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Oculomotor Capture by New and Unannounced Color Singletons during Visual Search

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Abstract The surprise capture hypothesis states that a stimulus will capture attention to the extent that it is preattentively available and deviates from task-expectancies. Interestingly, it has been noted by Horstmann (Psychological Science 13: 499–505. doi:10.1111/1467-9280.00488, 2002, Human Perception and Performance 31: 1039–1060. doi:10.1037/00961523.31.5.1039, 2005, Psychological Research, 70, 13-25, 2006) that the time course of capture by such classes of stimuli appears distinct from that of capture by expected stimuli. Specifically, attention shifts to an unexpected stimulus are delayed relative to an expected stimulus (*delayed onset account*). Across two experiments, we investigated this claim under conditions of unguided (Exp. 1) and guided (Exp. 2) search using eye-movements as the primary index of attentional selection. In both experiments, we found strong evidence of surprise capture for the first presentation of an unannounced color singleton. However, in both experiments the pattern of eye-movements was not consistent with a delayed onset account of attention capture. Rather, we observed costs associated with the unexpected stimulus only once the target had been selected. We propose an interference account of surprise capture to explain our data and argue that this account also can explain existing patterns of data in the literature.

Keywords Selective attention · Attentional capture · Eye movements · Visual attention

As we peer out at the world, a surplus of visual input hits the retina and feeds through to early visual areas, yet much of this information fails to reach our conscious awareness. This is the result of a cognitive system that is severely capacity-limited and can process only a subset of the visual input from a given scene at any one point in time. To compensate, mechanisms of selective attention allow us to prioritise the processing of a restricted number of events or objects in the visual world. Consequently, our conscious experience of the world is constructed primarily of visual input originating from information to which we have attended. How these selection mechanisms are controlled and the criteria by which (visual) input is selected for further processing versus input that is "discarded" earlier in the processing hierarchy has important consequences for how we interact with our environment. The decision of whether to attend to information that is relevant to our immediate goals or to prioritise signals that might be unexpected and signal a threat is one we often face. Thus, understanding what determines the events in the visual world to which we orient and attend has been a question of principal interest and importance to researchers in the field of cognitive psychology for decades.

Models of attentional guidance distinguish between two forms of attentional control: e*ndogenous* control, which is the ability to voluntarily allocate cognitive resources to processing task-relevant information, and *exogenous* control, which directs attention involuntarily towards signals of potential importance—but not necessarily task-relevance—in the environment (Jonides & Yantis, 1988; Posner, 1980; Remington, Johnston, & Yantis, 1992; Theeuwes, 1991; Yantis & Jonides, 1984). Understanding the stimulus conditions to which the exogenous attentional system is sensitive has been a topic of much debate. Specifically, research has focused on understanding the extent to which exogenous shifts of attention are governed by bottom-up factors, namely

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stimulus saliency versus the extent to which they are modulated by top-down processes. Proponents of bottom-up models of attentional guidance argue that the exogenous attentional system responds automatically to salient stimuli irrespective of top-down input. Under these models, modulation of attention by top-down processes is thought to occur late in processing, only after attention has initially been deployed towards the stimulus with the highest saliency value ("de-allocation hypothesis"; see Belopolsky, Schreij & Theeuwes, 2010; van Zoest, Donk, & Theeuwes, 2004). Conversely, according to top-down models of attentional guidance, such as the *Contingent Capture hypothesis*, shifts of attention are contingent on the goals of the observer. That is, a salient stimulus will only capture attention to the extent that it shares characteristics with the target of search (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). In their seminal paper, Folk, Remington & Johnston (1992) showed that a salient distractor presented immediately before the target in a spatial cueing paradigm produced differential effects according to its relationship with the target being searched for. When the target of search was a color singleton only matching-color distractors and *not* abrupt onset distractors had an effect on search performance. The opposite was true when the target of search was an abrupt onset. This result demonstrates that attention can be tuned to certain stimulus properties and that only those stimuli that share the defining features of the target will capture attention, seemingly irrespective of stimulus saliency. Subsequent research has explored this tuning mechanism across and within a range of stimulus dimensions. Greater capture by target-similar than target-dissimilar distractors has now been shown within the color dimension (Folk & Remington, 1998), as well as for onsets (Ludwig & Gilchrist, 2002), for size (Becker, 2010) and with a number of dependent measures (e.g., eye-movements: Becker, Ansorge & Horstmann, 2009; Ludwig & Gilchrist, 2002; Wu & Remington, 2003; EEG: Eimer, Kiss, Press & Sauter, 2009; Lien, Ruthruff, Goodin, & Remington, 2008; Wykowska & Schuboe, 2009).

The fact that top-down selection mechanisms can act, in a sense, as a filter to counteract effects of bottom-up saliency raises the question of how we become aware of stimuli that are not directly relevant to our immediate tasks and/or goals. A commonality across almost all the research that informs the debate over attentional control is that distractors in these paradigms are presented repeatedly and frequently throughout the experiments, and thus, presumably contribute, and importantly, conform to task expectancies that develop over the course of an experiment (Gibson & Jiang, 1998). It is possible then that the top-down control of attention is limited to stimuli that conform to these task expectancies and that task expectancies themselves may in fact play a role in determining how spatial attention is allocated throughout a scene. Indeed, the notion that unexpected and novel events in the world demand the resources of our perceptual system is consistent with early theoretical accounts of orienting and surprise. According to Sokolov (1963a, b) *Orienting Reflex*, a stimulus will elicit a reflexive orienting response to the extent that it violates expectations and generates a sufficient mismatch between the input from the environment and the established neuronal model or schema. Over-repeated expose to a novel stimulus the neuronal model is updated, consequently reducing the stimulus' propensity to elicit an orienting response. The role of expectations in determining that which we come to attend to also is emphasized by schema-based theories of perception and cognition (Meyer, Niepel, Rudolph & Schűtzwohl, 1991; Neisser, 1976; Rumelhart, 1984; Rumelhart, Smolensky, McClelland, & Hinton, 1986)

Theoretical models of surprise and the unexpected are supported by experimental work demonstrating a number of physiological and cognitive changes in response to new and unexpected stimuli in the environment (Asplund, Todd, Snyder, Gilbert & Marois, 2010; Burra & Kerzel, 2013; Geyer, Müller & Krummenacher, 2008; Gronau, Sequerra, Cohen & Ben-Shakhar, 2006; Horstmann, 2002, 2005, 2006; Horstmann & Becker, 2008; Becker & Horstmann, 2011; Meyer, Niepel, Rudolph & Schutzwohl, 1991; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Sayim, Grubert, Herzog & Krummenacher, 2010). Meyer et al. (1991) tested surprise experimentally by having participants respond to the location of a dot that appeared briefly (0.1 secs) either above or below two vertically arranged words. In the experimental group, the words were present for the first 29 trials as black against a white background. On the 30th trial, the color of one of the words and its background was inverted (white letters on a black background). In the control condition, the experimental procedure was identical except that there was no inversion of the colors on the 30th trial. Participants were probed on their experience of the "surprising" trial with a series of questions. Notably, recall for the surprising word was significantly better in the experimental condition than in the control condition suggesting that the novel stimulus was attended to. In addition, RTs to the dot on the surprise trial were elevated relative to the control and pre-surprise trials. Meyer et al. (1991) argued that elevated RTs on the surprise trial reflected the recruitment of additional processing resources used for reconciling the discrepancy between the expected and the actual input that is generated by attending to a novel stimulus.

Further evidence that task expectancies can modulate shifts of spatial attention specifically comes from the *surprise capture* (Horstmann, 2002, 2005) literature. Horstmann (2005) had observers search for the letter L or R in a circular array of 4 or 12 (varied between subjects) different letters. After a series of expectation congruent trials, the target letter was unexpectedly presented in a different colour (e.g., red, among all-grey items). The logic of the design is as follows: if the target fails to capture attention then a serial search for the target must ensue and thus search latency will be *dependent* on the set size; as the set size increases it takes on average longer to locate the target, resulting in a steep RT x set size function. Alternatively, if the target captures attention then search latencies should be *independent* of set size, which ought to result in a flat RT x set size function. Critically though, RT delays that are due to decision-level processes ought to be constant across set sizes and should not change the relationship between search efficiency and set size. Consistent with attentional capture, Horstmann (2005) found that RTs on the surprise trial were in fact independent of the number of nontargets (3 or 11). Given that observers had no prior knowledge of the unexpected color singleton, capture in this instance was, by definition, independent of any top-down attentional set for the unexpected item and therefore is difficult to reconcile with strictly top-down models of attentional guidance.

Interestingly, Horstmann (2002, 2005, 2006) has noted that the temporal profile of capture by unexpected stimuli appears distinct from top-down mediated capture and reports of salience based capture in the absence of top-down filtering. In a test of the *surprise capture* hypothesis, Gibson and Jiang (1998) failed to find an effect of an unexpected color singleton when it was presented for 86 ms and onset with the target display. A critical difference between the Gibson and Jiang (1998) and Meyer et al. (1991) paradigms—noted by Horstmann (2002)—is the presentation duration of the surprising stimulus. Meyer et al. (1991) presented the surprising stimulus for 500 ms before the onset of the target while the surprising stimulus was presented for only 86 ms and onset with the target in the Gibson and Jiang (1998) experiments. Horstmann (2002) proposed that the orienting component of a surprise response might be slowed by additional processing that occurs in response to surprising stimuli and that the absence of a surprise effect reported by Gibson and Jiang (1998) was due to the insensitivity of their measure. That is, the presentation duration of the surprising stimulus was too brief for a surprise response to be observed. Indeed, using the same paradigm as Gibson and Jiang (1998), Horstmann (2002) found that when the surprising stimulus appeared 500 ms before the onset of the target display, response accuracy was significantly improved on the surprise trial relative to pre-surprise trials—a pattern of results indicative of attentional capture by the surprising color singleton. Subsequent research into the temporal profile of surprise capture suggests that it takes *at least* 200 ms to manifest with pronounced effects observed 400 ms post the surprise stimulus onset (Horstmann, 2006). That is, surprise capture appears to manifest slowly. Critically, the time course of surprise capture has been attributed, in part, to a delay in the *onset* of the attention shift; this delay has been used to argue for distinct underlying mechanisms of control for expected and unexpected events (Horstmann, 2005, 2006). Gronau et al. (2006) have argued for a similar distinction between unexpected and task-relevant stimuli.

The present series of experiments

In the following paper, we used eye-movements to further investigate this apparent onset latency differential between capture by expected and unexpected events. To date, much of the work on surprise capture has quantified the effect using RTs and response accuracy; this includes the work suggesting its delayed onset. Disentangling the separate components of surprise using these methods is difficult though due the fact that RTs and response accuracy can be affected by decision and response level processes that are unrelated to search performance—a limitation that is of particular relevance in the study of surprise. More recently, research into attentional guidance has made use of the well-documented coupling between eye-movements and attention shifts and used eye-movements as an index of attentional capture. Although attentional selection does not always result in the execution of an eye-movement (Juan, Shorter-Jacobi, & Schall, 2004; Wu & Remington, 2003), eye-movements are preceded by shifts of attention (Deubel & Schneider, 1996; Peterson, Kramer, & Irwin, 2004). Using eye-movements to measure search performance can provide insight into the spatial and temporal aspects of visual search that other measures, such as RT and response accuracy are less sensitive to. As such, we used eye-movements to investigate the temporal profile of surprise capture.

Experiment 1

The aim of Experiment 1 was to assess whether and to what extent surprise-induced delays occur before shifting attention or the gaze to the target, and after selection of the target. As such, the design of Experiment 1 was similar to Horstmann (2002 exp. 3, 2005 exp. 1) with the exception of the set size manipulation. Because eye-movements may offer a more direct measure of how attention is allocated during search it was not necessary to manipulate set size here. Otherwise, the design was conceptually similar to previous studies: the experiments consisted of a single block that was subdivided into three phases; a precritical, a critical (surprise trial), and a postcritical phase. All three phases involved a visual search task in which participants were required to report the identity of a target letter (H or U) embedded amongst a circular array of heterogeneous non-target letters (difficult search). The critical and postcritical trials were identical to the precritical trials with the exception that a color singleton (surprise stimulus in the case of the critical trial) was presented at the target location. The colour singleton was always presented at the target location to allow us to measure the contributions of early and late processes to the RT delay that characterises surprise (without interference from further eye movements that would be required if the colour singleton were presented at a distractor location).

The predictions were as follows: first, if the unexpected color singleton induces a surprise response we should see an increase in RTs on the critical trial relative to the post critical trials. Second, if the unexpected color singleton attracts the gaze then we should see a reduction in the number of saccades to find the target on the critical trial relative to the precritical. Furthermore, we should observe a shift in the distribution of first saccades that go to the target on the critical trial compared with the precritical trials. Finally, if the slow time course of surprise capture is the result of a delay in the *orienting* component (early stage), then we should expect to see evidence of this in the *saccade latencies* on the surprise trial (i.e., the time from the onset of the search display to the start of the saccade). Specifically, saccade latencies of the first saccade should be longer on the critical trial relative to the post-critical trials where the color singleton should guide search but is no longer unexpected.

Method

Participants

Twenty-four participants (15 females) from Bielefeld University participated for course credit.[1] All reported normal or corrected to normal vision.

Apparatus

Experiment 1 was conducted using the computer software package Presentation (Neurobehavioural Systems). Stimuli were presented on a 19-inch CRT monitor attached to a (Pentium 4) personal computer. Stimuli were presented with a resolution of 1280 * 1024 pixels and a refresh rate of 75 Hz. Responses were recorded using a two-button mouse. Participants' eye-movements were measured using a video-based infrared eye-tracking system (Eyelink 1000, SR Research, Ontario, Canada) with a spatial resolution of 0.1 and a temporal resolution of 500 Hz.

Stimuli

Each trial consisted of a fixation display and a target display. The fixation display was comprised of a central fixation cross which subtended 0.3^{o} of visual angle. The target display consisted of 8 grey disks (RGB = 150) presented on an imaginary circle equidistant – radius = 10 ^{o} of visual angle - from the central fixation cross. Each disk subtended 2.9^{o} × 2.9^{o} of visual angle and contained one of eight letters. The target letters were H and U and the nontarget letters were C, E, F, L, O, P, and S. Letter stimuli subtended ~0.7^{o} of visual angle vertically 0.4^{o} of vials angle horizontally. All stimuli were presented against a white background and at a viewing distance of approximately 60 cm.

Design and Procedure

Participants completed 24 practice trials followed by 49 experimental trials. The experimental trials were divided in 24 precritical trials, 1 critical trial (surprise trial) and 24 postcritical trials but flowed continuously from one phase to the other. On the critical the otherwise grey disk at the target location was presented as red. The postcritical trials were identical to the critical trial with the target appearing at the position of the red singleton. Practice trials were excluded from all analyses.

Each trial began with the onset of a central fixation cross for 500 ms. This was followed by the target, which remained on the screen for a maximum of 3000 ms or until a response was made (Fig. 1). Participants' task was to search for the target and report its identity with a mouse click: left click for U and right click for H. The identity of the target and its location were randomised across trials with each target occurring equally often at each location. The locations of the seven nontargets also were randomised across trials. Participants were instructed that they could move their eyes to search and to respond as quickly and as accurately as possible. Following a response, participants were given feedback as to whether they were correct or not: correct or incorrect, respectively.

Results

Mean RTs for Experiment 1 are shown in Fig. 2. RTs exceeding 4000 ms and errors were excluded from RT and eye-movement and analyses. This criteria lead to a loss of 4.25 % of trials. Averages for the pre- and postcritical trials across all measures were computed over the 5 trials that preceded and succeeded the critical trial, respectively. All contrasts involving performance on the critical trial (RTs & eye-movements) were computed using these averages. This was done in an attempt to reduce noise in our estimates of performance on the pre- and postcritical trials. Eye movements were

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[1] In Experiment 1 we initially collected data from 12 participants. On inspection of the data, we noticed that the small delay in saccadic latencies (~40 ms) that we report appeared to be specific to participants who made only 1 saccade on the critical trial (8/12). In keeping with sound statistical practice, we collected data from another 12 participants to determine whether the trend observed in the original sample of participants might be a real effect. Although the effect was again present in the second sample of 12 participants, the effect did not reach significance. We report the interaction between the number of fixations and saccadic latencies as a trend in the manuscript. The same trend was not present in the data for Experiment 2.

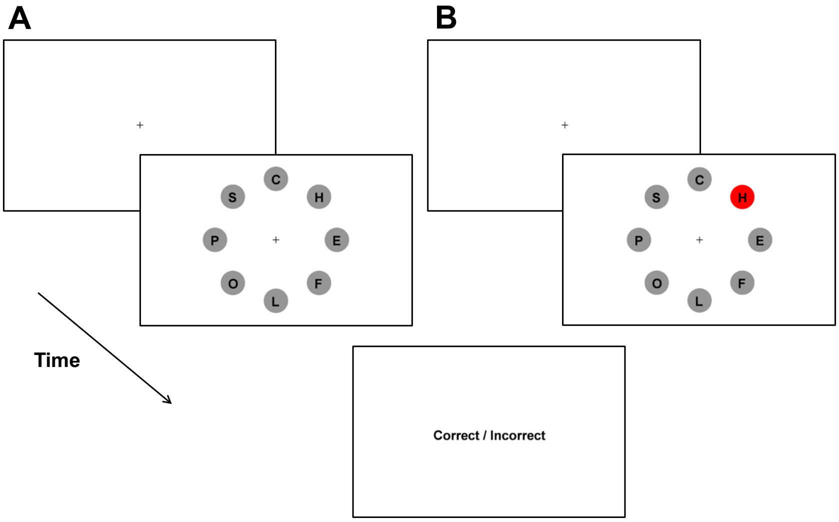

Fig. 1 Example trial sequences from Experiment 1. A Precritical trial. B Critical and postcritical trial. The location of target and non-targets was randomised on each trial. The red color singleton always appeared at the location of the target (H/U). The search display was presented for 3000 ms or until a response was made

parsed into saccades, fixations, and blinks using the standard parser configuration of the Eyelink software, which classifies an eye movement as a saccade when it exceeds a velocity of 30°/s or an acceleration of 8000°/s. The first eye movement on a trial was assigned to the target, a nontarget or the distractor if the gaze was within 100 pixels (1.0°) of the centre of the search item.

RT analysis

To test for an effect of the unexpected color singleton, we first contrast RTs on the critical trial with RTs on the precritical and postcritical trials. Planned pairwise comparisons revealed no RT difference between precritical trials and the critical trial, $t(23) = 0.74$, $p = 0.47$. Conversely, RTs on the critical trial were significantly slower than RTs on the postcritical trials, $t(23) = -5.79$, $p < 0.001$. As shown in Fig. 2, the RT delay for the critical trial was quite substantial (>300 ms), consistent with previous reports (e.g., Horstmann, 2005).

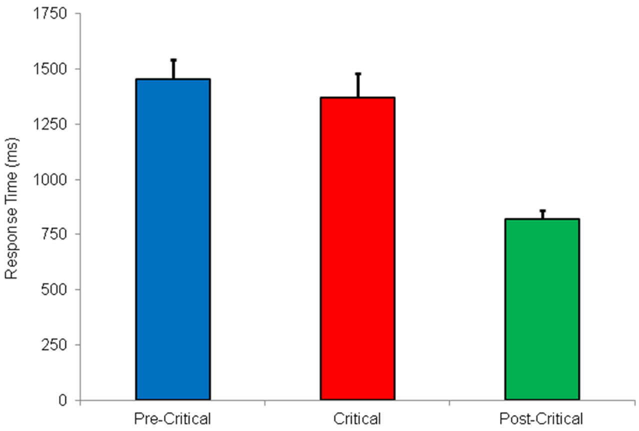

Fig. 2 Mean response times for the precritical, critical, and postcritical trials from Experiment 1. Error bars depict one standard error of the mean

Eye-movement analyses

To assess whether the unexpected color singleton attracted attention and the gaze, we compare the average number of fixations on the critical trials to that on the pre- and postcritical trials. A planned pairwise comparison between the critical and precritical trials revealed a significant difference such that there were *fewer* fixations on the critical trial than on the precritical trials, $t(23) = 3.17$, $p = 0.004$, consistent with the surprise capture view. Due to the lack of variability in the number of fixations on the postcritical trials (i.e., floor effects), a comparison between the critical trial and the postcritical trials was performed using a Wilcoxon's signed-rank test. This test revealed there to be significantly *more* fixations on the critical trial than on the postcritical trials, $Z = -3.53$, $p < 0.001$ (Fig. 3). It is worth noting that this difference appears to be driven by the fact that a number of participants did not execute a saccade on a small proportion of the postcritical trials. This explains why the mean number of fixations for the postcritical trials below one. Sixteen of the 24 participants saccaded in the first instance to the color singleton on the critical trial—a pattern indicative of attentional selection (Fig. 4).

In addition to analyzing the number of fixations on the critical trial, we looked at the percentage of first fixations that went to the target on the precritical, critical, and postcritical trials. As is shown in Fig. 5, 14.9 % of first fixations went to the target location during the precritical trials. In contrast, 66.7 % of first fixations went to the target location on the

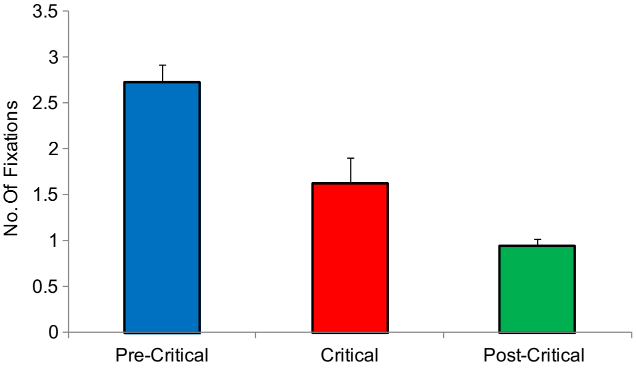

Fig. 3 Mean number of fixations per trial for the precritical, critical, and postcritical trials from Experiment 1. Error bars depict one standard error of the mean

critical trial. Wilcoxon's signed-rank test revealed this difference to be statistically significant, Z = 3.57, $p < 0.001$.

To test for delays in orienting associated with the unexpected color singleton we looked saccadic latencies (i.e., the time taken for the eyes to leave the central fixation region following the onset of the search display) on the critical trial relative to the pre- and postcritical trials. Planned comparisons revealed a significant difference between the critical trial and the *postcritical* trials such that saccade latencies on the critical trial were significantly *longer* (~40 ms) than saccade latencies on the postcritical trials, $t(23) = -3.57$, $p = 0.002$ (Fig. 6). We explored this effect further as a function of the number of fixations to test whether this effect was specific to observers who saccaded in the first instance to the unexpected color singleton. Saccade latencies for participants who made only one saccade on the critical trial were compared to saccade latencies for participants who made 2 or more saccades. Although the interaction was nonsignificant ($p = 0.12$), the pattern of results suggest that the effect of saccade latencies reported above was largely driven by participants who made only one saccade on the critical trial. This pattern is illustrated in Fig. 7 and Table 1. There was no difference in saccade latencies between the precritical trials and the critical trial, $p = -0.60$.

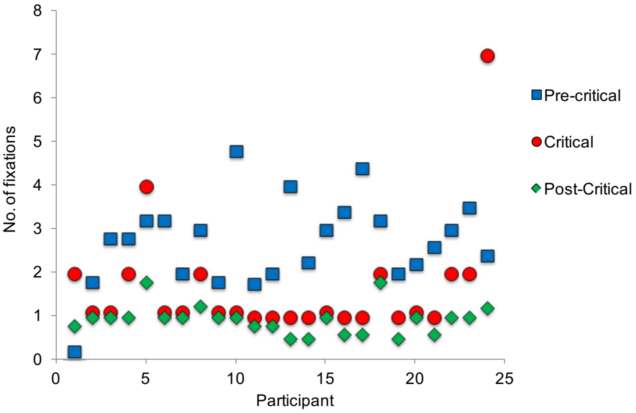

Fig. 4 Number of fixations for the precritical, critical, and postcritical trials for all 24 participants from Experiment 1. Note that the data have been jittered where they would otherwise overlap

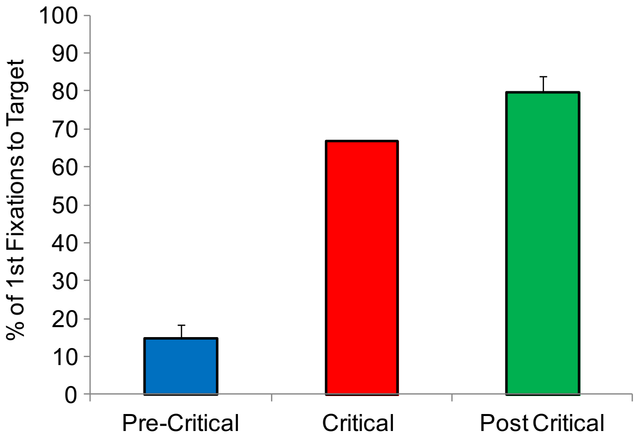

Fig. 5 The percentage of first fixations that went to the target location on the precritical, critical, and postcritical trials. Error bars depict one standard error of the mean. There is no error bar for the critical condition as participants either saccaded to the color singleton or did not

Finally, to estimate the contributions of postselection processes (i.e., decision and response level processes) to the large RT delay on the critical trial, we computed the duration between selecting the target with the eyes and executing a response to the target for each participant. We refer to this residual as the post selection duration (PSD); these data are plotted in Fig. 8. Planned comparisons revealed that the PSD on the critical trial (777 ms) was significantly longer than the PSD on both the precritical trials (523 ms), $t(22) = 4.28$, $p < 0.001$ and the postcritical trials (476 ms), $t(23) = 4.73$, $p < 0.001$.

Discussion

The results of Experiment 1 demonstrate that the new and unannounced color singleton induced surprise on its first presentation. Consistent with previous demonstrations of

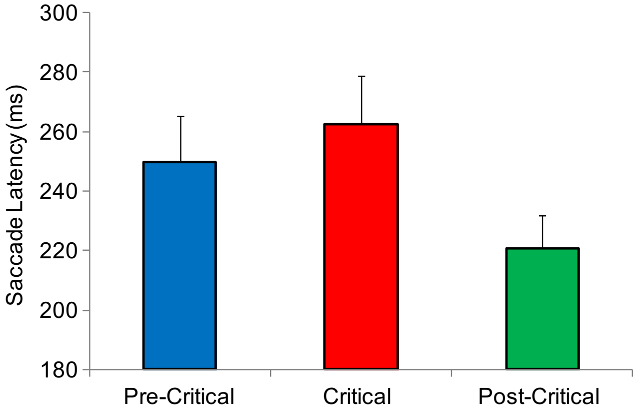

Fig. 6 Saccade latencies for the precritical, critical, and postcritical trials. Error bars depict one standard error of the mean

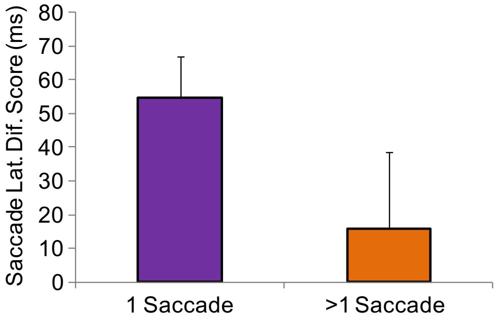

Fig. 7 Difference in saccade latencies between the critical trial and postcritical trials as a function of the number of fixations on the critical trial. Positive values reflect a slowing of saccade latencies on the critical trial relative to the postcritical trials. Error bars depict one standard error of the mean

surprise, RTs on the critical trial were elevated relative to the postcritical trials despite these trial types being identical with respect to their stimulus properties. Most notably, we observed a decrease in the number of fixations on the critical trial relative to the *precritical* trials and a large percentage (67 %) of first fixations towards the target on the critical trial. These results show that search was more efficient on the critical trial than on the precritical trials—a hallmark of surprise capture. The *greater* number of fixations on the critical trial relative to the postcritical trials reflects the ability of some participants to perform the search without saccading on the postcritical trials rather than a lack of guidance on the critical trial.

With respect to the time course of saccades to the unexpected color singleton, saccadic latencies were found to be significantly longer (~40 ms) on the critical trial compared with the postcritical trials (Fig. 6). Moreover, this effect appeared to be driven by participants who made only one saccade on the critical trial (Fig. 7), although the interaction was nonsignificant ($p = 0.12$). This delay is consistent with previous reports of surprise capture to the extent that it is a *delay*. However, the *magnitude* of this delay is smaller than previously reported.

Horstmann (2002, 2006) and Horstmann and Becker (2008) have reported that surprise capture takes at least 200 ms but more likely closer to 400 ms to manifest. Importantly, Horstmann argued that at least some component of this delay reflects a delay in the orienting component of the surprise response: "*The results were clear-cut: stimulus duration was a powerful moderator of surprise capture. Apparently, the stimulus must be presented for a minimal duration to exhibit its full effect on the deployment of spatial attention*" (Horstmann & Becker, 2008, p. 303). In Experiment 1, we observed a delay in saccadic latencies on the critical trial of ~40 ms, relative to the postcritical trials. For participants who made only one saccade on the critical trial, this delay was ~55 ms. This delay cannot account for, in its entirety, the temporal profile of surprise capture previously reported in the literature. Interestingly, the PSD for the critical trial in experiment 1 was ~780 ms. That is, once participants saccaded to the target, on average, they took another 780 ms to respond to the target. The difference between the PSD on the critical trial and the postcritical trials (~480 ms) was ~300 ms. That is, we observed a nonspatially specific interference effect specific to the critical trial of ~300 ms. Note that if we consider the delays associated with the spatial (saccadic latencies) and nonspatial components together (~40/55 ms + ~300 ms), the temporal profile of the surprise effect reported in Experiment 1 begins to resemble the temporal profile of surprise capture previously reported in the literature.

Table 1 Raw saccade latencies used to compute Fig. 7

No. saccades on the critical trial	Critical trial	Postcritical trial
1	273.72	219.18
>1	240.09	224.36

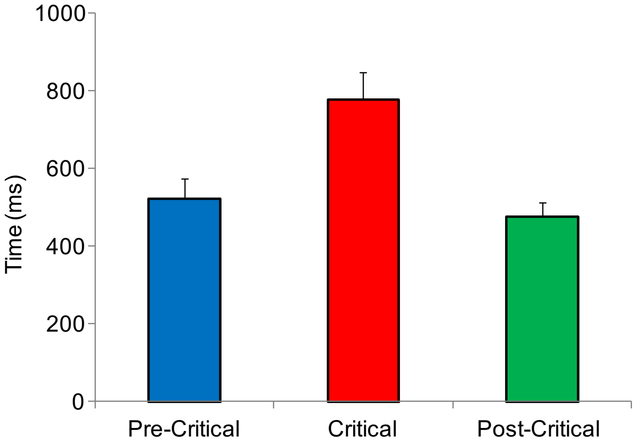

Fig. 8 Postselection duration (PSD) for the precritical, critical, and postcritical conditions in Experiment 1. PSD reflects the duration between selecting the target with the eyes and executing a response. Error bars depict one standard error of the mean

How might we explain the small delay in spatial orienting on the critical trial? One possibility is that the delay is indeed related to the "unexpectedness" of the color singleton and reflects, as Horstmann (2006) has suggested, a distinct temporal profile for capture by unexpected stimuli. Alternatively, the delay may be related to the conditions of search surrounding the unexpected color singleton rather than it's unexpectedness per se. Two possibilities come to mind. First, given the unguided nature of the search task during the precritical trials, participants may have adopted a narrow attentional focus and preprogrammed a saccade to a stimulus location prior to the appearance of the search display. It's possible that the delay in saccadic latencies on the critical trial may reflect the suppression of a preprogrammed saccade/the suppression of an existing search strategy. This could explain the trend for saccade latencies to be slower for participants whose first fixation went to the unexpected color singleton. A second possibility is that the delay in saccadic latencies on the critical trial reflects priming of the target during the postcritical trials where the target was always presented as a red singleton (Becker, 2008; Maljkovic & Nakayama, 1994; McPeek, Maljkovic & Nakayama, 1999).

Experiment 2

In Experiment 1, we observed a small delay in saccadic latencies associated with the critical trial when compared to the postcritical trials. We speculated that this delay might not be directly related to the unexpectedness of the color singleton on the critical trial, but rather related to the conditions of search leading up to and or following the unexpected stimulus. More specifically, the delay could reflect the need to suppress a preprogrammed saccade/existing search strategy on the critical trial and or reflet priming of the target on the postcritical trials. In Experiment 2, we investigated the temporal profile of surprise capture under conditions which precluded the potential for effects related to either of these possibilities. In Experiment 2, the target was consistently a shape singleton (diamond) that could be found efficiently. That is, without serially scanning the search items. Under these conditions, a switch in search strategy on the critical trial is unnecessary due to the preattentive availability of singleton target during the precritical trials. Furthermore, in Experiment 2 the color singleton was presented at a *nontarget* (invalid) location. This was done for two reasons: first, presenting the color singleton at a *nontarget* location rules out the possibility of the color singleton priming the target. Second, given that the target in Experiment 2 was preattentively available (guided search), it was necessary to present the color singleton at a *nontarget* location to distinguish between guidance related to the target and guidance related to the color singleton. If we observe a delay in saccadic latencies on the critical trial under these conditions, then we can more confidently conclude that the delay is indeed related to the unexpectedness of the color singleton.

Additionally, we were interested more broadly in the behavioural profile of surprise in the context of guided search. To date, studies of surprise capture have typically employed difficult search tasks such that the target itself could not guide attention. This raises the question whether an unexpected stimulus will attract attention and the gaze when the target is preattentively available and competes (strongly) for attention with the unexpected singleton. There is some evidence to suggest that unexpected stimuli can still capture attention and the gaze even when the target is preattentively available and able to compete for selection (Geyer, et al., 2008; Godijn & Kramer, 2008; Sayim et al., 2010). For instance, Godijn and Kramer (2008) found oculomotor capture by an unannounced new-onset distractor when participants had the task to saccade to a color singleton in a visual search paradigm. Consistent with the view that capture can be modulated by stimulus expectancies, the rate of oculomotor capture declined across repeated presentations of the onset distractor. However, the effect on other aspects of the surprise response, such as its temporal profile and signature RT increase, were not explored. Furthermore, Godijn and Kramer (2008) used onsets as the surprising stimulus, and there is evidence to suspect that the pattern of oculomotor capture associated with surprising stimuli may differ for different classes of stimuli (e.g., color singletons vs. onsets; Wu & Remington, 2003). Hence, it is still an open question whether an unexpected color singleton could elicit surprise and attract attention when it is forced to compete for selection with a preattentively available target. Thus, in Experiment 2 we tested the response to an unannounced color singleton during guided search.

If the new and unannounced color singleton can attract attention and the gaze even when it competes with a preattentively available target, then it should interfere with target selection on the critical trial, leading to an increase in RTs and an increase the number of fixations. Moreover, if the delay in orienting on the critical trial observed in Experiment 1 is related to the unexpectedness of the color singleton, we should again observe a delay in orienting in Experiment 2. If the delay is related to changes in search strategy or priming as we have speculated, we should not observe a delay in saccadic latencies in Experiment 2.

Method

Participants

Fifteen participants (9 females) from The University of Queensland participated in exchange for $10. All reported normal or corrected to normal vision.

Apparatus

The apparatus used in Experiment 2 was identical to that used in Experiment 1.

Stimuli

The stimuli used in Experiment 2 were similar to those used in Experiment 1. The critical differences being that in Experiment 2 the targets (H or U) always appeared in the centre of a shape singleton (diamond; 2.9° × 2.9°), and the colours of the stimuli varied *between* participants; stimuli in the precritical trials were either all red (RGB = 255 0 0) or green (RGB = 0 255 0) and the distractor in the critical trial and the postcritical trials was always green or red, respectively. Eight participants saw a red distractor against green stimuli

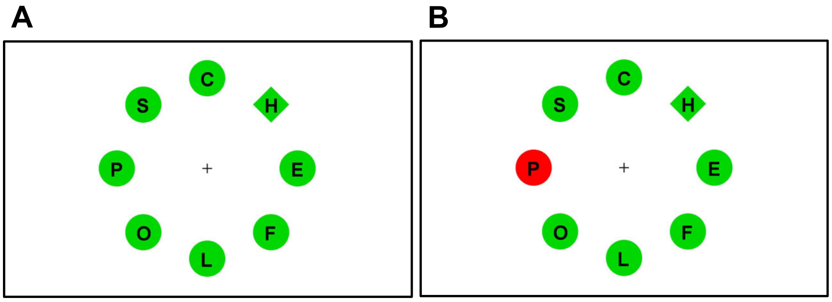

Fig. 9 Example search displays from Experiment 2. A Precritical trial. B Critical and postcritical trials. The diamond was the target shape and the distractor was always red

and seven saw the opposite. All other aspects of the stimuli were identical to Experiment 1 (Fig. 9).

Design and Procedure

In Experiment 2 participants completed 55 trials in search for a diamond target among circle nontargets: 5 practice trials, 25 precritical, 1 critical, and 24 postcritical trials. On the critical trial, a nontarget was randomly presented as a colour singleton, i.e., a red distractor amongst otherwise green stimuli or vice versa. That is, on the critical trial and the postcritical trials, the colour singleton was always presented at an *invalid* location. All other aspects of the design and procedure were identical to Experiment 1.

Results

Mean RTs Experiment 2 are shown in Fig. 10. RTs exceeding 4000 ms and errors were excluded from RT and eye-movement and analyses. This criteria lead to a loss of 4.5 % of trials. Eye movements were parsed into saccades, fixations and blinks using the same criteria as Experiment 1. As with Experiment 1, averages for the pre- and postcritical trials were computed over the five trials that preceded and trailed the critical trial, respectively, to arrive at a safer estimate of performance on pre- and postcritical trials. All comparisons were computed using these averages.

RT analysis

RTs on the critical trial were contrasted with RTs on the pre-critical and postcritical trials. Planned pairwise comparisons revealed that RTs on the critical trial were significantly slower than RTs on the precritical trials, $t(13) = -3.33$, $p = 0.005$, and RTs on the postcritical trials, $t(14) = -2.87$, $p = 0.01$ (Fig. 10).

Eye-movement analyses

Due to the distribution of number-of-fixations on the precritical trials, a comparison between the critical trial and the pre-critical trials was performed using a Wilcoxon's signed-rank test, which revealed significantly *more* fixations on the critical trial than on the precritical trials, Z = 3.03, $p = 0.002$. A planned comparison between the critical trial and the postcritical trials revealed a significantly greater number of fixations on the critical trial relative to the postcritical trials, $t(14) = -2.32$, $p = 0.04$ (Fig. 11).

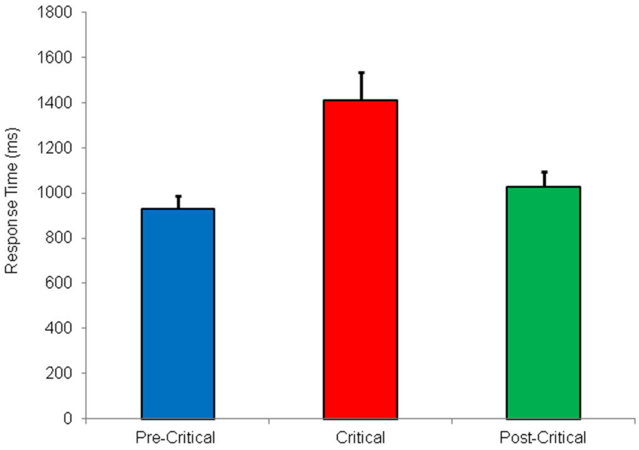

Fig. 10 Mean response times for the precritical, critical, and postcritical trials from Experiment 2. Error bars depict one standard error of the mean.

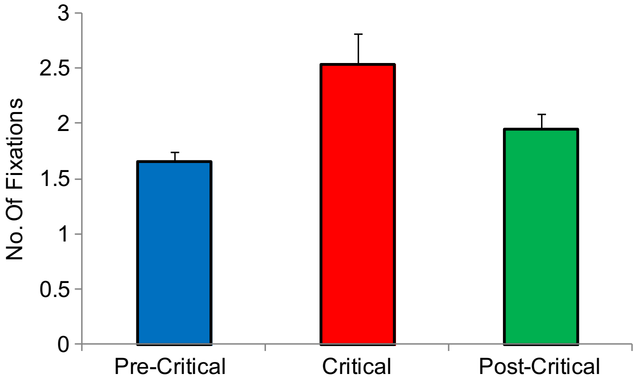

Fig. 11 Mean number of fixations per trial for the precritical, critical, and postcritical trials from Experiment 2. Error bars depict one standard error of the mean

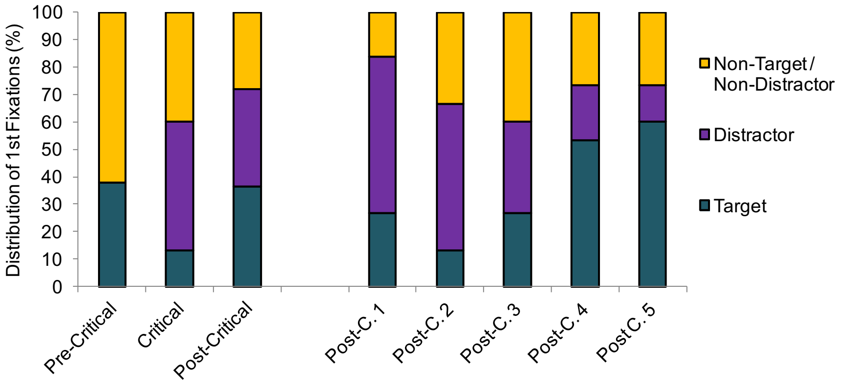

Fig. 12 Percentage of first fixations that went to the target, the distractor and to nontargets/nondistractors in each condition. We have expanded the postcritical data to show the distribution of first fixations for each of the first five postcritical trials

First fixations data showed that the target was selected on only 13.3 % of trials on the critical trial with the first saccade compared with 38 % and 36 % on the pre- and postcritical trials, respectively (Fig. 12). Two Wilcoxon's signed-rank tests revealed there were fewer first fixations to the target on the critical trials relative to the precritical, Z = 2.62, $p = 0.009$ and the postcritical trials, Z = 2.12, $p = 0.034$. Additionally, 47 % of first fixations went to the color distractor on the critical trial (Fig. 12). These results indicate that the color singleton interfered with search on its first unannounced presentation, despite the fact that the target was preattentively available and competed for selection with the distractor. There was no difference in the number of first fixations to the distractor on the critical trial compared with the post critical trials, $p = 0.48$ (Fig. 12). This result suggests that the color singleton continued to capture attention during the postcritical trials. However, further inspection of the data suggests that capture by the color singleton during the post critical trials dissipated across presentations (Fig. 12).

To test for delays in orienting associated with the unexpected color singleton, we again looked at saccadic latencies. Pairwise comparisons revealed no significant difference between the critical trial and the precritical trials, $p = 0.37$, or between the critical trial and the postcritical trials, $p = 0.61$ (Fig. 13). Similar to Experiment 1, in Experiment 2 we further explored the pattern of saccadic latencies as a function of the location of the first saccade; more specifically, whether the first saccade went to distractor or not. No differences were observed (Fig. 14a and b; Table 2).

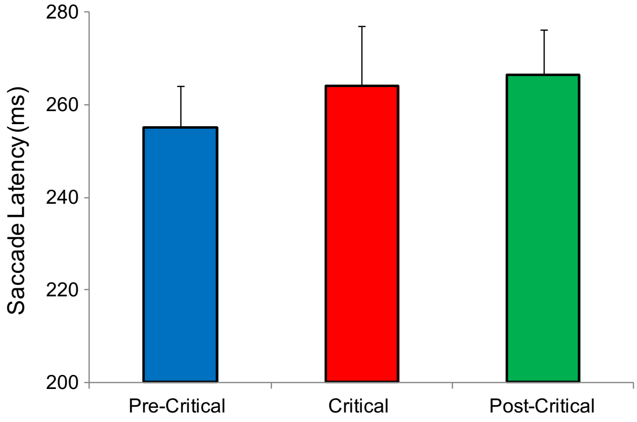

Fig. 13 Saccade latencies for the precritical, critical, and postcritical trials from Experiment 2. Error bars depict one standard error of the mean

Finally, as was done in Experiment 1, we again estimated the postselection delay (PSD) by computing the duration between selecting the target with the eyes and executing a response to the target. Pairwise comparisons revealed that the PSD was significantly longer on the critical trial (852 ms) than on both the precritical trials (577 ms), $t(13) = 2.56$, $p = 0.02$, and the postcritical trials (575 ms), $t(13) = 3.11$, $p = 0.008$ (Fig. 15).

Discussion

In Experiment 2, we presented an unannounced color singleton at a nontarget location during search for a shape singleton. Consistent with the view that unexpected stimuli can attract attention and interfere with search, RTs on the critical trial were elevated relative to both the precritical and postcritical trials as was the PSD. Importantly, there was an increase in the number of fixations on the critical trial relative to the precritical trials, suggesting a spatial component to the observed increase in RTs. Furthermore, 13.3 % (chance = ~7.5 %) of first fixations went to the target location on the critical trials compare with 38 % and 36 % on the pre- and postcritical trials, respectively, and 47 % of first fixations went to the distractor on the critical trial (Fig. 12a and b). Note that although we observed oculomotor capture by the color singleton during the postcritical trials, this effect dissipated quite quickly over repeated presentations of the color distractor (Fig. 12b). This suggests that the color singleton in Experiment 2 did not capture attention simply by virtue of its inherent saliency; rather the unexpectedness of the stimulus played an important role in its selection. With respect to the temporal profile of this spatial

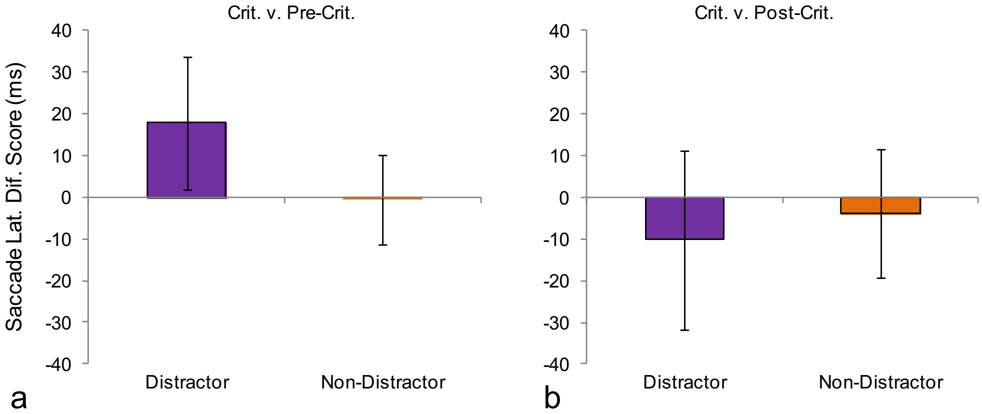

Fig. 14 Difference in saccade latencies between (**a**) the critical trial and (**a**) precritical trials and (**b**) the critical trial and postcritical trials as a function of the location of the fist saccade. Positive values reflect longer saccadic latencies and negative values reflect shorter saccade latencies on the critical trial relative to the respective comparison condition. Error bars depict ± one standard error of the mean

component, we did not observe a delay in orienting on the critical trial. Saccadic latencies on the critical trial were no slower than saccadic latencies on either the precritical or postcritical trials. This was true both for saccades that went to the distractor and those that did not (Fig. 14a and b). This pattern is in contrast to the result observed in Experiment 1 where we did observe a delay in orienting (~40 ms) on the critical trial relative to the postcritical trials. The fact that we did not observe a delay in orienting to the unexpected color singleton in Experiment 2 suggests that the delay orienting observed in Experiment 1 might not be directly related to the unexpectedness of the color singleton per se, but rather to the search conditions surrounding the critical trial.

However, it should be pointed out that the shape target was a singleton in Experiment 2 and it is possible that participants adopted a set for singletons or a set for the stimulus of highest contrast rather than the specific shape feature per se (Bacon & Egeth, 1994). Remembering that the surprising stimulus was a color singleton of high-feature contrast, it is possible that the color singleton in Experiment 2 captured attention by virtue of its "fit" with the task set rather than a "miss-fit" with the task expectancies. That is, the surprising stimulus may have engaged (fast) top-down selection mechanisms before any (slow) novelty detection mechanism could respond. This could conceivably account for why we failed to observe a delay in saccadic latencies in Experiment 2. However, regardless of the orienting mechanism at play, the decrease in RTs and number of fixations on the *postcritical* trials relative to the critical trial demonstrates that stimulus novelty was critical to the effects observed in Experiment 2. These results demonstrate that oculomotor capture was modulated by the first presentation of an unannounced color singleton, a result that has previously been demonstrated with onset transients (Godijn & Kramer, 2008) but not with color stimuli.

Table 2 Raw saccade latencies used to compute Fig. 14

Saccade target on the critical trial	Precritical	Critical	Postcritical
Distractor	244.47	262.29	272.54
Nondistractor	266.51	266.14	269.84

General Discussion

According to the surprise capture hypothesis, a stimulus will capture attention to the extent that it is preattentively available and deviates from task-expectancies. Importantly, capture by unexpected stimuli is thought to be governed by a mechanism separate from the underlying mechanism that governs capture by expected stimuli (Gronau et al. 2006; Horstmann, 2002, 2005, 2006; Horstmann & Becker, 2008). In the two experiments presented, we explored the phenomenon of surprise capture using eye-movements with the aim of disentangling the various components of the effect, namely the spatial,

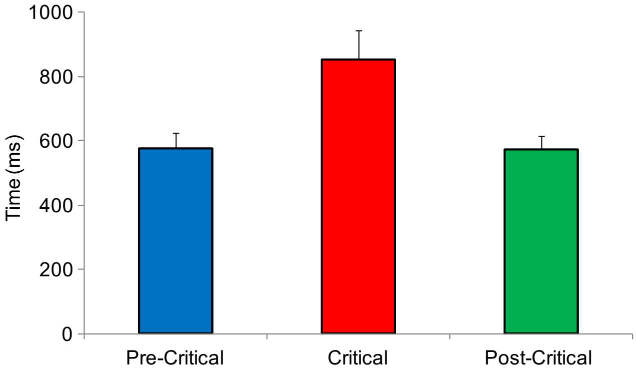

Fig. 15 Post-selection duration (PSD) for the precritical, critical, and postcritical conditions in Experiment 2

temporal, and decision/response-related components to better understand the mechanisms underlying surprise capture.

In Experiment 1, we presented an unannounced color singleton at the location of the target during unguided search. Conceptually, this experiment was very similar to previous designs employed to study surprise capture (Horstmann, 2002 exp. 3, 2005 exp. 1). Consistent with surprise capture, we found strong evidence of attentional capture on the critical trial that was accompanied by a nonspatially specific RT cost (~300 ms) related to the engagement of higher-order processes recruited to resolve the expectancy violation. However, regarding the temporal profile of the effect, we found evidence in the saccade latencies for only a modest delay in the orienting component of ~55 ms. In Experiment 2, under conditions of guided search, we again found strong evidence of a shift of attention towards the unannounced color distractor as well as a large RT cost; however, we found no modulation of saccade latencies by the unannounced color distractor.

As discussed previously, surprise capture is thought to manifest relatively slowly. Horstmann (2006) had participants perform an unguided search task for a series of trials before presenting an unannounced color singleton at the target location. The SOA between the presentation of the surprising stimulus and the target display was varied from 0–600 ms between subjects. Only when the surprising stimulus preceded the target by at least 400 ms was an effect of surprise observed. A similar pattern of results has been observed in other reports of surprise capture (Gibson & Jiang, 1998; Horstmann, 2002, 2005; Horstmann & Becker, 2008; Meyer et al., 1991). Critically, this effect has been attributed in part to a delay in the onset of the spatial orienting component of the surprise response—delayed onset model—and used to argue for an underlying mechanism distinct from other forms of capture.

In our view, the results of the two experiments presented are not consistent with a delayed onset model of surprise capture. In Experiment 1, we found a minimal delay in saccade latencies on the critical trial but a large RT cost once the target had been selected with the eyes. In Experiment 2, under conditions of guided search we found a similar pattern of results for an invalid color singleton; here though we did not observe the same delay in saccadic latencies on the critical trial despite observing large RT costs indicative of surprise. This pattern of data seems more consistent with an interference model of surprise capture where by attention shifts rapidly to an unexpected feature and the RT delays that characterize surprise reflect computations at a later stage in the system—after attention has been shifted to an unexpected stimulus—dedicated to reconciling the expectation discrepancy (Gibson & Jiang, 1998; Meyer et al., 1991). We suggest that modest delay (~55 ms) in orienting observed in Experiment 1 may reflect: 1) suppression or inhibition of the existing/active serial search strategy on the critical trial as the task switches from unguided to guided search, and/or 2) priming of the target during the postcritical trials. The fact that we did not observe a similar delay in orienting in Experiment 2 where both these factors were controlled for supports our speculation and critically suggests that the delay in orienting observed in Experiment 1 may not be driven by the unexpectedness of the color singleton per se. However, we acknowledge that we cannot rule out the possibility that the unexpected color distractor in Experiment 2 may have engaged (fast) top-down selection mechanisms before any (slow) novelty detection mechanism could be engaged. In this scenario, any delay inherent to the unexpected stimulus would go undetected given that the stimulus may have capture attention and the eyes by virtue of its fit with an existing top-down set and not by virtue of its unexpectedness. Further inquiry may be needed distinguish between these two possibilities. Regardless, the ~55-ms delay in saccade latencies we observed in Experiment 1 cannot account for time course of surprise capture currently proposed in the literature.

What then is the source of the discrepancy between our results and previous reports of surprise capture? One possibility is that there are genuine inconsistencies between the data reported here and previous results, possibly attributable to subtle differences in the methodologies used. Specifically, time-course analyses of surprise capture have in the past used very brief target presentation durations—in the order of 80-90 ms to detect variances in accuracy—and looked at covert attention shifts. We presented the target display until a response was made and studied eye-movements: serial processes that take time to be executed. However, it is not clear to us how these methodological differences could produce seemingly different temporal profiles of surprise capture. A second possibility is that the discrepancy lies in our interpretation. We suggest the latter and argue that previous demonstrations of surprise capture can be accounted for by an interference model and that this is a more parsimonious and ecologically valid account of the phenomenon. We discuss this in depth below.

As discussed, the majority of work addressing the time course of surprise capture has used very brief target presentation durations and a feature singleton presented at the location of the target to induce surprise (Gibson & Jiang, 1998; Horstmann, 2002, 2006). These studies invariably find that accuracy on the surprise trial remains close to chance unless the surprising stimulus is presented at least ~300-400 ms before the target presentation. A delayed-onset model accounts for some of this delay by proposing that the orienting component of the surprise response is slow and, therefore, for SOAs of less than ~300-400 ms, attention has not yet shifted to the location of the target and thus cannot facilitate identification of the target. On the other hand, an interference model proposes that orienting towards a surprising stimulus is fast; however, central processing resources are devoted to processing the expectation discrepancy ahead of the target. If the target presentation time is shorter than the time required to resolve the expectation discrepancy, then target identification will likely be impaired. These two models are of course not mutually exclusive; recent electrophysiological evidence suggests that both early and late processes contribute to attentional capture effects (Gaspar & McDonald, 2014). However, in both Experiment 1 and Experiment 2 we found a spatially nonspecific interference effect specific to the critical trial of ~300 ms and ~280 ms, respectively; a delay in responding that closely resembles the time course of surprise previously reported (Asplund et al. 2010; Horstmann, 2002, 2006) but that only manifested in both instances *once* the eyes had shifted to the target.

We are not the first authors to point out that the delayed-onset account and the interference account make similar predictions with respect to accuracy for valid unannounced singletons. Horstmann and Becker (2008) recognized this and ran a series of experiments to distinguish between the two accounts. They argued that the delayed-onset account and the interference account make opposite predictions for an unannounced *distractor*, i.e., a singleton *not* presented at the location of the target. Specifically, they reasoned that the delayed-onset account predicts minimal costs at short SOAs (e.g., 100 ms) and large costs at long SOAs (e.g., 400 ms). This is because at short SOAs (100 ms) the distractor does not attract attention to its location (away from the target); the opposite is true at long SOAs. The interference account, however, predicts the opposite; large costs at short SOAs that should dissipate as SOA increases. Across two experiments, they found results consistent with the delayed-onset prediction showing a minimal decrease in accuracy at the short (100 ms) SOA and close to chance performance at the long (400 ms) SOA. However, there is a notable difference between the experimental paradigm used by Horstmann and Becker (2008) and previous investigations into the time course of surprise capture (Horstmann, 2002, 2005, 2006; Meyer et al., 1991), which we believe is critical to understanding their results. Specifically, Horstmann and Becker (2008) presented the unannounced distractor for either 100 ms or 400 ms and *offset* it when the target display was presented. In previous experiments, where the unannounced singleton was always valid (Horstmann, 2002, 2005, 2006), the unannounced singleton was presented at varying SOAs and left on *until* a response was made. That is, the presentation duration of the surprising stimulus varies substantially across these experiments and we believe this is critical. Indeed, so too did Horstmann and Becker (2008) as they demonstrated in the same paper that *stimulus duration* is critical for surprise to manifest because surprise capture requires a "*sufficiently stable stimulus representation*" (Horstmann, 2008, p. 304). We suggest that the reason there is no effect of the unannounced color distract at the 100-ms duration in the Horstmann and Becker (2008) paper is not because attention is not allocated to the unannounced distractor, but because once attention has shifted to the unexpected stimulus 100 ms is not sufficiently long enough for surprise to manifest and interfere with target identification.[2,3]

Finally, the cost observed at the 400-ms duration condition can easily be reconciled with an interference account by referring to Horstmann (2006) where he shows that accuracy on the critical trial for a *valid* unannounced stimulus approaches ceiling at SOAs *beyond* 400 ms (i.e. 600 ms). The fact that there were accuracy benefits at an SOA of 600 ms demonstrates that participants were continuing to attend to the stimulus at the onset of the target display. Thus, based on this data we would *not* predict that the interference associated with the unannounced color distractor in Horstmann and Becker (2008) should have fully dissipated by 400 ms. Thus, the interference they observe at the 400-ms stimulus duration is, to us, *not* inconsistent with an interference account of surprise capture as Horstmann and Becker (2008) argue.

In summary, the two experiments reported demonstrate that unannounced color singletons modulate oculomotor capture and elicit surprise on their first occurrence, both under conditions of guided and unguided search. Saccadic latency data across two experiments suggest there is a small delay in orienting to an unannounced stimulus during unguided search, which we suggest may reflect a necessary suppression or inhibition of preexisting serial search strategies before the unexpected stimulus will guide attention/the eyes. Alternatively, this small delay may reflect feature priming on the postcritical trials. Critically, the temporal profile of saccadic latencies that we observed is not consistent with accounts of surprise capture that posit a delay in orienting as the primary source of the reduced accuracy at short SOAs. Rather, our data are more consistent with an interference model where by attention shifts rapidly to the location of an unexpected stimulus and central processing resources are diverted to reconciling the expectation discrepancy at the cost of target identification.

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[2] Note that Theeuwes, Atchley & Kramer (2000) showed that a color distractor presented 100 ms prior to the onset of a target display was sufficient for it to produce interference. Critically though, the color distractor remained present during the presentation of the target display. This may explain why they observed interference associated with the colour singleton and Horstmann and Becker (2008) did not.

[3] Regarding the necessary stimulus duration for surprise to manifest, Asplund et al. (2010) reported that interference from an unexpected salient stimulus presented for 120 ms presented 130 ms and 390 ms prior to the target in a modified RSVP stream. Similarly, Gronau et al. (2006) reported that interference from an unexpected letter stimulus presented for 100 ms. However, in both cases the stimuli were presented centrally, within the focus of attention. Here and in previous reports of surprise capture, the stimuli are presented in the periphery. We speculate that the temporal profile of surprise may vary as you move from central vision to the periphery. Indeed, when Gronau et al. (2006) presented the same unexpected stimulus for 100 ms outside the focus of attention, it failed to elicit surprise.

Distinguishing between these two accounts is important, because as Horstmann (2005, 2006) points out, the delayed-onset account points to a separate underlying mechanism for capture by unexpected events. Whereas the interference model is not inconsistent with theories of attentional control that propose that salient irrelevant stimuli are filtered out through a process that is dependent on prior exposure to irrelevant stimuli and *implicit* learning about their relevance (Becker, 2007; Folk & Remington, 1998; Thompson, Willoughby, and Milliken, 2014; Treisman & Sato, 1990) as well as models that posit a more active learning mechanism that contributes to distractor inhibition (i.e., *Dimension Weighting* accounts: Müller, Reimann & Krummernacher, 2003; Töllner, Zehetleitner, Gramann & Müller, 2010; Zehetleitner, Goschy & Müller, 2012).

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