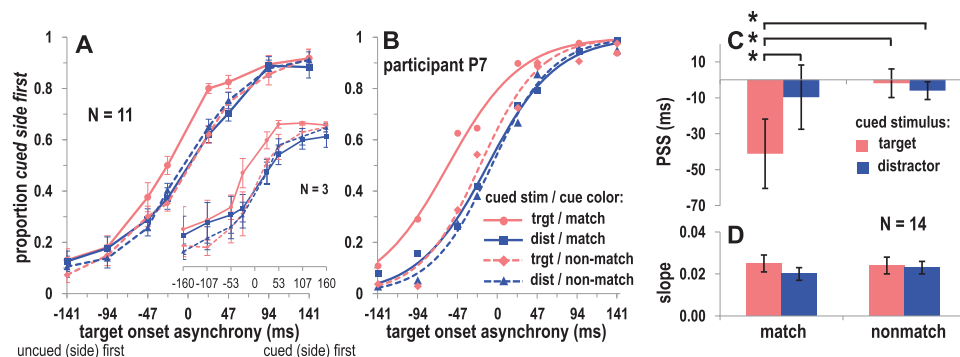
*Figure 3.* Results of Experiment 2. (A) Average proportion of *cued side first* responses as a function of TOA, separate for trials with cued targets (trgt, pale red) or distractors (dist, dark blue) and for target color matching (solid lines) and nonmatching (dashed lines) cues. The large graph shows the data averaged across the 11 participants tested with a monitor refresh rate of 85 Hz; the small inset shows the data of the three participants accidentally tested with 75 Hz. (B) Proportion of *cued side first* responses and psychometric functions of one representative participant (P7). (C) Average PSS for the four conditions across the 14 participants. (D) Average slope values of the logistic functions across the 14 participants. Error bar conventions in all panels as in Figure 2. See the online article for the color version of this figure.

condition was significantly different from all other conditions: $t$s(13) $> 4.62$, $p$s $< .001$. In contrast, there were no significant differences between the other three conditions, all $p$s $> .240$. We conclude that, in line with RT results from contingent capture studies, color singleton cues produce strong cuing effects in TOJs only when the singleton cue matches the participant's task set. A respective ANOVA on the slope values (see Figure 3D) revealed a marginally significant main effect of cued stimulus, $F(1, 13) = 3.67$, $p = .078$, and a marginally significant interaction, $F(1, 13) = 3.29$, $p = .093$. Those effects hint at slightly shallower slopes, that is, lower performance in target order discrimination when a distractor, compared to when a target was cued; an effect that was slightly more pronounced for target color matching cues. The main effect of cue-target color was not significant, $F(1, 13) = 1.64$, $p = .223$.

## Experiment 3

Experiment 3 was designed to examine an alternative nonattentional explanation for the results of Experiment 2. The cue may interact with the target in a purely sensory way: it may accelerate target processing simply through repetitive stimulation of the same neurons (Schneider & Bavelier, 2003), or by temporally fusing or "amalgamating" with the target (see Scharlau, 2007). These low-level sensory interactions between cue and target may be stronger when the two stimuli share the same color. To disentangle sensory from attentional effects, we instructed participants to monitor two target colors in Experiment 3. Thus, we could compare trials in which the cue was presented in the exact same color as the subsequent target disk to trials in which the cue was presented in a task-relevant, but nevertheless different color than the target. If contingent capture was responsible for the observed cuing effect in Experiment 2, we expect similar PSS shifts for same and different color cues, since both are matching the overall task set. If low-level sensory interactions contingent on an exact color match between cue and target contribute to the shift, we expect larger cuing effects in the same color condition.

## Method

**Participants.** Seventeen students (11 women) from the University of Toronto aged between 17 and 27 years participated in Experiment 3 for course credit. All reported normal or corrected to normal vision and gave informed consent prior to the experiment.

**Apparatus, stimuli, design and procedure.** Apparatus, stimulus characteristics, and procedure were identical to Experiment 2 with the following exceptions. First, we added a fourth stimulus color to our range: yellow ($x = 0.41$, $y = 0.51$; luminance adjusted to be equivalent to the other colors). Second, we instructed participants to monitor two target colors (e.g., blue *and* yellow). However, on any given trial, only one of the two possible target colors was presented in the target display (e.g., blue), whereas the other disks were always presented in preassigned distractor colors (e.g., always one red pair and one green pair of distractor disks). Thus, the targets for the TOJs on each trial were clearly defined by their color. But we could also change the target color unpredictably from trial to trial between the two target colors such that participants had to constantly keep both colors in mind. The assignment of target and distractor colors was counterbalanced across participants. Third, the cue was also presented in one of the two target colors, unpredictably changing from trial to trial and uncorrelated to the subsequent target color in the same trial. Therefore, the cue was *always* presented in a color matching the current task set of the participant. However, it was either of the exact same color as the target disks, or of the other monitored color.

## Results and Discussion

Data of three subjects was excluded from analysis as psychometric function fits were very poor (proportion *cued side first* responses in all conditions close to chance; $R^2$ of the fits <0.5). For the remaining 14 participants, a minimum of 13 trials was collected per data point, with an average of 32 trials in which the target was cued, and 64 trials in which a distractor was cued.

Figure 4A illustrates mean proportion of *cued side first* responses averaged across participants; Figure 4B illustrates example data and fits of one representative participant (P13). In general,
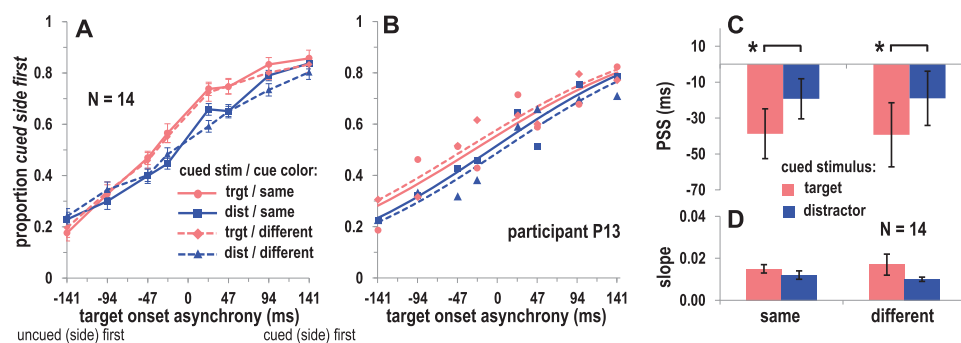


*Figure 4.* Results of Experiment 3. (A) Average proportion of *cued side first* responses as a function of TOA, separate for trials with cued targets (trgt, pale red) or distractors (dist, dark blue) and for cues of exactly the same color (solid) or a different color (dashed) as the target. (B) Proportion of *cued side first* responses and psychometric functions of one representative participant (P13). (C) Average PSS for the four conditions across the 14 participants. (D) Average slope values of the logistic functions across the 14 participants. Error bar conventions in all panels as in Figure 2. See the online article for the color version of this figure.

data show a shallower rise in *cued side first* responses across TOAs than in the previous experiments, suggesting that the more complex task assignment of monitoring two instead of only one target color interferes with performance in the TOJs. In the example data of participant P13, the rise is not always monotonous. This was the case for several participants, which affected the goodness-of-fit values (see Figure S3 in the supplementary material). Importantly, despite shallower slopes and individual nonmonotonies, the averaged data in Figure 4A shows that there were no systematic violations from a monotonous rise across all participants.

Figure 4C illustrates the average PSS across the 14 participants. A 2 (cued stimulus: target vs. distractor) × 2 (cue-target color: same vs. different) repeated-measures ANOVA revealed a highly significant main effect of cued stimulus, $F(1, 13) = 28.37$, $p < .001$, indicating larger PSS shifts in *target cued*, compared to *distractor cued* trials. Neither the main effect of cue-target color, $F(1, 13) < 0.01$, $p = .974$, nor the interaction reached significance, $F(1, 13) = 0.02$, $p = .903$, indicating that the larger shift in the PSS on *cued target* trials was not modulated by an exact color match of cue and target.

We also calculated a between-experiment analysis, comparing the results of Experiments 2 and 3. Critically, a significant three-way interaction (Experiment × Cued Stimulus × Cue-Target Color) was obtained, $F(1, 26) = 16.36$, $p < .001$. Subsequent separate ANOVAs for *target cued* versus *distractor cued* trials revealed that the differences across experiments were largely due to the differences in the *target cued* trials where an Experiment × Cue-Target Color interaction persisted, $F(1, 26) = 15.71$, $p = .001$, confirming a larger difference between same and different color trials in Experiment 2 compared to Experiment 3. In contrast, no significant main effects or interactions were found when comparing only the *distractor cued* trials of Experiments 2 and 3, all $Fs(1,26) < 2.25$, $ps > .146$. In sum, the results of Experiment 3 suggest that the extent to which a color singleton cue produces a cuing effect in TOJs is mostly determined by whether its color is included in the range of monitored target colors. In other words, contingent capture explains the prior entry effects in Experiment 2 and 3 better than low-level sensory interactions based on similar colors.

It is worth noting that significant negative shifts in the PSSs were also observed in the trials in which a distractor was cued (see Figure 4C). Note that this effect does not reflect any spatial advantage at the cued distractor location: We asked participants to judge the temporal order of the target pair. A cuing effect, favoring the target appearing at the same side as the cue over the target on the opposite side does not allow us to draw any conclusions as to what happens at the distractor location. We suggest that the shifts reflect that with increasing task difficulty, simple response biases (e.g., if unsure, to respond "left" if the cue was presented to the left) may start to have an impact. A between-experiments analysis of the slopes revealed a significant main effect of experiment, $F(1, 26) = 5.49$, $p = .027$, confirming shallower slopes in Experiment 3 than Experiment 2. Also, a significant main effect of cued stimulus was found, $F(1, 26) = 6.25$, $p = .019$, indicating more difficulty in temporal order discrimination when a distractor, compared with when a target, was cued. Despite better discrimination performance, however, the PSS shifts were much larger when a target was cued and we therefore think that task difficulty cannot explain all of the PSS shifts in Experiment 3. The three-way

interaction was marginally significant, $F(1, 26) = 2.95$, $p = .098$, hinting at more modulation of slopes across experiments and cue-target color on *distractor cued* trials. No further effect or interaction approached significance, all $Fs(1,26) < 0.52$, $ps > .478$.

In sum, Experiment 3 suggests that low-level sensory interactions contingent on an exact color match between cue and target are unlikely to have caused the differences between matching and nonmatching cues found in Experiment 2. The results need to be interpreted with some caution, though, since the overall poorer performance in Experiment 3 may have reduced the ability to detect more subtle changes in the PSS. Having said that, the average PSS values seen in Figure 4C are nearly identical between the same and different color cue conditions.

Some studies have suggested that with a two-color control set, nonmatching color singletons can be prevented from drawing spatial attention resources as effectively as with a single-color control set (e.g., Irons et al., 2012; Moore & Weissman, 2010). In contrast, evidence from event-related potentials (ERPs) suggests that salient nonmatching cues may produce orienting responses (i.e., an N2pc) toward them when task sets are more complex (e.g., two-color sets or space-color conjunctions; Adamo, Pun, & Ferber, 2010; Grubert & Eimer, 2013; Priess et al., 2014). Interestingly, the manual RT pattern in those studies did not follow the ERP results: if there were differences in the N2pc (e.g., delayed onset or smaller amplitude for nonmatching compared to matching items), there were no differences in RTs, or vice versa. The common explanation for those discrepancies between RTs and ERPs is that RTs are affected by later modulations whereas the ERPs only reflect the initial processing stages. Our Experiment 3 was solely conducted to examine color-based sensory interactions. Thus, we did not include a nonmatching singleton cue condition (which would have made the experiment too large to be feasible). It would be interesting to see whether TOJs are sensitive to those early effects by introducing a nonmatching cue when participants have to maintain a two-color set.

## General Discussion

In three experiments, we examined whether color singleton cues provoke shifts in the PSS in TOJs consistent with prior entry effects and whether those cuing effects would be contingent on attentional control sets. Experiment 1 showed that color singleton cues indeed produce cuing effects in TOJs, even in a cluttered and dynamic target display containing multiple heterogeneous distractors. In Experiment 2, we observed the typical PSS shifts in TOJs only when the singleton cue matched participants' current attentional control set. Experiment 3 suggests that a sensory interaction account of the differences found in Experiment 2 is unlikely, although the results of Experiment 3 have to be interpreted with some caution.

## TOJ Cuing Effects Are Contingent on Attentional Control Sets

Our pattern of results in TOJs follows the predictions of the contingent involuntary orienting hypothesis (Folk et al., 1992): nonmatching cues produced significantly smaller cuing effects than matching cues. And in most cases, we did not observe reliable

(i.e., statistically significant) shifts in the PSS away from a TOA of 0 ms for nonmatching cues. This is in line with results from manual RT studies and the idea that nonmatching cues do not capture attention. Our results confirm the contingent capture pattern found in a previous study with abrupt onset cues that were made invisible through metacontrast masking, and in which shape or color of cues and targets was varied (Scharlau & Ansorge, 2003). In contrast, seemingly inconsistent with contingent capture, Vingilis-Jaremko and colleagues (2008) reported cuing effects of similar magnitude for abrupt onsets and abrupt offset cues if the TOJ targets were onsets. With offset targets (i.e., participants report which of two targets *dis*appeared first), larger cuing effects for offset than for onset cues were found. However, in contrast to the current experiments in which the nonmatching cue's color always belonged to the set of distractor colors that had to be ignored during the target display, participants in the onset-offset study were never shown any distractors that had to be filtered out from the targets. Thus, as the authors point out, participants could have adopted a broad attentional set, looking for dynamic stimuli in general (see Burnham, 2007 for review). The varying degrees of contingent capture with onset and offset targets and the discrepancies to the current contingent capture pattern may therefore be seen as evidence for the variability in broadness of attentional sets, flexibly adjusting with task demands.

Our results are in line with contingent capture studies using manual RT as a dependent measure (Folk et al., 1992). However, TOJs and manual RTs do not always produce corresponding results. Comparing the results from different measures can help tease apart the different attentional or nonattentional components and manifestations of capture effects. In the following, we will therefore relate our findings to previous results and current debates and proposals surrounding (contingent) attentional capture effects.

## Attentional Capture and Inhibition

A very robust observation in manual RTs is the reversal of the cuing advantage when cue-target onset asynchronies (CTOAs) are prolonged: participants become faster to respond to an uncued target than a cued target. The classic interpretation for the reversed cuing effect states that the cue initially summons attention, producing regular cuing effects at short CTOAs. But then attention is quickly disengaged from the cued location and the reallocation of spatial attention resources to this location is inhibited (inhibition of return; Klein, 2000; Posner & Cohen, 1984). Thus, when the target is shown after a longer CTOA, participants take longer to react at the cued location. Interestingly, more rapid disengagement from nonmatching than matching cues has been invoked to explain contingent capture patterns in manual RTs (see Theeuwes, 2010). However, unlike inhibition of return, which is robustly found in manual RT studies, cuing effects in TOJ studies have never been reported to reverse to favor the uncued stimulus, even when using CTOAs as long as 1000 ms (Scharlau, 2007; Schneider & Bavelier, 2003).

In fact, reversed cuing effects are not only restricted to inhibition of return (IOR), but are a common pattern found in manual RTs in various conditions. For instance, reversed cuing effects have been observed with short CTOAs for nonmatching cues when the target display contained multiple colors (Irons et al., 2012; Lamy et al., 2004). Like IOR, these effects were attributed to a spatially specific inhibitory mechanism. Similar to those studies, we also had a heterogeneously colored target display. Thus, we could have expected a reversed cuing effect for nonmatching cues in Experiment 2 which should have been visible in a shift of the PSS toward positive TOAs, disfavoring the cued location. However, such an effect was not observed (see also Scharlau & Ansorge, 2003).

Apart from manual RTs, other measures have also provided evidence for spatial effects reflecting processes of inhibition or orienting *away* from cues or distractors. For instance, saccade trajectories deviate away from matching as well as nonmatching stimuli (Al-Aidroos & Pratt, 2010; Ludwig & Gilchrist, 2003; Mulckhuyse, Van der Stigchel, & Theeuwes, 2009). One may be tempted to assume that spatial effects away from cues or distractors may be essentially motor effects. However, recently Gozli and Pratt (2012) have found that the attention repulsion effect, a perceptual bias away from a peripheral cue in a Vernier alignment task, occurs for matching and nonmatching cues.

In sum, results consistent with contingent capture, but no biases away from the cued location, have been found for TOJs so far. Thus, the inhibitory mechanism(s) assumed to underlie the phenomena described above are probably independent from the processes responsible for contingent capture (see also Irons et al., 2012; Lamy et al., 2004; Priess et al., 2014).

## Sensory Sensitivity Changes Caused by Matching and Nonmatching Cues

In disagreement with the contingent capture hypothesis, feature singletons that do not match the attentional control set have been found to increase perceptual sensitivity for upcoming targets as measured by $d'$ or contrast thresholds (Theeuwes & Chen, 2005; White et al., 2014). Interestingly, RSVP results, on the contrary, suggest that sensory sensitivity at the central stimulus stream is only impaired by peripheral distractors matching the attentional control setting (Folk et al., 2002; Lamy et al., 2004; Moore & Weissman, 2010). We think our lack of cuing effects in TOJs by color singletons that do not match the attentional set of the observer in Experiment 2 does not contradict any of these findings: in TOJs, contrast sensitivity may not play a role. As such, an improvement of contrast sensitivity even at nonmatching cue locations may go unnoticed in the same way as a sensory sensitivity drop at noncued locations following a matching cue. The same may be true in quite a number of RT studies. Targets are usually easy to discriminate, error rates are typically low and do not vary systematically with conditions. Increased perceptual sensitivity may thus not improve perception of the target which is already at ceiling and consequently may likewise not affect RTs. Thus, it is possible that nonmatching cues do not produce cuing effects in TOJ and easy manual RT tasks while, at the same time, improving perceptual sensitivity. Note, however, that we cannot say whether matching cues may improve sensitivity even more than nonmatching cues. To our knowledge, this has not been systematically investigated, yet (see also White et al., 2014).

## Decision Biases in Serial Search Tasks

Prinzmetal and colleagues (2011) proposed that contingent capture reflects a bias in the decision where to start the search for the

target. They argue that even though the singleton cue may be noninformative, participants may be biased to start the search for the target at its location, but only when it is a target-matching cue. This should give a speed advantage when the target is actually presented at that location and lead to a disadvantage when the target is presented elsewhere (i.e., the basic cuing effect). Although this explanation may explain contingent capture in manual RTs, it is difficult to explain our TOJ results with such a serial search bias. As described, the search bias is essentially a speed advantage or disadvantage of finding the target that may directly translate into RTs. However, our TOJ cuing effects are not based on a speeded response. Further, it is not immediately obvious which impact searching first at the cued location could have in a TOJ paradigm in which the onsets of two stimuli have to be compared.

## Prior Entry and Response Biases

To summarize the discussion so far, we have highlighted a number of mechanisms (inhibition, improvements in sensory sensitivity, decision biases) suggested to account for (contingent) attentional capture patterns in RTs and other measures. We concluded that all of them may be difficult to apply to our TOJ results. Which mechanism may then account for our effects?

Cuing effects in TOJs have traditionally been linked to prior entry: accelerated processing of stimuli presented at the cued location leads to cued targets reaching the threshold for conscious perception earlier (see Scharlau, 2007; Schneider & Bavelier, 2003; Spence & Parise, 2010 for reviews). In this framework, our results suggests that attention-dependent accelerated processing may only occur for matching, but not for nonmatching cues (see also Scharlau & Ansorge, 2003). Prior entry can also explain RT effects: the earlier a stimulus is processed, the faster one can react to it. Further, prior entry in RT may combine with other mechanisms; for instance, search biases or inhibitory influences. Apart from separate decision criteria assumed for RTs and TOJ responses (Cardoso-Leite, Gorea, & Mamassian, 2007; Miller & Schwarz, 2006), multiple mechanisms adding up in RTs (e.g., Prinzmetal et al., 2005) may explain why cuing effects have been found to be larger in RTs than in TOJs (Neumann, Esselmann, & Klotz, 1993).

The additivity, or even interactivity, of several processes may obscure contingent capture in RTs such that TOJs may be seen as a "purer" measure. However, the use and interpretation of TOJs and in particular the prior entry hypothesis have also been heavily debated. One of the most debated issues concerns the question of whether prior entry truly reflects accelerated processing or may be a simple response bias: if unsure, participants may follow the strategy of reporting the stimulus at the cued side to have appeared first. Consequently, a lot of effort has been concentrated to devise tasks that may reduce the influence of response bias on prior entry effects (Schneider & Bavelier, 2003; Shore et al., 2001; Stelmach & Herdman, 1991; Weiβ & Scharlau, 2011, 2012). Nevertheless, in all cases cuing effects in the PSS persisted, indicating that the effects are not a simple response bias.

Another argument against the prior entry hypothesis is that neurophysiological and electrophysiological measures do not support shorter latencies for responses to cued versus uncued stimuli (see Schneider & Bavelier, 2003; Spence & Parise, 2010 for

discussion). Further, the interpretation of the PSS as truly being the TOA where participants perceive the two stimuli as simultaneous has been doubted. When a third "simultaneous" response category is introduced, participants almost never use this category on cuing trials (Stelmach & Herdman, 1991; Weiβ & Scharlau, 2011). Neither do participants frequently report to be uncertain about the temporal order of stimuli around the PSS (Weiβ & Scharlau, 2011), which is possible if processing times are noisy. Thus, the PSS may rather be the delay at which it is most unpredictable which of the two stimuli will "win the race" for conscious perception first on a given trial. Finally, in contrast to prior entry for cued stimuli compared to an uncued baseline, Weiβ and colleagues (Weiβ, Hilkenmeier, & Scharlau, 2013) propose that shifts in the PSS rather reflect *posterior* entry, that is, delayed perception of the uncued stimulus on a cuing trial.

These discussions and debates demonstrate that prior entry, much like contingent capture, is a lively and productive research field. No matter what the exact underlying mechanism of cuing effects in TOJs, current consensus is that at least one component of prior entry effects is attentional in nature (Scharlau, 2007; Schneider & Bavelier, 2003; Spence & Parise, 2010). In line with an attentional account, TOJ tasks that have not employed distinct peripheral cues but rather target features to bias attention (e.g., faces and facial threat, West, Anderson, & Pratt, 2009; low spatial frequency Gabor patches and fearful faces, West, Anderson, Bedwell, & Pratt, 2010) show robust prior entry effects. The current experiments demonstrate that this attentional component produces a contingent capture pattern potentially less camouflaged by other processes like inhibitory effects or decisions where to start the search. Since contrast sensitivity or perceptual accuracy at a specific spatial location does not play a major role in TOJs, contingent capture may stem from processes other than those responsible for increasing response gain. As such, TOJs could be a valuable tool for further study of contingent capture. For instance, it would be worthwhile to consolidate our proposal that spatial inhibitory processes do not affect TOJs. Further, contingent capture effects have also been found for nonsingleton color cues (e.g., Lamy et al., 2004). Testing cuing effects in TOJs for nonsalient cues matching attentional control settings should provide insights for the contingent capture, as well as the prior entry literature.

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