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Issue: *Competitive Visual Processing Across Space and Time***The surprise–attention link: a review**Gernot Horstmann^{1,2,3}¹Center for Interdisciplinary Research, ²Department of Psychology, ³CITEC, Bielefeld University, Bielefeld, Germany

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The surprise–attention hypothesis assumes a strong connection between surprise—expectancy discrepant events—and attention. Attention is easily engaged with surprising events, leading to long dwell times. In addition, if the expectancy discrepancy can be determined on the basis of simple, preattentively available information, attention can be captured by the surprising stimulus. This review summarizes different lines of research relevant to the proposed surprise–attention link: shifts of attention as indexed by accuracy gains and efficiency gains, validity effects, shifts of gaze, discrepancies in natural scenes, surprise-induced blindness, and action interruption. It is argued that there is convergent evidence for the surprise–attention link in general, and for the particular hypothesis that the underlying mechanism constantly tests expectancies on different levels of representation. Evidence also converges on a latency of an attentional engagement of nearly 400 ms. This seems to be a unique feature of surprise capture that also questions the validity of models proposing that saliency is an early automatic attractor of attention. Mechanisms possibly underlying the surprise–attention link are discussed.

Keywords: attention; prediction; expectation; surprise; novelty; singleton

Introduction: voluntary and involuntary attention

The voluntary (i.e., task-driven) control of cognitive processes, where task-relevant processes are prioritized over task-irrelevant processes, is an enormous evolutionary achievement. However, task-irrelevant processes cannot be entirely ignored, as they have to be monitored for important events. Voluntary—task-driven—attention must therefore be balanced by intelligent mechanisms of involuntary—task-independent—attention.

One way is to let the stimulus propose itself for selection, for example, by allowing stimulus properties like unique rapid luminance changes or movements to capture attention. This could be achieved by assigning a large attentional weight to these perceptually salient stimuli¹ or by giving them a high activation in an attention-controlling priority map (e.g., the superior colliculus (SC), lateral intraparietal area, or frontal eye field²). This approach is straightforward and computationally feasible to implement with simple physical filters.³ It could,

however, lead to a cognitive system that is overly responsive to external stimulation.

Research on the surprise–attention link pursues a different route. It is based on the assumption that stimuli can be either expected or unexpected. An expected stimulus is a stimulus whose presence and features are predicted on the basis of previously acquired information. Expected stimuli are the realm of voluntary attention, where top-down attentional-control settings are applied to known stimulus characteristics.⁴

If only expected stimuli that are readily classified as task relevant or task irrelevant existed, there would be little need for involuntary attention. Involuntary attention is necessary mainly because situations change and because knowledge about the current situation is incomplete, rendering planning and predictions fallible. It is, in particular, surprising and unforeseen stimuli that necessitate involuntary attention in the first place.

Humans and other mammals 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 chairs. Importantly, we do not need to actively search for these discrepancies. Thus, our expectations are constantly tested against reality in an automatic fashion.

The surprise–attention hypothesis^{5,6} entails that automatic discrepancy detection uses all perceptual information available, preattentive and postattentive, and engages attention with the surprise stimulus. All surprising stimuli bind attention; moreover, if the surprising stimulus is brought about by a preattentive feature channel, attention is automatically guided toward the surprising stimulus.

In the following, the available evidence for this hypothesis is reviewed. The review has seven sections that summarize the results for (1) shifts of attention as indexed by accuracy gains; (2) shifts of attention as indexed by efficiency gains; (3) validity effects; (4) shifts of gaze; (5) discrepancies in natural scenes; (6) surprise-induced blindness; and (7) action interruption. The review of empirical work is complemented by a discussion of theoretical and conceptual issues. The main part of the review focuses on studies that test the attentional response to the unannounced presentation of a novel feature presented for the first time in a critical trial. This procedure has the potential to induce strong expectancy discrepancies in the absence of an intention to search for discrepant stimuli. However, when discrepancies in natural scenes are discussed, studies are also reviewed that present discrepant items in many trials, although this repeated presentation conceivably minimizes expectancy discrepancy, and also introduces intentions to search for discrepant items. The relation of the surprise–attention link and electroencephalography research on novelty and discrepancy detection is not included in this review owing to space limitations and because this research uses rare events that may be perfectly expected (see section below “Is surprise just the same as rarity?”).

Accuracy gains

Gibson and Jiang⁷ were the first to test involuntary attention to a singleton color cue on its very first presentation. They presented eight letters for 86 ms, followed by a mask, with the task to discriminate the single target (H/U) among seven distractors (other letters). Because target–distractor similarity was high and search therefore was very inefficient,

the target was missed in many trials, and percentage correct was low during the precritical trials, where all letters were colored the same. When the target letter appeared in a different color in every trial in the second half of the experiment, performance was very good, showing that the singleton color could be processed preattentively and that attention could be voluntarily directed to the singleton. The very first presentation of the singleton, however, did not demonstrate this good performance; performance was not better than in the precritical trials. This result indicated that a surprise singleton does not capture attention.

Because other research already indicated that the surprise response might be slow,⁸ Horstmann *et al.*^{5,9,10} presented the surprising feature with a preview (Fig. 1). For instance, varying preview duration (0 ms versus 500 ms) revealed no indication of an attention shift with 0-ms preview (replicating Gibson and Jiang’s results⁷), but strong evidence for an attention shift with a 500-ms preview.⁵ These results were replicated and extended with additional preview durations.⁹ Here results indicated that with preview durations of 0, 100, and 200 ms, the attentional shift toward the surprise cue came too late to benefit performance, while performance improved relative to the precritical trials with stimulus-onset asynchronies (SOAs) of 400, 500, and 600 ms and was undistinguishable from the postcritical trials with previews of 500 and 600 ms. These results suggest that the latency of the attentional response to the surprise cue is about 400 ms under the tested conditions.

Some authors have argued that singletons should capture attention quickly, independent of surprise, and that this response occurs in a time range of 60–150 ms.^{11–13} Starting from this perspective, one might suspect that the singleton immediately captured visual spatial attention to its position, but that central processing was busy with the discrepancy and thus unable to process target–letter identity.⁷ Thus, the delayed benefits of the surprise cue would not be due to a delay in the attentional shift, but rather to interference between letter processing and discrepancy processing. These possibilities were tested¹⁴ by presenting the surprise cue at a distractor position such that shifting attention to the cue would be detrimental to performance (given the restricted presentation time of the letters). The delayed-shift account predicts that interference is

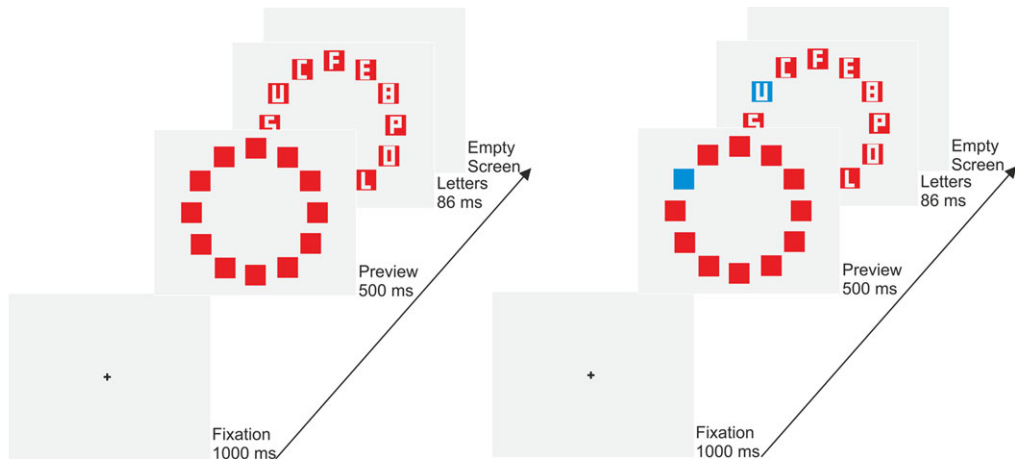


Figure 1. Schematic depiction of the two phases of a typical surprise experiment, including a preview display of the color patches that preceded the task-relevant letter stimuli by 500 ms. Left: in the precritical trials, all foreground display elements were of the same color. Right: in the critical trial and in the postcritical trials, the color of one display element was different. In most experiments, the oddly colored element was a cue to the target position.

low with short preview durations and high with long preview durations. In contrast, the interference account predicts the opposite, a fast onset of interference, possibly followed by recovery at longer previews. Results supported the delayed-shift account: there was little interference with a 100-ms preview, but strong interference with a 400-ms preview. Note that the letters were presented for 86 ms (unmasked) after the preview; thus, there was certainly enough time for an attentional shift with a latency of 60–150 ms to take place, even with short SOAs.

Reductions of the set-size effect

A standard measure of voluntary efficient selection and involuntary attentional capture is the reduction of the set-size effect in a visual-search paradigm. For a hard search, the time to find the target increases as the number of nontargets increases. This is the set-size effect. In contrast, in pop-out search, time to find the target is constant over set sizes.

A number of experiments^{5,6,14} thus presented the already-introduced three-block structure (precritical, critical, postcritical) in a two-group design varying set size (4 vs. 12). In the precritical trials, color-homogeneous displays were presented with no cues to the target, rendering search very inefficient. In the postcritical trials, where a color cue was always presented at the position of the target letter (either as a colored patch or as the color of the

letter itself), the set-size effect was strongly reduced. Importantly, the set-size effect in the critical trial was as small as in the postcritical trials, indicating that the time to select the cue was independent of set size, even on its first presentation.

One important question on the nature of the surprise effect is whether it is actually due to *surprisingness* or rather a somewhat late (see previous section) variant of singleton capture. This was tested by reducing the surprisingness of the color singleton in the critical trial.⁶ In one experiment, the precritical trials comprised all-red or all-green displays randomly intermixed, before a red singleton among green distractors was presented. In another experiment, the precritical trials comprised all-red displays in the first 24 precritical trials, and all-green displays in the second 24 precritical trials. In yet another experiment, each display contained both colors (red and green), arranged in an alternating (checkerboard) pattern. The effect in these three experiments was very similar: search in the critical trial was as inefficient as in the precritical trials. This result indicates that a singleton is not enough to capture attention on its first presentation; the singleton must also be surprising. This result pattern was replicated using (apparent) movement instead of color.¹⁴

A number of experiments presented irrelevant singletons during the precritical trials.⁶ For example, one experiment presented a green letter

among red letters in the precritical trials (always at a distractor location) and a white target among red distractors in the critical trial. There was no evidence of attention capture whatsoever in the critical trial. A number of candidate hypotheses could explain this result: (1) the surprisingness of the novel color was reduced because of the broadening of expectations in the precritical trials; (2) the surprisingness of the singleton was reduced to zero because a singleton was presented in each of the precritical trials; or (3) participants formed an attentional set that dealt with the irrelevant singleton.

First, it might be argued that the constant presentation of two colors in the precritical trials weakened the expectation and rendered the novel color in the critical trial less surprising. Indeed, it has been shown that surprise response (subjective, as well as reaction time (RT) interference) to the same stimulus is larger following constant versus varying stimulus layout in precritical trials.¹⁵ However, Horstmann and Becker¹⁴ found no detrimental effect of irrelevant color variation (all-gray and all-red displays, randomly intermixed) during the precritical trials on the attentional response to a novel color (green) in the critical trial. Apparently, two colors are not enough to broaden expectations to “any color.”

Second, the presence of singletons in all precritical trials should make their presence in the critical trial unsurprising. Singleton surprisingness alone did not seem to play an important role in surprise capture, as the first presentation of a singleton did not induce strong capture if its feature was familiar from the precritical trials (see previous section).

Third, presenting an irrelevant-color singleton on every trial will probably lead to a general task set to entirely ignore color singletons. One possibility to implement such a task set would be to filter out the irrelevant stimulation (e.g., by filtering out any color-feature contrast¹⁶), which could weaken the expectancy discrepancy of the novel feature. Another would be to tune attention to the relevant feature¹⁷ (e.g., by increasing its attentional weight), which would render the discrepancy less likely to drive attention.

To conclude, presenting salient events in every precritical trial renders them less expectancy discrepant. In addition, they become subject to

task-driven processing, which could lead an attentional set to entirely ignore salient events.

Validity effects

A third classical paradigm to reveal visuospatial attention shifts is the cueing paradigm, where visuospatial attention shifts are inferred from better performance when an attentional cue is presented at the position of the target (valid cue) than when the cue is presented at distance from the target at the position of a distractor (invalid cue). This paradigm has the advantage of avoiding possible problems associated with comparing different set sizes. For example, set size is necessarily confounded with either the density or the eccentricity of the stimuli.

Two experiments¹⁸ found the predicted validity effects for a color cue (red) after no-cue trials (medium gray). Although both groups performed equally well in the precritical trials, critical trial performance with the valid cue (the target letter was red) was much better than with the invalid cue (a distractor letter was red). This result was extended in a second experiment. First, the validity effect was not affected by presenting two homogeneous displays randomly intermixed in red or in gray in the precritical trials before presenting a green color cue among gray stimuli. This indicates that non-informative color variation does not (necessarily) corrupt the attentional response to a surprise color cue (we should expect, however, a corruption with higher variability¹⁵). Second, the critical trial either repeated the distractor color of the previous two precritical trials or presented the other distractor color. This manipulation had no effect on the validity effect in the critical trial, indicating that expectations are relatively global and that short-term expectations play a minor role.

Occulomotor capture

Does surprise capture the eyes? The tight coupling between attention and eye movements, both behaviorally¹⁹ and neurophysiologically,² suggests that attention and eyes should likewise be attracted by surprise. Few experiments so far have examined gaze shifts to a surprise stimulus. Godijn and Kramer²⁰ presented a surprise-onset stimulus on a surprise trial of a color singleton–search task, and found that it captured 28% of the first saccades. Unfortunately, the design of the experiment

leaves open the possibility that participants used “singleton-detection mode”²¹ to locate the target; with this uncertainty, it is unclear whether capture was due to surprise or rather to involuntary-contingent orienting.⁴

Horstmann and Herwig²² ported experiments on surprise color cues to the gaze-tracking domain: participants performed an inefficient letter search with letters presented on colored disks, which were uniformly colored until the critical trial, where the target was presented on a disk with a novel color. Main dependent variables were target-fixation latency and dwell time. Results showed a sharp drop in target-fixation latency from the precritical trials to the critical trial, indicating the capture of the gaze. Mean latency in the critical trial was 380–400 ms, matching estimates from the accuracy data. Dwell time on the target, in contrast, was strongly increased in the critical trial. The latter result supports previous theorizing that RT increases in the critical trial (which are almost always observed) mainly occur after the attentional shift. An analysis of the sequence of eye movements revealed that participants typically directed the second eye movement to the novel color, whereas the first eye movement typically targeted a distractor stimulus. This result can be understood in terms of biased competition: the first eye movement went to the stimulus that had been task relevant so far.

Episodic, semantic, and syntactic inconsistencies in natural scenes

The evidence reviewed so far used a clear-cut operationalization of expectancy and surprise: expectancies were induced by repeated and consistent experience with a familiar object feature, and surprise was induced by presenting a clearly distinct, novel object feature, unannounced, and for the first time. Karacan and Hayhoe²³ used a very similar paradigm in a virtual environment (see also Ref. 24). They found more fixations on unexpectedly displaced or changed objects within the virtual environment. This seems to be analogous to the increased dwell time in Horstmann and Herwig.²²

Other studies followed the lead of Loftus and Mackworth²⁵ and asked whether the eyes could be controlled by the relationship between global scene meaning and content of scene regions viewed in the visual periphery (for an overview, see Ref. 26). For example, Vö and Henderson²⁷ examined the ability

of semantically (a printer in the kitchen) or syntactically (a toaster floating in the air) displaced objects to capture or bind attention in computer-generated static scenes. Although Loftus and Mackworth²⁵ interpreted their results as showing that inconsistent objects drew attention and eye movements even if presented in the periphery, the later and often better-controlled studies found that these discrepancies affected dwell time but not fixation latency.

Still other studies looked at changes to scenes due to displacements, additions, or deletions of scene-congruent objects. That is, in contrast to the scene-inconsistency studies, these studies probed the availability of novel versus familiar scene content. For example, in one study (Ref. 28, experiment 3), participants were first familiarized with natural scenes, to which, in a second phase, a novel object was added during a saccade, such that the transient was masked by saccadic suppression of perception. They found early fixations on the novel object to be more frequent with than without familiarization. Vö *et al.* examined object displacements and found more fixations on the displaced objects;²⁹ they did not, however, find more early fixations on displaced objects.

To summarize, episodic, semantic, and syntactic inconsistencies in natural scenes bind attention and eye fixations. For the addition of novel objects (episodic inconsistencies), there might be a tendency for more early fixations after familiarization. For semantic and syntactic inconsistencies, however, there is little evidence that information before a fixation attracts attention and the eye from a different location. It should be noted that it is possible that participants in the reviewed studies actively searched for the inconsistent objects, as all studies tested quite a number of scenes with inconsistent objects, and inconsistent objects are arguably interesting parts of a scene. Moreover, the repeated presentation of inconsistent objects also compromises their expectancy discrepancy. After all, if inconsistent objects occur in each scene, they become perfectly expected.³⁰ Therefore, studies on scene inconsistencies do not examine involuntary attention. Rather, they test the degree to which observers have preattentive access to inconsistencies and novelty.

Why do simple color disks capture attention in sparse displays, but strange complex objects in cluttered scenes cannot easily be found? The most obvious explanation is that simple features

(color, movement) support efficient search, whereas the complex objects cannot be found efficiently. This fits well within classical visual search frameworks where basic features are processed spatially in parallel, whereas conjunctions and combinations of features have to be processed in a more serial fashion.³¹ That a basic feature–expectancy discrepancy is detected early and capacity free, whereas discrepancy detection for complex objects is late and capacity limited suggests that discrepancy detection works on whatever information is available.

Surprise-induced blindness

While the experiments discussed thus far explored visuospatial attention, Asplund *et al.*³² examined changes in temporal attention induced by a surprising event. They presented surprise stimuli within a rapid serial visual presentation (RSVP) stream and looked for effects analogous to an attentional blink. Surprise stimuli were repeated eight times, such that there was one surprise trial and seven repetitions. They found target discrimination at lag 1 (130 ms) and lag 3 (390 ms) impaired but not at lag 6 (780 ms). Target-detection rate was rather stable over repetitions for lag 1 and lag 6, which indicates that these effects are not surprise related. In contrast, the deficit at lag 3—which was the largest of all the lags—was much stronger in the first two presentations compared to later presentations. Further experiments showed that the relatively weak lag-1 deficit was probably due to the singleton status of the surprise stimulus within the RSVP, as the deficit disappears when the stimulus is presented frequently within a trial. The real surprise effect is, thus, at lag 3.

There is some indication that surprise-induced blindness (SiB) is a manifestation of the surprise–attention link. The relatively long latency with a peak at lag 3 (390 ms) reveals a time course very similar to surprise capture. That is, in both paradigms, the latency of the beginning of an attentional engagement with the surprise stimulus is around 400 ms. Disengagement followed a little later in surprise capture²² (e.g., around 600 ms) than in SiB³² (390 ms). It might be noted, however, that in surprise capture, disengagement is self-paced, whereas in SiB it is probably triggered by the target that has attentional priority as defined by the task. This

difference might well explain the somewhat different time course of attentional disengagement.

Action interruption

Experiments on surprise-induced action interruption yield some additional information on the time course of surprise. In addition, action interruption can be interpreted as indexing a shift in central attention that controls action.^{33,34} Meyer *et al.*^{8,35,36} were the first to examine RT interference in response to a surprising stimulus. They found pronounced delays in two-alternative forced-choice responses to the position of a dot induced by a centrally presented accessory surprise stimulus. The delay, however, was modulated by the SOA between surprise stimulus and reaction stimulus. With blocked SOA, interference was absent with simultaneous presentation, maximal after 500 ms, still present at 1000 ms, and absent again after 2000 ms. The time course was similar in an experiment where SOA varied within blocks, with the only difference being that strong interference was now also observed with simultaneous presentation. Results can be interpreted in a speed-race model, where surprise processes and response processes race toward a point of no return.³⁷ When the surprise process finishes first, action is interrupted and RT is delayed. When the response process finishes first, no delay is observed. Surprise beats RT only if given a head start, for example, when the surprise stimulus appears before the response stimulus, or when temporal uncertainty for the response stimulus is introduced (as in the variable-SOA condition). Niepel *et al.*³⁵ also tested an auditory version, where surprise was induced by a change from female to male voice, with a strong interference after 200 ms.

Horstmann examined whether surprise interrupts continuous action.³⁸ The continuous action was a bimanual, alternating tapping, which was performed in response to visual start, continue, and stop signals. Surprise was induced by single or multiple objects that were presented in the visual periphery. Results from four experiments showed that the majority (78%) of the participants interrupted tapping (criterion: >400 ms devoid of taps). Those who interrupted did so with a latency of 214 ms and a duration of 995 ms. The duration of the action interruption was related to the number and complexity of the surprise stimuli, indicating that the

novel stimuli were analyzed during the action interruption. The very high number of participants that interrupted and the very short latency may be seen as an optimal effect achievable under ideal conditions, because the surprising event had a unique onset³⁹ supporting attentional capture, which might have speeded up detection.

Overall, the studies on action interruption showed that surprise delays discrete action initiation and interrupts continuous action. These results are consistent with the assumption that surprise draws central attention away from the current task (e.g., the tapping) to an analysis of the surprise event, with the analysis probably related to some action-related aspects of the surprising event.

Is surprise just the same as rarity?

One might ask whether surprise is just the same as rarity. If so, previous research handicapped itself unnecessarily when testing only one critical trial (i.e., the unannounced first presentation). After all, there is only one surprise trial per participant, reducing experimental power and the chance to find small effects. There are at least three arguments against equating surprise and rarity.

The first is conceptual and relates to expectancy. If, as assumed, the surprise–attention link is actually mediated by expectancy discrepancy, then it follows that surprise and rarity are quite different things. Rare events are very often perfectly expected, or at least congruent with expectancy. For example, decision letters from peer-reviewed journals might be rare events in one's email traffic, yet their appearance is awaited and not unexpected (although sometimes their content is).

The second is theoretical and relates to intention. For a surprise presentation, there cannot conceivably be an intention to attend or ignore the surprise stimulus. (Note that in order to avoid transfer between experiments, participants are excluded from participation once they have completed one surprise experiment.) In contrast, rare events can be helpful or distracting, depending on the context of a task, and people learn quickly to adapt to these contingencies. Horstmann and Ansorge⁴⁰ presented color-cue trials either in pure blocks or with a frequency of <4% during mixed blocks, where the majority of trials were no-cue trials. The task was an inefficient letter search, and the cue (colored letter background) was either valid or invalid block-wise.

Accuracy was the dependent variable, and preview duration was varied as an additional independent variable to probe the time course of attention to rare events. Performance was very different with valid and invalid cues, even at short SOAs. Valid cues were immediately attended to, whereas invalid cues were completely ignored.

The third argument is empirical and relates to the time course. The time course of attention toward the rare-color cue is almost identical for rare as for frequent occurrences;⁴⁰ rare occurrences are only a little weaker in driving attention at very short preview durations than frequent occurrences. This contrasts with surprise presentations, where no attentional effects are observed with very short preview durations.

To summarize, although an examination of attention to rare events is important in its own right,⁴¹ testing rare events is no substitute for surprise presentations.

The time course of surprise capture: surprise versus saliency

The time course is probably the most contentious issue concerning surprise capture, because it questions the saliency-capture account that attention is quickly and involuntarily drawn to the most perceptually salient spot in a display.¹³

In particular, some studies found saliency capture in the range of 60–150 ms after stimulus onset.^{11–13} Moreover, some proponents specifically propose that saliency capture is an involuntary and early response, which might be countered by attentional control after 100–200 ms.¹³

If the saliency-capture account is true, why did the surprise stimulus—which was also a salient stimulus—not attract gaze much earlier? As Ansorge *et al.*⁴¹ pointed out, singleton capture (e.g., color) is almost exclusively found in experiments where participants search for a relevant singleton on another dimension (e.g., shape). Under these conditions, singleton capture can be accounted for by side effects of a top-down singleton-search task set^{4,21} rather than by pure stimulus-driven processes.¹³ In the surprise-capture experiments, care was taken to discourage a singleton-detection mode during the precritical trials: only one color was used in the display, and the target letters were constructed of the same horizontal and vertical line segments as the distractors. In

conclusion, one very plausible candidate for the absence of early capture on a surprise trial is that singleton capture was not triggered because the relevant attentional set (i.e., singleton-search mode) was missing. If this explanation is true, the implication is that the singleton-capture account^{11–13} is incorrect: singleton capture might be an early and unwanted form of distraction; however, it is not automatic but rather dependent on a relevant task set.

The cause of the time course of surprise capture

The time course of surprise capture cannot—at present—be fully accounted for. Candidates comprise at least (1) the perception of the surprise stimulus; (2) the detection of the discrepancy; and (3) the shift of attention.

First, the perception of the surprise stimulus might be delayed owing to its unexpectedness. It is a common assumption in theories of perception and cognition that expectedness speeds up processing, for example, by priming representations of objects before they appear.^{42–44} Unpredicted stimuli, however, may be at a disadvantage because recurrent processing loops between higher and lower perceptual areas that stabilize the percept need more time to become established.⁴⁵

Second, the detection of the discrepancy might also introduce a time lag. Unfortunately, little is known about the mechanism underlying discrepancy detection. One possibility that, however, does not explain the time course comes from predictive coding.⁴⁶ On this account, discrepancy detection is an emergent phenomenon that stems from an attenuation of familiar or predicted stimulation, and thus an indirect boosting of unpredicted and novel stimulation. As this suppression of predicted stimulation occurs early in visual processing, unexpected information would be available immediately. Thus, although such a system would easily explain the spatially parallel detection that characterizes surprise capture, it is less clear why the detection is delayed.

An alternative view starts from the assumption that the discrepancy is not in the stimulus but depends on the interaction between the stimulus and a memory representation. Depending on the stage of processing where expectancy and stimulus are compared, more or less time will elapse. The stage for comparison that suggests itself is working memory,

which is classically viewed as the stage where representations are compared.⁴⁷ Visual working memory, however, is highly limited in processing capacity. This capacity limitation would predict discrepancy detection to be strongly dependent on set size; the relevant experiments,⁶ however, clearly show that this is not the case. In recent years, a number of theorists have proposed a capacity-free path for the guidance of attention that uses global features of the scene to guide attention.^{48,49} Global nonselective image processing is assumed to extract statistical information rapidly from the entire image, such that observers have access to summary statistics such as mean and distribution of basic visual features.⁴⁸ This nonselective pathway may well be the basis of discrepancy detection in the studies reviewed here (see also Ref. 44, for a discussion of working memory versus online representations as a basis for change detection). Independently of the exact comparison stage, the discrepancy detection is not for free and will cost some time.

Finally, the shift of attention may be delayed, and this delay may result from competition for attentional resources. The surprise stimulus is presented together with stimuli that had been task relevant during the precritical trials. According to the biased-competition approach,⁵⁰ (visual) stimuli compete for representation in the brain. Competition, however, is not fair, but rather biased: stimuli that are related to the task have a higher probability of being encoded than task-unrelated stimuli. Thus, the surprise stimulus is in competition with stimuli to which task-driven attention is biased. This approach is in line with the finding that the first eye movement in the critical trial often went to one of the letters on a familiar color, to which selection is biased because it was the task-relevant color in the precritical trials. On a biased-competition account, the shift to the novel color can be delayed if priority signals from the biased color are initially stronger than a priority signal from the novel color.

To conclude, surprise capture might be rather slow for unattended objects, because of the way the cognitive system is built to achieve task-driven processing, when activation of expected information and biases in competition have to be overcome. From an evolutionary perspective, the fastest possible response to expectancy-discrepant events is predicted; however, the rather slow development of surprise might be as fast as is possible, given that

compromises have to be made between task-driven and task-independent processes.

Macrosurprise and microsurprise

Itti and Baldi proposed a Bayesian model to detect surprising events on video.^{51,52} Their approach contains similarities and differences to the present one. The main similarity is the emphasis on expectations to define informative events, and the authors provide a formal description of how expectancies are learned, are used to detect surprises, and are updated after the surprise by using Bayesian modeling. This formal description nicely converges with more cognitive accounts of surprise.^{5,6,15} The most important difference is probably the temporal and spatial grain of surprises. Bayesian surprise models evaluate essentially pixel-wise expectations and surprises on a time scale ranging from one video frame to seconds (microsurprises). This is reasonable, as their aim is to provide a framework to detect salient events that are better than previous saliency models,³ both practically and theoretically. The research reviewed here regards surprise as a response to object properties, and expectancies are assumed to build over rather long time periods (macrosurprises). For example, it has been shown that a color that is presented only in the beginning of an experiment is still expected in later trials.⁶ Nevertheless, the Bayesian surprise model might prove useful for future modeling of macrosurprises, as well.

Conclusions

The purpose of this review was to summarize the empirical basis of the surprise–attention link. It is argued that the surprise–attention link is supported by a large number of experiments using converging operations. Evidence for the capture of visuospatial attention comes from accuracy gains, reductions of the set-size effect, validity effects, and oculomotor capture. In addition, surprise-induced blindness and action interruption provide evidence for the capture of central attention by surprise.

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Conflict of interests

The author declares no conflicts of interest.

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