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BRIEF REPORT

Surprise attracts the eyes and binds the gaze

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Abstract In recent years, researchers have become increasingly interested in the effects that deviations from expectations have on cognitive processing and, in particular, on the deployment of attention. Previous evidence for a surprise–attention link had been based on indirect measures of attention allocation. Here we used eyetracking to directly observe the impact of a novel color on its unannounced first presentation, which we regarded as a surprise condition. The results show that the novel color was quickly responded to with an eye movement, and that gaze was not turned away for a considerable amount of time. These results are direct evidence that deviations from expectations bias attentional priorities and lead to enhanced processing of the deviating stimulus.

Keywords Surprise · Attention · Prioritization · Unexpectedness · Eye movements · Gaze · Fixation

Humans are highly sensitive to deviations from expectancies: We easily spot a change in the arrangement of furniture in a friend's living room, the new hairstyle of a colleague, or a change in the height of our office chair. Since we are usually not actively searching for discrepancies, these examples suggest that our expectancies are constantly tested against reality in an automatic fashion. Laboratory tasks support this notion. For example, a floating toaster or a printer in a kitchen is fixated longer than a toaster on the counter surface or a printer in an office (Võ & Henderson, 2009).

The surprise–attention hypothesis (e.g., Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Horstmann, 2002, 2005) assumes that automatic discrepancy detection uses preattentive and postattentive information to engage attention with the surprise stimulus. The floating toaster in the Võ and Henderson (2009) study binds, but does not guide, attention. This is reasonable, according to the assumption that the printer is identified postattentively. Attention, however, can also be guided by preattentive information. For instance, a unique color is efficiently found if it is the target of the current task (e.g., Yantis & Egeth, 1999). The surprise–attention hypothesis thus predicts that a stimulus can not only bind, but also guide attention to its position, if its surprising feature is preattentively available. A series of studies have supported this prediction: A novel feature on its first unannounced presentation in a search display guides attention to its position, as indexed by accuracy gains under restricted viewing conditions (e.g., Horstmann, 2002, 2006), set-size effect reductions in visual search (e.g., Becker & Horstmann, 2011; Horstmann, 2002, 2005), and validity effects (e.g., Horstmann & Becker, 2011).

Several key experiments have probed set-size effect reductions in visual search. The interpretation of their results, however, is complicated by response time (RT) increases in the surprise trial: Whereas the set-size effect for a surprise presentation is often as small as during efficient feature search, the overall RT is much slower than in feature search. On the basis of evidence that surprise delays (Meyer, Niepel, Rudolph, & Schützwohl, 1991) or even interrupts (Horstmann, 2005) responses in RT tasks, Horstmann (2005) argued that this increase is mostly due to postattentive, decision-level analyses of the surprising event. Yet other evidence indicates that the attentional response to the surprise stimulus also comes with a delay. In particular, there is little effect of surprise on attention

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in the first 100–200 ms (e.g., Gibson & Jiang, 1998), whereas attentional benefits accrue after about 300–400 ms in an accuracy task (Horstmann, 2006).

Delays before and after an attentional shift cannot easily be separated in common RT tasks. Fortunately, eyetracking provides a direct measure of orienting, and thus a means to disentangle the two possible origins of slowing in the surprise trial.

In two experiments, we analyzed fixation latencies and dwell times in three conditions: (I)when no cue to the target position was presented, rendering visual search inefficient; (II) when a color cue to the position of the target was presented for the first time and without prior announcement; and (III)when the color cue was presented at the position of the target in every trial. Contrasting the first two conditions can reveal the benefits of the surprise cue, with better performance in II than in I indicating attraction of the gaze by the surprise cue. Contrasting Conditions II and III should reveal the costs of surprise relative to a condition in which the predictive cue was expected and (presumably) used in a task-driven manner to direct attention to the target. Experiments 1 and 2 were close replications of each other, using two different rationales to match colors in intensity.

Experiment 1

Method

Participants A group of 16 students from Bielefeld University participated in return for a small compensation (€2). The data from three participants were useless because they rarely moved their eyes during the search task, including the critical trial. Sample size was chosen to be adequate for a large effect and was similar as in previous studies (e.g., Horstmann, 2005).

Apparatus and materials Participants were tested singly in a sound-attenuated cabin. A 19-in. CRT display with a resolution of 1,024 × 768 pixels and a refresh rate of 75 Hz was used to present the stimuli at a distance of 71 cm. Participants responded using two adjacent keys (←and ↓) on the computer keyboard. Experiment Builder (1.10.165) was used to present the experimental stimuli and to control the eyetracker. A video-based, tower-mounted eyetracker (EyeLink 1000, SR Research, Ontario, Canada), calibrated with a nine-point procedure, recorded the movements of the right eye with a sampling rate of 1 kHz. The participant's head was stabilized by a chin-and-forehead rest. The experimental stimuli consisted of nine colored disks (red or green), eight distractor letters, and one of two (possible) target letters (see Fig. 1). Letters were built from vertical and horizontal line segments, such that the target letters (H and U) were not discriminable from the distractor letters on a single simple feature. Disks subtended 2.7°, and letters subtended 1.2° × 2.0° of visual angle. They appeared equidistantly on the circumference of an invisible circle with a radius of 5.5° of visual angle. The background and the letters were black. The two colors red (34 cd/m^2) and green (92 cd/m^2) were used at their respective 100 % intensities (RGB: [100 %, 20 %, 20 %], and [20 %, 100 %, 20 %], respectively), at which both have similar subjective intensities, providing conditions similar to those used in previous experiments (e.g., Horstmann, 2002, 2005).

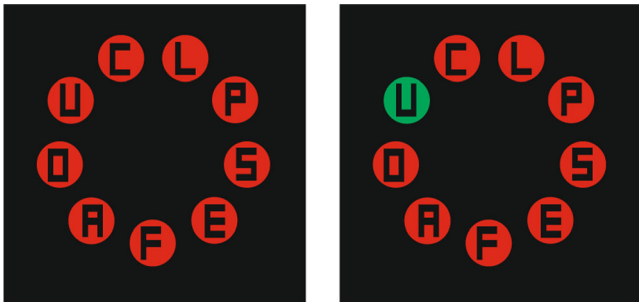

Fig. 1 Layouts of stimuli in the precritical trials (left) and in the critical and postcritical trials (right). Note that the figures are not drawn to scale

Procedure The task was to find the target letter, H or U, among eight distractor letters, and to press one of two response keys accordingly. The speed and accuracy of responses were both emphasized. Ten practice trials accompanied the instruction.

Each trial began with a drift control, in which participants fixated a marker and then pressed the space bar. Then the fixation marker disappeared and the target display was presented until one of the two response keys was pressed. False responses were signaled by a short tone.

The single experimental block consisted of two parts, with no noticeable transition other than the change in color. In the first part, all disks were of the same standard color (red or green, balanced over participants); these trials will be referred to as the *precritical* trials henceforth. In the second part, the target disk had a novel color (green or red, respectively). The surprise trial was the first trial of the second part, with the remaining trials constituting the postcritical trials. Each part consisted of 18 trials, realizing 18 combinations of two targets and nine possible positions (20°–340° in 40° steps). Two warm-up trials (not analyzed) of the same type as the precritical trials preceded the experimental trials.

Scoring and response definition Eye movements were parsed into fixations and saccades. Saccades were eye movements that exceeded an acceleration threshold of 8,000 deg/sec^2 or a velocity threshold of 30 deg/s. Fixations were inferred when none of these thresholds was exceeded for 20 samples.

The analyses focused on fixations on the target disk. Circular interest areas were defined that subtended 3.6° of

visual angle and were centered on the letter–disc compounds. The two measures of main interest were fixation latencies, which were the times of the first fixations in an interest area relative to the onset of the search display, and dwell times, which were the summed fixation durations within the interest area. Fixation latencies <100 and >4,000 ms were excluded from the analysis, to reduce variance (this exclusion applied to only five trials altogether). No filtering was done of dwell times, which seemed to have a rather continuous distribution ranging from 35 to 2,677 ms. Only trials with correct target discrimination were analyzed.

Results

Errors in the RT task were very rare (<1 %), indicating that participants followed the task instructions. The main results are summarized in Fig. 2a.

Target fixation latencies With the introduction of the novel color, fixation latencies decreased rapidly. The last four precritical trials provided a reasonably stable baseline for precritical trial performance near the critical trial. The difference between baseline (746 ms) and the critical trial (386 ms) was significant, $t(12) = 7.26$, $p < .001$ (here and elsewhere, alternative baselines do not change the result patterns). Critical-trial fixation latencies also differed significantly from those of the 17 postcritical trials (276 ms), $t(12) = 3.67$, $p = .003$.

Target dwell time Dwell times showed a sharp rise from the precritical (387 ms) to the critical (1,046 ms) trials, $t(12) = 3.47$, $p = .005$. Critical-trial dwell times also differed from the 17 postcritical trials (436 ms), $t(12) = 3.20$, $p = .008$.

RT Critical-trial RTs (1,742 ms) were significantly longer than the postcritical-trial RTs (790 ms), $t(12) = 3.93$, $p = .002$, and

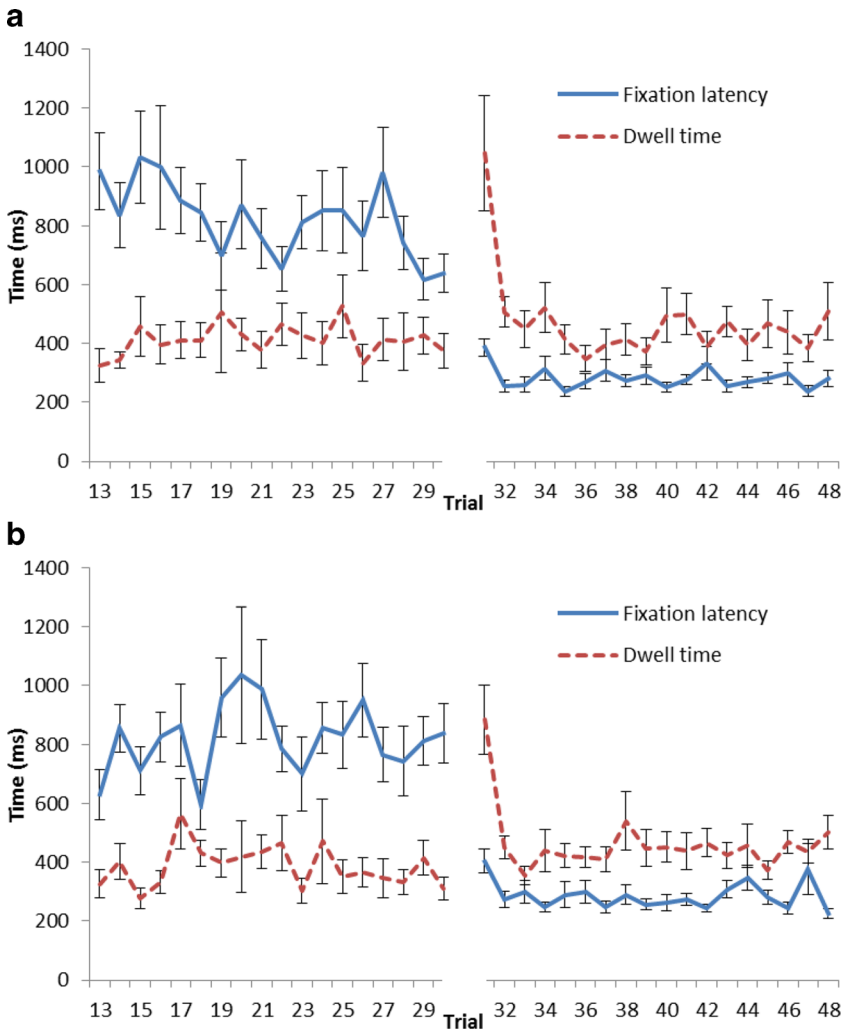

Fig. 2 Results of Experiments 1 and 2 (panels a and b, respectively): Fixation latencies (solid lines) and dwell times (dashed lines) on the target area (in milliseconds) for the precritical trials (13–30), the critical trial (31), and the postcritical trials (32–48). Error bars depict the standard errors of the means. Trials 1–12 were practice trials

also tended to be significantly longer than the baseline (1,329 ms), $t(12) = 1.87$, $p = .086$.

Components of the RT increase The RT was 952 ms longer in the critical trial than in the postcritical trials. The RT increase can be decomposed into three components: increases in (1)fixation latency (110 ms), (2) dwell time (610 ms), and (3) processes after the first fixation (e.g., further fixations on other stimuli and refixations on the target) (233 ms). As can be seen, most of the increase incurred at or after the first fixation on the target.

To further explore the composition of the RT increase, we tested whether the RT increase was statistically related to the slowing in fixation latencies and dwell times. As is shown in Fig. 3, slowing before the first fixation accounted for little variance ($R^2 = .17$) in RT slowing, whereas slowing of the first dwelling on the stimulus accounted for substantial variance ($R^2 = .81$).

Gaze before target fixation in the critical trial

Is it possible that the gaze shift to the target did not occur earlier because the eyes were immobilized by surprise? Gaze behavior before the target, however, did not corroborate this possibility. On average, 1.15 fixations occurred before the target fixation in the critical trial, which was less than in the precritical baseline (3.18), $t(12) = 10.69$, $p < .001$, but more than in the postcritical trials (0.48), $t(12) = 3.75$, $p = .003$. Moreover, although the mean latency of the first fixation[1] in the critical trial (166 ms) was somewhat shorter than in baseline (195 ms), $t(10) = 2.16$, $p = .056$, the mean duration (163 ms) and amplitude (3.66°) were unaffected (ts < 1). Excentricity was also not affected (3.45 vs. 4.08), $t(10) = 1.43$, $p = .18$. About half of the first fixations (precritical, 57 %; critical, 46 %; postcritical, 40 %) were not on a stimulus. Almost all of them were near the fixation marker, and thus seem to be corrective or exploratory fixations. Having the first fixation land on the target was rarer in the precritical (3 %) than in the postcritical (47 %) trials, $t(12) = 8.24$, $p < .001$. First fixations on the target in the critical trial occurred in only two cases (15 %).

Discussion

The surprise color cue quickly drew attention to its position, as indexed by the sharp decrease in target fixation latencies. More detailed analysis supported previous hypothesizing and helped clarify some open questions. (1) The gaze shift to the surprise stimulus followed display onset with a latency of 386 ms, consistent with indirect measures of covert attention shifts (Horstmann, 2006); (2) as compared to expected color cues, for which the gaze shift was presumably task-driven, the shift was slowed by 110 ms; (3) the shift was followed by a long dwelling period on the surprise stimulus, exceeding the typical dwell time by 610 ms, which is consistent with the proposition that the surprise stimulus is the target of slow, decision-level processing; (4) the results clarify that most of the RT increase previously observed occurred after, not before, the shift to the surprise stimulus.

Before the results are discussed more deeply, in Experiment 2 we tested how well the results would replicate.

Experiment 2

Method

Participants, apparatus, procedure, and materials Another 16 students were recruited. The experimental set up was the same, with the exception that instead of subjective color strength, the objective luminance was matched at 31 cd/m^2. This was done to enhance comparibility with research on involuntary attention that used stimuli matched for luminance rather than subjective intentisty (e.g., Theeuwes, 1994)

Results and discussion

The general result pattern was very similar to that in Experiment 1 (see Fig. 2b). Two observations in the critical trial were lost, due to a target discrimination error or because no eye movement was observed.

Target fixation latencies Target fixation latencies dropped from 773 ms (precritical baseline) to 403 ms (critical trial), $t(13) = 6.03$, $p < .001$. Critical-trial fixation latencies also differed significantly from those on the postcritical trials (272 ms), $t(13) = 3.26$, $p = .006$.

Target dwell times The data of one participant were discarded because a blink during the first target fixation compromised determination of the dwell time. Dwell times increased from 333 ms (precritical baseline) to 923 ms (critical trial), $t(12) = 4.82$, $p < .001$. The critical-trial dwell time also differed from those on the postcritical trials (379 ms), $t(12) = 4.49$, $p = .001$.

RT The mean RT in the precritical trials (1,310 ms) was not significantly different from that in the critical trial (1,596 ms), $t(13) = 1.57$, $p = .141$, but it was longer in the critical than in the postcritical trials (782 ms), $t(13) = 5.11$, $p < .001$.

Components of RT increase An analysis was conducted on the 13 participants with data on RTs, fixation latencies, and dwell times. The RT was 791 ms longer in the critical than in

[1] An alternative analysis, selecting the last fixation before the target rather than the first fixation in the trial, revealed a very similar data pattern.

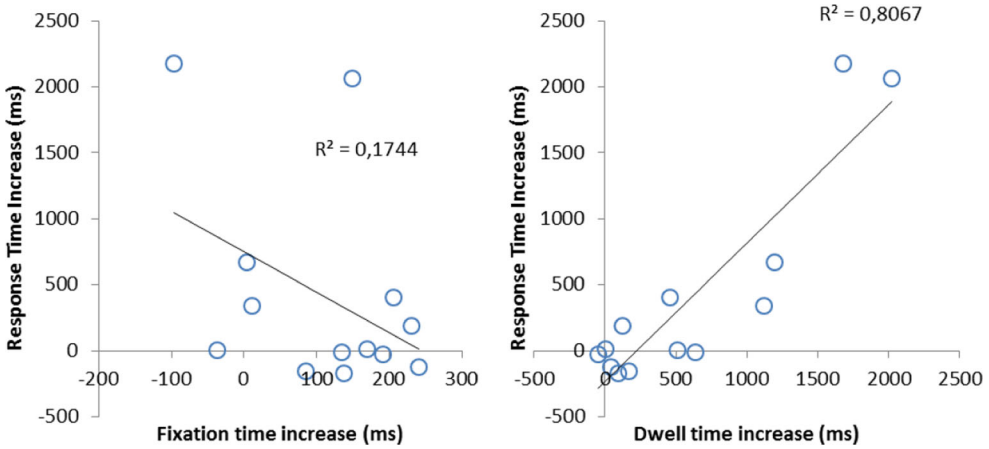

Fig. 3 Relationship between the response time increase in Experiment 1 and slowing before versus during the first fixation on the target (all differences expressed as $time_{crit} - time_{precrit}$)

the postcritical trials. The RT increase can be decomposed into three components: increases in (1) fixation latencies (103 ms), (2) dwell times (545 ms), and (3) processes after the first fixation (143 ms).

Regressing the RT increase on the fixation latency increase and dwell time increase showed little relationship between the RT increase and the fixation latency increase, $R^2 = .04$. The relationship between RT increase and the dwell time increase was substantial, $R^2 = .37$, although weaker than in Experiment 1.

Gaze before target fixation in the critical trial The number of fixations before the target was 1.14 in the critical trial, which was less than in the precritical baseline (3.17), $t(13) = 7.17$, $p < .001$, but more than in the postcritical trials (0.62), $t(13) = 2.51$, $p = .026$. Only three participants immediately fixated the target. The first fixation latency (191 ms), duration (181 ms), and amplitude (3.53°) were not different from baseline, $ts < 1$, nor was eccentricity (3.14), $t(10) = 1.24$, $p = .24$.

As in Experiment 1, many of the first fixations (precritical, 61 %; critical, 92 %; postcritical, 42 %) were not on a stimulus, but near the fixation marker. The first fixation landing on the target was rare in the precritical trials (3 %), but not in the postcritical trials (44 %), $t(11) = 7.18$, $p < .001$. There were no first fixations on the target in the critical trial in Experiment 2.

General discussion

Two experiments showed that the surprise color attracted the eyes and bound the gaze. The first fixation on the surprise color occurred much earlier than would be expected on the basis of an inefficient visual search, as in the precritical trials. The target dwell time and RT in the critical trial, on the other hand, were dramatically increased. The increase in dwell time explained substantial variance in the RT increase, supporting the assumption that the surprise-induced RT increase is primarily due to a postattentive analysis of the surprising stimulus.

Target fixation latencies were shorter in the critical trial than in the precritical trials, but longer than in the postcritical trials. This slowing seems to be to a large degree due to an additional fixation. The first fixation in the trial was unsuspicious, in terms of its latency, duration, amplitude, and eccentricity. The data thus suggest that eye movements proceeded unaffected until the critical stimulus was fixated; only then did gaze duration increase. The additional fixation also argues against the possibility that gaze was arrested by surprise-related response interruption processes.

We suggest three plausible explanations of the delay in fixation latencies: competition among priority signals, delayed discrepancy detection, and preplanned eye movements. Beginning with competition (see Desimone & Duncan, 1995), priority signals from the surprise stimulus have to compete with task-related priority signals. In the surprise trial, however, the distractors have greater similarity with the assumed target appearance (learned in the precritical trials) than does the surprise stimulus. The target-dissimilar surprise stimulus thus must compete with the target-similar distractor stimuli for priority, and it might not win this competition immediately.

For delayed discrepancy detection, consider that expectancy discrepancy is not *in* the stimulus, and is therefore not part of the first feed-forward sweep of processing in the brain, implying that discrepancy can be used relatively late. In contrast, task-related stimuli are favored already in the first feed-forward sweep (see Hopfinger, Jha, Hopf, Girelli, & Mangun, 2001). This difference predicts a delayed gaze shift to the surprise stimulus relative to an expected cue.

Finally, the first fixation in a trial might be part of a strategic or habitual search pattern that was preprogrammed before the onset of the display. For example, if a participant prefers to start at the top position, he or she might program the first eye movement in advance.

The target fixation latency results in the surprise trial concur with previous psychophysical results. Horstmann (2006) used presentation times of a letter array that were too short to allow for the scanning of all letters, but long enough to identify the target once the target's position was signaled by a color cue. Discrimination performance in that study did not gain from the first 200 ms of presentation of the cue in the critical trial; when the colored patch was presented for 400 ms or longer, however, benefits accrued. This indicated that covert shifts of attention occurred around 400 ms after the onset of the surprise stimulus. Covert shifts of attention are tightly correlated with eye movements (Deubel & Schneider, 1996), and in fact precede them in time (Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011). Thus, the present experiment supports previous results that attention to a surprising color has a latency in the range of 400 ms.

The setup of the experiment ensured that the gaze shift to the surprise stimulus would be involuntary: Because the participants did not know about the novel color, they could not have formed an intention to attend it prior to its appearance. This contrasts with the results of almost all studies on involuntary attention, in which the to-be-tested attention-capturing stimulus has been presented on most or all trials (see Burnham, 2007), while conditions were set up such that participants were motivated to ignore it. These two paradigms address slightly different questions concerning involuntary attention. While the traditional paradigm probes the ability to intentionally filter out unwanted information, the surprise paradigm probes selection without prior intention.

Does the latency of the gaze shift invalidate the claim that it was involuntary? Automatic attention has frequently been characterized as fast (e.g., Theeuwes, 2010). We contend that being fast is not an ideal criterion to distinguish automatic and voluntary processes. Having a short latency is neither a sufficient nor a necessary condition of involuntariness: It is not sufficient because task-driven attentional processes are often very fast (see Ansorge, Horstmann, & Scharlau, 2011); it is also not necessary, since many examples for involuntary processes are rather slow (e.g., pupil dilation or blushing).

Involuntary attention to a surprise stimulus contrasts with previous demonstrations of fast attention capture by singletons. Some studies have revealed saliency capture in the range of 60–150 ms after stimulus onset (e.g., Kim & Cave, 1999; Theeuwes, Atchley, & Kramer, 2000; see Theeuwes, 2010). If so, why did the surprise stimulus, which was also a salient stimulus, not attract gaze much earlier? For once, as Ansorge et al. (2011) pointed out, demonstrations of singleton capture (e.g., color) were obtained when participants searched for a relevant singleton on another dimension (e.g., shape). Thus, attention capture might be a side effect of a top-down singleton-search task (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992), rather than being purely stimulus-driven (Theeuwes, 2010). The task in the precritical trials did not allow for singleton search, which could explain the absence of very early capture of attention. It might be noted also that a color singleton (Horstmann, 2005), or a motion singleton (Becker & Horstmann, 2011), on its first unannounced presentation has captured attention only if the singleton's feature was novel, but not when it was familiar due to previous presentations. Thus, being a singleton does not seem to be enough to capture attention on an unannounced first presentation.

How do the present results relate to other paradigms for investigating the surprise–attention link? Asplund et al. (2010) found a similar time course for surprise-induced blindness, in which a surprising stimulus rendered observers blind for trailing stimuli. Noting that Asplund et al. (2010) examined temporal (rather than spatial attention) suggests that the blindness period corresponds to the dwell time increase of the present work. Interestingly, Strayer and Johnston (2000) found reliable differences in event-related potentials toward four-element displays of novel versus familiar items beginning at 200 ms. Although it is debated whether the novel popout paradigm measures involuntary attention, the relatively long latency of novelty detection is suggestive of a common underlying process.

A final remark concerns some speculations about the detailed causes of the prolonged dwelling on a surprise stimulus. Theorizing about surprise processes has suggested both low- and high-level contributions. Among the low-level processes proposed are changes of the memory structure on which expectancies are based (Horstmann & Schützwohl, 1998; Schützwohl, 1998), as well as thorough perceptual analyses (Horstmann, 2006). The greatest part of the delay, however, is probably due to high-level processing (Meyer, Reisenzein, & Schützwohl, 1997), including analysis of the antecedents and consequences of the surprising event.

To summarize, a surprising stimulus attracts the eyes and binds the gaze. The eyes are quickly drawn to the surprising stimulus, often following a single fixation to a distractor. When they are located on the stimulus, the eyes stay for a considerable time.

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