

# The Interaction Between Stimulus-Driven and Goal-Driven Orienting as Revealed by Eye Movements

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It is generally agreed that attention can be captured in a stimulus-driven or in a goal-driven fashion. In studies that investigated both types of capture, the effects on mean manual response time (reaction time [RT]) are generally additive, suggesting two independent underlying processes. However, potential interactions between the two types of capture may fail to be expressed in manual RT, as it likely reflects multiple processing steps. Here we measured saccadic eye movements along with manual responses. Participants searched a target display for a red letter. To assess contingent capture, this display was preceded by an irrelevant red cue. To assess stimulus-driven capture, the target display could be accompanied by the simultaneous onset of an irrelevant new object. At the level of eye movements, the results showed strong interactions between cue validity and onset presence on the spatiotemporal trajectories of the saccades. However, at the level of manual responses, these effects cancelled out, leading to additive effects on mean RT. We conclude that both types of capture influence a shared spatial orienting mechanism and we provide a descriptive computational model of their dynamics.

*Keywords:* attentional control, attentional capture, oculomotor control, oculomotor capture

Visual spatial attention can be controlled in what appears to be two fundamentally different ways. Stimulus-driven processes prioritize information based on the physical salience in the environment. Goal-driven processes prioritize information based on its relevance for the task at hand. How these two effects combine in determining attentional priority is still a topic of fierce debate (see Theeuwes, 2010).

The debate is complicated by the fact that both influences can occur automatically. For example, numerous studies have provided evidence that a stimulus with a strong bottom-up signal (i.e., one that is salient in its surroundings) evokes an involuntary shift of attention to its location, and that there is little that goal-driven processes can do to stop this (Belopolsky, Theeuwes, & Kramer, 2005; Franconeri, Simons, & Junge, 2004; Theeuwes, 1992; Wolfe, 1994; Yantis, 1993). One event that is known to emit such

a strong bottom-up signal is an *abrupt onset*: a stimulus that suddenly appears out of nowhere in the visual field. Such a stimulus is thought to capture attention, even when it is completely irrelevant to the observers' current goals or intentions (Franconeri et al., 2004; Jonides & Yantis, 1988; Theeuwes, 1994).

At the same time, attentional capture can occur on the basis of top-down settings, as has been shown by Folk and colleagues (Folk & Remington, 1998, 2006; Folk & Remington, 2008; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wu, 2009). In a typical experiment, observers respond to the identity of a target character (e.g., X or =), which in one condition is defined by a unique color (e.g., red), relative to the nontargets (e.g., white). Shortly before presentation of the target display, a cue in the form of four red dots appears around any one of the target or nontarget locations (while concurrently all other locations are surrounded by white dots and the red cue is not the only item with an onset). Notably, the color cue is not predictive of the target location and so is formally irrelevant to the primary task. Nevertheless, when the cue aligns with the target location, response times (RT) are shorter than when the cue aligns with a nontarget location, implying the cue captured attention. No such benefit is present when the cue is defined in a different dimension or a different color than the target color (Anderson & Folk, 2010). In this case, we have an automatic form of attentional capture that is specific to the goals of the observer. Because of its contingency on the attentional set of the observer, Folk and colleagues refer to this as *contingent attentional capture*.

Because both stimulus-driven and contingent capture occur automatically (Folk & Remington, 1998; Ruz & Lupianez, 2002; Yantis & Jonides, 1990) it is tempting to suspect that they share

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underlying mechanisms. As such, one would expect to find an interaction of the two capture effects whenever they co-occur. However, Schreij and colleagues (Schreij, Owens, & Theeuwes, 2008; Schreij, Theeuwes, & Olivers, 2010a, 2010b) have consistently found an *additive* relationship instead. Schreij et al. adopted Folk et al.'s precueing paradigm as described above (i.e., a red target display preceded by an irrelevant red cue), but occasionally let an irrelevant abrupt onset appear simultaneously with the red target. They reasoned that the red precue would capture attention in a contingent fashion as with Folk et al. (1998, 1992), while the abrupt onset distractor was likely to capture attention in a stimulus-driven fashion (Jonides & Yantis, 1988; Yantis & Jonides, 1990). Schreij et al. indeed found that both an invalid cue and the presence of an onset distractor slowed responses to the target and concluded that both distractors were able to capture attention. However, the relation between these capture effects was always additive, suggesting that the two forms of capture operate independently of each other. This is consistent with other studies that have also found a robust additive relationship between stimulus- and goal-driven orienting effects (Berger, Henik, & Rafal, 2005; Juola, Koshino, & Warner, 1995).

In fact, the absence of an interaction in the results of Schreij et al. (2008) led Folk et al. (2009) to argue that the effect elicited by the abrupt onset could not involve a spatial orienting mechanism—otherwise it would have interacted with the spatial validity effect of contingent capture. Instead, what they proposed was that the interference caused by the abrupt onset reflected a time-consuming, nonspatial filtering process, which has to eliminate the competition for attentional allocation by the onset (Kahneman, Treisman, & Burkell, 1983). From this perspective, an abrupt onset delays the allocation of attention to the target, but the onset location is not visited by attention. That is, the filtering process operates before spatial orienting and thus, should combine additively with the contingent capture effect (that does involve spatial orienting), consistent with the pattern found by Schreij et al. (2008).

The fact that Folk, Remington and Wu (2009) attributed these onset effects to a filtering operation appears at odds with an earlier study by Wu and Remington (2003), who showed that an irrelevant onset distractor can attract eye movements even when observers are looking for color (see also Peterson, Kramer, & Irwin, 2004; Theeuwes & Belopolsky, 2012; Theeuwes, Kramer, Hahn, & Irwin, 1998; Todd & Van Gelder, 1979). By their very nature, eye fixations are spatially specific, and related research has indicated a close coupling to spatial attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Rizzolatti & Craighero, 1998; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Shepherd, Findlay, & Hockey, 1986). This work has indicated that it is possible to shift attention covertly without a concurrent shift in gaze, but it is not possible to shift the eyes without first shifting attention. Before an eye movement is executed to a new location, spatial attention is first covertly shifted to it. Nevertheless, Wu and Remington (2003) argued that oculomotor capture and attentional capture effects can be dissociated. They argued this on the basis of their finding that an onset distractor was able to capture one's gaze when the task required participants to make saccades, but caused no delays in RT when the same task could be performed without making eye movements. Because of the absence of such RT effects, Wu and Remington

concluded that the onset could not possibly have captured attention and attributed the oculomotor capture to “the sensitivity of the oculomotor system to orient to transients” (Breitmeyer & Ganz, 1976). However, we believe that this sensitivity to transients is exactly what attentional capture by abrupt onset entails. Moreover, as will be the take-home message of the current study, RT results (or the absence thereof in the case of Wu and Remington, 2003) should be treated with real caution, as they may camouflage underlying interactions that can be expressed in oculomotor data.

The present study was not aimed at challenging the contingent capture framework as such. It was aimed at challenging the specific interpretation of onset-driven interference as recently offered within the contingent capture framework—namely in terms of nonspatial mechanisms. We measured the eye movements of observers when they were engaged in a task that combined both irrelevant abrupt onsets and target-related color cues. On each trial, participants had to identify a red target character, whose presentation could be accompanied by the appearance of a task-irrelevant abrupt onset and which was always preceded by a task-irrelevant cue that shared the target color. On each trial, we tracked saccades made toward the abrupt onset, the color-cue, and the target, on the assumption that these saccades would be an external expression of the spatial orienting response. This allowed us first to see whether abrupt onsets elicit an orienting response in this task (i.e., despite the fact that observers are looking for a color). If so, it would speak against the idea that onsets result in filtering costs without spatial reorienting. Second, if stimulus-driven orienting and contingent-capture both occur in this task, the eye movement data may reveal how the manual RT data follows an additive pattern for these factors, as observed in all previous studies.

To anticipate, the results showed that at the level of eye movements strong interactions existed between cue validity and onset presence on the spatiotemporal trajectories of the saccades. However, because there was an intricate tradeoff between the frequency of (suboptimal) saccade trajectories and their durations, the effects of cue validity and onset presence turned out to be approximately additive on manual mean RT. The results lead us to propose that both types of capture influence a shared spatial orienting mechanism.

## Method

### Participants

Fourteen students from the University of British Columbia between 18 and 23 years of age (average 20) participated in return for course credits. All had normal or corrected-to-normal vision and none reported color blindness or any other visual deficits.

### Apparatus

Stimuli were presented in a dimly lit and sound-proof room, using a PC and a 19" CRT monitor (resolution 1024 × 768 px), which participants viewed with their head on a chinrest from a distance of 75 cm. OpenSesame experiment builder (Mathot, Schreij, & Theeuwes, 2012) was used for stimulus presentation and response recording. Eye movements were recorded with an EyeLink CL (SR Research), a video-based eye-tracker with a sampling rate of 2 kHz.

## Stimuli

The stimuli were presented on a black background. The basic display consisted of a white (CIE [0.286, 0.311], 109 cd/m<sup>2</sup>) fixation cross in the center, surrounded by four white placeholder boxes (0.7° wide). These were positioned above, below, to the left and to the right of the fixation cross, at a distance of 9.5°. As a result of this spatial layout, the placeholders' contents were indiscernible when the eyes were fixated on the central cross, and required participants to make an eye movement to a placeholder to identify its contents. In the cue display each box was surrounded by a set of four dots (0.4° wide), of which all were white except for those at the cued location, which were red (CIE [0.621, 0.345], 39.7 cd/m<sup>2</sup>). Each box contained a bright white masking figure consisting of overlapping "M" and "N" symbols. We chose these symbols instead of the usual X and =, because the former are harder to discriminate with peripheral vision and should further incline participants to make an eye movement to the element they want to inspect. In the target display, the irrelevant line segments were removed, revealing an M or an N in each box and the color of the target character turned to red. There were always two Ms and two Ns present. In the onset condition an extra box was added to the display, equiprobably containing a white M or N distractor character. It appeared at a randomly selected location equidistant from two adjacent placeholders, at the same distance from fixation.

## Design and Procedure

There were two main factors, both varied within subjects: Onset Presence (no onset, onset) and Cue Validity (valid, invalid). The

red cue before the target was uninformative about the location of the upcoming target. When the cue was valid, its location corresponded to that of the target (25% of the cases); when it was invalid, it specified with equal probability one of the three other locations. The onset appeared in 50% of the trials and always contained a white M or N distractor character. Cue Validity and Onset Presence were randomly mixed within 10 blocks of 80 trials each. There was one additional practice block of 80 trials preceding the experimental blocks.

Figure 1 shows the experimental procedure. To familiarize participants with the task, they were first given oral and written instructions in which they were told to always look for a red M or N character inside one of the placeholders, and press the corresponding key on the keyboard. They were requested to keep their index fingers on each response button. Initially the fixation display was presented for 1,000 ms, after which the fixation cross blinked for 100 ms, to indicate the start of a trial; 500 ms after this event, the red cue appeared for 50 ms. After an interstimulus interval of 100 ms, the search display was presented until response (with a maximum of 2,000 ms). When the given response was incorrect, the fixation dot turned red momentarily and a buzzer sounded. Between blocks, participants took a mandatory break. The experiment took around 1 hr to complete.

## Eye Movement Data Processing

A saccade was defined as an eye movement of which the acceleration was greater than 9,500 deg/s<sup>2</sup> and the velocity exceeded 35 deg/s. A saccade was assigned to a particular object if the angular deviation between the center of the object and the

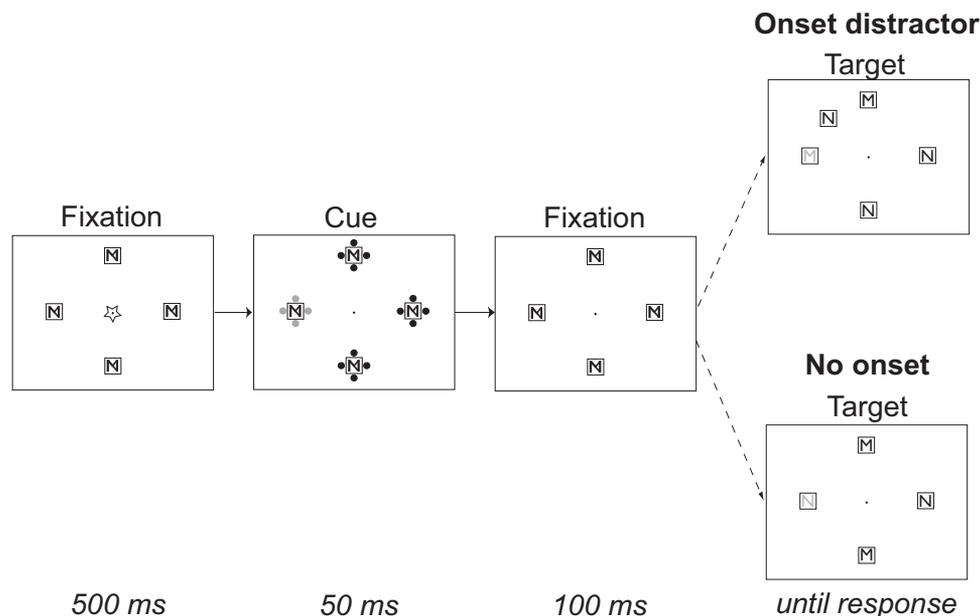


Figure 1. Illustration of the trial procedure in which the cue was valid. A trial started with the presentation of the fixation display containing placeholders with overlapping M and N characters for 1,000 ms. Then the fixation cross briefly flashed, and 500 ms later the cue display was briefly presented for 50 ms. After an interstimulus interval of 100 ms, the target display appeared containing the red target letter, and occasionally an extra onset placeholder. Participants responded to the identity of the red letter, which was either M or N. Stimuli are shown in negative contrasts, with red stimuli shown in light gray; displays are not drawn to scale.

saccade's endpoint was less than 11.25° (corresponding to half the angular distance between an onset and its adjacent objects) along the imaginary circle on which the objects were positioned. Latencies of first saccades and manual response were time locked to the onset of the target display.

## Results

We present our analyses in four sections. First, we examine mean manual RT and mean latency of the first saccade in each condition. Next, we examine how cue validity and onset presence influenced the trajectories of the eyes toward the target. We then present a descriptive model that integrates the findings with respect to saccade latencies and saccades trajectories. Finally, we examine how the spatial layout of target, cue, and onset influenced the spatial distribution of first saccades.

### Latency Data

For all participants, on all trials, manual responses were produced within the maximum time limit of 2,000 ms. We discarded practice trials and all trials on which the manual response was incorrect (5%). Figure 2A depicts manual mean RT, irrespective of eye movements, as a function of cue validity and onset presence. Participants responded slower when the cue was invalid than when it was valid, and they also responded slower when an onset was present than when it was absent. These effects were approximately additive. These observations were supported by an analysis of variance (ANOVA) with Cue Validity (invalid, valid) and Onset Presence (no onset, onset) as repeated measures. The effects of Cue Validity and Onset Presence were both significant ( $F(1, 13) = 175.06, p < .001$  and  $F(1, 13) = 63.16, p < .001$ , respectively) but the interaction between them was not,  $F(1, 13) = 2.66, p > .1$ . The corresponding ANOVA on the error rates revealed only a significant effect of Cue Validity,  $F(1, 13) = 7.93, p < .05$ . Participants made more errors when the cue was invalid.

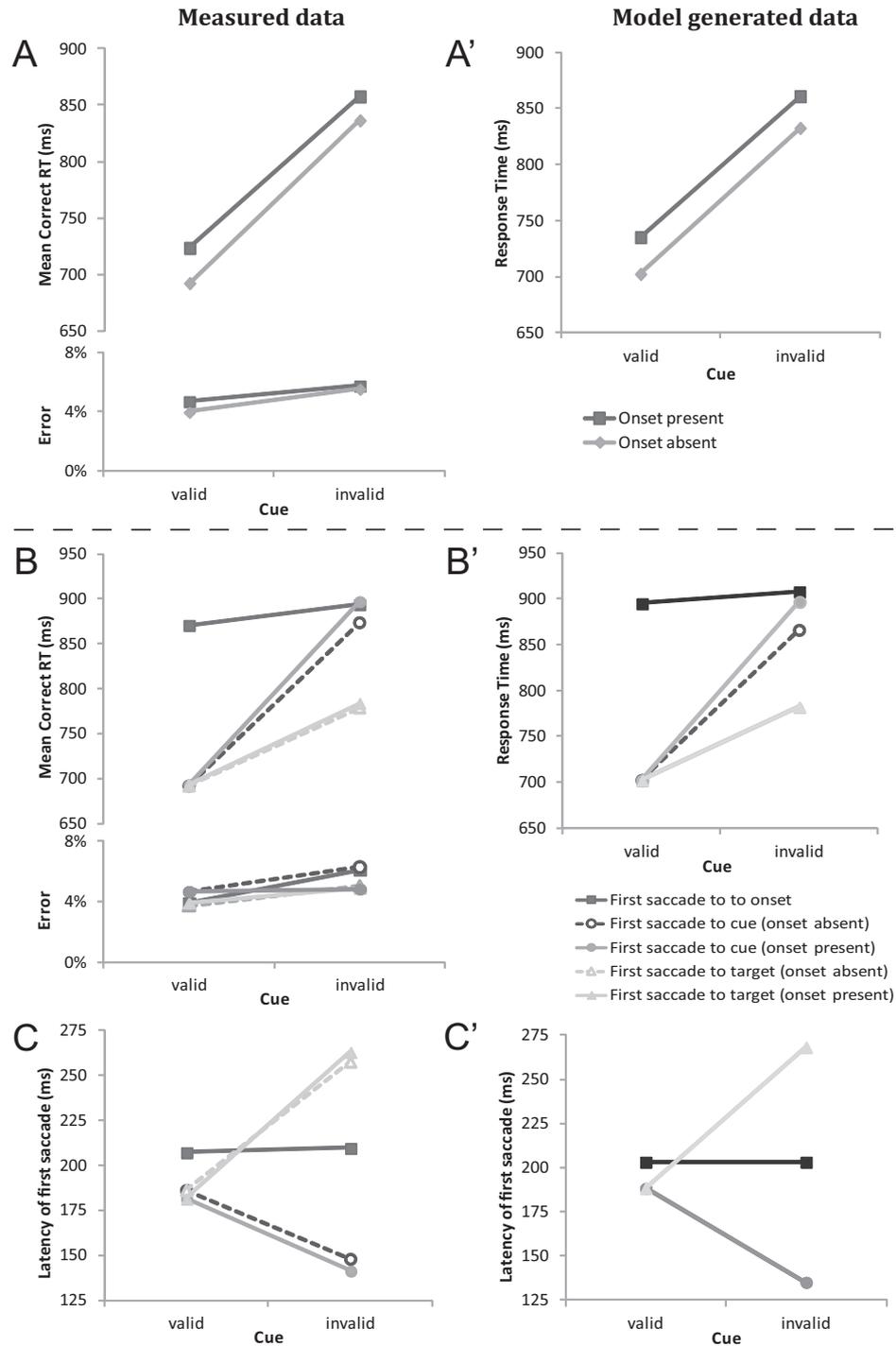
Figure 2B shows mean correct RT subdivided according to whether the first saccade was directed to the target, the cue, or the onset. An ANOVA on these data was not possible because in the valid-cue condition, the cue and target location are shared, thus breaking the factorial structure of the design. Therefore, in this and all following analyses (where the same problem applied), we tested the onset and cue effects separately. All reported effects were significant after correction for multiple tests ( $p < .01$ ) except when explicitly indicated otherwise. There were three main findings. First, when the first saccade went to the onset, there was no significant effect of cue validity. Second, when the first saccade went to the cue, its validity had a strong effect on RT. The presence of an onset distractor only affected RT in this situation if the cue was invalid: participants responded 24 ms slower when there was an onset than when there was no onset. Third, when the first saccade went to the target, there was an effect of cue validity but not of onset presence. In the valid-cue condition, mean RT was 87 ms shorter than in the invalid-cue condition.

Figure 2C shows the latency of the first saccade as a function of cue validity and onset presence, subdivided according to the end point of the saccade (i.e., onset, target, or cue). The most noteworthy aspect of this data pattern is that in the invalid-cue condition, saccades to the target were much slower than saccades to the cue (about 265 and 140

ms, respectively), while in the valid-cue condition (where target and cue locations were identical) saccade latencies were intermediate (about 180 ms). This pattern suggests that on some trials, saccades were driven by the cue, leading to short latencies, because the cue was presented 150 ms before the target display. On other trials, saccades were driven by the target (defying the cue), leading to long latencies. In the invalid-cue condition these types of saccades can be distinguished, leading to the observed pronounced difference in latency. By contrast, in the valid-cue condition, in which the cue and target location are identical, these saccades cannot be distinguished. This raises the possibility that in the valid-cue condition, saccade latency is a mixture of fast saccades driven by the cue and slow saccades driven by the target, leading to the observed intermediate latencies (the distributional analysis described in the Appendix confirms this assumption). In the model that we discuss later, we build on the idea that these trials involve a mixture of fast and slow saccades. A related observation comes from a comparison of the data in Figure 2B and 2C: Given that the first saccade goes to the target (the light gray lines in both figures), the effect of cue-validity was similar. In particular, for the first saccade latency (Figure 2C) this effect was 71 ms; for mean correct manual RT (Figure 2B) this effect was 87 ms. This strongly suggests that the relatively slow saccade to the target location in the invalid-cue condition propagates to manual RT. As noted above, this may in turn reflect that the first saccades to the target in the invalid-cue condition are slow, as they are merely driven by the target itself, whereas the first saccades in the valid-cue condition consists of fast saccades driven by the earlier-presented cue, intermixed with slow saccades driven by the target.

### Saccade Trajectories

Figure 3 shows the conditional probabilities of first, second, and third saccades to each item of interest in the visual field, for all possible combinations of cue validity and onset presence. Again all effects reported here were significant under correction for multiple tests ( $p < .01$ ). In all conditions there were a few cases in which the eyes went to locations other than those of the cue, onset, or target. As the proportion of these (erroneous) eye movements was low in each condition (below .05) and for the sake of simplicity in our analysis, they are not depicted in Figure 3 nor taken into account in the calculations of the probabilities. In the valid cue condition, in absence of an onset, first saccades always went to the cued target location. However, if the onset was present, it attracted a significant number (16%) of saccades to its location at the cost of saccades to the cued target location (84%). When the cue was invalid and the onset was absent, the majority of first saccades went to the cue (60%) and the remainder almost always to the target (40%). However, if the onset was present it attracted a significant number of first saccades (17%), resulting in a significant and proportional decrease of first saccades to the cue (48%) or target (35%). Notably, in this condition there were also a number of three-saccade trajectories to the target: When the first saccade was made to the location of the cue, the eyes still visited the onset location on a substantial proportion of the trials (15%) before going to the target, indicating stimulus-driven capture of the second saccade. Likewise, when a saccade was first made to the onset, the cue still managed to capture a significant proportion of second saccades (12%) after which the third and final saccade was made to the target. This is important, because it shows that both contin-



*Figure 2.* Results of the experiment. The left column shows data as measured from participants. The right column shows corresponding data generated by the descriptive model introduced in the Results section. The top row shows the mean manual RTs for each experimental condition. In the middle row these RTs are mapped to the direction of the first saccade in a trial. The bottom row shows the latencies of the first saccades to the various relevant positions in the search field as a function of cue validity and onset presence.

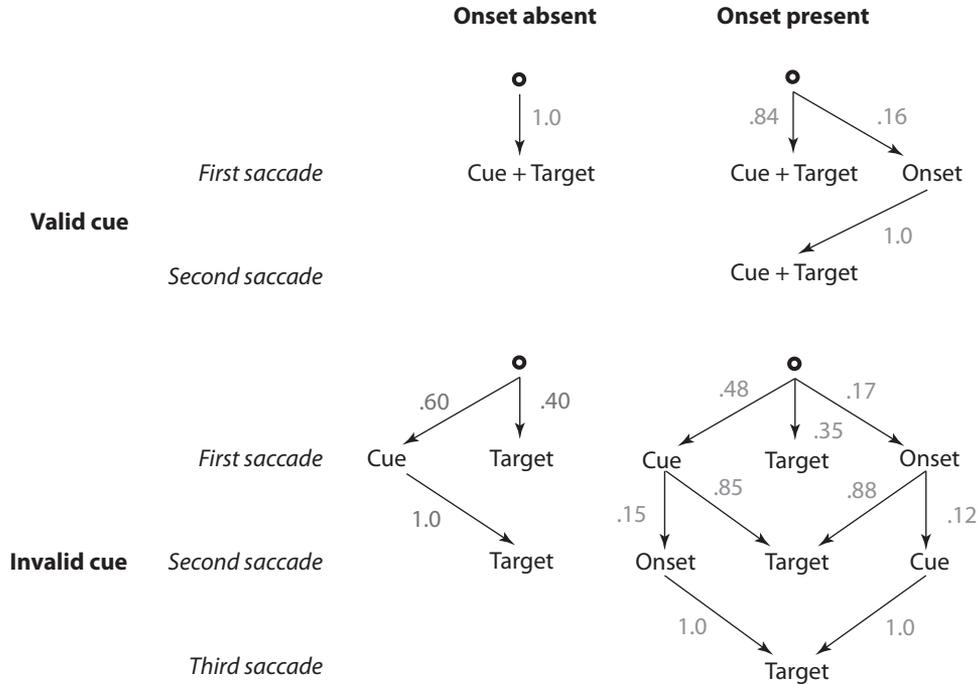


Figure 3. Conditional probabilities of first, second, and third saccades to each item of interest in the visual field, for all possible combinations of cue validity and onset presence. Saccades to locations other than those of the cue, target, or onset rarely occurred and are therefore not taken into account.

gent capture and abrupt onset capture occurred within the same trial.

**Descriptive Model of Saccade and Response Latencies**

Figure 4 shows a descriptive model that integrates the reported findings on saccade latencies and saccade trajectories. It describes the various potential trajectories of the eyes to the target location along with their probabilities in each experimental condition. For example, the eyes could first go to an invalid cue location, and then to the target. On other trials, they might go first to the onset, then to an invalid cue location, and then to the target. Each of these steps would cost a certain amount of time. Specifically, let  $i$  denote the onset-presence condition ( $i = 0$  for onset absent and 1 for onset present) and  $j$  the cue-validity condition ( $j = 0$  for valid and 1 for invalid). Then, at the most general level, the expected RT in condition  $i, j$ , can be described as

$$E[RT_{ij}] = E[S_1] + E[S_r] + c, \tag{1}$$

where  $S_1$  is the time needed to complete the first saccade since the onset of the target display,  $S_r$  the time needed for remaining saccades (if any) to reach the target location, and  $c$  the time needed to initiate the manual response since arrival of the eyes at the target location. For the sake of simplicity, the model does not distinguish between saccade latencies and saccade durations. That is, all  $S$ -terms in Equation 1 and subsequent equations comprise the saccade latency plus the duration of the subsequent saccadic eye movement (and, if relevant, corrective saccades). The expected time needed to complete the first saccade is given by

$$E[S_1] = \alpha_i S_O + (\beta - \beta \alpha_i) S_C + (1 - \beta - (1 - \beta)\alpha_i) S_T \tag{1a}$$

Table 1 describes each parameter of this equation along with its observed value. Consider first the onset-absent condition, in which case  $\alpha_i$  is 0, and Equation 1a reduces to  $E[S_1] = \beta S_C + (1 - \beta) S_T$ . That is, in the onset-absent condition, the first saccade is directed to the cue on a proportion  $\beta$  of the trials and to the target on the remaining trials. An important assumption of the model is that  $\beta$  is independent of cue validity. Accordingly, we estimated  $\beta$  in the

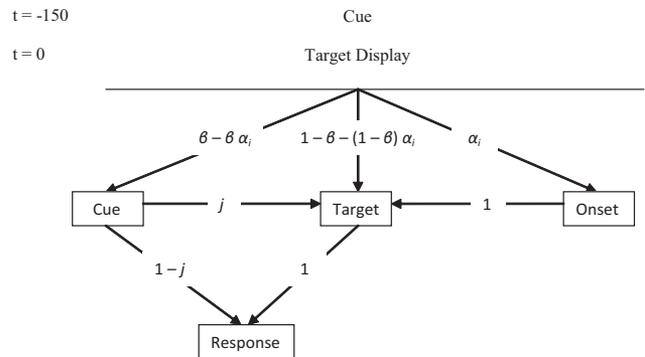


Figure 4. A descriptive model showing the various eye movement trajectories toward the target stimulus, along with their probabilities of occurrence in each experimental condition. Onset-presence condition is indexed by  $i$  (0 for onset absent; 1 for onset present) and cue-validity condition is indexed by  $j$  (0 for valid cue; 1 for invalid cue).

Table 1  
*The Parameters of Equations 1, 1a, and 1b (See Also Figure 3), Along With Their Observed Values*

Parameter	Description	Observed value
$S_T$	First saccade latency plus movement to target (invalid-cue condition)	268 ms
$S_C$	First saccade latency plus movement to invalid cue	135 ms
$S_O$	First saccade latency plus movement to onset	203 ms
$S_{O-T, j}$	Saccade latency plus movement from onset to target	178 ms ( $j = 0$ ); 191 ms ( $j = 1$ )
$S_{C-T, i}$	Saccade latency plus movement from cue to target	217 ms ( $i = 0$ ); 248 ms ( $i = 1$ )
$c$	Response latency after arrival of the eye at the target location	514 ms
$\beta$	Proportion first saccades to invalid cue (onset-absent condition)	.60
$\alpha_i$	Proportion first saccades to onset	$\alpha_0 = 0$ ; $\alpha_1 = .17$

Note.  $i$  specifies onset condition (0 for onset absent, 1 for present),  $j$  specifies cue validity condition (0 for valid, 1 for invalid).

invalid-cue condition, where the target and cue occupy separate locations, and assumed that the same proportion applied in the valid-cue condition, where these locations are shared. As a result, in the valid-cue condition, the set of first saccades is a mixture of  $\beta$  fast saccades driven by the cue and of  $1 - \beta$  slow saccades driven by the target (defying the cue). In either case, the eyes arrive at the target location, so, in this condition, the segregation between the cue and target location in Figure 4 only pertains to the difference in the corresponding saccade latencies.

Now, consider the onset-present condition, where a substantial proportion of the first saccades ( $\alpha_1 = .17$ , as given by the data) goes to the onset. As implied by Equation 1a, the value of  $\alpha_1$  is proportionally deducted from saccades that would have gone to either the cue or the target in the onset-absent condition (i.e.,  $\beta \alpha_1$  and  $[1 - \beta] \alpha_1$ , respectively). The data support this principle. In the invalid-cue condition, 60% of the first saccades went to the cue in the onset-absent condition vs. 48% in the onset-present condition. This reduction of 12% is close to the predicted reduction of  $(\beta \times \alpha_1 =) .60 \times .17 = 10.2\%$ . The corresponding figures for first saccades to the target are 40 and 35%. This reduction of 5% is close to the predicted  $((1 - \beta) \times \alpha_1 =) .40 \times .17 = 6.8\%$ . Here and in subsequent cases, we consider the slight discrepancies between data and model predictions less important than simplicity of the model. Furthermore, the proportion of first saccades to the onset (when present) was nearly equal in the valid-cue condition (16%) and in the invalid-cue condition (17%; see also Figure 2). This is consistent with the assumption that  $\alpha_i$  is independent of cue validity ( $j$ ). Finally, it is noteworthy that the mean first saccade latency to any given object was very similar across experimental conditions (cf. Figure 2C). This justified the use of single values for  $S_O$ ,  $S_C$ , and  $S_T$ , irrespective of experimental condition.

If and only if the first saccade does not arrive at the target location, one or more additional saccades are necessary to bring the eyes to the target location, as given by

$$E[S_r] = \alpha_i S_{O-T, j} + j(\beta - \beta \alpha_i) S_{C-T, i} \quad (1b)$$

Table 1 describes the parameters and observed values of this equation. First, note that in the onset-absent, valid-cue condition,  $\alpha_i$  and  $j$  are both 0, so  $S_r$  equals 0 ms. This is consistent with the observation that nearly all first saccades in this condition (see Figure 3) arrived at the target location, such that no additional saccades were necessary. Second, in the onset-present, valid-cue condition, Equation 1b is reduced to its left term (since  $j = 0$ ), which expresses that, on a proportion  $\alpha_i$  of the trials, a second

saccade is needed to bring the eyes from the onset to the target location. Third, in the onset-absent, invalid cue condition, Equation 1b reduces to  $E[S_r] = \beta S_{C-T, i}$  (because  $\alpha_0 = 0$ ), which expresses that, on a proportion  $\beta$  of the trials, a second saccade is needed to bring the eyes from the invalid cue to the target location. Finally, in the case of the onset-present, invalid-cue condition, we need the full expression of Equation 1b. Regarding this condition, two things are crucial to note. First, the proportion of trials on which more than one saccade is needed to bring the eyes to the target location is less than the sum of  $\alpha_1$  and  $\beta$ , because first saccades to the onset are proportionally deducted from first saccades to the cue, as discussed earlier. In particular, taking the observed values for  $\alpha_1$  and  $\beta$  of .17 and .60, respectively (see Table 1), the proportion of trials with more than one saccade is not .77, but  $(.17 + .60 - .60 \times .17 =) .67$ , which is in agreement with the observed proportion of .65 (i.e.,  $.17 + .48$ ; see Figure 3). Second, whereas in both the onset-absent, invalid-cue condition and in the onset-present, valid-cue condition, the eyes arrive at the target in maximally two saccades on all trials, in the onset-present, invalid-cue condition, three saccade trials occasionally occurred (see Figure 3). Because explicit modeling of these three-saccade trajectories would considerably increase the complexity of the model, we instead defined  $S_{O-T}$  and  $S_{C-T}$  as the average time needed by the eye to go from the onset or the cue to the target regardless of whether or not it also visited the other item in between. This was achieved by cross indexing these variables by the presence of the other condition, that is,  $S_{O-T}$  by  $j$  (cue validity) and  $S_{C-T}$  by  $i$  (onset presence).

When these contributions to  $S_r$  are considered jointly, it should be noted that they work in opposite directions. In the onset-present, invalid-cue condition, the proportion of multisaccade trials is less than the sum of  $\alpha_1$  and  $\beta$ , but once the eyes engage on a multi-saccade trajectory it takes relatively long to complete on average (in view of occasional three-trajectory saccades). To the extent that these contributions balance out, this would result in additive effects of onset presence and cue validity on manual mean RT.

The outcomes of the model are shown in the right panels of Figure 2. Clearly, the model captures the main characteristics of the data very well with root mean squared deviations between model and data amounting to 7.9, 4.2, and 6.9 ms, for the top, middle, and bottom panels, respectively. The Pearson correlation between observed and modeled data was over .99 in all cases. Note that the good fit of the model to the first saccade latencies (Figure 2C and 2C') provide substantial support for the mixture assump-

tion of the model. That is, mean first saccade latency to the combined cue/target in the valid cue condition can be well described as a weighted average of trials in which the saccade is driven by the cue and trials in which the saccade is driven by the target. In the Appendix, we provide further evidence for this assumption on the basis of the corresponding distribution of saccade latencies. Finally, it is important to note that the model reproduces the additive effects of onset presence and cue validity on manual mean RT (Figure 2A and 2A') very well. This shows that the just described opposing contributions to  $S_r$  indeed balanced out.

**Spatial Configuration of Display Elements**

Finally, we assessed if the proportion of first saccades that were directed to the onset differed depending on its positioning relative to the cue and target. Figure 5 shows the effects of the spatial configuration of the display elements on the distribution of saccades. The data sets for display configurations that could be regarded as mirror images or rotations of each other were pooled. Effects reported here were significant under correction for multiple tests ( $p < .01$ ), unless indicated otherwise. As the top row of

Figure 5 shows, the onset captured more saccades when it was positioned closer to the valid cue/target conglomerate than when it appeared further away. As a result, the cue/target conglomerate received reliably fewer saccades when the onset appeared close by compared to when it appeared further away.

A similar pattern was found for invalid cue trials. When the cue was presented opposite of the target location (Figure 5, middle row), the onset drew a larger proportion of saccades when it was closer to the cue than to the target. Consequently, the cue and target positions received fewer saccades when the onset was found closer to the cue than closer to the target, although these differences did not reach significance,  $t(13) = 1.3, p = .2$  for the target and  $t(13) = 2.00, p = .07$  for the cue.

For trials on which the cue was adjacent to the target (Figure 5, bottom rows) the effect of Onset was considered in relation to how far it was from the cue (near, far) and the target (near, far). Onsets appearing near the cue or the target (especially when appearing in between) received a larger proportion of saccades than those positioned far away from other items in the display. This increase in saccades to the onset resulted in a proportional decrease of saccades directed to cue and target.

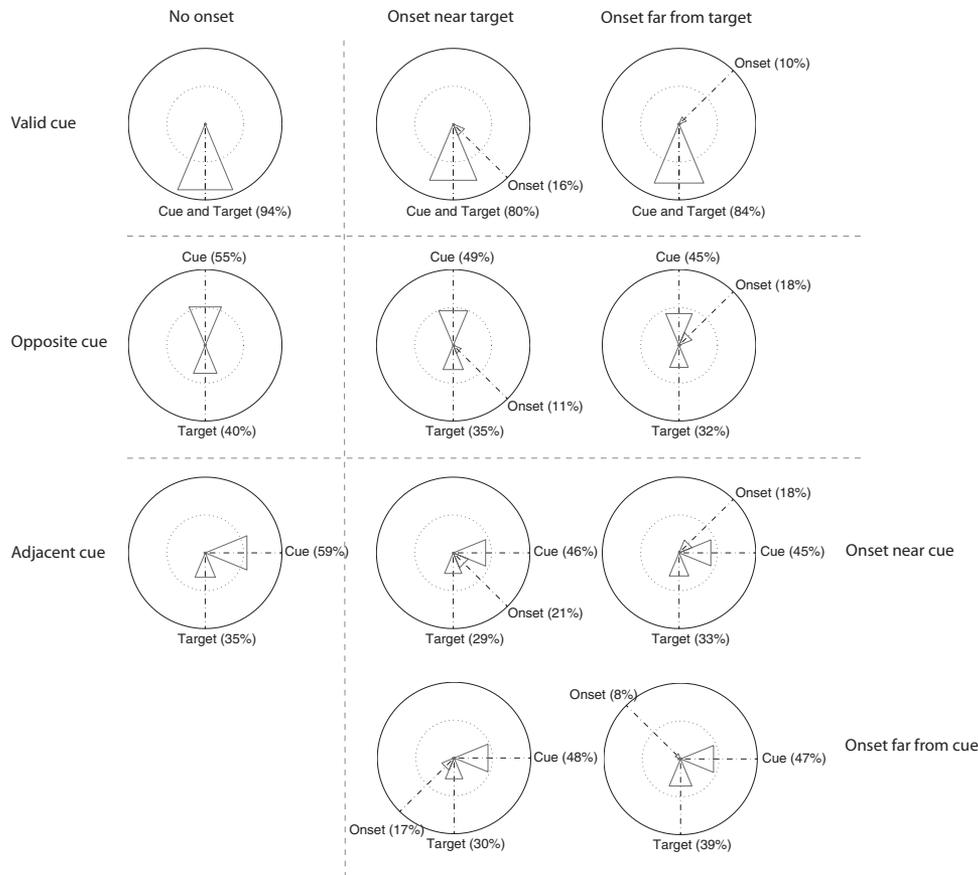


Figure 5. Relative proportions of the first saccades to the cue, target, or onset positions as a function of their spatial configuration. The data for symmetrical spatial display configurations (mirror images or rotations) were collapsed. In each plot, the dotted inner circle demarcates the 50% boundary and the outer solid circle the 100% one. Note that the displayed percentages do not add up to 100; the remaining (infrequent) first saccades went to locations other than target, cue, or onset.

## Discussion

The pattern of manual RTs in this study replicated previous demonstrations of interference by abrupt onsets within the contingent capture paradigm (Schreij et al., 2008, 2010a, 2010b). That is, although the observers looked for the red target (as indicated by a color cueing effect), responses were slowed by an onset distractor presented together with the target. The new insight offered by this study is that this RT slowing was almost entirely caused by those trials on which the eyes went to the onset location. It is particularly noteworthy that even when the first saccade went to the cue, the onset still managed to pull a considerable proportion of second saccades to its position, exerting further effects on manual RT. Taken together, this implies that the interfering effect of a suddenly appearing new object is to attract *spatial* attention to its location (Jonides & Yantis, 1988; Theeuwes, 1994; Yantis & Hillstrom, 1994), and as such, there is no need to evoke a non-spatial filtering mechanism to account for it (Folk & Remington, 1998). Similarly, even though the cueing effect was mostly driven by those trials in which the eyes (and thus, presumably attention) first went to the (invalid) color cue, the effect is also partly attributable to those trials in which the eyes were captured by the onset first, but shortly visited the location of the cue (that by that time had long been gone) before arriving at the target. Thus, although the occurrence of stimulus-driven and contingent capture seems reciprocal, both events can take place on subsequent saccades, within one and the same trial. This implies that both top-down attentional biases (leading to contingent capture) and bottom-up attentional signals (leading to stimulus-driven capture) were present simultaneously.

It is important to note again that we do not argue against the existence of contingent capture as such. Our data clearly show a bias toward targets and target-matching cues, in terms of RT validity effects as well as eye movements. In fact, and as would be expected, this bias is overall considerably stronger than the bias toward the task-irrelevant abrupt onsets. What we claim is that the extreme version of contingent capture theory, namely that attentional capture occurs only through top-down goals, and what appears to be bottom-up capture is merely a nonspatial side effect of filtering (Folk & Remington, 1998; Folk et al., 2009), does not hold. We conclude that contingent and noncontingent capture interact. Note that this conclusion cannot be reached by examining only mean manual RT. From Figure 2 (top panels) it appears that the effects of cue validity and onset are largely additive. This is the same pattern as reported for the manual responses in Schreij et al. (2008). At first sight, and as argued by Folk et al. (2009), such additivity appears to go against the idea that onsets capture spatial attention. Indeed, from the hypothesis that the cue and the onset both capture attention (and the eye) one would predict that the cueing effect in the onset present condition would be smaller than the cueing effect in the onset absent condition (i.e., an underadditive interaction between cue validity and onset presence). The reasoning would be as follows. First, one would expect a large cue-validity effect in the onset absent condition, reflecting that the target is reached in one saccade on nearly all trials in the valid-cue condition, but in two saccades on the majority of the trials in the invalid-cue condition. Second, when an onset is added, it attracts the eyes in a certain proportion of trials, thereby reducing the proportion of eye movements to the

cue. Thus, the emergence of the onset effect should result in a reduction of the cueing effect, culminating in an underadditive interaction.

Interestingly, this underadditive interaction hypothesis is exactly supported by our eye movement data when considering first saccade proportions. As Figure 3 shows, in the onset-present, invalid-cue condition, the proportion of trials directed to either the invalid cue or the onset ( $.48 + .17 = .65$ ) was less than the sum of these events in the onset-absent, invalid-cue condition and the onset-present, valid cue condition ( $.60 + .16 = .76$ ). However, this underadditive effect of onset presence and cue validity did not propagate to manual mean RT. The reason is that, whereas the eyes reached the target location in maximally two saccades on nearly all trials in both the onset-present, valid-cue condition and the onset-absent, invalid cue condition, they occasionally did so after only three saccades in the onset-present, invalid cue condition. These three-saccade trials contributed to lengthening the mean total saccadic movement time, thereby balancing the relatively low frequency of first saccades deflected from the target location. The net result was that onset presence and cue validity combined about additively on manual mean RT.

To further substantiate this conclusion, we adjusted our descriptive model to produce data in which three-saccade trajectories to the target are excluded. Recall that these trajectories were incorporated in the model by cross-indexing the saccade latency from onset to target ( $S_{O,T}$ ) by  $j$  (cue validity) and the saccade latency from cue to target ( $S_{C,T}$ ) by  $i$  (onset presence; cf. Equation 1b). In particular, the mean saccade latency was longer from onset to target in the invalid-cue condition (that included trials with three saccade trajectories via the invalid cue) than in the valid-cue condition. Similarly, mean saccade latency was longer from invalid cue to target in the onset-present condition (that included trials with three saccade trajectories via the onset) than in the onset absent condition. To exclude three-saccade trajectories, we abolished the cross-indexing. In particular, we set  $S_{O,T}$  to 178 ms,

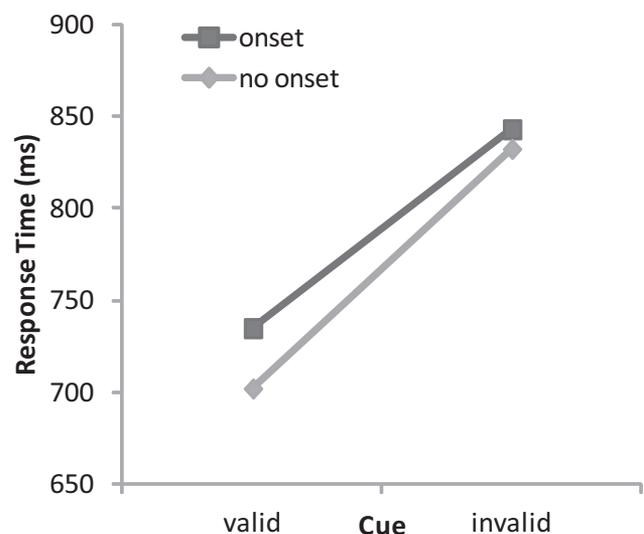


Figure 6. Model generated response times as a function of cue validity and onset presence obtained after exclusion of three-saccade trajectories to the target.

regardless of the value of  $j$  and we set  $S_{C,T}$  to 217 ms, regardless of the value of  $i$  (cf. Table 1). Adjusted this way, the model produced an underadditive interaction on mean RT, as shown in Figure 6. This analysis supports the conclusion that cue validity and onset presence have additive effects on mean RT, not because the onset fails to capture attention (Folk et al., 1992, 2009), but because the onset captures attention even *after* attention had initially been captured by the invalid cue. Note that this also precludes the argument that observers are only captured by the onset when they have a lapse in volitional attentional control (Leber, 2010; Leber & Egeth, 2006). On these trials observers go to the red precue, thus demonstrating the activation of the task set.

Further evidence for the interplay of contingent and stimulus-driven capture comes from analyses of saccade direction as a function of display lay-out. Figure 5 shows that an onset tended to elicit involuntary saccades when it was presented close to the cue/target rather than far away from it. This shows that the onset causes spatially specific interactions with (task-relevant) competing objects, consistent with the notion of biased competition (Desimone & Duncan, 1995). According to this theory, two objects that are positioned close together fall within the same receptive field and therefore compete more strongly for representation than objects that fall in distinct receptive fields (also see Mathot, Hickey, & Theeuwes, 2010). This notion is also consistent with reports that responses are facilitated when the target and onset location happen to coincide (Schreij et al., 2010a, 2010b), as in this case there is only one object whose signal is boosted by both its bottom-up (onset) and top-down (the red target letter) properties, while it has no competition from other objects.

Furthermore, it seems appropriate to point out the merits and limitations of the descriptive model that we developed in this study. The main limitation is that, by its nature, the model does not attempt to explain top-down and bottom-up influences on eye movement behavior from principled theoretical assumptions about mental states. It is conceivable that a theoretical model can be developed that accounts for the present findings in a more efficient way, requiring less free parameters. However, the large number of free parameters that was required in our descriptive model should not be considered problematic, because the values of these parameters were all strictly constrained by the observations. That is, all free parameters were fixed a priori and none of them was adjusted in the process of generating the predictions of the model. Consequently, the obtained good fit of the model to the data indicates that, despite several simplifying assumptions (e.g., ignoring the spatial layout of the display; omitting highly infrequent trajectories), the model represents the most important sources of variance. Stated more simply, the model yields a fairly accurate description of what actually happened.

Modest as this accomplishment may seem, it perfectly serves our purpose of making transparent how onset presence and cue validity jointly influence eye movement behavior, the presumed underlying attentional orienting, and the ensuing manual RT. Indeed, the model not only provides clear insight in how an additive relationship between the experimental factors on RT was obtained in the present study, but also allows the specification of circumstances under which this additive relationship might turn into an underadditive one. In particular, if experimental conditions can be created that block the occurrence of three-saccade trajectories in the onset-present, invalid-cue condition, the model predicts an

underadditive relationship (see Figure 6); a prediction now under scrutiny in our lab. Another interesting result that our model revealed is related to its sole theoretical assumption that the set of first saccades to the target location in the valid-cue condition is a mixture of fast saccades driven by the cue and slow saccades driven by the target. Consistent with this assumption, the latency of the first saccade to the combined cue/target in the valid-cue condition, could be very well described by a weighted average of first saccade latencies to the target and the cue in the invalid-cue condition (cf. Figure 2C and 2C'; see also the Appendix). Finally, the descriptive model holds promise as a possible theoretical model of contingent capture paradigms where eye movements are prohibited. The guiding idea here is that the eye movements observed in the present study may mimic the movement of covert spatial attention when the eyes are voluntarily prevented from moving.

The eye-movement pattern found in the current study may also shed more light on findings of other studies that have looked into the joint effects of exogenous and endogenous attention. Like us, Juola et al. (1995) and Berger et al. (2005) both found an additive relationship between top-down and bottom-up effects of orienting on mean manual RTs. Both studies pitted endogenous cues (e.g., central arrows) against exogenous cues (e.g., flashes in the periphery), and examined the combined effects of their validity. Both studies reported additive effects, suggesting that endogenous and exogenous cueing effects can exist alongside each other without any mutual modulation. This led both Juola et al. and Berger et al. to conclude that endogenous and exogenous processes operate independently on the control of attention. However, in light of the current findings, it is possible that the effectiveness of either cue type varied on a per trial basis: in one trial the endogenous cue may have led attention, while in the other attention was drawn to the exogenous cue. As with our data, the additive pattern in manual RTs between these effects may be a result of the averaging process over these conditions.

What are the relative contributions of endogenous and exogenous influences on selection here, and how do they interact? The conclusion that onsets capture attention *despite* an attentional set for color relies on the premise that both endogenous and exogenous mechanisms were in operation simultaneously. Virtually any model of attention would allow for such simultaneous biases (TVA of Bundesen, 1987; Biased competition of Desimone & Duncan, 1995; Itti & Koch, 2001; Guided search of Wolfe, 1994). Capture then occurs when the exogenous signal is, if only occasionally, strong enough to outweigh the top-down control signal. This could be because of trial-to-trial fluctuations in the strength of the bottom-up representation, but it could also be because of trial-to-trial fluctuations in the strength of the attentional set. Note that the latter possibility leaves us with a way to save the stronger version of the contingent capture account, which states there is only selection of objects that match the attentional set. It is possible that on some trials the task set fails to exert strong attentional control, because observers have refrained from preparing it. Leber (2010) has indeed provided evidence for the existence of such oscillations in the degree of one's volitional control over attention. It could be that a weakly instantiated attentional set would allow abrupt onsets to take control of the selection process. In our experiment, this would amount to at least 16% of the trials (discarding potential covert shifts). However, there is one aspect of our data that goes

against such a completely independent and alternating scheme of endogenous and exogenous selection across trials: Even on those trials in which the eyes went to the invalid red cue (thus providing good evidence that these were trials on which observers were looking for red) there was still a highly reliable effect of the abrupt onset. In particular, from the invalid cue, the eyes were captured by the onset on no less than 15% of the trials, thereby inflicting a 24 ms delay on average on manual RT relative to the onset absent condition. A similar pattern is observed for saccades going to the cue, after having initially been attracted by the onset. Such patterns suggest that both the strength of target representation and the bottom-up signal of the onset waver *within* the period of a trial and that the degree in which either target-relevant items or the onset are able to attract attention varies from moment to moment.

The notion that the bottom-up and top-down components of attention operate on a single orienting mechanism has been suggested before by Itti and Koch (2001). Their *priority map* model assumes that all objects or features perceived in a scene provide input to an activation map, which topographically codes for local potential areas of interest over the entire visual scene. Spatial attention uses this information to determine which area it needs to inspect next. The relative activation associated with an object or feature on this map is an accumulation of the activation caused by the object's salience (the bottom-up component) and its current relevance to the observer (the top-down component). For instance, if an observer is looking for a tomato, the signals of all objects possessing features similar to that of the tomato, such as its red color, are boosted on the activation map. If this tomato is furthermore only surrounded by yellow lemons, making its red color very conspicuous, the signal it creates will be even stronger. Objects that have the highest accumulated activation are inspected by attention first, followed by the object with the second-highest activation, and so on. Importantly, only one object is inspected at the time, and its selection is determined by the joint contribution of the bottom-up and top-down components to the priority map. This is in accordance with our findings, in the sense that if the observer's attentional set is strong enough to boost the task-relevant feature (in this case red) and thereby overcomes any competition by salient distracting items like the onset, attention goes straight to the target or the cue. On other trials in which this top-down boost for the red items is insufficient, the bottom-up saliency of the onset causes the largest activation, winning attention to its location.

In conclusion, the current study demonstrates that both abrupt onset stimuli and contingent distractor stimuli capture attention involuntarily and that their effects interact through their influence on a common spatial orienting mechanism. Although this interaction may not be seen when measuring only mean manual RT, it is very prominent in direct measurements of eye movements. These data show that at a first approximation, only one type of capture occurs on any given trial; either spatial attention is captured by the abrupt onset or it is captured by the color cue. Closer inspection revealed that either of these items is still capable of capturing the second saccade after the other item captured the initial saccade. Thus, the occurrence of one type of capture does not rule out the other type to occur subsequently. In fact, both our data and model analysis show that the occurrence of these second saccades are for a large degree responsible for the additive pattern observed in manual RT. Most importantly for the theoretical debate over the mechanisms underlying these two forms of capture, the present

data show that both forms of capture involve involuntary *spatial* reorienting.

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(Appendix follows)

## Appendix

## Distributional Analysis of First Saccade Latencies

The sole theoretical assumption of our descriptive model is that, in the valid-cue condition, the set of first saccades to the combined cue/target is a mixture of fast saccades driven by the cue and slow saccades driven by the target. This mixture property was supported by the finding that the mean first saccade latency to the combined cue/target could be well described by a weighted average of the mean first saccade latencies to the target and the invalid cue in the invalid-cue condition (cf. Figure 2C and 2C'). To provide a more detailed test of the mixture property, we examined whether a similar relationship applies to the distribution of saccade latencies. To this end, we computed cumulative density functions (CDFs) of the latencies of first saccades directed to the cue/target in the valid-cue condition and to the cue, target, and cue or target in the invalid-cue condition. First, we rank-ordered the raw first saccade latencies for each condition, saccade direction (to the cue, target, or cue/target), and participant. We subsequently divided the ordered saccade latencies in deciles (i.e., 10% bins), and calculated the mean saccade latency for each decile. Finally, we averaged corresponding deciles across participants (i.e., Vincent averaging; Ratcliff, 1979).

Figure A1 shows the resulting CDFs<sup>1</sup>. For the invalid-cue condition, the figure shows three CDFs (solid lines): one for first saccades to the cue (left-most CDF), a second one for first saccades to the target (right-most CDF) and a third one for first saccades to either the invalid cue or the target (i.e., based on the union of the saccade latencies composing the first two CDFs). The third CDF is obviously a mixture of the first two CDFs, with a mixture ratio corresponding to  $\beta$ , that is, the proportion of first saccades to the invalid cue (.60 in the present experiment). In the valid-cue condition, the CDF of first saccade latencies to the combined cue/target is very similar to the mixture CDF in the invalid-cue condition. Overlap is nearly perfect at the extreme ends of the CDFs, which is a strong indication that the set of saccades in the valid-cue condition is also a mixture of fast saccades driven by the cue and slow saccades driven by the target (Dixon, 2012; Yantis, Meyer, & Smith, 1991). The CDFs only diverge in their middle segments, where the deciles in the valid-cue condition were slightly shifted to the left compared with those of the invalid-cue condition. One plausible reason for this divergence is that saccades to the target may benefit from preprogramming by the cue in the valid-cue condition, but not in the invalid-

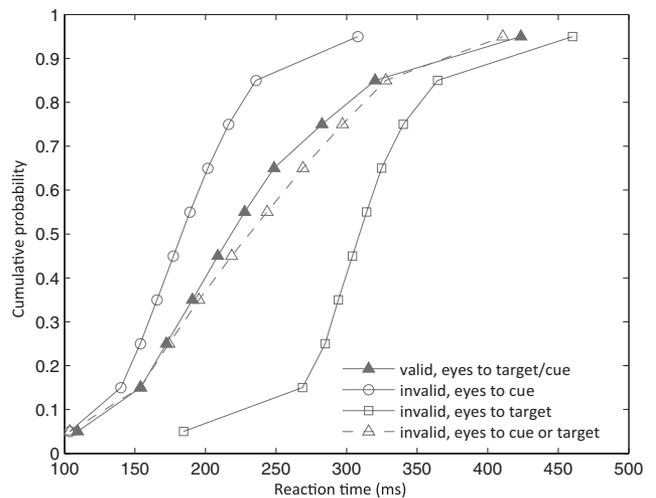


Figure A1. Vincitized cumulative density functions of latencies of first saccades to the combined cue/target in the valid-cue condition and to the cue, target, and cue or target in the invalid-cue condition.

cue condition (e.g., Klein, 2000). Although this possible contribution is interesting and worthy of further exploration, we decided not to incorporate it in the descriptive model, because it explains little variance over and above the variance explained by the mixture itself.

In conclusion, both mean saccade latencies (Figure 2C and 2C') and corresponding latency distributions (Figure A1) strongly support our theoretical assumption that, in the valid-cue condition, the set of first saccades to the cue/target is a mixture of fast first saccades driven by the cue and slow first saccades driven by the target.

<sup>1</sup> The influence of onset presence on the reported distributions was negligible, so we collapsed across the onset present and onset absent conditions.

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