How unexpected features capture visual attention and the gaze

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Summary

In visual attention research, a current topic of debate is to what extent visual attention is biased by bottom-up factors (e.g., stimulus saliency), and by top-down factors (e.g., goal contingent orienting). The present work centers on the specific factor of expectation discrepancy, which likewise attracts attention, but does not fit clearly into either of the two categories. The effect of expectation discrepancy is usually tested by first familiarizing participants with a number of search displays containing color homogeneous stimuli, such that they expect the continuous presentation of the stimulus features also for the following trials. If then a single stimulus with a novel color (a "singleton") is shown unannounced and for the first time in a surprise trial, it captures visual attention and the gaze. Over the course of three studies, the present work demonstrates that a novel feature must not necessarily be presented by means of a novel singleton to attract attention; that is, feature novelty alone is sufficient. The first study shows that a task irrelevant color singleton that was shown in every search trial strongly captured the gaze if it was presented unannounced with a novel color. Furthermore, the study tested an alternative explanation, being that surprise solely interrupts attentional control settings, which causes a reorientation towards perceptual saliency. However, results showed that such an effect does not contribute substantially to surprise capture. The second study yields evidence that surprise capture of the gaze by a novel color covaries with expectation narrowness of the familiar color. It was assumed that an expectation about a color becomes narrower with lower previously perceived color variability and with an increasing number of sampling occasions. Thus, expectation discrepancy of a novel singleton color should be high with a narrow color expectation and low with a broad color expectation. Experiments using a similar paradigm as the first study demonstrated that higher color variability of an irrelevant singleton and fewer familiarization trials reduced surprise capture of the gaze as an indicator for expectation discrepancy. An

approach to mathematically model the emergence of an expectation was proposed. The third study shows that novelty can compete with saliency for attentional prioritization. More precisely, it was demonstrated that gaze capture of a novel color singleton in a surprise trial is attenuated if the remaining non-singletons likewise have a novel color, which in turn receive increased attention. The data pattern can be predicted by assuming novelty as an additional source of activation in a noisy priority map for visual attention. Together, the three studies contribute to a more precise specification of the mechanisms that link expectation discrepancy with visual attention.

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1 Introduction

Every day we conduct a high number of visual searches. Some searches are fast, like the search for a coffee mug in an assorted cabinet, whereas the search for our keys on a messy desk can take longer. When driving, we are constantly seeking out any hazards on the road, allowing us to accurately react to any signs of danger. While we are awake, there is hardly a time when we are not searching and sometimes we find things, even though we might not have had an intention to search for them. For instance, if our partner has decided to secretly exchange the antique ceiling lamp for a spacy green one, we would probably detect the novel object immediately when we enter the room for the first time. One cognitive mechanism that guides our searches, such that we can orient efficiently through our environment, is visual attention.

Our visual system cannot effectively process every stimulus that is mapped by the retinas of our eyes, such that we become aware to all of them at the same time. Attention is the mechanism that selects a smaller subset of objects for further processing. However, previous research shows that attention allocation is not always voluntary with only focusing on objects in a goal orientated manner. For instance, sometimes we can quickly react to an approaching snowball, even though we have not yet realized that we got into a snowball fight and should search for or attend to snowballs. In scientific literature, such phenomena are described as attention capture effects, which occur automatically or involuntarily (e.g., Jonides, 1981; Theeuwes, 1992, 2010). Often, attention capture is categorized into stimulus driven and goal driven effects.

1.1 Saliency capture

Stimulus driven attention capture is postulated to depend on the physical characteristics of a stimulus. The most decisive factor for stimulus driven attention capture is the saliency of a

stimulus, which is high when a stimulus has a high feature contrast to its surrounding stimuli (Itti & Koch, 2000, 2001; Parkhurst, Law, & Niebur, 2002). Hence, this form of attention capture is often called "saliency capture" (Theeuwes, 1991, 1992, 2010). Theeuwes (2010) states that saliency capture occurs at the initial (parallel) stage of visual processing where it is completely unsusceptible to goal driven influences. A widely used experimental method to demonstrate saliency capture is the additional singleton paradigm (for a detailed overview see Becker, 2007; Simons, 2000). In every trial, participants are presented with a number of stimuli that are evenly arranged on an imaginary circle. Often, it is the participants' task to search for a shape singleton (e.g., a single diamond among circles) and to give a manual response depending on a stimulus that is situated within the form singleton (also called compound search; "identify the letter inside the singleton"). A saliency capture effect is interpreted when the presence of an additional color singleton (e.g., a red circle among green circles) increases manual response times as compared to search trials where it is absent. This method is called additional singleton paradigm because the distractor singleton can never contain the target. Usually, participants are informed about the anti-predictiveness of the additional singleton. Thus, if it still captures attention, the mechanism is often assumed to be purely stimulus driven (e.g., Theeuwes, 1991, 1992, 1994, 2004).

1.2 Contingent capture

In contrast, goal driven attention capture is postulated to occur contingent on the current visual features we are searching for. At first glance, it might be confusing why goal driven attention capture matches the criterion of being involuntary. However, experiments show that if participants search for an object with a specific stimulus feature like red color, other stimuli with red color can capture attention in an accidental manner (Folk, Remington, & Johnston, 1992, 1993; see also Yantis & Egeth, 1999). In its strongest version, the "contingent capture" hypothesis

states that attention is never purely stimulus driven and solely depends on the attentional set of the observer. In similar theories, like the dimensional weighting account, it is assumed that observers can voluntary increase the weight of a feature dimension (e.g., color), but not the weight for a specific feature (e.g., red) within a dimension (Found & Müller, 1996; Müller, Reimann, & Krummenacher, 2003; but see also Wolfe, 1994, for "Guided Search", which assumes prioritization of specific features, for instance).

It has also been proposed that participants can adopt a search mode where they generally search for salient stimuli ("singleton detection mode"), regardless of their feature dimension (Bacon & Egeth, 1994). Consequently, any salient stimulus receives increased attention as a more convenient search strategy. Singleton detection mode has been taken as an alternative explanation for the saliency capture account in additional singleton paradigms. Bacon and Egeth (1994) prevented participants from using a singleton search strategy by either adding additional target shapes to the search display (Experiment 2) or by adding additional non-target shapes, such that the target shape was not the only unique shape anymore. With both measures, an additional color singleton distractor did not increase manual response times, which further questioned the existence of saliency capture.

1.3 Contingent capture vs. saliency capture

Theeuwes (2004) argued that higher shape variability in the experiments of Bacon and Egeth (1994) also resulted in lower saliency of the color singleton distractor, reducing its potential to bias attention in a stimulus driven manner. Previous studies showed that the pop-out effect of a salient stimulus can be reduced by increasing feature heterogeneity of the remaining stimuli (Duncan & Humphreys, 1989, 1992; Nothdurft, 1993) Thus, Theeuwes (2004) further pronounced the saliency of the red color singleton distractor by adding additional green stimuli

and found increased reaction times in distractor trials. Note that a red singleton is perceived as more unique when it is surrounded by 19 green stimuli than when it is surrounded only by four green stimuli.

It becomes obvious that there is a controversy between authors who advocate strong versions of either the contingent capture hypothesis or saliency capture hypothesis, which is still present today. One problem for the demonstration of purely stimulus driven attention capture is that in most experiments the salient distractor is presented repeatedly over several hundred trials and thus is highly expected. The expectancy of a salient stimulus makes it difficult to exclude top-down explanations, such as singleton search mode. Gibson and Jiang (1998) proposed to test the very first presentation of a salient stimulus in order to demonstrate the existence of purely stimulus driven attention capture that is not influenced by top-down effects; that is, either top-down prioritization of salient stimuli but also inhibition. The authors conducted an experiment with search displays where several letters of white color were evenly distributed on an imaginary circle. Participants had to decide whether the display in a trial contained either the letter H or U, one of which was always present. The search display was only shown for 86ms, which is too fast to use eye movements to facilitate search. As we will see later, the presentation time is a crucial factor for attention capture. The 193rd trial was the critical surprise trial where the target letter was shown with a red color without prior announcement (Experiment 1), resulting in a singleton. In the following 192 post-critical trials, the red color was presented repeatedly at the target position. However, Gibson and Jiang (1998) could not find any differences between pre-critical trials and the critical trial, as indexed by the proportion of correct responses. In post-critical trials, participants could respond highly correct as the expectation of a red target resulted in an easy feature search. Gibson and Jiang (1998) interpreted this result such that pure stimulus saliency is

not sufficient to capture attention, whereas an intention to search for salient stimuli is a necessary condition.

However, this result is at odds with studies that investigated the presentation of unannounced events from a cognitive-evolutionary perspective. Several studies contained experiments where an unexpected change was implemented into a single stimulus choice task (Meyer, Niepel, Rudolph, & Schützwohl, 1991; Schützwohl, 1998). In every trial, two irrelevant words were presented for three seconds in different rows at the center of the screen. The participant's task wo to indicate whether a dot appeared above or below these two words. After a number of pre-critical trials, a critical surprise trial followed where one of the two words was presented with a new background color. Results demonstrated an increased manual response time in the critical trial. The authors concluded that the attentional focus was involuntary directed towards the unexpected stimulus, accompanied by the interruption of the ongoing task and an analysis of the unexpected event.

With respect to the experiment of Gibson and Jiang (1998), Horstmann (2002) argued that the presentation duration of 86ms for the search display could have been too short for the emergence of a saliency effect if a singleton is presented for the first time. A closer look at the experiments of Meyer et al. (1991) with varying stimulus onset asynchronies (SOA) reveals that the effect of the new background color on manual response times was stronger when the surprising event was presented 500ms before the imperative stimulus (Experiment 1) as compared to when they were presented simultaneously (Experiment 4). Horstmann (2002) used a similar experimental design to Gibson and Jiang (1998). However, search letters were placed within colored squares (e.g., green). Before the search letters appeared, a preview display has been presented for 500ms that only contained the squares as placeholders (without the letters). In the 49th trial, the square at the target position was presented for the first time with a novel color

(e.g., red), resulting in a color singleton. Attention capture was illustrated by the unannounced color singleton as indexed both by the proportion of correct answers (Experiment 1) and the reduction of a set-size effect with manual response times (Experiment 3, without preview display but with 4000ms presentation time of the search display). Overall, results of Gibson and Jiang (1998), Horstmann (2002), and Meyer et al. (1991) demonstrate that without an intention to search for singletons, a salient stimulus takes more than 86ms to elicit an attentional bias, whereas a period of 500ms is sufficient. However, Horstmann (2002) did not ascribe this effect to purely stimulus driven processes but to a specific mechanism where attention is directed towards stimuli that induce surprise as the result of violated expectations or schema discrepancy.

1.4 Surprise

The phenomenon of surprise has already been discussed by Aristotle (cf. Reisenzein, Horstmann, & Schützwohl, 2017). From an early emotion psychological perspective, Darwin (1872/1965) described that focused attention is universally accompanied by a slight elevation of the eyebrows, and that surprise is an even more focused state of attention where the eyebrows further increase and additionally the eyes and the mouth are widely opened (although empirical support is relatively weak, Reisenzein, Studtmann, & Horstmann, 2013). In the 20th century, it could be empirically demonstrated that within a series of letters, a specific one can be remembered better if it is presented unannounced with a novel color (Wilcocks, 1928). It was inferred, that better memory must have been due to increased attention to a letter with an odd color. A similar phenomenon has been described as the orienting reflex (Sokolov, 1963), which is elicited when perceived information does not fit into a neuronal model of the environment. However, the orienting reflex decreases with repeated presentation of the unfamiliar information, which causes an update process of the neuronal model.

1.4.1 The cognitive-evolutionary model of surprise

More recently, a cognitive-evolutionary model of surprise has been formulated that integrates several earlier theories of surprise (Meyer, Reisenzein, & Schützwohl, 1997; Reisenzein et al., 2017). To explain the basic mechanism that elicits surprise, the model uses a cognitive approach basing on schema theory (Mandler, 1984; Rumelhart, 1984; Rumelhart & Ortony, 1977). It is assumed that humans are equipped with schemas that serve to understand external input and to interact with the environment on both the cognitive and behavioral level. A schema represents theories or beliefs about objects, situations and events. For instance, schemas for a psychological conference can include colleagues, talks, posters, and snacks. Furthermore, these objects and events come along with typical features, which are also represented in schemas. Posters are usually printed on white background, and beamer presentations are usually in landscape format. Schemas organize information as derived from current situations, but they can also be used to predict future states (Rumelhart & Ortony, 1977). Furthermore, it is assumed that schemas are continuously controlled with respect to their functionality to comprehend the current input. This proceeds automatically and without conscious intentions. If a discrepancy between a current schema and external information is detected, a state of surprise is elicited, and the current schema will be revised such that in can comprehend the new information in the future. Crucially, if schema discrepancy exceeds a specific threshold, several mechanisms will be activated that motivate the observer to reach a state where the strong schema discrepancy is corrected (Schützwohl, 1998). The mechanisms include the automatic interruption of ongoing behavior followed by the orientation of attention towards the unexpected event (see also Darwin, 1872/1965). Furthermore, a conscious feeling of surprise is perceived. When attention is focused on the unexpected event, it will be analyzed with respect to a) the verification of schema

discrepancy, b) its causes, c) relevance for current and future actions, and d) implications for the individual's well-being (Meyer et al., 1997).

1.5 Surprise capture

The automatic interruption of ongoing behavior followed by the orientation of attention towards surprising events seems to match the general criteria of attention capture as described before. Furthermore, these processes yield a good explanation for the mechanism that caused attention capture of an unannounced color singleton in Horstmann (2002). To establish surprise capture as a distinct form of attention capture besides saliency capture and contingent capture, Horstmann (2005, 2006) closely investigated the specific conditions of surprise capture. Time course analyses with a similar experimental design as described above for Horstmann (2002) were conducted. However, the SOAs between the singleton at the target position in the preview display and the onset of the search letters were varied (Horstmann, 2006). Results showed that the very first presentation of a singleton at the target position could only improve search performance with an SOA of 400ms or higher. A later study showed that that the effect of surprise capture reduces if the novel singleton is not presented continuously within the SOA (Horstmann & Becker, 2008). However, as soon as the singleton at the target position was presented repeatedly, participants used a feature search mode where search performance was readily improved if singleton and search letters were presented simultaneously.

A distinction between contingent capture and surprise capture is already obvious for theoretical arguments, because it is unlikely that participants have an intention to search for a specific feature that is both irrelevant and unexpected. Overall, contingent capture appears to play a crucial role for focused attention towards task relevant features without distraction from

task irrelevant features. In contrast, surprise capture directs attention towards stimuli that are unknown, however can be relevant.

The results of Horstmann (2006) show that surprise capture and contingent capture phenomenally differ by the very slow nature of the former and the relatively fast nature of the latter. The results, however, are less clear with respect to the distinction between surprise capture and saliency capture. Note that a surprising singleton is both unexpected and salient. Thus, attention capture in the critical trials of Horstmann (2002, 2006) could also be explained by saliency capture.

Time course analyses for effects of salient stimuli that have been interpreted as stimulus driven suggest a latency of 60-150ms (Kim & Cave, 1999; Theeuwes, 2010). Thus, if a salient stimulus always receives the most attention at the initial stage of visual processing (Theeuwes, 2010), one would have already expected the emergence of a singleton effect in Gibson and Jiang (1998) and following replications as in Horstmann (2002, Experiment 2) and Horstmann (2006, Experiment 2 with 0ms SOA) since in these experiments, the color singleton was presented for 86ms together with the target. Possible interpretations would be that saliency capture was either absent in these experiments or only exists of the salient stimulus has been presented before, while the latter questions the postulated purely stimulus driven nature of saliency capture.

Attention capture of an unannounced color singleton can occur because of several reasons. First, the unexpected feature of the singleton; second, the unexpected presence of salient stimulus per se; third, purely stimulus driven saliency capture that does not depend on unexpectedness. On principal, these sources of attentional prioritization are not mutually exclusive. Horstmann (2005) disentangled these potential sources within a series of visual search experiments, which all had the same critical trial with an unannounced color singleton at the target position that was either red among green non-singletons or vice versa. The experiments differed, however, with

respect to stimulus features presented in pre-critical trials, and thus which expectations were built up in advance of the surprise trial. In Experiment 5, for instance, 50% of pre-critical trials contained stimuli that were homogeneously green in color, whereas stimuli within the remaining trials were all red. Stimulus color randomly altered between pre-critical trials. Thus, the red or green singleton in the critical trial had pure singleton novelty without feature novelty. However, results suggested that pure singleton novelty is not sufficient to capture attention. An equivalent experiment by Becker and Horstmann (2011), who tested a motion singleton instead of a color singleton and still yielded the same result. If all search stimuli in 50% of pre-critical trials rotated, a single rotating stimulus in the surprise trial did not capture attention (Experiment 2), whereas it captured attention if no stimulus rotated in pre-critical trials (Experiment 1). Thus, feature novelty seems to be the more decisive factor for surprise capture in contrast to singleton novelty (and stimulus driven saliency). Experiment 3 of Horstmann (2005) presented an irrelevant singleton of the orientation dimension already in the pre-critical trials. However, the color singleton at the target position still captured attention. Thus, specific expectations appear to be built up for different feature dimensions and pure feature novelty in the absence of singleton novelty is sufficient to capture attention.

That a feature can capture attention is in line with models of visual attention that assume two stages (Neisser, 1967; Treisman & Gelade, 1980; Wolfe, 1994, 2007). Within the first stage, basic stimulus features in the color, shape or orientation dimension are processed in parallel and "pre-attentively". However, if observers intentionally search for objects that are constituted by a composition of several features, these features must be bound at a second stage of visual processing, which needs the serial allocation of attention in space. Thus, the expectation-discrepancy hypothesis for surprise capture states that features, which can be processed pre-attentively and in parallel capture attention to the degree that they are discrepant from

expectations (Horstmann, 2005, 2015). However, complex stimuli whose unexpected aspect refers to a combination of basic features cannot capture attention, although they can bind attention after they have been selected (e.g., Võ & Henderson, 2009; Võ, Zwickel, & Schneider, 2010).

1.5.1 Surprise capture and inattentional blindness

On principal, the repetition-change paradigm used in surprise capture experiments is similar to the paradigm that is used in experiments for inattentional blindness (IB, Mack & Rock, 1998). However, surprise capture experiments are analyzed with respect to attentional prioritization of the unannounced stimulus, whereas experiments on IB seem to center on the opposite; that is, how often the stimulus was not attended.

Models of IB consider saliency and target similarity of the unannounced stimulus, such that both reduce IB rates (Most, Scholl, Clifford, & Simons, 2005). Horstmann and Ansorge (2016) showed that expectation discrepancy likewise reduces inattentional blindness rates in that participants had increased awareness of a stimulus with a novel color that deviated both from the target and the previous distractors, while saliency was controlled. The authors proposed to integrate expectation discrepancy into the model of inattentional blindness.

1.5.2 Unexpectedness of events

In the literature of visual attention, there is a variety of opinions about when an event or a stimulus is described as unexpected. In the studies discussed so far, only the very first presentation of a novel stimulus has been interpreted as unexpected. Testing the effect of a novel feature solely with a single surprise trial is a safe method to exclude attentional processes that could otherwise be attributed to strategical orienting. Some authors refer to unexpected events

even if they are presented in 10-20% of search trials (e.g., Brockmole & Boot, 2009; Folk & Remington, 2015). However, even rare events can be completely expected. For instance, rolling two sixes in a game of dice is a rare event but it is not unexpected. Accordingly, Horstmann and Ansorge (2006) showed that participants reacted faster to target letters that were presented in a salient fashion with a probability of only 4%, than when the target letter is shown for the very first time in a salient fashion (Horstmann, 2006). Another example yields Experiment 6 of Horstmann (2005). The pre-critical trials were divided into two sub-blocks. Overall, there were 48 pre-critical trials. Within the first 24 trials, all search stimuli had the color that was used in the critical trial for the singleton (e.g., red). Within the following 24 pre-critical trials, all search stimuli had the color that was not used for the singleton (e.g., green). Even though the first presentation of the singleton and the last presentation of the singleton's color were separated by 24 pre-critical trials, results suggested no surprise capture in the critical trial.

Furthermore, in the following text, the words novelty and unexpectedness (or surprise) will be used synonymously for the sake of simplicity and increased readability. In most cases, a novel event is also surprising (Barto, Mirolli, & Baldassarre, 2013). However, differences between novelty and surprise will be discussed at a later point of this work.

1.5.3 Inferring surprise capture from manual response times

The studies described so far inferred attention capture by the proportion of correct manual responses and manual response times. If the surprising singleton cues the target position, there will be a higher probability to give a correct response (for limited presentation duration) and manual response time will be decreased as the target can be found faster (see also Horstmann & Becker, 2011, for more on validity effects). In case of manual response times, authors often infer attention capture from the reduction of a set-size effect. Basically, a set-size effect emerges if an

increased number of search stimuli results in increased search times for the target. However, searches for color singletons, for instance, have been found not to increase with display size, which has been taken as evidence that the respective target feature can guide attention pre-attentively and in parallel (Treisman & Gelade, 1980). Search times for targets that are constituted by a conjunction of features usually increase with higher numbers of distractors. In this case, search and attention allocation is assumed to occur in a serial manner. Although the theoretical dichotomy between parallel and serial search has been revised in favor of a continuous transition from efficient to inefficient searches (see the Guided Search model, Wolfe, 1994, 1998, 2007), reductions of set-size effects in trials where target and singleton position coincided can still indicate attentional capture and guidance. However, as outlined before in the cognitive-evolutionary model of surprise, involuntary orienting of attention towards the surprising event is immediately followed by an analysis of the present conditions (Meyer et al., 1997). Accordingly, results of Horstmann (2005) suggest that even with small display sizes of four items, a surprising singleton at the target position can increase manual response times as compared to pre-critical trials without a salient target position. This increase can be attributed to processes that occur after the first selection of the surprising singleton (Horstmann, 2005). It is assumed that the same increase likewise occurs in larger display sizes. Thus, a reduction of a set-size effect in the critical trial is still an indicator for attentional prioritization of the surprising singleton (Horstmann, 2005). However, a better method to disentangle attentional prioritization into processes that occur before, at, and after the first attentional selection of a stimulus is given by the analyses of gaze behavior.

1.5.4 Surprise capture of the gaze

Within a fixation, only the central region of about 2° of visual angle can be processed with high spatial resolution by our visual system (Strasburger, Rentschler, & Jüttner, 2011). We compensate this inhomogeneity with eye movements, such that the area of interest in our environment is mapped at the center of our retina. Accordingly, studies have demonstrated that covert shifts of attention (within a fixation) precede overt shifts of attention in the form of eye movements (Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995). Therefore, gaze behavior is often interpreted as a proxy for visual attention.

Horstmann and Herwig (2015) conducted similar experiments like in Horstmann (2005), where the target letter in the critical trial was singled out by a distinct color. Here, they also found that manual response times tended to increase in the critical trial, even though it should have facilitated the search for the target. However, the analysis of gaze data revealed that the first fixation of the target marked by a surprising singleton in the critical trial had an average latency of about 400ms, which replicates the findings of Horstmann (2006), while it was about 760ms in pre-critical trials with homogeneous search displays. Importantly, the authors also found that the gaze dwelled relatively long at the surprising singleton after its first selection. It could be shown that increased dwell time contributed substantially to the increase of manual response time in the critical trial. This result was important to confirm whether the increase in manual response times in previous studies of Horstmann and colleagues with small display sizes, was actually due to effects that occurred after the surprising stimulus had captured attention. Crucially, Horstmann and Herwig (2015) demonstrated that surprising singletons do not only capture covert attention but also attract the gaze.

2 Present studies of the project

In the following, three present studies of the project are introduced that tie in with the previous research on surprise capture. The first study "Pure colour novelty captures the gaze" (Ernst & Horstmann, 2018) established a paradigm to test feature novelty in the absence of singleton novelty. Furthermore, the study tested an alternative explanation of surprise capture, being that the unannounced presentation of a novel feature induces a breakdown of the previously acquired attentional set, causing a reorientation towards perceptual saliency. The second study "Unexpectedness increases singleton capture of the gaze" (Ernst & Horstmann, submitted) used the paradigm of Ernst and Horstmann (2018) to examine whether expectation discrepancy of a novel color feature can be varied by manipulating expectation narrowness prior to the surprise trial by distinct mechanisms, and proposes an approach to mathematically model expectations. The third study "Novelty competes with saliency for attention" (Ernst, Becker, & Horstmann, submitted) deals with the question of how surprise capture can be integrated into prevalent models for visual attention deployment. The study tests if surprise capture by an unannounced singleton with a novel color is attenuated when the remaining non-singletons likewise have a novel color, which would be predicted by priority maps with the additional assumption that feature novelty always attracts attention, regardless of saliency. Together, these three studies focus on the question of how feature novelty in the absence of singleton novelty affects attentional prioritization and gaze behavior, and how these effects are mediated by expectations.

2.1 Pure feature novelty is sufficient to attract attention

Several previous studies already suggested that for surprise capture by an unannounced singleton, feature novelty is the more decisive factor than singleton novelty. In Horstmann (2005), an announced singleton captured attention when it had both singleton novelty and color novelty.

However, if the singleton color had already been presented in pre-critical trials, novelty in the critical trial only referred to singleton status and no surprise capture could be found. Another study used displays that included only two stimuli with equal size and luminance, rendering both stimuli comparable with respect to saliency (Horstmann & Ansorge, 2016). Participants had to perform a target indication task. In the critical trial, the distractor was replaced by a novel shape. Inattentional blindness rates indicated that the novel shape was noticed more frequently when it was presented simultaneously with a novel color as compared to when it had a familiar color. Similarly, Horstmann and Herwig (2016) presented color homogeneous search displays with eight stimuli that were evenly arranged on an imaginary circle. In the critical trial, however, four adjacent stimuli had a novel color, whereas the remaining four adjacent colors still had the familiar color. Thus, the display in the critical trial was divided into a familiar and a novel side with comparable saliency. Gaze data showed that the first fixation after search display's onset went equally often to both sides. From the second to the fifths fixation, however, the novel side was fixated more frequently. Horstmann and Herwig (2016) did not explicitly label the effect attention "capture", possibly because the novel side had a chance level of 50% to be fixated and attentional prioritization was not pronounced enough to clearly justify an interpretation in the sense of attention "capture".

Ernst and Horstmann (2018) used a different approach to test the effect of pure feature novelty. They presented a search irrelevant singleton along with seven non-singleton stimuli already in the pre-critical trials. The surprising event in the critical trial was an unannounced color change of the singleton (e.g., from red in pre-critical trials to green in the critical trial). A similar design was already used in Horstmann (2005), but yielded negative results for surprise capture. It was argued that surprise capture in Horstmann (2005) could have been weaker as participants in pre-critical trials were already familiarized with two colors (the singleton and the

non-singleton color), such that a third color in the surprise trial resulted in lower expectation discrepancy. Furthermore, gaze behavior, which has been recorded in Ernst and Horstmann (2018), should yield more sensitive dependent variables than set-size effects of manual response times. As an additional measure to find weaker effects, Ernst and Horstmann (2018) also used a target detection task where participants had to indicate the presence or the absence of a closed ring among several rings with a gap. The critical trial was always a target absent trial, such that attentional prioritization of the singleton could be measured that was not confounded with the presence of a target.

Results suggested only a slight attentional bias towards the color singleton in pre-critical trials, as indexed by a somewhat higher fixation probability for the singleton than on the remaining non-singleton stimuli within the first three fixations after search display's onset. In the critical trial where the singleton was presented with a novel color, a strong gaze capture occurred as indicated by an average latency of the first singleton fixation of 425ms (average singleton fixation latency was 1070ms in pre-critical trials). Thus, there was a similar time course to surprise capture effects of previous studies where both singleton and color novelty were present (e.g., Horstmann, 2006; Horstmann & Herwig, 2015). It was mainly the second fixation, which targeted the singleton with the novel color. Furthermore, the effect of increased dwell times that was observed in Horstmann and Herwig (2015), could also be found in this experiment. However, not only did the singleton in the critical trial received longer dwell times. Likewise, non-singleton stimuli that still had the familiar color were gazed at longer compared to pre-critical trials. For the latter effect, it was proposed that participants could have used a more conservative decision criterion. However, that any stimulus in a surprise display is inspected more thoroughly could also reflect causal analyses of the surprising event as postulated by the cognitive-evolutionary model of surprise (Meyer et al., 1997).

Ernst and Horstmann (2018) discussed an alternative explanation of surprise capture, being that the surprising presentation of a novel feature causes an error signal, which disrupts search on the basis of the previously acquired attentional set (see also Folk & Remington, 2015, for a similar account). According to this hypothesis, prioritization of a novel object would not be due to an active orienting towards unexpected stimuli. Instead, the breakdown of the previously acquired attentional set leads to a reorientation towards perceptual saliency. This hypothesis could alternatively explain surprise capture in experiments where the novel feature is presented by means of a singleton. On principle, however, the attentional control interruption account and the surprise capture account are not mutually exclusive.

Mind that in Ernst and Horstmann (2018), a singleton was already presented in every pre-critical trial and the data suggested only a very slight attentional prioritization. Thus, it is likely that participants inhibited the singleton color at least to some extend as a strong prioritization of the search irrelevant singleton would have rather impeded search performance. In line with this hypothesis, suppression effects of singleton distractors have been found to increase with more frequent presentations of the singleton, and crucially being strongest if a color singleton distractor is presented in all trials from the beginning of the experiment (Müller, Geyer, Zehetleitner, & Krummenacher, 2009).

To test this attentional control interruption account in isolation, Ernst and Horstmann (2018) conducted a second experiment, which was similar to Experiment 1. However, instead of a singleton color change, they presented a novel background color as a novel non-local feature in the critical trial, whereas the singleton color remained the same as in pre-critical trials. It was assumed that if a novel singleton color would interrupt attentional control, a novel background color of the screen would likewise do so. Even though there was a slight descriptive but non-significant tendency for a somewhat higher singleton prioritization in the critical trial, results

clearly suggested that the attentional control interruption account could not explain the strong surprise capture effect of Experiment 1.

2.2 The causal role of expectation discrepancy for surprise capture

Previous studies on surprise capture argued that attentional prioritization of a novel feature is caused by its discrepancy to the expectation that was built up in pre-critical search trials. However, this has been more an assumption than directly supported from experimental data. To that aim, Ernst and Horstmann (submitted) proposed a mechanism about the emergence of expectations towards features to derive predictions about the extent of expectation discrepancy of a novel feature. Their model based on schema theory (Mandler, 1984; Rumelhart, 1984; Rumelhart & Ortony, 1977) and on a previous study by Schützwohl (1998), showing that schema strength covaries with the surprise induced interruption of the current task. More precisely, Schützwohl (1998) argued that the strength of a schema depends on the feature constraints of the schemas content. Feature constraints, in turn, depend on the variability of the schema's features that have been perceived in the past and on the frequency of previous schema activations. For instance, schema strength for TV screens should be relatively high for most individuals. Usually, TV screens are flat, rectangular, and their bezels are black or grey. For most people, entering a living room and encountering a TV screen with a yellow bezel would induce schema discrepancy. However, a child that has only seen three TV screens in her or his life that were either black or grey would be less surprised about yellow TV screen as compared to an adult who has already seen hundreds of screens that were either black or grey.

Ernst and Horstmann (submitted) tied in with these hypotheses and proposed to model an expectation about a color feature with the formula for the sampling distribution of the arithmetic mean. According to this model, an expectation about a color feature becomes narrower with

lower variability of the previously perceived color feature and with a higher number of sampling occasions. If a novel color is perceived, its expectation discrepancy depends on the narrowness of the color expectation. Ernst and Horstmann (submitted) tested these predictions with a similar experimental paradigm as used in Ernst and Horstmann (2018). A search irrelevant singleton of magenta color was already presented in pre-critical search trials. The authors varied the magenta color by altering the proportion of red and blue color between search trials, such that in some trials the magenta singleton was more blueish and in other trials more reddish. In the critical trial, the singleton was either pure red or blue, counterbalanced between participants. Results showed that surprise capture of the gaze was attenuated for a group were the singleton color in pre-critical trials varied strongly as compared to a group where it varied slightly. This was taken as evidence that strong color variation leads to a broader expectation rendering the presentation of a novel color less expectation discrepant.

To test the effect of sampling occasions, Ernst and Horstmann (submitted) varied the number of pre-critical trials between groups. In the first experiment, surprise capture after a number of 17 pre-critical trials did not differ from surprise capture after a number of 49 pre-critical trials. It was suspected that a number of 17 pre-critical trials was too high, such that expectation breadth had already reached an asymptote. In a second experiment, the authors tested a number of 9 pre-critical trials against a number of 41 pre-critical trials and could show that surprise capture was stronger after a higher number of familiarization trials.

Together, the experiments demonstrated that surprise capture covaries with the number of sampling occasions and prior feature variability. Thus, the results supported that the intensity of surprise capture can be explained by assuming that expectations towards the surprising feature behave like the sampling distribution of the arithmetic mean.

2.3 Novelty as a source of activation in a priority map

To further confirm the role of novelty in guiding visual attention, Ernst et al. (submitted) tested predictions derived from a priority map that assumes novelty as an additional source of activation. A priority map (e.g., Zelinsky & Bisley, 2015) is described as a neuronal spatial representation of the visual view field. The amount of activity at different locations in the priority map determines attentional prioritization, in that attention shifts follow the gradient of activation. Essentially, sources of activation in a priority map are categorized into bottom-up factors such as saliency, and top-down factors like the perceived target-distractor similarity (e.g., Moran, Zehetleitner, Müller, & Usher, 2013; Wolfe, 1994, 2007). Several sources of activity can cumulate to a strong peak of activity. However, empirical data show that indicators of attention (e.g., eye movements or search slopes) do not always perfectly reproduce attention shifts as predicted from the priority map. Therefore, it is assumed that the priority map is affected by random noise (Koch, Müller, Zehetleitner, 2013; Wolfe, Cave, & Franzel, 1989; Zehetleitner, Koch, Goschy, & Müller, 2013).

Ernst et al. (submitted) designed an experiment to test predictions that were based on the assumption that novelty contributes to activity in a priority map– both for high-salient and low-salient stimuli. In pre-critical trials, two groups of participants were familiarized with color homogeneous search displays (e.g., red) that were similar to Ernst and Horstmann (2018), but without a singleton. As participants had to search for a specific shape (a closed ring among rings with a gap) in color homogeneous search displays, there was no need for participants to either prioritize or inhibit a specific color. In the critical trial, both groups were presented unannouncedly with a singleton of a novel color (e.g., green). Both groups differed, however, with respect to the color of the remaining non-singleton stimuli. In one group (“one-new”), the singleton was the only stimulus with a novel color (e.g., a green singleton among red non-

singletons). In the other group ("all-new"), the non-singletons likewise had a novel color (e.g., a green singleton among blue non-singletons). All colors were matched for physical luminance.

As the pre-critical trials did not induce the need for an attentional set towards a specific color and the singletons in the critical trial were unexpected, color prioritization of the novel colors in the surprise trial due to top-down factors is unlikely. Thus, attentional prioritization should only be driven by saliency and novelty. Given that top-down prioritization for a specific color can be neglected, saliency based models (e.g., Itti & Koch, 2000, 2001; Theeuwes, 2010) seem to adequately predict attentional prioritization in the critical trial. They would predict that early attention is always directed towards the singleton as it is the most salient item in the display. Crucially, saliency based models would predict no difference between the one-new and the all-new group. Priority maps that consider both saliency and novelty as a source for activation would likewise predict that early attention should be strongly directed towards the singleton, since its position in the priority map receives activity both because of saliency and novelty. However, the difference in activation between the singleton location and the non-singleton locations would be smaller in the all-new group as the non-singleton locations likewise receive activation because of color novelty. Thus, as the priority map is assumed to be noisy, it predicts a lower probability for early attention on the singleton in the all-new group than on the singleton in the one-new group.

Ernst et al. (submitted) inferred early attentional prioritization from gaze behavior. More precisely, to test their hypothesis, they focused on the destinations of the first three fixations after search display's onset in the critical trial and analyzed whether a fixation targeted the singleton or a non-singleton. Due to the binary nature of this dependent variable (stimulus fixated vs. stimulus not fixated), the authors used Generalized Estimation Equations (GEE, Liang & Zeger, 1986). GEEs allow for the implementation of a logit link function, which is commonly used to

model binary dependent variables. Furthermore, they control for correlated data due to repeated measurements in order to prevent underestimation of standard errors. Overall, results showed that a high number of early fixations targeted the singleton. However, within the first two fixations, the singleton was fixated less often in the all-new group than in the one-new group. Accordingly, results also showed that non-singletons were targeted more often in the all-new group than in the one-new group within the first three fixations. Thus, the analyses confirmed the prediction that novelty always increases attentional prioritization, regardless of saliency. Overall, the result pattern is consistent with commonly used noisy priority maps and the additional assumption of novelty as a source of activation (e.g., Moran et al., 2013; Wolfe, 1994, 2007; see also Zehetleitner et al., 2013).

Additional analyses revealed that gaze dwell times were prolonged on any stimulus type in the critical trial of both groups. However, dwell times were shorter on the singleton in the all-new group than in the one-new group, possibly because of a faster disengagement that was driven by higher attentional prioritization of non-singletons with a novel color.

Furthermore, the proportion of revisits was increased on the singletons in the critical trial of both groups. The increase of revisits on non-singletons was stronger in the all-new group than in the one-new group, which shows that revisits increase specifically for non-salient stimuli with novel features. Together, increased dwell times could be driven by interference due to causal searches for the surprising event and increased revisits could reflect verification of expectation discrepancy in that participants compare several stimulus types with different colors. As mentioned before, causal search and verification of expectation discrepancy are postulated in the cognitive-evolutionary model of surprise (Meyer et al., 1997).

4 Discussion

All three studies of the project answered several questions with respect to attentional prioritization of stimuli with novel features. However, there are further interesting questions that could not yet be answered, and other questions raised because of the new insights from these studies. Furthermore, there are still alternative explanations, which shall likewise be addressed in the present work.

4.1 Attention capture in difficult search paradigms

As mentioned in the introduction, research on surprise capture often centers on the distinction between surprise capture and saliency capture (Gibson & Jiang, 1998; Horstmann, 2002, 2005, 2006). Both saliency capture (Itti & Koch, 2011; Theewues, 2010) and surprise capture predict attentional prioritization of an unannounced singleton. However, pre-cueing paradigms revealed that the effect of the first unannounced presentation of a singleton emerges at 400ms (Horstmann, 2006), whereas effects due to expected singleton distractors that were attributed to saliency capture occurred with a latency smaller than 150ms (Kim & Cave, 1999; Theeuwes, Atchley, & Kramer, 2000).

Previous research on surprise capture did not address the point that pre-cueing experiments for surprise capture and saliency capture often differ with respect to target-distractor similarity. While surprise capture studies with pre-cueing paradigms included a letter search (Horstmann, 2002, 2006), participants in saliency capture experiments usually search for a relatively salient target singleton (e.g., Kim & Cave, 1999; Theeuwes et al., 2000).

According to Theeuwes (2004, 2010), saliency capture can hardly be elicited in a difficult search because of a smaller attentional window to allow for better discrimination between target and distractors, and several studies supported this hypothesis (Lu & Han, 2009; Proulx & Egeth,

2006; but see also Barras & Kerzel, 2017a, 2017b). It is assumed that participants in difficult searches direct and focus attention on a specific stimulus location at the beginning of the search trial. This prevents saliency capture as parallel processing is only possible within the attentional window (see also Belopolsky, Zwaan, Theeuwes, & Kramer, 2007).

If there is actually a smaller attentional window at the beginning of a difficult search trial that does not cover all stimulus positions, the attentional window account also yields a possible alternative explanation for the emergence of a singleton effect not before 400ms in Horstmann (2006). Given that the attentional window does not remain completely stable at one location at the pre-display, but varies its position to some extent randomly, there is a higher probability that the singleton in the surprise trial enters the attentional window accidentally with more time that elapses before the presentation of the search stimuli.

In most eye tracking studies on surprise capture, target-distractor similarity is increased such that participants are expected to fixate every stimulus (e.g., Ernst & Horstmann, 2018; Horstmann et al., 2016). Those studies suggest that it is mainly the second saccade that targets the surprising singleton. On the one hand, one could argue that surprise capture at the second fixation is too late to call the effect "surprise *capture*", as this is relatively slow compared to saliency capture and contingent capture, which are usually measured at the first fixation (e.g., Geyer, Müller, & Krummenacher, 2008; Theeuwes, De Vries, & Godijn, 2003; Weichselbaum & Ansorge, 2018; van Zoest, Donk, & Theeuwes, 2004). Thus, the late effect could also be interpreted as an indicator of rather voluntary attention orienting. One the other hand, however, one could also argue that involuntary capture can even be elicited at a later fixation. Similar to the (covert) attentional window account for surprise capture, it is possible that a smaller functional view field (Hulleman & Olivers, 2017) attenuates gaze capture by a novel singleton such that it mainly occurs at the second fixation. This hypothesis would be in line with

experiments showing that also saliency effects are not restricted to the first fixation (de Vries, van der Stigchel, & Hooge, 2018; see also Martin & Becker, 2018).

In the case of saliency capture, a premise for this hypothesis is that the functional view field is still large enough, such that the singleton is sufficiently salient to induce capture. For unexpected stimuli, however, previous studies suggest that singleton status is not necessary to attract the gaze (Ernst et al., submitted; Horstmann & Ansorge, 2016; Horstmann & Herwig, 2016). As a consequence, the reduction of gaze capture due to reduced saliency with smaller functional view fields should be less dramatic for surprise capture than for saliency capture. In line with this hypothesis, gaze capture by surprising singletons can still reliably be demonstrated in studies with difficult searches (e.g. Ernst & Horstmann, 2018; Horstmann et al., 2016; Horstmann & Herwig, 2015); although somewhat delayed, possibly because of a small functional view field.

To conclude, the relatively late emergence of the surprise capture effect as compared to the saliency capture effect can be explained alternatively by higher search difficulty in previous surprise capture experiments, given that a smaller attentional window or functional view field attenuates surprise capture to some extent. This alternative explanation could be partly supported by a study on surprise capture where participants searched for a salient shape singleton (Retell, Venini, & Becker, 2015, Experiment 2). According to Hulleman and Olivers (2017) lower target-distractor similarity should result in a larger functional view field. The first presentation of an additional color singleton in the surprise trial of Retell et al. (2015) captured 46% of first fixations (in a display containing eight stimuli), which appears to be an earlier effect than in surprise capture studies with difficult searches. However, since in Retell et al. (2015) a singleton was already presented in pre-critical trials, early capture by the surprising distractor singleton can also be interpreted as the result of singleton detection mode (Bacon & Egeth, 1994).

Overall, the latency of a capture effect might be no reasonable criterion for whether an effect should be interpreted as attention capture or not as the latency can be affected by search difficulty. To distinguish saliency capture and surprise capture, another dependent yields more consistent support for different forms of capture: A surprising singleton usually receives prolonged dwell times on its first fixation as compared to expected singletons (e.g., Ernst & Horstmann, 2018; submitted; Ernst et al., submitted; Horstmann et al., 2016; Horstmann & Herwig, 2015). This effect has not been reported for gaze capture that was assumed to be stimulus driven (Theeuwes, De Vries, & Godijn, 2003). According to Theeuwes (2010), attention is only very shortly engaged by salient stimuli and quickly disengaged towards goal relevant stimuli. Thus, prolonged dwell times seem to be specific for surprise capture.

4.2 Pure singleton novelty

In the introduction, it was mentioned that Horstmann (2005, Experiment 4-6) and Becker and Horstmann (2011, Experiment 2) did not find an effect of an unannounced singleton if participants were already familiarized with the singleton's feature in pre-critical trials. As the pre-critical trials did not include a salient stimulus, the presence of a salient stimulus was the only novel aspect of the critical trial. Horstmann (2005) and Becker and Horstmann (2011) tested this condition to distinguish between several accounts for attention capture of an unannounced singleton. The expectation discrepancy account refers to feature novelty and would predict no attention capture as participants were already familiarized with the singleton's feature in pre-critical trials. However, the saliency capture account (Theeuwes, 1991, 1992) would predict that initial attention is always biased by saliency, regardless of expectation discrepancy and goal specific feature prioritization (if present). Yet, results showed no attentional prioritization of the unannounced singleton in the critical trial, which was taken as support that feature novelty is the

dominant factor for surprise capture, whereas the role of both singleton novelty and saliency per se is neglectable in such a surprise condition (Becker & Horstmann, 2011; Horstmann, 2005).

In Ernst et al. (submitted) it was predicted that within the all-new condition, the singleton is highly prioritized (although to a lesser extend as compared to the one-new condition). It was assumed that in a priority map, the singleton location receives activation both from novelty and saliency, whereas the remaining positions only receive activity due to novelty. However, this assumption appears not to be in accordance with results from Horstmann (2005) and Becker and Horstmann (2011, Experiment 2).

As mentioned before, a recent eye tracking study demonstrated that pure singleton novelty in a surprise trial can indeed capture the gaze. Horstmann et al. (2016) presented pre-critical search trials where all of eight search stimuli had a grey color. In the critical trial, seven stimuli had a novel color (e.g., green), whereas a single stimulus still had the old grey color as in pre-critical trials ("one-old"). Thus, the display of the surprise trial contained a novel color singleton that had no color feature novelty. Gaze data like singleton fixation latencies and the proportion of singleton fixations within the first three fixations after search display's onset showed a substantial prioritization of the novel singleton within this group. How can this divergence between the results of Horstmann (2005) and Becker and Horstmann (2011) on the one hand, and Horstmann et al. (2016) on the other hand be explained? Crucially, the studies that could not support prioritization of pure singleton novelty inferred attention capture from reductions in set-size effects of manual response times. Horstmann (2005) tested a group with four and a group with twelve search stimuli. In line with an inefficient search, search times in pre-critical trials were longer in the group with a larger set-size (Wolfe, 1998). Horstmann (2005) argued that if the surprising singleton is located at the target position and captures attention, the set-size effect should be reduced. He furthermore pointed out that in both set-size conditions,

manual response could actually increase if surprise capture is elicited because of effects that occur after attention capture and interrupt ongoing behavior as postulated by the cognitive-evolutionary model of surprise (Meyer et al., 1997). It was assumed that effects after the first selection of the unannounced singleton would occur in equal measure in both set-size conditions. Thus, a reduction of the set-size effect in the critical trial can still be interpreted as evidence for surprise capture.

Results of Horstmann et al. (2016) showed that the singleton was fixated more frequently within the first two fixations after search display's onset if it had both feature and singleton novelty as compared to when it had only singleton novelty. This result can be explained by assuming that several sources of novelty can add up to an increased prioritization (Ernst & Horstmann, 2018). Following this argument, within the Experiments 4-6 of Horstmann (2005) and Experiment 2 of Becker and Horstman (2011), attention capture could actually have been present, although to a lesser extent. Possibly, set-size effects as the dependent variable were not sensitive enough to detect a weaker effect of pure singleton novelty, such that the reduction of the set-size effect could not be revealed by a significant interaction between set-size (4 vs. 12) and trial type (pre-critical vs. critical). Furthermore, support for a neglectable effect of pure singleton novelty should be interpreted with caution in Horstmann (2005) and Becker and Horstmann (2011), as it would rely on the interpretation of the non-significance of the interaction, which in general is no reliable support for the absence of an effect (Anderson, Burnham, & Thompson, 2000).

Another reason why set-size effects should be interpreted with caution in surprise conditions refers to the assumption that the interruption of ongoing behavior does not differ between small and large display sizes. Results from eye tracking data of the present project suggest that any stimulus in a surprise trial receives prolonged gaze dwell times and increased

revisits (Ernst & Horstmann, 2016; Ernst et al., submitted). This could result in a stronger increase of manual response times in a display with a high number of stimuli than in a display with a low number of stimuli. On the one hand, a smaller number of stimuli reduces the potential for stimuli being revisited. On the other hand, the increase in manual response time is attenuated in a display where only four stimuli can receive longer dwell times as compared to a display with twelve stimuli. Accordingly, studies demonstrated that dwelling and revisiting of distractors have a substantial impact on manual response times in difficult searches (Horstmann, Becker, & Ernst, 2017; Horstmann, Herwig, & Becker, 2016). Nevertheless, specific experiments are necessary to test whether this reasoning is true and whether these effects could have biased set-size effects of previous surprise studies in a relevant manner.

4.3 Adaptiveness of surprise capture

It has been argued that surprise capture is an important complement to contingent capture (Horstmann, 2005). Contingent capture is crucial to quickly focus on features that match with current goals while it helps to ignore irrelevant features. However, a system that only attends to goal relevant stimuli would possibly fail to notice relevant but unexpected information in a situation. In contrast to contingent capture, surprise capture can direct attention to highly informative stimuli, which may signal the need for adjustment of current goals and behavior.

However, one premise for surprise capture is that unexpectedness refers to a simple feature that is pre-attentively available such as color or orientation (see also Treisman & Gelade, 1980). Thus, the expectation discrepancy hypothesis for visual attention would predict no surprise capture if the unexpected aspect of an object is constituted by a combination of features (Horstmann, 2005). Accordingly, it was demonstrated that objects whose unexpectedness refers to semantical (e.g., a printer in a kitchen) or syntactical properties (e.g., a floating toaster) do not

draw attention spatially (however, they bind attention and the gaze when they are encountered by coincidence, Võ & Henderson, 2009; see also Võ et al., 2010).

Considering this premise and the fast nature of contingent capture, it is difficult to find realistic examples for the importance of surprise capture outside the laboratory. For instance, a tiger that suddenly jumps out of a bush should be quickly attended to. One could argue that the (fast) motion feature of the tiger is salient and can guide attention pre-attentively. Therefore, a premise for surprise capture is given. However, tigers usually jump out of bushes within their natural habitats. Even though being attacked is possibly a rare event, most observers will still fear and anticipate attacks when they are in regions where predators live. Thus, it is more likely that observers have an attentional set for features that signal predators and attacks. If so, observers would benefit from the faster attention orienting of the contingent capture mechanism (cf. Horstmann, 2006; Horstmann & Ansorge, 2006).

A better example for surprise capture would be a white polar bear that wanders around in the German woodlands. Relatively big and white objects are not expected by observers in such a region (with the exception of cars near the road) and would probably elicit surprise capture as the white color has the potential to preattentively guide visual attention (Treisman & Gelade, 1980). Crucially, a polar bear in a German woodland would be highly informative and observers would analyze the event with respect to its causes and relevance for current actions (Meyer et al., 1997). Accordingly, neurophysiological studies suggest a hard-wired “novelty bonus” (Kakade & Dayan, 2002), which enhances dopamine signals in case a novel stimulus has been encountered and thus engages to explore the situation (Knutson & Cooper, 2006; Krebs, Schott, Schütze, & Düzel, 2009; Schultz, 1998).

That being said, automatic orienting towards unexpected stimuli, followed by their closer examination seems to be more adaptive in that it engages learning behavior and to constantly

update the individual world model of the observer (Itti & Baldi, 2009). Surprise capture would be less effective (than contingent capture, for instance) in situations where a fast reaction is decisive.

4.4 Novelty vs. surprise

In the present work, the words surprise (or unexpectedness) and novelty have been used synonymously. A precondition for surprise is the presence of an expectation or a belief about a specific feature, for instance. The expectation can vary with respect to its certainty; that is, the expectation can be either narrow or broad (Ernst & Horstmann, submitted). If a perceived feature is unlikely under a given certainty of the feature's expectation, it elicits surprise. With larger expectation discrepancy, there will be also a larger difference between the expectations prior and posterior to the surprising event (Itti & Baldi, 2009).

Novelty tends to center more on the question whether something has been encountered before (Barto et al., 2013). For instance, different forms of novelty depend on the time something has not been perceived before (short-term novelty vs. long-term novelty vs. complete novelty). According to Barto et al. (2013), novelty is detected by searching through memory contents, whereas detection of expectation discrepancy does not involve memory. On the one hand, novelty is not necessary for expectation discrepancy as the latter can also occur if a known object occurs within an unexpected context (e.g., a polar bear in a German woodland). On the other hand, Barto et al. (2013) state that a novel stimulus possibly always elicits surprise as a novel item could never be predicted.

With respect to Ernst and Horstmann (2018) and Ernst et al. (submitted), the stimuli with deviant colors in the surprise trial should have been unexpected as in pre-critical trials, participants were familiarized with different colors, which they anticipated for the following

trials. However, it is unlikely that the participants have never seen similar colors to those of the surprising stimuli before. Thus, for most participants, the surprising colors would not have been detected as completely novel but rather as short-term or long-term novel (see also Berlyne, 1960).

4.5 Selection history

For some factors of attentional prioritization, it is debated whether they should be ascribed to the bottom-up or to the top-down category. Following Theeuwes (2010), attention capture is bottom up driven if it cannot be completely suppressed in a top-down fashion. According to this criterion, phenomena like inter-trial priming (Maljkovic & Nakayama, 1994) and reward learning (Della Libera & Chelazzi, 2006) would be categorized as stimulus driven. Inter-trial priming is the increased prioritization of objects in trial *N* that have the same feature as the target in trial *N*-1 (Pinto, Olivers, & Theeuwes, 2005). This effect can even occur if participants know in advance what the target feature will be in trial *N* (Theeuwes & Van der Burg, 2011). Similarly, studies suggest that prioritization of a stimulus that was previously associated with reward cannot be completely suppressed (e.g., Anderson, Laurent, & Yantis, 2011).

However, as attentional prioritization due to previously selected stimuli depends on previous experience, it cannot be *purely* stimulus driven. Therefore, the factor of selection history has been proposed as a distinct source of activity in priority maps (Awh, Belopolsky, & Theeuwes, 2012). Expectations discrepancy likewise fits into the category of selection history. In contrast to reward learning and inter-trial priming, however, attentional prioritization due to expectation discrepancy occurs without prior exposure of the capturing feature (Ernst & Horstmann, submitted). Reward learning and inter-trial priming can still be interpreted in the sense of a lingering top-down prioritization, whereas the novel feature that induces surprise capture has

never been part of the attentional set before (Horstmann & Herwig, 2016). Nevertheless, surprise capture is still not purely stimulus driven as it depends on the observer's expectation.

5 Take home message of the three studies

To sum up, the three studies of the present project demonstrate that color novelty alone is sufficient to attract attention (Ernst & Horstman, 2018, submitted; Ernst et al., submitted). Furthermore, expectation discrepancy has been supported as the driving factor for surprise capture in that expectations become narrower with decreased feature variability and a higher number of sampling occasions of the perceived feature (Ernst & Horstmann, submitted). It was also shown that expectation discrepancy competes with saliency for attention, which fits into the theoretical framework of priority maps that are commonly used to predict attention allocation and gaze shifts (Ernst et al., submitted).

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APPENDIX

Study 1

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Pure colour novelty captures the gaze

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ABSTRACT

While it is common wisdom that a salient visual event draws attention, experimental research provided mixed support for this hypothesis. The present experiment seeks evidence that a singleton draws attention to the degree that its feature is novel or unexpected. Two visual search experiments were conducted where an irrelevant colour singleton is presented on each pre-critical trial to familiarize participants with the presence of the singleton. In the critical trial of Experiment 1, the singleton was presented in a novel colour without prior announcement. The singleton was gazed at significantly earlier and longer in the critical trial, as compared to pre-critical trials. This result is consistent with predictions from the expectancy discrepancy hypothesis that colour novelty is sufficient to capture attention. Experiment 2 tested the alternative explanation that a surprising event mainly leads to a breakdown of the previously acquired attentional set, which in turn causes a reorientation towards perceptual salience. An unannounced change of the background colour in the critical trial while the singleton colour remained unchanged did not induce an attentional capture by the singleton like in Experiment 1. This result further confirms that surprising events capture attention in a spatial manner.

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It is common wisdom that a salient visual stimulus attracts attention even if the stimulus does not relate to the ongoing task: a bright light in the dark, a colourful flower on the lawn, a dog quickly approaching. In experimental research, however, this proposition has received mixed support. One group of researchers proposed that a salient event quickly draws attention even against intention ("saliency capture", e.g., Theeuwes, 2010), while another group argued that apparent evidence for saliency capture is an effect, or side effect, of intentional processing ("contingent capture", e.g., Folk, Remington, & Johnston, 1992).

The key evidence for the *saliency capture hypothesis* comes from the additional singleton paradigm (Simons, 2000) where a colour singleton – a single perceptually salient object in the colour domain such as a red object among green objects – is presented as a distractor, while participants are searching for a shape singleton – a single salient object in the shape domain such as a circle among diamonds. Under these conditions, attention is biased towards the irrelevant colour singleton even though participants know perfectly that the colour singleton is never the target, and that selecting it impedes task performance (for an overview see Theeuwes, 2010; for a critical view see Ansorge, Horstmann, & Scharlau, 2010). This effect is particularly strong when the singleton feature changes from trial to trial (Becker, 2010; Müller, Heller, & Ziegler, 1995; Theeuwes, de Vries, & Godijn, 2003).

Evidence for the *contingent capture hypothesis* – stating that stimuli are biased for selection if and only if they share features with the searched-for target – mainly comes from the cueing paradigm, where cues near the possible target positions are presented 150 ms before the target display (Folk et al., 1992). Here, singletons (e.g., a red cue) sharing the defining feature of the target (e.g., a red letter) do capture attention, while singletons that are dissimilar to the target (e.g., a single onset) do not. Hence, selection is contingent on the task of the participant and is thus dependent on intention.

One reason for some impasse in the controversy is that researchers present salient stimuli recurrently within an experimental session, usually in every trial. One consequence of this practice might be that salient events become part of the intentional

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strategies used by the participants. If so, it is unclear which of a number of possible strategies are actually used. Participants might for instance inhibit a task-irrelevant salient event, thereby reducing the chance of the researcher to find evidence for attention capture. Alternatively, they might also use the salient stimulus in some way to accomplish their task, even though in some cases the fully rational *homo economicus* might not do so. Among the strategies discussed in the literature on attention capture is singleton-detection mode (Bacon & Egeth, 1994), contingent capture by display-wide features (Gibson & Kelsey, 1998), or probability matching (Remington, Johnston, & Yantis, 1992). The plausibility that one of these strategies is applied depends on the exact task requirements; however, it is often difficult to exclude with certainty any of these strategies in a given task. Another consequence of repeated presentations is that the mechanism that biases attention may be habituated, similarly as the orienting response is strong for a novel object, but quickly habituates to repeated presentations, given that the object is not followed by a reinforcer (Retell, Venini, & Becker, 2015; Sokolov, 1960). Relatedly, Horstmann and colleagues (e.g., Horstmann, 2015; Horstmann & Ansorge, 2016) propose that a novel feature captures attention to the degree that it is expectancy discrepant, whereas the same feature does not capture attention when it is familiar.

There is indeed evidence that attention is reliably drawn to a novel salient object on its unannounced first "surprise" presentation, while the response to the repetitions of that object is governed by its usefulness for the task (Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Becker & Horstmann, 2011; Foerster, 2016; Horstmann, 2002, 2005, 2006; Horstmann & Ansorge, 2016; Horstmann & Becker, 2008, 2011; Horstmann & Herwig, 2015, 2016; for a review see Horstmann, 2015). Such an attentional response towards a novel feature on its unannounced first presentation will be dubbed surprise capture henceforth.

Surprise capture is examined often in a three-part experiment, comprising the pre-critical trials, the critical trial, and the post-critical trials. The pre-critical trials familiarize participants with stimuli containing a particular set of features. In the critical trial, a familiar feature is replaced for the first time with a novel feature without prior announcement. The post-critical trials test the novel feature's intentional processing when it is repeatedly presented. Results from a diversity of attention paradigms including classical visual search (Horstmann, 2002, 2005), detection (Horstmann, 2002, 2006), cueing (Horstmann & Becker, 2011), and eye-tracking (Horstmann & Herwig, 2015, 2016; Horstmann, Becker, & Ernst, 2016) have shown that a novel salient object strongly attracts attention on its unannounced first presentation.

The novel salient object has two features: saliency and novelty. Therefore, surprise capture may be explained in two ways. The traditional saliency capture explanation would link this result to the saliency of the novel colour. On this account, saliency caused an attentional shift, while novelty is not necessarily an important feature.

The second explanation relates the result to novelty. On the expectation-discrepancy account, surprise capture is not a direct function of saliency per se, but rather of the discrepancy between an expectation built up during the pre-critical trials and the presentation of the novel colour singleton in the critical trial (e.g., Horstmann, 2015). Similarly, on an orienting response account, a novel feature will capture attention to the degree that there is no neuronal model accounting for that feature, which will, however, eventually build up with repeated presentations of the (previously novel) feature (Retell et al., 2015). We will not properly distinguish between expectation discrepancy and novelty here, as the subtle differences between these two concepts are not relevant to the present research.

Several lines of evidence support the expectation discrepancy explanation for attention to a novel singleton. First, the time course of surprise capture differs from the time course proposed for saliency capture. While saliency capture has been portrayed to be effective as early as 60–150 ms after stimulus onset (Kim & Cave, 1999; Theeuwes, 2010), surprise capture has a later average latency of about 400 ms, as revealed by a number of paradigms such as efficiency gains with short presentations (Horstmann, 2006; Horstmann & Becker, 2008) and eye-tracking during a visual search task (Horstmann & Herwig, 2015). Second, experiments showed that a surprise singleton does not strongly attract attention after a feature-familiarizing procedure. When the pre-critical trials presented all-red and all-green displays in the pre-critical trials, a red colour singleton among green distractors on its unannounced first presentation did

not capture attention (Horstmann, 2005). Third, there is evidence that a discrepant feature draws attention even though it is not a singleton, either because half of the stimuli in a multi-element display have the discrepant feature (Horstmann & Herwig, 2016), or because only two stimuli are presented, rendering none (or both) of them a singleton (Horstmann & Ansorge, 2016).

Setting traditional saliency capture accounts aside and focusing on expectation discrepancy, one might observe that the critical stimulus in many experiments on surprise capture had actually *two* novel features: colour novelty and singleton novelty. *Colour novelty* refers to the fact that the colour has not been presented before during the experiment. *Singleton novelty* refers to the fact that no perceptually salient singleton had been presented before.

As already reported, colour-familiarizing experiments (Horstmann, 2005) suggested that singleton novelty (in the absence of colour novelty) does not strongly capture attention. But what about the complementary test on whether colour novelty alone is sufficient to drive surprise capture? In a decisive experiment, a task irrelevant colour singleton (say red among grey) is presented in every pre-critical trial, and the singleton is presented with a novel colour (say green) in the critical trial. In theory, this singleton-familiarization procedure would render the presence of a singleton unsurprising (expectancy congruent), leaving alone the novel colour expectancy discrepant.

Two previous experiments (Horstmann, 2005) used such a design but obtained negative results. While a stimulus that was both colour-novel and singleton-novel at the position of the target led to a strong reduction of the set size effect in visual search for a conjunction target, a stimulus that was colour-novel but not singleton-novel did not influence search efficiency in that experiments.

One obvious interpretation of this result is that colour novelty alone is insufficient to bias attention. The implication would be that neither colour novelty nor singleton novelty alone induces surprise capture, which is only observed when both novelty types combine. Recently, however, Horstmann and Herwig (2016) tested colour novelty in the absence of visual saliency. Instead of presenting a single stimulus with a novel colour in the critical trial, they presented half of the search stimuli with a novel colour, such that none of them was singled out by saliency. Yet the novel colour was prioritized for gaze position in the second and third fixation (Experiment 1) or second–fifth fixation (Experiment 2). Horstmann and Ansorge (2016) additionally showed that colour novelty, without singleton novelty, affected attention, as indicated by inattentional blindness rates in a two-item display.

We consider two possible causes for the divergence of results between the studies of Horstmann (2005) on the one hand, and Horstmann and Herwig (2016) and Horstmann and Ansorge (2016) on the other hand: (a) the effects are subtle when testing feature novelty or singleton novelty alone, and (b) the dependent measures to infer attention were more sensitive.

There are at least two reasons why the attentional effects could have been subtle in Horstmann (2005). First, it is plausible that several sources of novelty add up for a strong attentional bias to be established (see Horstmann et al., 2016). Assuming that novelty is accumulated over different features and dimensions, the attentional bias would be higher with more discrepant features. Second, the expectancy discrepancy should be highest with low variation of features in the pre-critical trials (e.g., only one colour), and decrease when more features (e.g., two or more colours) are presented (see Schützwohl, 1998). According to Schützwohl, and probably also consistent with common sense, the expectation discrepancy or novelty of a colour drops monotonically with the number of colours presented during the expectation induction phase.

As to the sensitivity of the task, the singleton-familiarization experiments in Horstmann (2005) implemented a between-subjects manipulation of set size: two groups of subjects saw a search array of four items or 12 items, respectively. Attention capture is revealed in this design when the set-size effect in the pre-critical trials (where no cue to the target is present and the target can be found only through inefficient search) is eliminated in the critical trial (where the novel colour at the target position is presented for the first time). The between-subjects manipulation of set size was chosen (instead of a within-subject manipulation) on the assumption that the presentation of a novel colour is strongly expectancy discrepant only once. One possible problem with this design is that the novelty-triggered

processes could affect search times only if they are faster than the search processes. In a target present trial of an inefficient visual search task, however, search processes are not infinitely long but finish on average after half of the display items have been inspected (see also Horstmann, Becker, & Ernst, 2017). If the novelty-triggered process finishes later, search efficiency is not affected, even if there was a biasing of attention.

If this reasoning is correct then colour novelty in the absence of singleton novelty still may bias attention after a singleton-familiarization procedure, although possibly to a lesser extent. In addition, if a more sensitive measure is chosen than the reduction of set-size effects, this effect could be revealed.

The present experiments

The present design used eye tracking to directly measure gaze fixations, rather than a set-size variation to indirectly measure covert or overt attentional deployment. Several studies recently demonstrated that surprise capture is strongly revealed in an eye tracking paradigm (Horstmann et al., 2016; Horstmann & Herwig, 2015, 2016). Moreover, eye tracking can dissociate spatial object selection (gaze shifts) from more temporal aspects of attention (gaze duration). Horstmann and Herwig (2015) found that a novel colour singleton at the target position both attracts attention to its position (which would in isolation reduce manual response times) and binds attention to the object with the novel feature (which would in isolation increase manual response times). Thus, as attraction and binding of attention have opposing effects on manual response times in a visual search task, eye tracking is probably more sensitive to reveal surprise capture.

In order to further increase the sensitivity of our dependent variables, the present experiment implemented a target detection task rather than a target discrimination task. The target was presented on half of the trials, and the participants had to respond with a presence versus absence judgment. A singleton was presented on each trial, and its position was stochastically independent from the target position, if a target was present. The critical trial, in which the singleton had a novel colour, was always a target absent (blank) trial. Thus, the potency of the novel singleton to attract attention can be observed in isolation, independently from possible attentional effects of the target.

Experiment 1 is our first test of the proposition that a novel (expectancy discrepant) colour captures attention following a colour singleton-familiarization procedure. Experiment 2 tests a specific alternative to the expectation discrepancy account, being that surprise itself does not bias spatial attention, but only interrupts attentional control in a non-spatial manner, which in turn causes the reorientation towards perceptual salience.

Experiment 1

Experiment 1 tested whether feature novelty alone, in the absence of singleton novelty, captures attention. Search stimuli were presented on colour patches in the pre-critical trials. One of the colour patches had a colour different from the rest and thus was a colour singleton. The singleton's position was uncorrelated with the target position. In the critical trial, a new colour was used for the singleton. If colour novelty alone, in the absence of singleton novelty, is able to trigger surprise capture, the singleton should be fixated earlier in the critical trial than in the pre-critical trials.

Previous eye tracking studies found that the first fixation after search display's onset is unaffected by surprising events (Horstmann, 2015; Horstmann et al., 2016). Because of concerns that such results might have been influenced by pre-planned eye movements (see Horstmann & Herwig, 2015), a variable "non-aging" fore-period was implemented such that participants could not predict the onset of the search display (Näätänen, 1971). Thus, the fore-period duration in each trial was randomly chosen from an exponential distribution which is characterized by a constant hazard rate.

Method

Participants

Twenty students or visitors of Bielefeld University (14 female, six male) with a mean age of 21.8 ($SD = 2.53$) years participated. All were tested for normal or corrected-to-normal vision and for normal colour vision and gave written informed consent. They received 2 € for their 10-min service. Studying was approved by the Ethics Committee of University of Bielefeld (EUB).

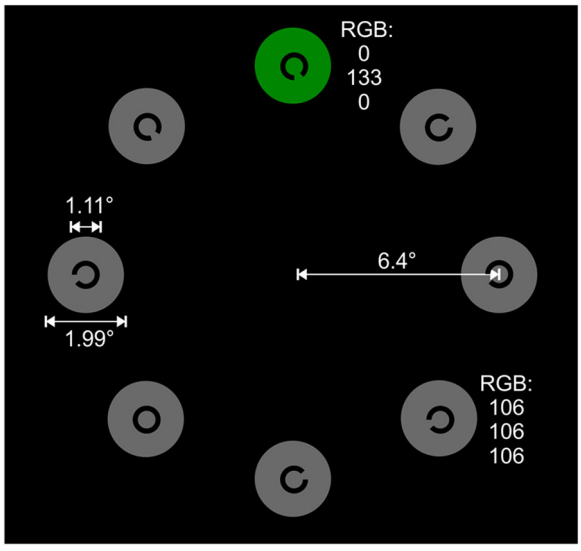

Figure 1. Arrangement of an exemplary target present trial with green singleton colour.

Stimuli

Figure 1 shows the arrangement of the search display for a target-present trial. The target was a 1.11° diameter ring with stroke of 0.23° (viewing distance 71 cm). The distractor rings were identical to the target with the only difference of a small radial gap of 0.09°. Sixteen different gap positions were used, evenly distributed between 22.5° and 360°. The rings were black as was the background. The rings were presented on circular colour patches with diameters of 1.99°.

Three colours were used: grey (RGB: 106, 106, 106; CIE: x = .277, y = .286) for the non-singletons, and red (RGB: 220, 0, 0; CIE: x = 0.605, y = .329) or green (RGB: 0, 133, 0; CIE: x = .281, y = .590) for the singletons. With the exception of the black background (RGB: 0, 0, 0; CIE: x = 0.280, y = 0.226; 0.114 cd/m^2), all colours had a matched physical luminance of 24 cd/m^2 (±1).

Eight compound-stimuli of a colour patch and a ring were presented in each display. The stimuli were evenly distributed on the imaginary circumference with a radius of 6.4°.

Apparatus

Stimuli were presented on a 19-inch display monitor (85-Hz refresh rate, 1024 × 768 pixels resolution) at a distance of 71 cm. Before testing, the monitor was warmed for at least 30 minutes, to ensure temporal stability of luminance and colour (Poth & Horstmann, 2017). A video-based eye tracker (EyeLink 1000, SR Research, Ontario, Canada) with a sampling rate of 1000 Hz (monocular) was used to record eye movements. A chin rest stabilized participants' head.

Procedure

The experiment comprised one single block of 48 trials: 32 pre-critical trials presented the singleton in one colour (the familiar colour) and 16 trials in the second colour (the novel colour). The first trial with the novel colour was the critical trial, and the remaining 15 were the post-critical trials. The novel singleton colour was red or green for half of the participants, randomly assigned. Randomly chosen, half of the displays in each condition were target present trials, and half were target absent trials, with the exception of the critical trial, which was always a target absent trial. The participants' task was to report the presence or absence of the target with a corresponding key press. The singleton's position was determined randomly. All eight possible distances between singleton and target (including their coincidence) were presented equally often. Each trial began with a fixation control: participants fixated the centre of the screen and confirmed fixation with a key press. This started a variable fore-period during which a central fixation cross was presented. The duration of the fore-period was the sum of (a) a variable time period drawn from an exponential distribution with an expectation value of 0.5 s (λ = 2) and a maximum of 2682 ms, (b) a period of 100 ms in which the cross had to be fixated continuously after the variable time period has elapsed, and (c) the possible additional time until the central continuous fixation was successfully executed for 100 ms. In the last pre-critical trial (the 32nd), and the following critical trial (the 33rd), the variable time periods (a) were fixed to 1000 ms and to 500 ms, respectively. Duration fixing was done to reduce additional variation in the critical trial. The interval for the critical trial was the expectancy value for the chosen distribution. The interval for the last pre-critical trial was somewhat longer than the expectancy value, based on the empirical result that a longer fore-period in trial *n*-1 than in trial *n* results in relatively low action readiness in trial *n* (Los, 2010). Thereby, at the search display's onset of the critical trial, we intended to counteract the execution of saccades which were already pre-planned before the surprising stimulus has been presented.

Results

Data preprocessing

Eye movement data were parsed into fixations and saccades using the standard laboratory settings of DataViewer 2.3.22 (SR research, Ontario, Canada). The eyes were assumed to fixate when two saccade thresholds, an acceleration threshold (8000 degrees/sec^2), and a velocity threshold (30 degrees/sec), are not exceeded for a period of 20 ms or more. Fixations were assigned to a stimulus when they fell within a circular region with a radius of 2.41° from the centre of the stimulus, which is nearly the maximum radius possible without overlap from adjacent positions. Further preprocessing and statistical analysis was done using R 3.3.1. (R Core Team, 2016). Only correct trials (i.e., trials in which the target present judgment was correct) were analysed for all dependent variables but accuracy. The first 10 trials were considered practice and not analysed.

Data analysis

Greenhouse-Geisser corrections of the degrees of freedom were applied wherever the sphericity assumption was violated. This is indicated by reporting the Greenhouse-Geisser epsilon; for better readability the uncorrected degrees of freedom are reported. For those mean differences that are crucial for the central questions of this study, d_z is additionally reported as an effect size for repeated measurements where the mean of the difference variable is divided by its standard deviation. In the case of binomially distributed response data like accuracy and fixations, we used dummy coded Generalized Estimation Equations (GEE) with a logit link function in order to control for dependencies between measurements. Due to its parsimony, we used an exchangeable working correlation structure which assumes equal correlations between any pair of measurements within a participant. GEEs yield robust estimates, however, even if the correlation structure is misspecified (Liang & Zeger, 1986). For better interpretability of effects, the mean proportions of the categories which are coded with 1 (vs. 0) are reported for the tested conditions.

Accuracy and reaction times

Proportion correct was .96, .95, and .98 in the pre-critical, critical, and post-critical target absent trials. With a GEE model (logit link function), we regressed trial responses (1 = correct; 0 = false) on the dummy coded factor trial type (pre-critical vs. critical vs. post-critical) with the critical trial serving as the reference category. Correctness did not significantly differ between pre-critical trials and the critical trial, *Wald* $\chi^2(1) = 0.03$, $p = .864$, or between post-critical trials and the critical trial, *Wald* $\chi^2(1) = 0.53$, $p = .466$. For target present trials, another GEE model found no significant difference between pre-critical trials (.91) and post-critical trials (.92), *Wald* $\chi^2(1) = 0.12$, $p = .725$. All further analyses included only correctly responded trials. One participant with an error in the critical trial had to be excluded completely from further analyses.

An ANOVA of target absent RTs with the variable trial type (pre-critical vs. critical vs. post-critical) revealed a significant main effect, $F(2, 36) = 23.77$, $\varepsilon_{GG} = .74$, $p < .001$. The critical trial RT (3621 ms) differed both from pre-critical (2993 ms) and post-critical (2805 ms) trials, $ts(18) > 4.15$, $ps < .001$. Mean RT in pre-critical target present trials (2051 ms) was significantly higher than in post-critical target present trials (1846 ms), $t(18) = 2.47$, $p = .024$.

Pre-critical trials

For an overall assessment of task performance, fixation probabilities and latencies for pre-critical trials were analysed. Target absent trials comprised two stimulus types: non-singleton and singleton distractors. Target present trials comprised four stimulus types: non-singleton targets, non-singleton distractors, singleton targets, and singleton distractors. Target absent and present trials are therefore analysed separately.

In pre-critical target absent trials, the probability of fixating a stimulus was high (.95), with no differences between singleton (.95) and non-singleton distractors (.94), *Wald* $\chi^2(1) = 0.60$, $p = .440$. Singleton distractors were first fixated somewhat earlier than non-singleton distractors (1070 ms vs. 1216 ms), yet not significantly, $t(18) = 1.70$, $p = .112$.

In pre-critical target present trials, two participants had errors in all trials in which singleton and target coincided. The remaining participants fixated singleton distractors almost equally often as non-singleton distractors (.56 vs. .53), *Wald* $\chi^2(1) = 0.53$, $p = .465$. Nearly all non-singleton targets (.99) and all singleton targets (1.00) were fixated. Here and in the following analyses for binomial data, we do not report significance tests if a category provides homogenous values as standard errors cannot be estimated

adequately in this case. There was no difference in fixation latency between singleton targets and non-singleton targets (1149 ms vs. 1169 ms), $t(16) = 0.10$, $p = .922$. RTs did not differ significantly between singleton (2306 ms) and non-singleton target trials (2012 ms), $t(16) = 1.36$, $p = .193$.

The critical trial

The critical trial was always a target absent trial. Performance was therefore compared to target absent pre- and post-critical trials. In most analyses, singleton fixations in the critical trial were compared with singleton fixations in pre- and post-critical trials. Where informative, we also included fixations on non-singleton distractors.

The proportion of stimulus visits was high with a mean of .95 (Table 1). Mean latencies for the first visit on singleton and non-singleton (averaged over the seven non-singletons per trial) distractors are shown in Figure 2 (upper panel). An ANOVA of the singleton fixation latencies with the variable trial type (pre-critical vs. critical vs. post-critical) revealed a significant main effect, $F(2, 36) = 30.84$, $p < .001$. Planned comparisons indicated that the latency for a singleton visit in the critical trial (425 ms) was lower compared to pre-critical trials (1070 ms), $t(18) = 9.02$, $p < .001$, $d_z = 2.07$, and to post-critical trials (957 ms), $t(18) = 5.67$, $p < .001$, $d_z = 1.30$. As the singleton fixation latency is the main depended variable for the hypotheses of this study, we tested whether summarizing pre- and post-critical trials in our analyses might have obscured a trend within the trial course of this experiment. Therefore, linear trends were tested separately within the pre- and post-critical trials. Linear Mixed Models predicting the raw singleton fixation latencies by trial number while controlling for participants as random effects, however, did not yield any significant slopes ($|ts| < 0.53$).

Table 1. Proportions of fixations on singleton distractors and non-singleton distractors in Experiment 1.

Trial type	Stimulus	Mean proportion of fixations	*SE*
pre-critical	non-singleton	.94	.019
	singleton	.95	.022
critical	non-singleton	.94	.025
	singleton	1.00	.000
post-critical	non-singleton	.96	.016
	singleton	.90	.034

Note: *SE* = Standard error (i.e., *SD* / $\sqrt{N}$) of the mean proportion with a sample size of $N = 19$ each.

Next, we asked whether the dwell times were different on the singleton and non-singleton distractors in the critical trial (Figure 3, upper panel). Dwell time is defined here as the sum of fixation durations on the first continuous visit of a stimulus (not including possible revisits). A 3 (trial type: pre-critical vs. critical vs. post-critical) × 2 (stimulus type: singleton vs. non-singleton) ANOVA revealed main effects for trial type, $F(2, 36) = 17.50$, $\varepsilon_{GG} = .53$, $p < .001$, stimulus type, $F(1, 18) = 11.06$, $p = .004$, and a significant Trial type × Stimulus type interaction, $F(2, 36) = 9.39$, $\varepsilon_{GG} = .52$, $p = .006$. On singleton distractors, dwell times in the critical trial (439 ms) differed from pre-critical (227 ms), $t(18) = 4.02$, $p < .001$, $d_z = 0.92$, and post-critical trials (244 ms), $t(18) = 3.41$, $p = .003$, $d_z = 0.78$. On non-singleton distractors, dwell times in the critical trial (252 ms) were significantly higher than in pre-critical trials (227 ms), $t(18) = 2.32$, $p = .032$, $d_z = 0.53$, and higher by tendency than in post-critical trials

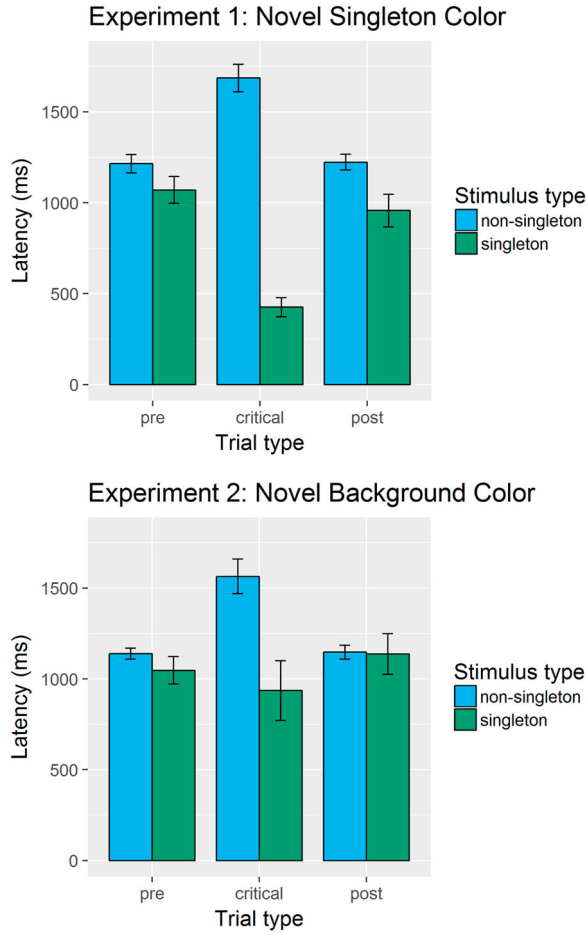

Figure 2. Mean latency of first visits on a stimulus in Experiment 1 (upper panel) and Experiment 2 (lower panel). Error bars indicate the standard errors (i.e., *SD* / $\sqrt{N}$) of the mean.

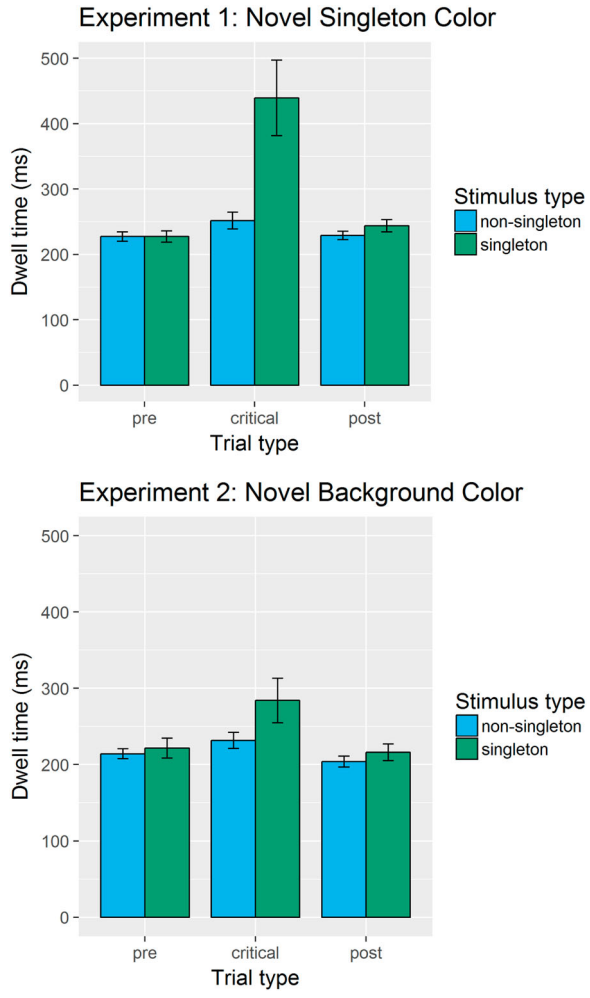

Figure 3. Mean duration of the first continuous visit of a stimulus in Experiment 1 (upper panel) and Experiment 2 (lower panel). Error bars indicate the standard errors (i.e., SD / $\sqrt{N}$) of the mean.

(229 ms), $t(18) = 1.95$, $p = .067$, $d_z = 0.45$. To further clarify the interaction, *t*-tests on the differences between dwell times on singleton vs. non-singleton distractors were run. The difference was higher in the critical than in the pre-critical or the post-critical trials, $ts(18) > 2.83$, $ps < .011$.

We also examined the cumulative distributions of the first three fixations on the singleton and the non-singletons (Figure 4, upper panel). Table 2 summarizes three GEE models with a logit link function for the binary dependent variable. Predictors were trial type (pre-critical vs. critical), stimulus type (singleton vs. non-singleton), and their interaction. The cell including singletons in pre-critical trials was set as the reference category. For simplicity, we did not include post-critical trials here and only relevant comparisons are described in the text.

The first model refers to the initial fixation after search display's onset. The significant negative slope for non-singletons in pre-critical trials indicates that for the first fixation, a non-singleton visit was less probable than a singleton visit in pre-critical trials (.09 vs. .18). The positive slope for singletons in the critical trial shows that fixation probability increased somewhat compared to singletons in pre-critical trials (.37 vs. .18), yet only significantly by trend. The Stimulus type × Trial type interaction was not significant for the first fixation.

The second model analyses the initial and the second fixations together. The significant negative slope for non-singletons in pre-critical trials indicates that fixation probability was lower compared to singletons in pre-critical trials (.17 vs. .26). The significant positive slope for singletons in the critical trial shows a higher fixation probability compared to singletons in pre-critical trials (.63 vs. .26). Accordingly, the significant negative slope for the Stimulus type × Trial type interaction indicates that the difference between non-singletons and singletons in pre-critical trials (.17−.26 = −.09) got larger in the critical trial (.13−.63 = −.50).

The third GEE model included the first to the third fixation. For pre-critical trials, non-singleton fixations were less probable than singleton fixations (.27 vs. .42) as indicated by the significant negative slope. The significant positive slope for singletons in the critical trial shows an increased fixation probability compared the pre-critical trials (.95 vs. .42). The difference between non-singletons and singletons in pre-critical trials (.27−.42 = −.15) got larger in the critical trial (.21−.95 = −.74) which is indicated by the significant negative slope for the Stimulus type × Trial type interaction.

We evaluated the mean index of the first fixation on a stimulus (Figure 5, upper panel) as an additional measure of prioritization. An ANOVA with the factor trial type (pre-critical vs. critical vs. post-critical) revealed a significant main effect, $F(2, 36) = 35.31$, $p < .001$. The index of the first fixation on a singleton distractor in the critical trial ($M = 2.05$) was lower than in pre-critical trials ($M = 4.84$, $d_z = 1.92$) and in post-critical trials ($M = 4.55$, $d_z = 1.59$), $ts(18) > 6.94$, $ps < .001$.

Discussion

The singleton was gazed at earlier when it had a novel feature (in the critical trial) than when it had a familiar

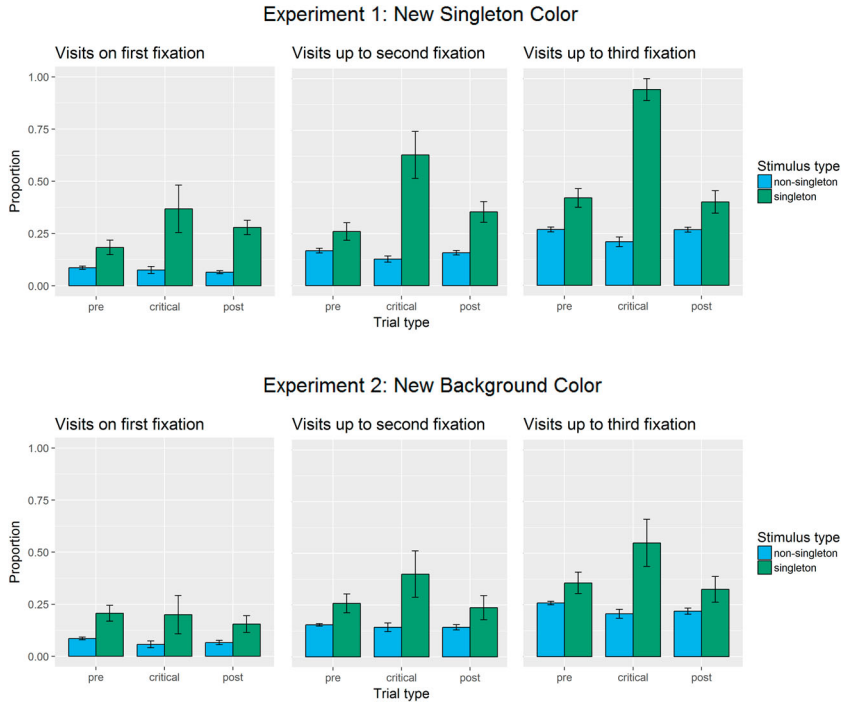

Figure 4. Cumulative fixation proportions on a stimulus from the first to the third fixation after search display's onset for Experiment 1 (upper panel) and Experiment 2 (lower panel). Error bars indicate the standard errors (i.e., SD / $\sqrt{N}$) of the mean.

feature (in the pre-critical or the post-critical trials). This result is consistent with the assumption that colour novelty is sufficient to bias attention. Once the singleton with the novel colour was fixated, it was also gazed at longer than a familiar singleton in the pre-critical or post-critical trials.

Table 2. GEE models for stimulus visits within the first three fixations in Experiment 1.

Fixation		*b*	*Wald* $\chi^2(1)$	*p*
1st Fixation	Intercept: singleton, pre-critical trials	−1.48	41.79	< .001*
	Non-singleton, pre-critical trials	−0.89	10.11	.002*
	Singleton, critical trial	0.94	2.85	.091
	Stimulus type × Trial type	−1.08	2.25	.133
1–2nd Fixations	Intercept: singleton, pre-critical trials	−1.03	23.07	< .001*
	Non-singleton, pre-critical trials	−0.58	4.69	.030*
	Singleton, critical trial	1.56	8.70	.003*
	Stimulus type × Trial type	−1.88	10.47	.001*
1–3rd Fixations	Intercept: singleton, pre-critical trials	−0.30	2.81	.094
	Non-singleton, pre-critical trials	−0.70	10.04	.002*
	Singleton, critical trial	3.19	9.79	.002*
	Stimulus type × Trial type	−3.51	11.10	< .001*

Note: GEEs comprised a logit link function. Singletons in pre-critical trials were set as reference category which is represented by the intercept. Signs of non-interaction slopes indicate whether fixation probability increases or decreases compared to the reference category. See text for further details. *p < .05.

The mean latency of the first singleton fixation in the critical trial was 425 ms which is in accordance with previous studies examining the time course of surprise capture (Horstmann, 2002, 2006; Horstmann & Herwig, 2015). This latency is sufficiently different from a latency of 200–250 ms which has been measured for oculomotor capture by expected colour singletons (Theeuwes et al., 2003; but see Geyer, Müller, & Krummenacher, 2008) to rule out that the present results are an instance of saliency capture.

First fixations in pre-critical trials targeted more probably the salient singleton than a non-salient stimulus, indicating prioritization of the expected singleton. The central hypothesis, however, was that colour novelty alone, in the absence of singleton novelty, is capable of biasing attention. This colour novelty effect is revealed as the differences between the novel and the familiar colour. This effect emerges with the second fixation. The present result thus reveals an early saliency effect and a later novelty effect. Accordingly, an analysis of the fixation index revealed that in the critical trial, on average, the second fixation targeted the singleton with the novel colour, whereas in pre- and post-critical trials, roughly the fifth fixation targeted the singleton. To

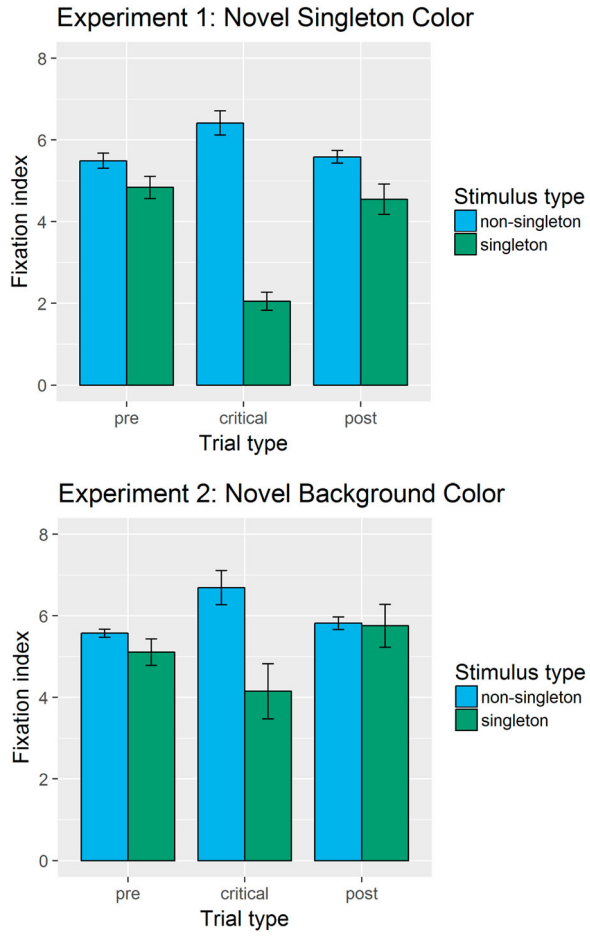

Figure 5. Mean index of the first fixation on a stimulus in Experiment 1 (upper panel) and Experiment 2 (lower panel). Error bars indicate the standard errors (i.e., $SD / \sqrt{N}$) of the mean.

summarize, while a weak singleton effect occurred early in the critical trial (e.g., on the first fixation), a novelty effect occurred later in the trial (i.e., on the second fixation).

Experiment 2

Our account of surprise capture assumes that novelty (more precisely, expectation discrepancy) changes the attentional priorities that guide the deployment of attention and eye movements. Assuming a central attentional priority map (see Zelinsky & Bisley, 2015), this means that novelty is included here in addition to stimulus saliency (Itti & Koch, 2000), match to attentional-control settings (Folk et al., 1992), and memory related factors (such as priming of pop-out; Awh, Belopolsky, & Theeuwes, 2012).

One might, however, propose a completely different account of surprise capture. The attentional capture by unexpected events might be due not to an (active) orienting towards the surprising stimulus but rather to the interruption caused by a general mismatch between a previously acquired attentional set and the processing demands of the present trial, restoring the ability of saliency to attract attention (for a similar account, see also Folk & Remington, 2015). In Experiment 1, the change appears at the most salient location in the display. Therefore, it is not sure which mechanism mainly caused the attentional bias towards the singleton. The *expectation discrepancy account* would attribute the result to the active orienting towards the surprising event. The *control interruption account*, however, would attribute the result to a facilitated capture by the most salient location in the display. With a regular presentation of a singleton in every pre-critical trial, the attentional set might have included an inhibition of saliency information to the effect that this information does not affect attention. The surprising event, in turn, might have interrupted this attentional set, enabling saliency to attract attention again (see also Müller, Geyer, Zehetleitner, & Krummenacher, 2009, for learned suppression of colour singletons in visual search).

Note that the control interruption account and the expectation discrepancy account are not necessarily mutually exclusive. Both effects might have added up inducing the strong attention attentional bias towards the singleton with a novel colour in Experiment 1. Thus, in Experiment 2 we tested the control interruption explanation in isolation by presenting an unexpected background colour in the critical trial as a non-local novel feature while keeping the singleton's and non-singleton's colours constant.

Method

Participants

As in Experiment 1, we recruited 20 students or visitors of Bielefeld University (five male, 15 female) and rewarded them with 2€. Mean age was 21.6 (SD = 4.07).

Stimuli

Stimulus sizes and their arrangement were identical to Experiment 1 as were the colours of the singletons and the non-singleton distractors. In Experiment 2, two background colours were used: black (RGB: 0, 0, 0; CIE: x = 0.280, y = 0.226; 0.114 cd/m^2) and blue (RGB:

70, 70, 240; CIE: x = 0.170, y = 0.102). Once again, with the exception of the black background colour, all colours were matched for physical luminance with 24 cd/m^2 (±1).

Apparatus

This was the same as in Experiment 1.

Procedure

Procedure was the same as in Experiment 1 except for three changes. First, the singleton distractor colour remained the same (red or green among grey distractors for half of the participants) throughout the experiment. Second, from the 33rd trial on, simultaneously with the offset of the fixation cross in the pre-display, the background colour changed from black to blue. Third, from the 33rd trial on, simultaneously with the offset of the search display, the background colour changed from blue to black.

Results

Data preprocessing and analysis

The same as in Experiment 1.

Accuracy and reaction times

Proportion correct was .95, 1.00, and .97 in the pre-critical, critical, and post-critical target absent trials. Target present trial performance was lower in pre-critical trials (.91) than in post-critical trials (.96), *Wald* $\chi^2(1) = 5.03$, $p = .025$. An ANOVA of the target absent RTs with the variable trial type (pre-critical vs. critical vs. post-critical), revealed a significant main effect, $F(2, 38) = 22.88$, $\varepsilon_{GG} = .57$, $p < .001$. The critical trial RT (3621 ms) differed both from pre-critical (2677 ms) and post-critical trials (2681 ms), $ts(19) > 4.69$, $ps < .001$. For target present trials, mean RTs in pre-critical trials (1874 ms) and post-critical trials (1981 ms) did not differ significantly, $t(19) = 1.16$, $p = .262$.

Pre-critical trials

The probability of fixating a stimulus in pre-critical target absent trials was high (.94), with non-singleton distractors being visited more frequently (.96) than singleton distractors (.91), *Wald* $\chi^2(1) = 4.98$, $p = .026$. There was no significant difference in fixation latency of non-singleton distractors (1134 ms) and singleton distractors (1047 ms), $t(19) = 1.24$, $p = .232$.

Analysis of the pre-critical target present trials was performed on the data of 18 participants, as two participants had no correctly answered trial in which singleton and target coincided. The remaining participants fixated singleton distractors more frequently (.64) than non-singleton distractors (.51), *Wald* $\chi^2(1) = 6.82$, $p = .009$. Almost all non-singleton targets (.99) and all singleton targets were fixated (1.00). For stimuli visited at least once, first fixation latency was not significantly different for singleton targets and non-singleton targets (1017 ms vs. 1077 ms), $t(17) = 0.39$, $p = .700$. Also RTs did not differ significantly between target singleton trials (1863 ms) and non-singleton target trials (1891 ms), $t(17) = 0.16$, $p = .874$.

Critical trial

The mean proportion of stimulus visits was .91 (see Table 3 for the detailed descriptives).

Mean latencies for the first fixation on a stimulus were computed as before (Figure 2, lower panel). An ANOVA of the singleton fixation latencies with the variable trial type (pre-critical vs. critical vs. post-critical) revealed no significant main effect, $F(2, 38) = 0.65$, $\varepsilon_{GG} = .50$, $p = .472$. Unlike in Experiment 1, fixation latencies for singleton distractors in the critical trial (935 ms) did not differ significantly from the pre-critical (1047 ms), $d_z = 0.13$, or post-critical trials (1136 ms), $d_z = 0.20$. As the singleton fixation latency represents our main depended variable, we additionally ran a cross experiment analysis. An ANOVA with the variables trial type (pre-critical vs. critical vs. post-critical) and experiment (Experiment 1 vs. Experiment 2) revealed significant effects of trial type, $F(2, 74) = 7.25$, $\varepsilon_{GG} = .76$, $p = .004$, and experiment, $F(1, 37) = 6.44$, $p = .016$. The interaction was significant as well, $F(2, 74) = 3.58$, $\varepsilon_{GG} = .76$, $p = .046$, showing that the novel background colour in the critical trial of Experiment 2 resulted in a higher singleton fixation latency ($M = 935$ ms) than a novel singleton colour

Table 3. Proportions of fixations on singleton distractors and non-singleton distractors in Experiment 2.

Trial type	Stimulus	Mean proportion of fixations	*SE*
pre-critical	non-singleton	.96	.020
	singleton	.91	.028
critical	non-singleton	.85	.037
	singleton	1.00	.000
post-critical	non-singleton	.85	.034
	singleton	.91	.027

Note: *SE* = Standard error (i.e., *SD* / $\sqrt{N}$) of the mean proportion with a sample size of $N = 20$ each.

as in Experiment 1 ($M = 425$ ms), $t(22.84) = 2.95$, $p = .007$, $d_{between} = 0.92$.

For dwell time, a 3 (trial type: pre-critical vs. critical vs. post-critical) × 2 (stimulus type: singleton vs. non-singleton) ANOVA (Figure 3, lower panel) revealed a main effect for trial type, $F(2, 38) = 9.90$, $\varepsilon_{GG} = .66$, $p < .001$, a marginally significant effect for stimulus type, $F(1, 19) = 3.63$, $p = .072$, but no significant interaction, $F(2, 38) = 1.24$, $\varepsilon_{GG} = .45$, $p = .290$. The significant main effect for trial type was due to longer dwell times at any stimulus type in the critical trial (258 ms) both compared to the pre-critical (218 ms), $t(39) = 2.52$, $p = .016$, $d_z = 0.40$, and the post-critical trials (210 ms), $t(39) = 2.93$, $p = .006$, $d_z = 0.46$. The marginally significant effect for stimulus type was due to longer dwell times on singleton distractors (241 ms) than on non-singleton distractors (217 ms).

As in Experiment 1, we examined the cumulative fixation distribution for the first three fixations (Figure 4, lower panel). The three corresponding GEE models are shown in Table 4. As before, singletons in pre-critical trials serve as reference category.

For the first fixation, there was only a significant negative slope due a lower probability for fixating a non-singleton (.09) than a singleton (.21) within pre-critical trials.

With the first and the second fixation included, the model still only yielded a significant negative slope that indicates a lower fixation probability for non-singletons (.16) than for singletons (.26) within pre-critical trials.

For the model including the first three fixations there was a marginally significant negative slope for non-singletons in the pre-critical trials, due to a lower fixation probability compared to singletons in the pre-critical trials (.26 vs. 36). Moreover, there was a significant negative slope for the Stimulus type × Trial type interaction indicating that the difference between non-singletons and singletons was smaller in the pre-critical trials (.26−.36 = −.10) than in the critical trial (.21−.55 = −.34).

The mean first fixation indices are shown in Figure 5 (lower panel). An ANOVA for the index of the first fixation on a singleton with the factor trial type (pre-critical vs. critical vs. post-critical) yielded no significant main effect, $F(2, 38) = 2.19$ ($\varepsilon_{GG} = .43$), $p = .148$. Contrary to Experiment 1, the mean first fixation index for singleton distractors in the critical trial ($M = 4.15$) was not significantly lower than in pre-critical ($M = 5.11$, $d_z = 0.28$) and post-critical trials ($M = 5.76$, $d_z = 0.36$).

Table 4. GEE models for stimulus visits within the first three fixations in Experiment 2.

Fixation		*b*	*Wald* $\chi^2(1)$	*p*
1st Fixation	Intercept: singleton, pre-critical trials	−1.34	34.36	< .001*
	Non-singleton, pre-critical trials	−1.03	12.86	< .001*
	Singleton, critical trial	−0.05	0.01	.938
	Stimulus type × Trial type	−0.39	0.22	.639
1–2nd Fixations	Intercept: singleton, pre-critical trials	−1.04	21.09	< .001*
	Non-singleton, pre-critical trials	−0.64	6.74	.009*
	Singleton, critical trial	0.63	2.02	.155
	Stimulus type × Trial type	−0.75	1.87	.172
1–3rd Fixations	Intercept: singleton, pre-critical trials	−0.60	7.55	.006*
	Non-singleton, pre-critical trials	−0.44	3.37	.066
	Singleton, critical trial	0.80	2.93	.087
	Stimulus type × Trial type	−1.10	3.99	.046*

Note: GEEs comprised a logit link function. Singletons in pre-critical trials were set as reference category which is represented by the intercept. Signs of non-interaction slopes indicate whether fixation probability increases or decreases compared to the reference category. See text for further details. *$p < .05$.

Discussion

The surprising background colour in the critical trial did not strongly influence the attentional priority of the singleton item as fixation latencies and fixation indices did not differ significantly from the pre-critical trials. This result cannot be attributed to an insufficiently strong surprise, because RTs indicated general interference by the surprising change. The null-result can of course not rule out completely the control interruption account as the non-significance could be due to insufficient statistical power. However, a comparison of the experiments revealed a significant interaction effect of trial type and experiment, meaning that the capture effect was stronger in Experiment 1 than in Experiment 2. The results thus further support the hypothesis that stimuli with expectation discrepant features attract attention in a spatial manner.

While the results of Experiment 2 do not conform with the strongest form of an interference account, it seems that a weaker version might well explain the very late effects for singleton fixations in the critical trial. Remember that the singleton in the present experiment had a familiar colour in all trials, including the critical trial. Thus, the discrepancy account cannot

explain the late effect, and it is well possible that the interference account provides an adequate explanation. However, it would be a rather late effect, and later than surprise capture.

Notably, in the critical trial, there were longer dwell times on any stimulus type, not just on the novel stimulus. A similar tendency was also present in Experiment 1. As this effect was non-anticipated and not directly related to the aim of the experiment, proper control conditions to narrow possible explanations were missing. The effect might indicate that a surprising colour change led also to a generalized change in the processing strategy, for example towards a more conservative criterion for stimulus processing.

General discussion

The goal of the present study was to test whether colour novelty alone, in the absence of singleton novelty, captures attention. To that aim we used a singleton-familiarization procedure where we presented a target-uncorrelated colour singleton in all pre-critical trials to eliminate singleton novelty in the critical trial. The results show that feature novelty is sufficient to capture attention. The novel singleton in the critical trial was fixated earlier than the familiar singletons in the pre-critical trials. Concerning time course, prioritization emerged within the first two fixations, and the latency of the first fixation on the novel singleton was on average 425 ms. Experiment 2 tested an alternative account to surprise capture: that what was observed in Experiment 1 was not an expectation discrepant colour attracting attention but an expectation discrepant colour that reset an established attentional set and restored the ability of the singleton to capture attention. This was tested with a change of the background colour. There was, however, no significant fixation latency gain for the singleton due to a changed background, which further supports that the surprising singleton colour in Experiment 1 mainly attracted attention in a spatial manner.

Previous experiments provided inconsistent support for the hypothesis that colour novelty alone, without additional singleton novelty, triggers surprise capture: While newer Experiments using eye-tracking (Horstmann & Herwig, 2016) and inattentional blindness rates (Horstmann & Ansorge, 2016) to indicate attention showed that singleton novelty is not essential for surprise capture, older experiments using a between-subjects set-size variation in a visual search task to indicate attention failed to support the hypothesis. That the present study did find evidence in a visual search task gives support to our contention that the methods used in the older studies might have been less sensitive for more subtle effects, and that presenting a non-informative singleton in each pre-critical trial might attenuate effects of a novel colour in the critical trial.

It might be argued that the effects in the present study do not seem to be subtle, as the mean latency of the first novel-colour singleton fixation in the critical trial is very similar to results by Horstmann and Herwig (2015), where singleton novelty and colour novelty were confounded. It is of note, however, that the present experiments implemented, for the first time, a pre-display with a variable fore-period to discourage pre-planned eye movements. This measure seemed to be partly successful, as we found significant saliency effects on the first eye-movement. Thus, comparisons of the absolute latencies between studies have to be interpreted with caution.

The presence of these early salience effects might be viewed as evidence for saliency capture. We would, however, contend that these effects could also be due to top-down effects. As discussed in the introduction, with a singleton presented in every trial, participants may have included the singleton in their top-down strategies, for example, by using the salient stimulus as a convenient starting point for their search. Other authors have suggested other top-down strategies using the salient singleton, such as contingent capture for display-wide feature (Gibson & Kelsey, 1998) or probability matching (Remington et al., 1992). Given these ambiguities, it is difficult to attribute the prioritization of the salient stimulus to either bottom-up or top-down mechanisms.

One possible interpretation of the attention biasing by the novel colour in the critical trial of Experiment 1 is that the mechanism for bottom-up saliency capture habituated during the pre-critical trials, but was dishabituated by the novel colour. However, the effects of the novel colour do not match the proposed time-course of bottom-up selection of salient stimuli: it emerged later, that is, at the second fixation, and with an overall mean latency of the first singleton fixation of 425 ms. This contrasts with theoretical proposals assuming early effects both for covert attention

shifts below 150 ms (Theeuwes, 2010) and initial fixations on the singleton (Itti & Koch, 2000), and for overt attention shifts which have been measured with a fixation latency of 200–250 ms (Geyer et al., 2008; Theeuwes et al., 2003).

We propose that the effects of the novel colour are not caused by bottom-up saliency capture, but rather by expectation discrepancy. On this account, the pre-critical trials induced an expectation of the already presented colours. This expectation was refined in the course of the pre-critical trials and ends up rather narrowly tuned at the end of the pre-critical trials. The novel colour in the critical trial, in turn, deviates from the narrowly tuned expectations, and it is this deviation that changes attentional priorities. We prefer to term this deviation expectation-discrepancy, while others prefer the concept of novelty (Retell et al., 2015). We regard these differences in terminology rather as a matter of taste. The crucial point is that the pre-critical trials gave rise to a standard which defines what is expected, or familiar, respectively, and the novel feature in the critical trial deviates from that standard. A more important aspect regarding the interpretation of expectation discrepancy is that some authors refer to a novel or to an unexpected event in the case of rare events (e.g., Brockmole & Boot, 2009; Folk & Remington, 2015). However, even rare events might be completely expected after few occurrences and their effects seem to emerge earlier than those of the first occurrence (Horstmann & Ansorge, 2006).

Experiment 1 also showed that gaze dwelled longer on the singleton in the critical trial as compared to the pre-critical or the post-critical trials (see Horstmann et al., 2016; Horstmann & Herwig, 2015). We interpret this as a second attentional effect of expectation discrepancy being the capture of central (or internal; see Chun, Golomb, & Turk-Browne, 2011) attention. The binding of central attentional resources to the processing of an expectation discrepant event has been observed previously in quite different settings, such as scenes with objects that semantically or syntactically deviate the scene context (Võ & Henderson, 2009), or scenes in which episodic discrepancies had been introduced (Võ, Zwickel, & Schneider, 2010). The effect of surprise induced blindness may also be interpreted in this way (Asplund et al., 2010).

In Experiment 2, we tested whether surprise capture might also be explained by a failed inhibition of saliency prioritization. To test this, we changed the procedure of Experiment 1 in two respects. First, the singleton feature in the critical trial was not novel but the same as in the pre-critical trials. Second, the novel feature was presented at a different position and as a spatially distributed feature consisting in a background colour change. With these modifications, Experiment 2 did not yield the same results as Experiment 1: singleton selection latency was not significantly different from the pre-critical trials, and a prioritization only emerged if all the first three fixations were taken into account. These results suggest that the surprise capture effect in Experiment 1 should mainly be driven by spatial attentional bias of the novel feature.

Experiment 2 also revealed a general increase in gaze dwell time in the critical trial. This effect was also observed in Experiment 1, where the unchanged non-singletons were gazed at longer in the critical trial than in the pre-critical trials. These effects might indicate a general shift towards a more conservative decision criterion in the critical trial.

To summarize, the present experiment sought and obtained evidence that colour novelty alone is sufficient to bias attention. This was done by using a singleton-familiarization procedure where a singleton was presented on every trial before the presentation of the novel colour. With this procedure, the confounding of colour novelty and singleton novelty was avoided. The present results are compatible with an expectation discrepancy account of surprise capture, and emphasize the independence of surprise capture from other forms of attentional capture, in particular singleton capture.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Study 2

Unexpectedness increases singleton capture of the gaze

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Abstract

Much of the literature on involuntary attention has been devoted to the conflict between goal contingent capture and saliency capture. A further variant has been proposed as surprise capture, which is thought as the attraction of attention instigated by expectation-discrepant, surprising, or novel stimuli. In a previous study, participants were familiarized with a search irrelevant color singleton. Consistent with surprise capture, the irrelevant singleton strongly captured and bound the gaze when it was unannounced presented with a novel color. In the present study, we used the same experimental paradigm to closer investigate how an expectation about a specific color feature emerges such that a novel color can be perceived as more or less expectation discrepant. We proposed that an expectation about a feature can be modelled by the sampling distribution of the mean and predicted that it gets narrower both with increasing sampling occasions and lower variability of the feature. We tested these predictions by inferring expectation discrepancy of a novel singleton color from attentional prioritization. Experiment 1 confirmed that gaze capture in the surprise trial was weaker with higher variability of the singleton's color hue in the preceding familiarization trials. Experiment 2 showed that gaze capture in the surprise trial was weaker with a lower number of prior familiarization trials. Further approaches to mathematically model expectations are discussed as well as several indicators for expectation discrepancy.

Keywords: attention capture, surprise, novelty, expectations, singleton, salience

Publicity statement

Outside the laboratory, we regularly encounter novel or unexpected visual stimuli. Inside the laboratory, however, the factor of expectation discrepancy is often eliminated because of highly repeated presentations of the same stimuli. Specific experiments demonstrated that surprising visual features induce capture of attention and the gaze. In the present study, we extended our knowledge about the construct of expectations by investigating perceived feature variability and the number of sampling occasions as two factors that determine the emergence of a narrow expectation. Our experiments show that gaze capture by a novel color is attenuated if participants have been previously exposed to intensive color changes. Furthermore, gaze capture is weaker if participants have had a shorter familiarization period with the old colors. Overall, our study demonstrates how expectations can differentially affect gaze behavior.

Unexpectedness increases singleton capture of the gaze

In attention capture literature, it is debated to which extent capture by salient stimuli is attributable to pure bottom-up salience (Theeuwes, 1991, 1992, 2010) and to top-down influences like goal contingent orienting (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992). This does not need to be an either-or decision. For example, the framework of priority maps for attention deployment (e.g., Zelinsky & Bisley, 2015) details that both can contribute to activity within a spatial neuronal representation that determines attentional priorities (Moran, Zehetleitner, Müller, & Usher, 2013; Wolfe, 1994, 2007). However, some authors argue that some phenomena, such as inter-trial priming and reward learning, where attention is directed towards previously selected stimuli, do not fit in either the top-down or to the bottom-up category (Awh, Belopolsky, & Theeuwes, 2012; Kristjánsson & Campana, 2010) and selection history has thus been proposed as an additional source of activity within priority maps for visual attention allocation (Awh et al., 2012). In the present paper, we closer investigate the *un*expectedness of a stimulus as another aspect in the sense of selection history that so far has received limited consideration in visual attention research. Contrary to intertrial-priming and reward learning, attention capture due to unexpectedness occurs when there has been no prior exposure of the respective stimulus.

The capacity of unexpected salient stimuli to attract attention, which has been termed surprise capture (Horstmann, 2002, 2015), can be induced in a visual search task with a repetition-change paradigm. For instance, participants are first presented with a number of pre-critical search trials that do not contain a salient stimulus and familiarize participants with a certain range of stimulus features. It is assumed that during this familiarization, participants build up increasingly firm and narrow expectations about the to be presented stimuli and their features,

and that they base their expectations on the characteristics of the stimuli that they have seen repeatedly. The surprise trial follows the familiarization trials where a feature singleton is shown for the first time and without prior announcement. Several studies demonstrated that the novel singleton captures attention, as indicated by the reduction of set size effects (Becker & Horstmann, 2011; Horstmann, 2002, 2005, 2006), the reduction of inattentional blindness rates (Horstmann & Ansorge, 2016), increased performance accuracy with short presentation durations (Horstmann & Becker, 2008), validity effects (Horstmann & Becker, 2011), and reduced singleton fixation latencies as well as increased proportions of early fixations (Ernst & Horstmann, 2018; Horstmann, Becker, & Ernst, 2016; Horstmann & Herwig, 2015; Retell, Venini, & Becker, 2015).

Attention to an unannounced singleton with a novel feature that is presented after a number of search trials without a salient stimulus is difficult to explain by top-down factors like singleton search mode or goal contingent orienting (Gibson & Jiang, 1998). If so, however, why is surprise capture of an unexpected singleton not just saliency capture? One argument is that the time course of surprise capture differs from that of saliency capture. Covert and overt attention shifts that were attributed to saliency capture have been reported to occur with a latency of 60-150ms (Kim & Cave, 1999; Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000), and 200-250ms, respectively (Theeuwes, De Vries, & Godijn, 2003; van Zoest, Donk, & Theeuwes, 2004; Weichselbaum & Ansorge, 2018). In contrast, surprise capture has been found to occur with a mean latency of 400-500ms, for both covert (Horstmann, 2002, 2006) and overt attention shifts (e.g., Ernst & Horstmann, 2018; Horstmann et al., 2016; Horstmann & Herwig, 2015). Asplund, Todd, Snyder, Gilbert, and Marois (2010) likewise found surprise induced blindness for a target in a rapid visual presentation (RSVP) stream to occur around 400ms. Accordingly, it is often the

second but not the first fixation after search display's onset that it biased towards the unexpected stimulus. Horstmann (2006) discussed two processing steps in the process sequence that lead to surprise capture which could explain the relatively late effect as compared to saliency capture. First, some time is needed to detect the discrepancy between the expected and the actual input. Second, attention must be directed towards the unexpected stimulus and this process must be strong enough to interrupt an already ongoing visual search process.

Another specific characteristic of surprise capture is that it is followed by increased gaze dwell times on the unexpected stimuli (Ernst & Horstmann, 2018; Horstmann et al., 2016; Horstmann & Herwig, 2015, 2016; see also Võ & Henderson, 2009; Võ, Zwickel, & Schneider, 2010, for unexpected real-world objects within natural scenes, which, however, do not capture attention). Furthermore, recent studies also suggest a higher number of refixations in a surprise trial (Foerster, 2016; see also Horstmann et al., 2016; Retell, Venini, & Becker, 2015). Together, increased dwell times and stimulus revisits are in line with the theory that higher-level processes follow after the first detection of surprise, such as the verification of the expectation violation, the need to understand the causes of the unexpected change in the course of things, and whether it is action relevant (Meyer, Reisenzein, & Schützwohl, 1997; see Reisenzein, Horstmann, & Schützwohl, 2017, for a review of a cognitive-evolutionary model of surprise).

However, that surprise capture in visual search occurs because of a violated expectation or expectation discrepancy so far has not been tested directly and tends to be more a premise underlying the repetition-change paradigm. For instance, if a target uncorrelated singleton is shown in all search trials, the singleton only captures the gaze strongly in the critical trial where it is presented unannounced with a novel feature, but not in the pre-critical and post-critical trials when its feature is presented repeatedly (Ernst & Horstmann, 2018). It is a reasonable

interpretation that the expectation discrepancy of the color is the factor that distinguishes the critical trial from the other trials and causes attention capture. However, this interpretation would be even more convincing on the basis of a model where it is explicitly formulated how expectations are built up and which factors determine several extents of expectation discrepancy of a novel color in a critical trial.

As a side note, the latter finding also demonstrates that a singleton must not necessarily be presented for the first time in the surprise trial. An unexpected color change of a previously presented singleton ("pure feature novelty" as opposed to "both singleton and feature novelty") is already sufficient to trigger an attentional capture. Furthermore, novelty prioritization has also been found when the novel feature was not singled out by salience (Horstmann & Ansorge, 2016; Horstmann & Herwig, 2016).

More direct evidence for the effects of unexpectedness comes from a series of experiments that did not require visual search but rather a single stimulus choice. Participants repeatedly had to indicate whether a dot appeared above or below two irrelevant distractor words, which were presented closely to each other in two different rows at the center of the screen (Meyer, Niepel, Rudolph, & Schützwohl, 1991). In the critical surprise trial, one of the two distractor words was presented with a new background color. Here, the authors found increased reaction times as compared to a familiarized control group where one word was already presented on a different background color in every pre-critical trial. The increase in reaction time was interpreted as an indicator of the surprise induced interruption of ongoing processes (see also Meyer et al., 1997). Furthermore, improved recall both for the dot position and the irrelevant word, as measured by an unexpected memory test, indicated that the word had been attended to and encoded into memory. Schützwohl (1998) more closely investigated the

effect of “schema strength”. The term schema has been coined to for organized and structured representation of knowledge about objects, scenes, situations, and actions. The theoretical construct of a schema is specifically designed such that it best serves the purpose to process and interpret mundane, everyday events, which includes in particular the understanding of current input as well as the predicting of future input (Rumelhart, 1984; Rumelhart & Ortony, 1977; see also Reisenzein, Horstmann, & Schützwohl, 2017). If a discrepancy is detected between an event and the predictions generated by the schema that exceeds a certain threshold, surprise is elicited and the schema will be updated such that it can predict the new information in the future.

According to Schützwohl (1998), schema strength varies in that the constraints of the schema variables that represent the diverse features of the concept can be narrow or broad. For instance, schema strength for societally important vehicles should be high as they usually come along with specific colors and shapes (e.g., red and spacious for ambulances). Schema strength for private vehicles, however, should be low as they can have any color and shape (Hout, Robbins, Godwin, Fitzsimmons, & Scarince, 2017). Moreover, a person that has only seen three red ambulances in her or his life should have lower schema strength and would be less surprised about a green ambulance compared to someone who has already seen hundreds of ambulances that were all red. According to this theory, schema strength also increases with more frequent instantiations of the schema. Schützwohl (1998) tested these predictions using the same task as described above for Meyer et al. (1991). He found that the surprise induced increase of response time in the critical trial was attenuated both with a lower number of pre-critical trials and with more feature variability within the pre-critical trials. This result was interpreted such that the surprised induced interruption of ongoing behavior was reduced because low schema strength reduces the potential to detect schema discrepancy for novel events. In the following, we use the

terms “expectation” and “schema” synonymously because of their conceptual similarities. Furthermore, we do not distinguish between novelty and surprise (or unexpectedness) within the present study although there are differences that can be important in other contexts (see Barto, Mirolli, & Baldassarre, 2013, for an overview).

The present study

Within the present study, we investigate whether surprise capture of the gaze can likewise be manipulated by inducing different expectations within a visual search task. Following Schützwohl (1998), broader expectations are caused by higher feature variability and fewer sampling occasions. If surprise capture depends on expectation discrepancy, broader expectations should result in weaker attention capture by a novel feature than narrow expectations. Furthermore, this study is intended to contribute to a more detailed analysis of the construct of expectation in the research field of visual attention, as there is a variety of opinions about when an event is characterized as unexpected. In some studies, an event is described as unexpected if it occurs in 10-20% of search trials (e.g., Brockmole & Boot, 2009; Folk & Remington, 2015). However, one could argue that even rare events can be completely expected. For instance, a train that arrives in time when you are traveling to an important meeting might be a rare event, yet you anticipate that there is a chance that the train could arrive in time (see also Horstmann, 2015). Accordingly, previous experiments have shown that participants can shift attention almost as fast to rare salient targets as to frequent salient targets, even if the target is salient only on 4% of the trials and non-salient on 96% of the trials (Horstmann & Ansorge, 2006), and much faster than typically observed when the salient item is presented for the very first time. Thus, we only refer

to the very first presentation as a potentially surprising or unexpected event. Keeping this in mind, we will propose and discuss some possibilities of how expectations can be modelled.

Besides surprise capture of the gaze, additionally revisits and dwell times as indicators for surprise induced explorative behavior shall be inspected within the experiments of this study. We expect dwelling and revisiting likewise to increase with higher expectation discrepancy. However, these variables will be investigated in a rather explorative manner and discussed with respect to the cognitive-evolutionary model of surprise (Reisenzein et al., 2017).

Experiment 1

For the purpose of the present study, we adapted the experimental design used by Ernst and Horstmann (2018) which has already been described above. An irrelevant magenta color singleton is shown at a random stimulus position in every search trial while participants search for a specific shape (a closed ring among rings with a gap). In the critical trial, the surprising event is constituted by an unannounced color change of the singleton (i.e. to pure red or blue). Between participants, we kept the color change of the critical trial constant and only varied the pre-critical trials by two factors: a) The variability of the magenta singleton color, in more or less subtly altering the proportion of red and blue color between search trials (resulting more blueish or reddish magenta color hues); and b) the number of sampling occasions due to fewer or more pre-critical trials. According to previous theories about expectation narrowness (or schema strength, respectively; Schützwohl, 1998), we expect attentional prioritization of a novel singleton color to be attenuated with a higher variation of the magenta singleton color hue in pre-critical trials. Furthermore, we expect attentional prioritization to be attenuated with fewer pre-critical trials. That is, both manipulations should result in broader expectations at the surprise

trial, rendering the first presentation of a pure red or blue singleton color less expectation discrepant.

We tentatively propose that an expectation towards a singleton color behaves like the sampling distribution of the arithmetic mean with an expectation value (magenta) and a standard error, which is the standard deviation of the already presented singleton color values divided by the square root of the number of presentations. The distribution becomes broader with higher standard deviation of the singleton's color feature, and with fewer trials which represent the sample size. Given that magenta as the "mean" color of the presented color hues in the pre-critical trials corresponds to the expectation value of the expectation's distribution, the same pure red singleton color in the surprise trial can be either highly expectation discrepant as its color value is located at the tail of a narrow distribution (e.g., two standard error units away from the expectation value) or hardly expectation discrepant if its feature value lays more centered within a broader distribution (e.g., only a half standard error unit away from the expectation value).

To test these predictions, we tracked gaze behavior as a proxy for visual attention deployment (Deubel & Schneider, 1996). In line with our previous eye tracking studies about surprise capture, we inferred unexpectedness of the novel singleton color in the critical trial from the latency of the first singleton fixation as a measure for spatial attentional prioritization.

Method

The sample size of each experimental group was oriented on Ernst and Horstmann (2018) who used a similar design. The study was approved by the Ethics Committee of University of Bielefeld (EUB).

Participants

96 students or visitors of Bielefeld University (53 men and 43 women) participated in the 5 to 10-min experiment. Participants were approached in the central hall of the university main building and asked to participate in a short experiment in return for candies. Mean age was 21.28 (*SD* = 2.38). After informed consent, all participants were tested for normal or corrected-to-normal vision and for normal color vision.

Apparatus

Stimuli were presented on a 19-in. display monitor (85-Hz refresh rate, resolution 1,024 x 768 pixels) at a distance of 71 cm. Before testing, the monitor was warmed for at least 30 minutes, to ensure temporal stability of luminance and color (Poth & Horstmann, 2017). A video-based eye-tracker (EyeLink 1000, SR Research, Ontario, Canada) with a sampling rate of 1 kHz was used for the recording of eye movements. The participants' head was stabilized by a chin rest, and the right eye was monitored in all participants.

Stimuli

Eight stimuli (color patches plus search stimuli, see Figure 1) were presented in each search display of the experimental trials. The viewing distance was 71cm. Stimuli were evenly distributed on an imaginary circle with a radius of 6.4°. The target was a 1.11° diameter ring with a line-width of 0.23°. Distractors were identical to the target with the only difference of a small radial gap of 0.09° height. 16 different gap positions were evenly distributed between 22.5° and 360°.

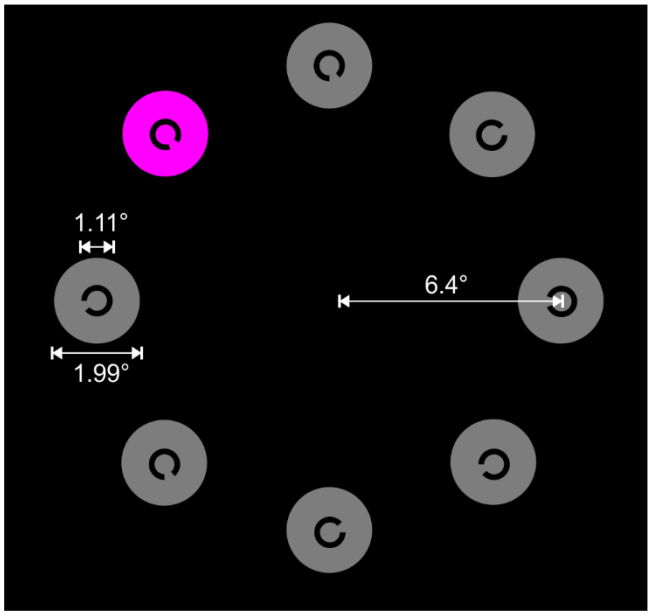

Figure 1. Exemplary display of a pre-critical trial with "mean" magenta singleton color in Experiment 1.

In practice trials, the rings were grey (RGB: 125, 125, 125; CIE: x = 0.274, y = 0.288; 28.855 cd/m^2) and presented directly against a black background (RGB: 0, 0, 0; CIE: x = 0.298, y = 0.290; 0.422 cd/m^2) without color patches. In experimental trials, however, the rings were black and presented on circular color patches (diameter: 1.99°). In each experimental trial, there was one singleton patch at a random position with a unique color, whereas the remaining non-singleton color patches had a grey color (RGB: 128, 128, 128; CIE: x = 0.277, y = 0.288; 29.884 cd/m^2). Possible singleton colors are shown in Table 1.

Table 1. Singleton colors

	sample	RGB	CIE (x, y, cd/m)
Low color variation (pre-critical trials)		195, 0, 255	0.230, 0.116, 29.960
		225, 0, 255	0.254, 0.130, 34.875
		255, 0, 255	0.279, 0.144, 40.338
		255, 0, 225	0.307, 0.160, 37.491
		255, 0, 195	0.341, 0.179, 35.590
High color variation (pre-critical trials)		135, 0, 255	0.190, 0.093, 22.449
		195, 0, 255	0.230, 0.116, 29.960
		255, 0, 255	0.279, 0.144, 40.338
		255, 0, 195	0.341, 0.179, 35.590
		255, 0, 135	0.429, 0.230, 32.190
Critical trial		0, 0, 255	0.152, 0.072, 16.082
		255, 0, 0	0.601, 0.329, 29.143

Note. RGB = values in Red-Green-Blue color space; CIE = values in Commission International de l'Éclairage 1976 color space; cd/m = luminance in candela per square metre.

Design

Between participants, two factors were crossed: a) the number of pre-critical trials (17 vs. 49), and b) the intensity of the singleton's color variation in pre-critical trials (low vs. high), resulting in four different groups of participants. Within participants, we compared performance in pre-critical trials (serving as a baseline) with performance in the critical surprise trial where

the singleton color changed to pure red or blue, counterbalanced between participants. Intraindividual performance differences were compared between groups.

Procedure

The participants' task was to report the presence or absence of the target with a corresponding key press (arrow left and arrow down keys in the lower row of the keyboard, operated with the right index and middle fingers), and participants were instructed to perform the search task as fast as possible while avoiding any response errors.

The experiment started with a practice block of 16 search trials without color patches which was not recorded. After the practice block, a message at the display informed participants that the experimental trials will start and that search stimuli will be presented on color patches. Furthermore, participants were explicitly informed about the non-predictiveness of the color singleton. Thereafter, a single experimental block of either 18 or 50 trials started. The last trial was the critical trial in which the singleton color was either pure red or blue. The singleton color both in the first and last pre-critical trial was fixed to the "mean" magenta color. Within every single trial of the remaining pre-critical trials, the singleton color was randomly chosen from five possible magentaish colors, depending the color variation condition (see Table 1). Randomly chosen, half of the displays in each condition were target present trials, and half were target absent trials; however with the exception of the critical trial and the last pre-critical trial. These were always target absent trials to reduce variance between participants, and in order to measure surprise effects unconfounded with the presence of a target (Ernst & Horstmann, 2018). The target position was determined randomly. The singleton position was likewise random with the restriction that all possible distances between singleton and target (including their coincidence) were presented equally often.

Each trial began with a fixation control: participants fixated the center of the screen and confirmed fixation with a key press. This started a variable fore-period during which a central fixation cross was presented. The duration of the fore-period was the sum of (a) a variable time period drawn from an exponential distribution with an expectation value of 0.5s ($\lambda = 2$), (b) a period of 100ms in which the cross had to be fixated continuously after the variable time period has elapsed, and (c) the possible additional time until the central continuous fixation was successfully executed for 100ms.

The exponential distribution of the "non-aging" (Näätänen, 1971) fore-periods is characterized by a constant hazard rate, rendering the onset of the search display less predictable by the time the fore-period already has elapsed. Thereby, we intended to reduce possible pre-planned eye movements at the onset of the search display. In the last pre-critical trial, and the following critical trial, the variable time periods were fixed to 1,000ms and to 500ms, respectively. Duration fixing was done to reduce additional variation in the critical trial. The time period of the critical trial was the expectation value of the exponential distribution. Thus, the interval for the last pre-critical trial was somewhat longer than the expectation value, based on the empirical result that a longer fore-period in trial *n*-1 than in trial *n* results in relatively low action readiness in trial *n* (Los, 2010). Thereby, at the search display's onset of the critical trial, we intended to furtherly counteract the execution of saccades which were already pre-planned before the surprising stimulus has been presented. The search display was presented until a key press was registered. An error sound occurred whenever an incorrect response had been recorded.

Finally note that we do not claim that the RGB differences between the singleton colors are actually perceived with the same differences, which implies that the "mean" magenta color

might not exactly be perceived as the expectation value of the singleton color. However, the different color values chosen in each group should lead to an ordinally higher and a lower level of singleton color variation, which is sufficient for the purpose of this experiment.

Results

Following the practice block, the first 10 trials of the experimental block were excluded as warm-up trials. Thus, there were 7 or 39 pre-critical trials for the analysis plus the single critical trial, depending on the number of trials condition. Raw gaze data were pre-processed using the EyeLink Data Viewer (2.3.22), which parses eye position data into saccades and fixations according to an acceleration threshold (8,000 degrees/sec^2), and a velocity threshold (30 degrees/sec). Fixations were classified as eye data that exceeded neither of these thresholds for a period of 20ms or more. Fixations were assigned to a stimulus when they fell within a circular region with a radius of 2.41° from the center of the stimulus. Further preprocessing and statistical analysis were done using R 3.4.3 (R Core Team, 2016). All reported *p*-values are two-tailed and compared with a significance level of $\alpha = .05$, regardless of whether we predicted the direction of the effect.

As the critical trial was always a target absent trial, in the following analyses we only considered pre-critical target absent trials for comparisons with the critical trial.

Accuracy and Manual response times

Overall, mean accuracy was .96. An ANOVA for the proportion of correct responses with the factors color variation (low vs. high), number of trials (18 vs. 50), and trial type (pre vs. crit) did not reveal any significant differences, Fs$(1,92) < 1.31$, ps $> .166$, η_G^2s $< .012$. In the following analyses, we only included trials that were answered correctly. Four participants were

excluded completely because of a response error in the critical trial, reducing the sample size to 92 participants.

Manual response times are depicted in Figure 2. An ANOVA with the factors color variation (low vs. high), number of trials (18 vs. 50), and trial type (pre vs. crit) only yielded a significant main effect for trial type, $F(1,88) = 31.41$, $p < .001$, $\eta_G^2 = .063$, with longer response times in the critical trial (M = 2,982ms) than in pre-critical trials (M = 2,693ms). The Trial type × Color variation interaction just failed to reach significance, $F(1,88) = 3.67$, $p = .059$, $\eta_G^2 = .008$. By tendency, the increase of mean response time in the critical trial was more pronounced within the low color variation group (2,992ms vs. 2,601ms) than in the high color variation group (2,973ms vs. 2,784ms). The Trial type × Number of trial interaction just failed to reach significance as well, $F(1,88) = 3.34$, $p = .071$, $\eta_G^2 = .007$. The increase of mean response time in the critical trial tended to be more pronounced with 50 trials (3,015ms vs. 2,632ms) than with 18 trials (2,947ms vs. 2,755ms), other $F(1,88)$s < 0.62, ps > .434, η_G^2s < .006.

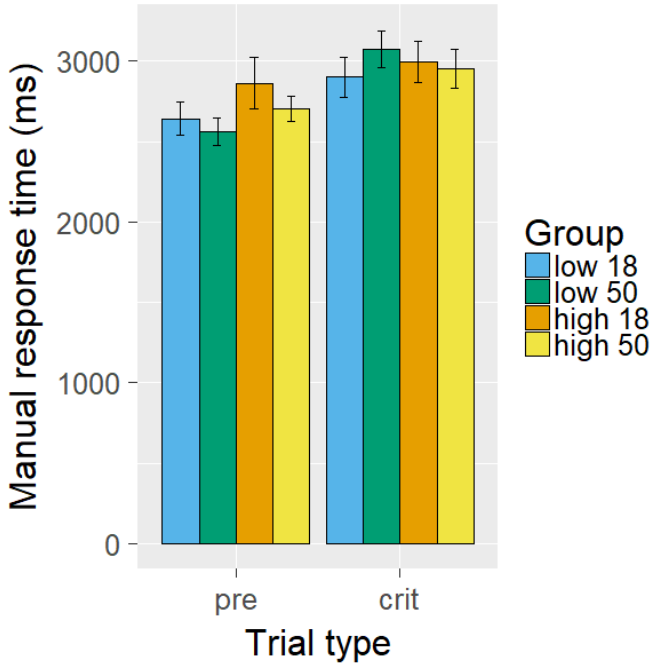

Figure 2. Mean manual response times in pre-critical trials and in the critical trial, separately for the groups with different color variations and numbers of trials. Error bars indicate standard error of the mean.

Gaze data

In most analyses, singleton fixations were compared within and between groups. Where appropriate, also fixations on non-singletons were considered. Overall, participants fixated 95% of the presented stimuli. The singletons in the critical trial were always fixated.

Singleton fixation latencies

Our main dependent variable for attentional prioritization is the latency of the first singleton fixation relative to the search display's onset. Figure 3 gives an overview of the mean singleton fixation latencies. An ANOVA with the factors color variation (low vs. high), number of trials (18 vs. 50), and trial type (pre vs. crit) yielded a significant main effect for color

variation, $F(1,88) = 4.12$, $p = .045$, $\eta_G^2 = .028$, with longer singleton fixation latencies in the high color variation group (M = 1,000ms) than in the low color variation group (M = 810ms). Furthermore, the predicted Trial type × Color variation interaction was significant, $F(1,88) = 6.91$, $p = .010$, $\eta_G^2 = .030$. In the low color variation group, there was a lower mean singleton fixation latency in the critical trail than in the pre-critical trials (677ms vs. 942ms), $t(45) = 2.86$, $p = .006$, $d_z = 0.42$. Yet, there was no significant singleton prioritization within the high color variation group (1,069ms vs. 931ms), $t(45) = 1.16$, $p = .252$, $d_z = 0.17$. The remaining effects of the ANOVA were not significant, $F(1,88)$s < 1.06, ps > .306, η_G^2s < .008.

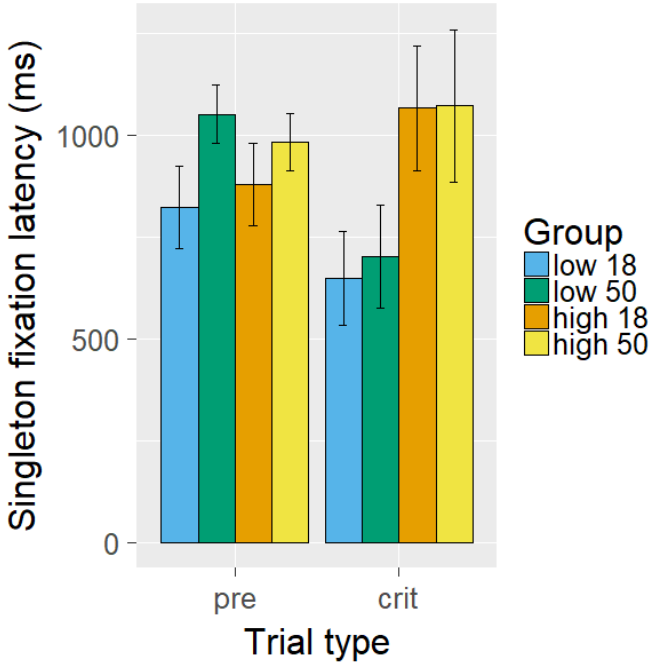

Figure 3. Mean latencies of the first singleton fixation in pre-critical trials and in the critical trial, separately for the groups with different color variations and numbers of trials. Error bars indicate standard error of the mean.

Dwell times

As another specific component of surprise capture, we also analyzed gaze dwell times which are defined here as the summed fixation durations of the first continuous visit on a stimulus. Mean dwell times are depicted in Figure 4. An ANOVA with the factors color variation (low vs. high), number of trials (18 vs. 50), and trial type (pre vs. crit) yielded a significant main effect for trial type, $F(1,88) = 31.52$, $p < .001$, $\eta_G^2 = .137$, with longer dwell times at the singleton in the critical trial ($M = 329$ms) than in pre-critical trials ($M = 232$ms). The Trial type × Color variation interaction did not reach significance, $F(1,88) = 2.90$, $p = .092$, $\eta_G^2 = .014$. By tendency, however, there was a higher increase of mean dwell time in the critical trial of the low color variation group (230ms vs. 356ms) than in the group with high color variation (234ms vs. 302ms). The remaining effects of the ANOVA were likewise not significant, $F(1,88)$s < 1.65, ps $> .203$, η_G^2s $< .011$.

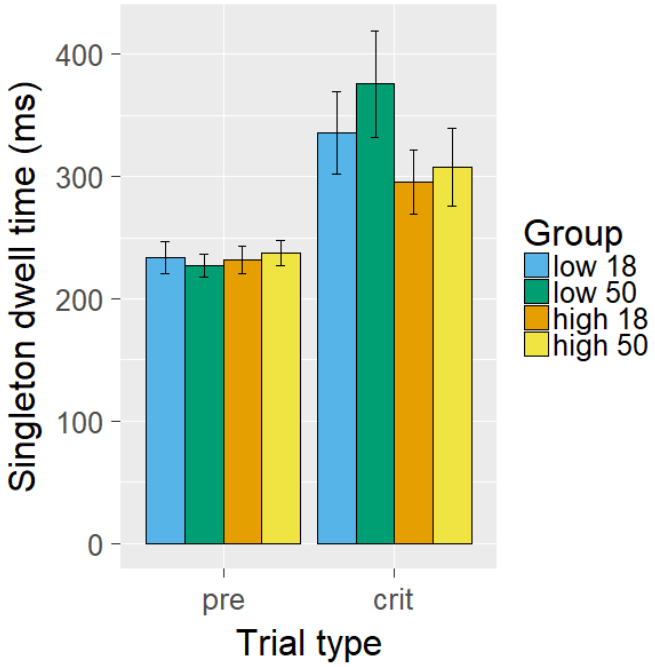

Figure 4. Mean dwell times of the first singleton visit in pre-critical trials and in the critical trial, separately for the groups with different color variations and numbers of trials. Error bars indicate standard error of the mean.

Revisits

We finally analyzed the proportion of stimuli that have been refixated at least once. The proportion of singleton revisits are shown in Figure 5. An ANOVA with the factors color variation (low vs. high), number of trials (18 vs. 50), and trial type (pre vs. crit) revealed a significant main effect for trial type, $F(1,88) = 3.50$, $p < .001$, $\eta_G^2 = .159$, with more revisits on the singleton in the critical trial (.62) than in pre-critical trials (.30). Furthermore, there was a significant Trial type × Number of trials interaction, $F(1,88) = 5.02$, $p = .028$, $\eta_G^2 = .026$. Somewhat unexpectedly, the increase of revisits from pre-critical trials to the critical trial was more pronounced in the group with 18 search trials (.29 vs. .73) than in the group with 50 search

trials (.31 vs. .51). The remaining effects of the ANOVA were not significant, $F(1,88)$s < 3.32, ps > .072, η_G^2s < .020.

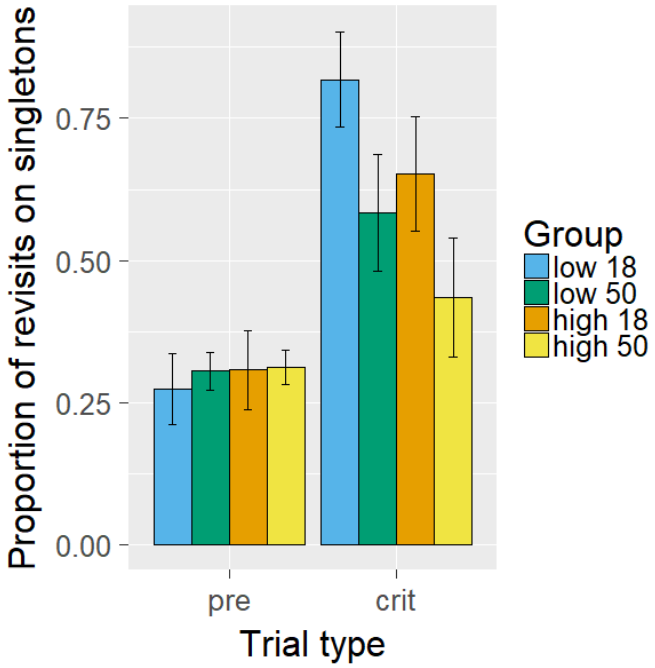

Figure 5. Mean proportions of revisits on the singleton in pre-critical trials and in the critical trial, separately for the groups with different color variations and numbers of trials. Error bars indicate standard error of the mean.

Discussion

We investigated whether manipulating expectation breadth concerning the singleton color prior to the surprise trial results in an attenuated surprise capture effect. Based on schema theory (Rumelhart, 1984; Schützwohl, 1998), we assumed that both fewer sampling occasions and more feature variability result in broader expectations, reducing the expectation discrepancy of an unannounced singleton color change in a critical trial. Reduced expectation discrepancy, in turn,

should lead to reduced surprise capture, premised by the assumption that surprise capture is caused by expectation discrepancy. Predictions were tested in a visual search experiment with an irrelevant color singleton that was presented in every trial. Between-group factors were the number of familiarization trials (17 vs. 49) and the intensity of singleton color variability (low vs. high) prior to the critical surprise trial.

The main dependent variable to test our predictions was the latency of the first singleton fixation, which was reduced in the critical trial of the group with low color variation but not in the group with high color variation. Thus, in line with our prediction, surprise capture attenuated with high color variation, suggesting broader expectations prior to the surprise trial that resulted in lower expectation discrepancy of the novel color. However, singleton fixation latencies did not support the predicted effect for the number of trials factor on surprise capture, which will be the subject of Experiment 2.

Gaze dwell times on the singleton in the critical trial were increased for all combinations of number of trials and color variation. That is, dwell times on the singleton were also increased in the high color variation groups where no surprise capture occurred. Possibly, there are distinct thresholds for expectation discrepancy that determine when an unexpected feature elicits increased dwell times and when it draws the gaze. Binding of attention on expectation discrepant stimuli without prior spatial guidance has already been reported previously (Võ & Henderson, 2009; Võ, Zwickel, & Schneider, 2010). For instance, a printer in a kitchen scene which is semantically expectation discrepant does not draw the gaze but dwell time is increased when the printer is encountered coincidentally (Võ & Henderson, 2009). Note, however, that the expectation discrepancy hypothesis (Horstmann, 2005) only predicts spatial guidance of attention if unexpectedness refers to a visual feature that is pre-attentively available (e.g.,

Treisman & Gelade, 1980). Accordingly, the lack of attentional guidance towards a printer in a kitchen scene can be better explained by the fact that unexpectedness did not refer to a basic feature (but to semantic aspects) than by low expectation discrepancy that did not reach a certain threshold.

We expected that the increase of dwell times is more pronounced in groups with higher expectation discrepancy. Yet, the difference of the increase did not reach significance for any expectation discrepancy manipulation. There was, however, a tendency for a stronger increase of dwell times in the critical trial of the group with low color variation than with high color variation.

We also expected revisits to gradually covary with expectation discrepancy. Similar to dwell times, there was a general increase of revisits in the surprise trial. A specific increase was only present for the number of trials factor. However, the increase of revisits on the singleton in the critical trial was higher in the group with 17 pre-critical trials than in the group with 49 pre-critical trials, which runs counter our expected direction. We will come back to this result after the second experiment.

Experiment 2

In Experiment 1, the number of pre-critical trials was varied in order to manipulate schema strength, which however did not have an effect on surprise capture. This raises the question whether our manipulation was not successful to induce differences in schema strength strong enough to have an observable impact on surprise capture, or whether feature variability and the number of sampling occasions do not have the same effect on schema strength.

On the one hand, the number of 17 pre-critical trials in the group with few sampling occasions was chosen somewhat arbitrary because of technical reasons (16 trials were needed to realize all possible target-singleton distances equally often in target present trials). On the other hand, based on the literature we were not able to predict how fast an expectation about a varying singleton color builds up, such that a strong color change induces surprise capture. Schützwohl (1998) tested 2, 12, 22, and 32 pre-critical trials without additional feature variation and found that the effect of schema strength did not further increase after 22 pre-critical trials. Possibly, 17 trials in Experiment 1 were already sufficient to reach an asymptote in expectation narrowness about the singleton color such that surprise capture in the critical trial does not differ substantially from surprise capture after 49 pre-critical trials.

In the following experiment, we reduced the number of pre-critical trials in the group with fewer sampling occasions to nine and compared the effect of a novel singleton color with a group that has 41 pre-critical trials. This time, the singleton color in pre-critical trials remained completely stable prior to the color change in the critical trial, as in Ernst and Horstmann (2018).

Method

We doubled the size of each experimental group as we expected a relatively small effect on the basis of Experiment 1.

Participants

As in Experiment 1 but with 96 different participants (33 men and 63 women). Mean age was 22.50 (*SD* = 3.40).

Apparatus

Same as in Experiment 1. However, monitor refresh rate was set to 100Hz.

Stimuli

Stimulus sizes and arrangement were the same as in Experiment 1. However, in Experiment 2 the singleton color was either blue (RGB: 65, 65, 255; CIE: x = 0.165, y = 0.094; 24.179 cd/m^2) or green (RGB: 0, 135, 0; CIE: x = 0.282, y = 0.590; 23.916 cd/m^2). The remaining non-singleton color patches had a grey color (RGB: 111, 111, 111; CIE: x = 0.278, y = 0.285; 23.909 cd/m^2).

Design

Two groups of participants differed in the number of pre-critical trials (9 vs. 41). Within participants, we compared performance in pre-critical trials with performance in the critical surprise trial where the singleton color was presented with a novel color. Intraindividual performance differences were compared between groups.

Procedure

Same as in Experiment 1, apart from the following differences. In the critical trial, the singleton color changed from either green to blue or vice versa, counterbalanced between participants. After the practice block of 16 trials without a color singleton, the group with few search trials had nine pre-critical trials. The first eight trials had an expectation value of 50% for target presence. Singleton and target positions that were drawn randomly and independently from each other. The ninth trial, which was the last pre-critical trial, was always a target absent trial. The tenth trial was the critical trial (likewise target absent).

The group with many pre-critical trials only differed in that the experimental block started with 32 search trials, half of which were target present trials with random target position. As in Experiment 1, the singleton position was likewise random with the restriction that all possible distances between singleton and target (including their coincidence) were presented

equally often. This block of 32 trials was followed by ten search trials with the same structure as in the group with few pre-critical trials, resulting in a total of 42 search trials. In other words, the group with many pre-critical trials only differed from the group with few pre-critical trials by 32 additional search trials which preceded the last sub-block of 10 search trials (including the critical trial), which was present in both groups. Thus, the critical trial was either the tenth trial or the 42th trial. All experimental trials were presented to the participants as one single block without any interruptions.

Results

Data pre-processing and statistical analyses settings were the same as in Experiment 1 with the only difference that for pre-critical trials, only the target absent trials of the last nine pre-critical trials as a baseline were included (cf. Schützwohl, 1998), which were structurally equal in both groups.

Accuracy and Manual response times

Overall, mean accuracy was .98. An ANOVA for the proportion of correct responses with the factors number of trials (10 vs. 42), and trial type (pre vs. crit) did not yield any significant differences, Fs(1,94) < 2.71, ps > .103, η_G^2s < .015. In the following analyses, we only included trials that were answered correctly. Two participants had to be excluded because of a response error in the critical trial, reducing the sample size to 94 participants.

Manual response times are depicted in Figure 6. An ANOVA with the factors number of trials (10 vs. 42) and trial type (pre vs. crit) revealed a significant main effect for trial type, $F(1,92) = 31.98$, $p < .001$, $\eta_G^2 = .066$, with longer response times in the critical trial (M = 3,409ms) than in pre-critical trials (M = 2,925ms). Furthermore, the Trial type × Number of trials

interaction was significant, $F(1,92) = 6.29$, $p = .014$, $\eta_G^2 = .014$. The mean increase of response times in the critical trial was more pronounced in the group with 42 search trials (2,737ms vs. 3,441ms) than in the group with 10 trials (3,106ms vs. 3,378ms). The main effect for number of trials was not significant, $F(1,92) = 0.79$, $p = .376$, $\eta_G^2 = .007$.

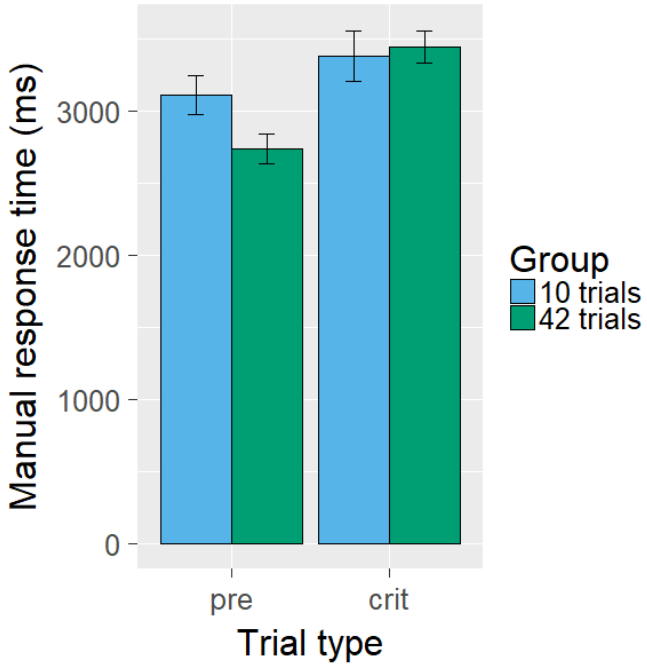

Figure 6. Mean manual response times in pre-critical trials and in the critical trial, separately for the groups with different numbers of trials. Error bars indicate standard error of the mean.

Gaze data

As in Experiment 1, we compared fixations on the singleton in the critical trial with fixations on the singletons in pre-critical target absent trials. Where appropriate, we also considered non-singleton stimuli. Participants fixated 96% of the presented stimuli.

Singleton fixation latencies

The latencies of the first singleton fixation are depicted in Figure 7. An ANOVA with the factors number of trials (10 vs. 42) and trial type (pre vs. crit) revealed a significant main effect for trial type, $F(1,92) = 23.64$, $p < .001$, $\eta_G^2 = .094$, with shorter singleton fixation latencies in the critical trial (M = 736ms) than in pre-critical trials (M = 1,112ms). Furthermore, the predicted Trial type × Number of trials interaction was significant, $F(1,92) = 4.28$, $p = .043$, $\eta_G^2 = .018$, indicating that the reduction of singleton fixation latencies was higher with 42 search trials than with 10 search trials. With 42 search trials, singleton fixation latencies were significantly lower in the critical trial than in pre-critical trials (636ms vs. 1,177ms), $t(45) = 5.59$, $p < .001$, $d_z = 0.82$. In the group with 10 trials, there was a smaller reduction of singleton fixation latency in the critical trial (831ms vs. 1,049ms) that just failed to reach significance, $t(47) = 1.80$, $p = .080$, $d_z = 0.26$. The ANOVA's main effect for number of trials was not significant, $F(1,92) = 0.12$, $p = .726$, $\eta_G^2 = .001$.

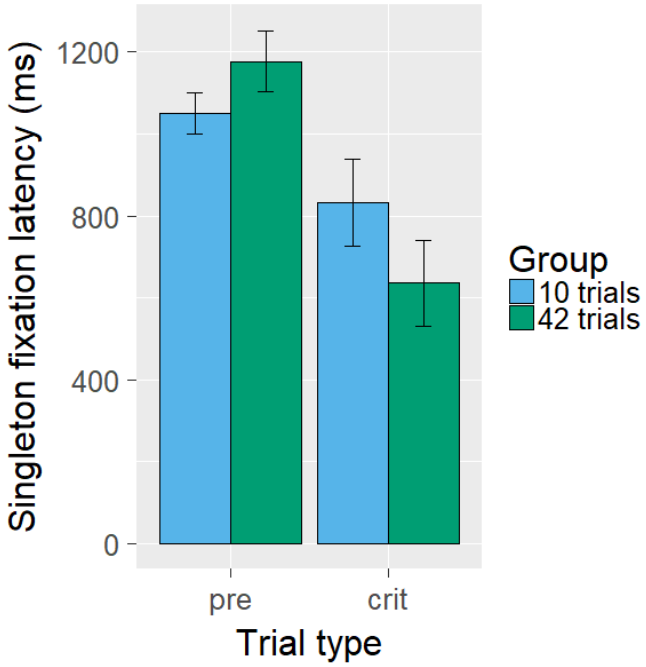

Figure 7. Mean latencies of the first singleton fixation in pre-critical trials and in the critical trial, separately for the groups with different numbers of trials. Error bars indicate standard error of the mean.

Dwell times

Mean dwell times of Experiment 2 are shown in Figure 8. An ANOVA with the factors number of trials (10 vs. 42) and trial type (pre vs. crit) yielded a significant main effect for number of trials, $F(1,92) = 9.23$, $p = .003$, $\eta_G^2 = .054$, a significant main effect for trial type, $F(1,92) = 14.11$, $p < .001$, $\eta_G^2 = .062$, and a significant interaction, $F(1,92) = 14.81$, $p < .001$, $\eta_G^2 = .065$. Only within the group with 42 search trials, mean singleton dwell times increased in the critical trial (392ms vs. 255ms), $t(45) = 4.14$, $p < .001$, $d_z = 0.61$. There was no significant difference in the group with 10 search trials (259ms vs. 261ms), $t(47) = 0.11$, $p = .915$, $d_z = 0.02$.

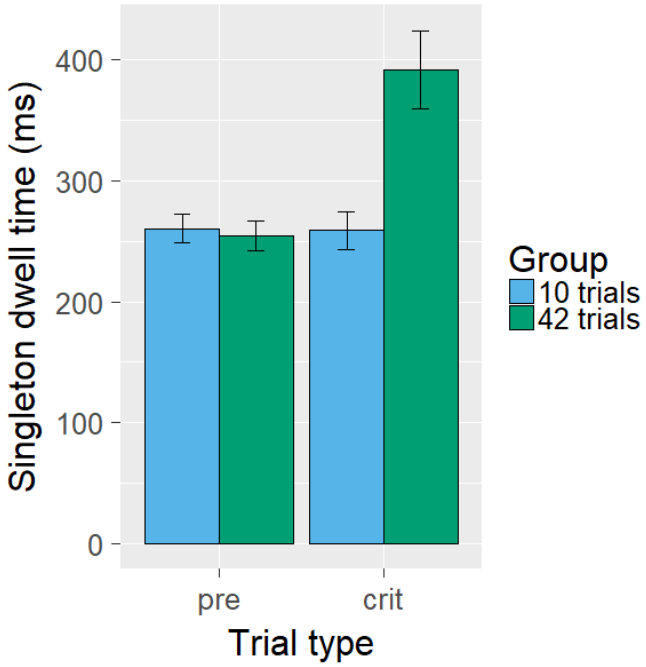

Figure 8. Mean dwell times of the first singleton visit in pre-critical trials and in the critical trial, separately for the groups with different numbers of trials. Error bars indicate standard error of the mean.

Revisits

The proportion of singleton revisits are shown in Figure 9. An ANOVA with the factors number of trials (18 vs. 50) and trial type (pre vs. crit) only revealed a significant main effect for trial type, $F(1,92) = 5.20$, $p = .025$, $\eta_G^2 = .025$, with more revisits on the singleton in the critical trial (.37) than in pre-critical trials (.25), other $F(1,92)$s < 0.44, ps $> .508$, η_G^2s $< .003$.

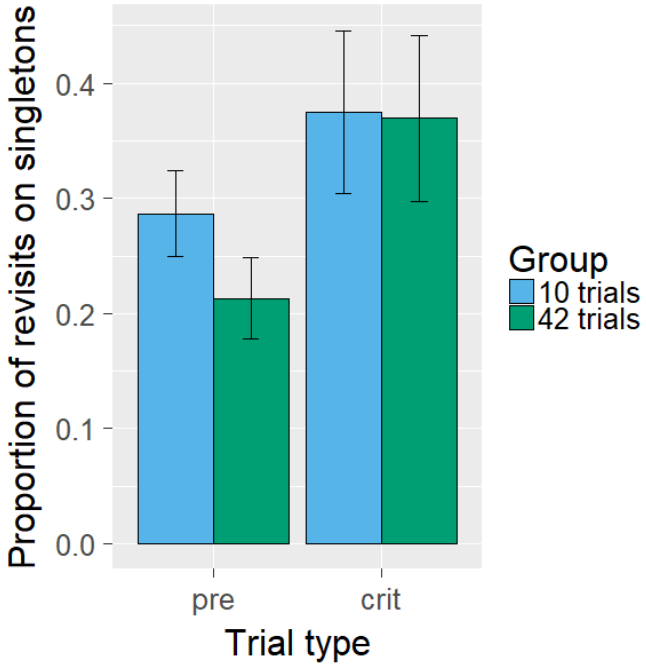

Figure 9. Mean proportions of revisits on the singleton in pre-critical trials and in the critical trial, separately for the groups with different numbers of trials. Error bars indicate standard error of the mean.

Discussion

Experiment 2 focused on the question whether surprise capture caused by a novel color feature can be attenuated by reducing the number of sampling occasions prior to the color change. We assumed that participants start with rather broad expectations, that are refined with repeated examples of the displays. This process is gradual, and the expectations get narrower with each trial. Therefore, with only limited sampling opportunities, the expectation is still broad, rendering a novel color feature less expectation discrepant. In other words, as long as a participant is not sufficiently familiar with the old color, he or she is not surprised by a novel color. Because we could not find empirical support for this proposition in Experiment 1 where

we tested 17 vs. 49 pre-critical trials, we suspected that expectation narrowness already reached an asymptote after 17 search trials. Thus, in Experiment 2 the number of pre-critical trials was reduced to nine for one group and surprise capture was compared with another group that had 41 pre-critical trials. The singleton color was kept constant in pre-critical trials (e.g., green) until the singleton with a novel color was presented in the surprise trial (e.g., blue).

The results show that in the surprise trial, the singleton in the group with only nine pre-critical trials was less strongly prioritized than in the group with 41 pre-critical trials, as indicated by singleton fixation latencies. Hence, our main hypothesis that expectation discrepancy of a novel color feature attenuates with fewer sampling occasions was confirmed. Together, Experiment 1 and 2 suggest that an expectation towards a color feature builds up within few trials and that after a certain number of trials, expectation narrowness reaches an asymptote such that the extent of surprise capture due to a color change does not increase with further sampling occasions prior to the critical trial (see also Schützwohl, 1998).

Gaze dwell times on the singleton in the critical trial only increased in the group with 41 pre-critical trials, whereas revisits were increased in both groups. On the one hand, revisits could be more sensitive to the effects of expectation discrepancy than dwell times. On the other hand, dwell times and revisits could also be mediated (at least partially) by distinct mechanisms. Revisits may be generally increased within the early phase of an experiment with an irrelevant singleton because participants are still suspicious of the singleton's role and compare it with the remaining stimuli (even though participants were explicitly informed about its task irrelevance in the present experiments).

Experiment 2 did not replicate the effect of Experiment 1 with a stronger increase of revisits on the singleton in the group with few pre-critical trials than in the group with many pre-

critical trials. As mentioned before, the extent of increase in a surprise trial could be driven by several mechanisms and may not solely reflect the increase of expectation discrepancy. Possibly, in Experiment 1 the pronounced increase of revisits on the surprising singleton after few pre-critical trials in some way interacted with the presence of singleton color variation in pre-critical trials, which was not present in Experiment 2.

From a general perspective, it is of note that dwelling and revisiting have a substantial impact on manual response times (Horstmann, Becker, & Ernst, 2017; Horstmann, Herwig, & Becker, 2016). For studies which infer attention capture solely from manual response times, it is of special interest whether increased revisits and dwell times only occur at the first presentation of a novel stimulus or likewise when distractors are presented in a low proportion of search trials (e.g., Folk & Remington, 2015; Horstmann & Ansorge, 2006; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Retell, Becker, & Remington, 2016a, 2016b). As the present study shows, increased dwelling and revisits can occur even without attention capture, which can be problematic if attention capture is solely inferred from manual response times.

General discussion

In the present study, we tested whether attention capture by surprising stimuli is in fact induced by the discrepancy between expectations and the actually perceived input, which hitherto has been more an assumption than directly supported by empirical evidence. Given that an unexpected color change of an irrelevant singleton strongly captures the gaze (Ernst & Horstmann, 2018), two visual search experiments were conducted to test whether gaze capture due to expectation discrepancy is attenuated with broader expectations about the singleton color. We reduced the number of sampling occasions and increased the singleton's color variation prior

to the surprise trial to interfere with the emergence of a narrow expectation about the singleton color. Experiment 1 supported the hypothesis that surprise capture by an unannounced color change is attenuated with more singleton color variation in pre-critical search trials as indicated by singleton fixation latencies. However, the second hypothesis stating that a similar effect would occur when the number of pre-critical trials is reduced could not be supported in Experiment 1. Based on the assumption that 17 pre-critical trials were already sufficient to build up a narrow expectation, a second experiment was conducted where the group with a low number of sampling occasions only had 9 pre-critical search trials. Here, we found an attenuated prioritization of an unannounced color change in the surprise trial as compared to a group with 41 pre-critical trials.

Overall, our prediction that surprise capture attenuates with a lower number of sampling occasions and higher color variability prior to the surprise trial could be confirmed. These results yield insights about the conditions for the emergence of expectations and which determine the degree of expectation discrepancy of a novel feature.

Possible models for expectations

We already mentioned the approach to model an expectation in analogy to the sampling distribution of the arithmetic mean as a very simple approach. The expectation about a color feature, for instance, gets narrower with lower feature variance between sampling occasions. Furthermore, the narrowness of the expectation increases with a higher number of sampling occasions. As a consequence, a novel color value (e.g., red) can either be more or less discrepant from the expectation value (e.g., magenta), which is inferred from previous sampling occasions. More precisely, the discrepancy depends on the specific probability the expectation distribution

attributes to the novel color. Note that the physical distance between the novel color (red) and the mean expected color (magenta) is always the same. What can differ because of the trial history is the expectation's breadth, or its "uncertainty", and thus how many standard error units the novel color value is apart from the expectation value at the center of the distribution; that is, at which percentile of the expectation distribution the novel color value is situated.

However, modelling the expectation towards a singleton color by the sampling distribution of the arithmetic mean could be an oversimplification, especially with respect to how fast the expectation value and the expectation narrowness adapt after a surprising singleton color change. The problem becomes obvious by a closer look at the post-critical trials of previous surprise experiments: Results of Ernst and Horstmann (2018) showed that the singleton fixation latency in the post-critical trials was comparable to pre-critical trials. Hence, after the singleton's color change in the critical trial, the singleton fixation latency must have returned quickly to baseline in the first post-critical trials. Accordingly, Schützwohl (1998) did not find any significant differences in manual response times between the first two post-critical trials and the last two pre-critical trials in a choice reaction task, whereas the critical trial in between significantly differed from both. The author took this as support that expectations (or schemas, respectively) can be revised much faster than would be predicted by simple neural network models of learning (e.g., McClelland & Rumelhart, 1988; Rumelhart, Smolensky, McClelland, & Hinton, 1986). Furthermore, Schützwohl (1998) stated that expectations could be revised independently of the number of prior sampling occasions which determine expectation narrowness (Mandler, 1984). Though it still needs to be demonstrated how quick surprise capture in visual search experiments actually attenuates in post-critical trials, empirical data at least suggest that modelling expectations by the sampling distribution of the mean underestimates the

learning rate, and especially how fast expectations adapt to the repeated presentation of a novel feature.

A closely related but more appropriate algorithm to model an expectation could be the Kalman filter (Kalman, 1960), which is commonly used in technical domains to reliably predict states by the given input (e.g., a car's position by the GPS with a low signal in a tunnel) but also to model behavioral learning in a Bayesian manner (e.g., Dayan, Kakade, & Montague, 2000; Kakade & Dajan, 2002; see also Barto et al., 2013). The hallmark of the Kalman filter is that it combines several sources of input to reduce its prediction error relatively quickly with every new measurement in a linear or linearized gaussian manner (Welch & Bishop, 1995). The Kalman filter yields more flexibility in that it considers the variability of its own prediction (or its expectation uncertainty) as well as the variability of the measured values in that both are combined to the "Kalman Gain" parameter which determines how strongly a new measurement changes the following expected value. Basically, if there is higher uncertainty about the expected value, a new measurement will have a stronger impact on the subsequent expected value, whereas the impact of new measurements on the subsequent expected value will be lower with higher variability of the measurements. In other words, as long as there is uncertainty about what to expect, the Kalman filter results in a high learning rate (Dayan et al., 2000).

Regarding the experimental paradigm of this study, the Kalman filter would result in higher certainty about the expectation towards the singleton color with more search trials that yield a color sample to reduce the prediction error. Variability of the singleton color would reduce the influence of every measurement to the subsequent expected value and thus slows down the increase in certainty over the trial course. Overall, expectations as inferred from a simple version of a Kalman filter algorithm would be in line with the results of the present

experiment. Moreover, predictions from a Kalman filter algorithm can be derived about how fast expectations adapt after the repeated presentation of a novel singleton color. Expectation discrepancy should reduce faster in the post-critical trials if a color change occurred in the 10th trial, for instance, as compared to a color change in the 42nd trial. According to the algorithm, information of the novel singleton color will have a higher influence on subsequent expected color values if there is lower certainty about the expected color value, which however increases with every trial.

However, a simple version of the Kalman filter might still not appropriately deal with the adjustment of expectations when it has already reached a high and steady state of certainty, which increases monotonically and independently with every new measurement. The algorithm needs a priori information about how the measured variable changes in time, that is whether it changes linearly or remains constant, for instance. In other words, the Kalman filter might adapt inappropriately to a feature change that is not caused by measurement error but by an "unexpected" change of the system (like a surprising singleton color that will be presented repeatedly). However, advanced versions of the Kalman filter can detect such changes. One method would be to constantly control the system with *t*-tests of the input values (Yu, Watson, & Arrillaga, 2005). If the test reaches the significance criterion, a change of the systematic conditions is assumed and the Kalman filter can switch into an adaptive mode. A possible solution for an adaptive mode would be an adjustment or a complete reset of the Kalman Gain parameter. Thereby, the filter returns to a more uncertain state where it tends to rely more on the measurements than on its expectation. The challenge for future studies would be to figure out fine-grained algorithms such that the Kalman filter that can accurately model the effects of surprise.

The link between unexpectedness and visual attention

Another question that still needs closer investigation is how expectations about a singleton color can actually be inferred from the singleton's gaze fixation latency. For instance, in behavioral learning it is often assumed that the expectedness of an unconditioned stimulus is directly mapped by a specific behavior like the extend of salivation after a bell-ringing (Courville, Daw, & Touretzky, 2006). The expectation discrepancy hypothesis for attention capture states that surprising stimuli can only draw spatial attention if unexpectedness refers to a feature that is available pre-attentively (Horstmann, 2005). As a consequence, only specific novel stimuli can be used to potentially measure expectation discrepancy. Another candidate for measuring expectation discrepancy could be the gaze dwell time on a stimulus which is also increased in the case of syntactically and semantically unexpected stimuli like a floating toaster in the kitchen, that cannot pre-attentively draw attention (Võ & Henderson, 2009; see also Võ, Zwickel, & Schneider, 2010), as described before. However, it still needs to be demonstrated whether these dependent variables covary metrically with expectation discrepancy. Surprise capture could also be a binary process that either occurs or not. If so, this must not necessarily be obvious from fixation latency distributions as they could be diffused by other random processes that together result in a normal distribution; for instance, if within a proportion of participants surprise capture could not be elicited but the singleton position is inspected with the first or second fixation randomly or only because of an additional saliency capture effect.

Post-selective gaze behavior

As an additional research question of rather explorative nature, it was evaluated whether dwell times and revisits likewise covary gradually with expectation discrepancy in a surprise

trial. Already a previous study by Horstmann et al. (2016) showed that after a number of color homogeneous pre-critical trials, the gaze dwelled longer on an unannounced color singleton when it had both singleton novelty and color novelty than when it only had singleton novelty, while the singleton's color was already familiar from pre-critical trials. Different sources of novelty could likewise result in different degrees of expectation discrepancy.

In Experiment 1 of the present study, dwell times generally increased in the critical trial. However, group differences of the increase were not significant, although there was a tendency for longer dwell times with low color variation than with high color variation. In Experiment 2, however, dwell times only increased after a high number of pre-critical trials, which was in line with our expectation. Revisits were generally increased in the critical trial of both experiments but did not covary with the different expectation discrepancy manipulations as we expected. Overall, the result pattern of revisits and dwell times was inconsistent and could not support that these variables gradually increase with expectation discrepancy. They only increased generally in a surprise condition.

Foerster (2016) also found increased refixations on a stimulus whose font has been unannounced changed after 65 search trials. This effect has been termed "check-after-surprise" mode. Meyer et al. (1997) argue that surprise induces higher-level processes such as verifications of expectation discrepancy and causal analyses. Possibly, such processes are reflected in increased dwell times and revisits in the present study. Revisits on the singleton could be caused by comparisons between several stimulus types in the display, which are performed for the verification of expectation discrepancy. Increased dwell times could be due to causal analyses which interfere with the process of target-distractor discrimination (see also Becker, 2011). Likewise in line with increased gaze activity in a surprise trial, neurophysiological studies posit

an unconditioned hard-wired novelty bonus (Kakade & Dayan, 2002) that enhances dopamine signals and engages humans and animals to actively explore the environment, possibly for further reward (Knutson & Cooper, 2006; Krebs, Schott, Schütze, & Düzel, 2009; Schultz, 1998).

Summary

As postulated in schema theory, expectations towards a visual feature depend on the number of sampling occasions and on feature variability between sampling occasions. Accordingly, we demonstrated that surprise capture of the gaze reduces with fewer sampling occasions and with higher feature variability before the presentation of a novel color feature. These findings support that both manipulations result in broader expectations, rendering the same novel color feature less expectation discrepant.

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Disclosure statement

The authors report no conflicts of interest.

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Study 3

Novelty competes with saliency for attention

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Abstract

A highly debated question in attention research is to what extent attention is biased by bottom-up factors such as saliency versus top-down factors as governed by the task. Visual search experiments in which participants are briefly familiarized with the task and then see a novel stimulus unannounced and for the first time support yet another factor, showing that novel and surprising features attract attention. In the present study, we tested whether gaze behavior as an indicator for attentional prioritization can be predicted accurately within displays containing both salient and novel stimuli by means of a priority map that assumes novelty as an additional source of activation. To that aim, we conducted a visual search experiment where a color singleton was presented for the first time in the surprise trial, and manipulated the color-novelty of the remaining non-singletons between participants. In one group, the singleton was the only novel stimulus ("one-new"), whereas in another group, the non-singleton stimuli were likewise novel ("all-new"). The surprise trial was always target absent and designed such that top-down prioritization was unlikely. Current prevalent models of visual attention usually do not consider novelty and would predict that early attention should be equally directed towards the singleton in both groups, as it is the most salient item. However, our results show that the singleton in the all-new group initially captured the gaze less strongly, with more early fixations being directed to the novel non-singletons. Overall, the fixation pattern can accurately be explained by noisy priority maps where saliency and novelty compete for gaze control.

Keywords: attention capture,visual guidance, surprise, novelty, expectations, saliency

Novelty competes with saliency for attention

In the field of visual attention research, many experiments have been conducted to clarify whether attentional deployment is driven by bottom-up or by top-down factors– or more recently, how they interact (e.g., van Zoest, Donk, & Theeuwes, 2004). An important part of the early theoretical and empirical development centers on the question whether it is the bottom-up factor of physical saliency (Theeuwes, 1991, 1992, 2010) or goal-driven factors such as the task goals and intentions (Folk, Remington, & Johnston, 1992) that primarily drive attentional section. Current theories assume that both factors play a role within a priority map that determines the deployment of visual attention and eye movements (e.g., Moran, Zehetleitner, Müller, & Usher, 2013; Wolfe, 1994, 2007; Zelinsky & Bisley, 2015). In the present study, we focus on the specific factor of feature novelty (or unexpectedness) and examine how it affects attention and eye movements. Several studies already demonstrated that the presentation of a stimulus with an unexpected feature captures attention (for a review see Horstmann, 2015).

The attentional prioritization caused by unexpected simple features has been termed *surprise capture* (Horstmann, 2002, 2015). Note that for the purpose of the present study, we use the terms novelty and surprise (or unexpectedness) synonymously, as the differences between the concepts are not the focus of the current study (see Barto, Mirolli, & Baldassarre, 2013, for an overview), and can be neglected here for simplicity. Surprise capture experiments usually comprise a number of familiarization trials, followed by a single surprise trial that contains a stimulus with a novel feature (repetition-change paradigm). In the majority of studies, the surprising item was a singleton, that is, a salient item with a unique feature (e.g., a red item among all green items), not contained in the familiarization trials (e.g., all green items).

At a first glance, analyzing the first presentation of an unannounced salient item seems a good way to test stimulus-driven attention that is not confounded with goal-directed behavior like the strategical prioritization of singletons (Bacon & Egeth, 1994; Gibson & Jiang, 1998). Multiple studies showed that surprising singletons attract attention and the gaze at their first unannounced occurrence, even in the absence of corresponding goals to attend to it (e.g., Becker & Horstmann, 2011; Horstmann, 2005; Horstmann & Becker, 2008, 2011; Horstmann & Herwig, 2015; Horstmann, Becker, & Ernst, 2016; Retell, Venini, & Becker, 2015). However, attention to the surprising singleton was attributed to a distinct surprise capture mechanisms rather than to saliency-based mechanisms, because the time course of surprise capture seems to differ from the time course of saliency capture (Theeuwes, 2010), which is assumed to be purely stimulus-driven. Saliency capture has been postulated to occur after 60-150ms for covert attention shifts (Kim & Cave, 1999; Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000), and after about 200-250ms for overt attention shifts (i.e., oculomotor capture, Theeuwes, De Vries, & Godijn, 2003; van Zoest et al., 2004; Weichselbaum & Ansorge, 2018). Surprise capture instead has been found to mainly occur after about 400ms for covert attention shifts (Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Horstmann, 2006), and 400-500ms for overt attention shifts (Ernst & Horstmann, 2018; Horstmann et al., 2016; Horstmann & Herwig, 2015). Once an unexpected item is visually selected, further post-selective attentional prioritization follows as indicated by longer gaze dwells times (e.g., Ernst & Horstmann, 2018; Horstmann, 2015), and increased revisits (Foerster, 2016; see also Horstmann et al., 2016; Retell et al., 2015). With respect to dwell times, results of Ernst and Horstmann (2018) showed that within a surprise trial not only the surprising stimulus is gazed at longer but that this is also true for the remaining familiar stimuli which are not salient. Increased dwell times have also been found for complex

unexpected stimuli that do not automatically draw spatial attention but are encountered during serial search (Võ & Henderson, 2009; Võ, Zwickel, & Schneider, 2010). Furthermore, Foerster (2016) found increased refixations on a stimulus that has been changed in a surprise trial while participants performed a manual motor task. Together, increased dwell times and revisits could reflect high-level processes like verification of expectation discrepancy, causal analyses and action relevance checks, which have been postulated in a cognitive-evolutionary model of surprise (Meyer, Reisenzein, & Schützwohl, 1997; Reisenzein, Horstmann, & Schützwohl, 2017; see also Horstmann, Becker, & Ernst, 2017, for the impact of dwelling and revisiting on search times).

In most studies, surprise capture was elicited by means of an unexpected singleton with a novel feature (e.g., Becker & Horstmann, 2011; Horstmann & Becker, 2011; Retell, Becker, & Remington, 2016; Retell, Venini, & Becker, 2015). However, recent studies suggest that surprise capture is not necessarily bound to the combination of feature and singleton novelty. For instance, Ernst and Horstmann (2018) presented a color singleton already in the familiarization trials of a visual search experiment, which was not predictive of the target. This expected irrelevant singleton only weakly attracted the participants' gaze (which could be either because of its saliency or a strategy to attend to singletons; e.g., Bacon & Egeth, 1994). However, when the singleton was presented for the first time with a novel color, it strongly captured the gaze. Yet, other studies suggest that singleton status is not necessary for a surprising feature to attract attention: In Horstmann and Herwig (2016), participants encountered a display with half novel and half familiar search items on either side of the display (four adjacent search items each of a familiar color and a novel color), and the results showed more early fixations on the novel side than on the familiar side. As the physical saliency was equal on both sides, and saliency did not

single out a particular stimulus, these results indicate that physical saliency is not necessary for prioritized selection of novel items. In line with this conclusion, Horstmann and Ansorge (2016) also found prioritization of a novel color within a two-stimulus display, as reflected by reduced inattentional blindness rates. Together, these studies demonstrate that color novelty alone is sufficient for attentional prioritization.

So far, prevalent models of visual attention have mainly neglected novelty as a factor driving attention and eye movements (but see Itti & Baldi, 2009, for an exception), and it has even been doubted that novelty plays a role in attentional guidance (e.g., Wolfe & Horowitz, 2004, 2017). In the present study, we examine how attentional prioritization due to novelty can be integrated into the framework of priority maps for visual attention. To that aim, we designed an experiment that will show how novelty affects attentional deployment within displays that contain both salient and novel stimuli. Moreover, we designed the surprise trials such that additional top-down influences like goal driven feature prioritization or inhibition are unlikely (Gibson & Jiang, 1998), allowing us to focus on the effects of novelty and saliency on attentional prioritization.

Priority maps (see Zelinsky & Bisley, 2015, for a recent review) are an integrated representation of bottom-up stimulus saliency and top-down target information. Saliency and task-relevance both contribute to location-specific activation in the priority map, whereby the activation signals are higher for more salient stimuli, and higher for target-similar stimuli. Attention then serially follows the activation gradient, though not always perfectly as either the activation calculation (e.g., Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989) or the process of following the activation gradient itself is assumed to be noisy (e.g., Moran et al., 2013).

We propose novelty as an additional source of activation within priority maps. Crucially, as previous experiments showed that also feature novelty of non-salient stimuli attracts attention (Horstmann & Ansorge, 2016; Horstmann & Herwig, 2016), we conceptualize the novelty's activity contribution such that the novel feature must not necessarily be presented in a salient manner in order to increase activation. However, if a stimulus is both novel and salient like a color singleton that is presented for the first time, activity due to novelty and saliency can add up to induce a strong peak in activity within the priority map, resulting in attention capture of the singleton. An implication that is tested within the present study is that the activity peak for such a novel salient stimulus can be attenuated if other low-salient stimuli in a display likewise have a novel feature.

To test the assumption of novelty as an additional source of activation in a priority map, we conducted an eye tracking experiment with a difficult visual search task and used gaze behavior as a proxy for visual attention deployment (Deubel & Schneider, 1996). First, we familiarized two groups of participants with search displays only containing stimuli of the same single color (e.g., red; see Figure 1). In the surprise trial, one group was presented for the first time with a novel color singleton (e.g., one green stimulus) whereas the remaining non-singleton distractors were unchanged ("one-new"). The surprise trial of the other group contained likewise a singleton with a novel color; in addition, however the remaining non-singleton stimuli also had a novel color (e.g., green singleton among blue other items; "all-new"). Thus, the displays of the surprise trials only differ with respect to the novelty of the non-singleton stimuli. If novelty acts as an additional factor besides saliency within a priority map, in both groups the singleton position would still have the highest activation as it receives activity both from saliency and novelty information. Consequently, we expect a high number of early fixations on the singleton

in both groups. However, if novelty always contributes to activation in the priority map, the difference in activation between the salient stimulus' position and the positions of the remaining stimuli would be smaller in the all-new condition as any stimulus in the display is novel and activation differences should only be due to saliency information. Assuming a stochastic process where fixation probability is a function of the activation in the priority map plus noise (e.g., Wolfe, 1994, 2007), there should be fewer early fixations on the singleton in the all-new than in the one-new condition. Accordingly, more early fixations should be directed on the non-singletons in the all-new condition than in the one-new condition.

As already mentioned before, by using only one critical surprise trial we solely focus on saliency and novelty as factors for attentional prioritization. Strategic orienting towards any of the stimuli is unlikely, because the pre-critical trials do not induce an attentional set towards any color: As the target only has a distinct shape (a closed ring among rings with a gap) but does not differ in color from the other items, color is completely irrelevant for selection. Thus, the present study allows for a relatively clear-cut discrimination between novelty and saliency effects for the color features.

Given that top-down influences can be neglected, current saliency based models (e.g., Itti & Koch, 2000; Theeuwes, 2010) would be first choice to explain attention deployment as guidance due to novelty is not commonly accepted or unknown. Yet, saliency based models would predict no difference in singleton prioritization between the critical trial of the one-new and the all-new group as in both displays the singleton is equally salient. The feature novelty account, however, predicts that the singleton in the critical trial of the all-new group will receive lower early prioritization than in the one-new group as an increased amount of attention will be directed to the non-singleton stimuli with a novel color. To test these predictions, our main

dependent variable will be the proportion of fixations that hit singletons and non-singletons within the first three fixations after search display's onset. Other variables like fixation latencies, dwell times, and revisits will be analyzed additionally for comparisons with other studies on surprise.

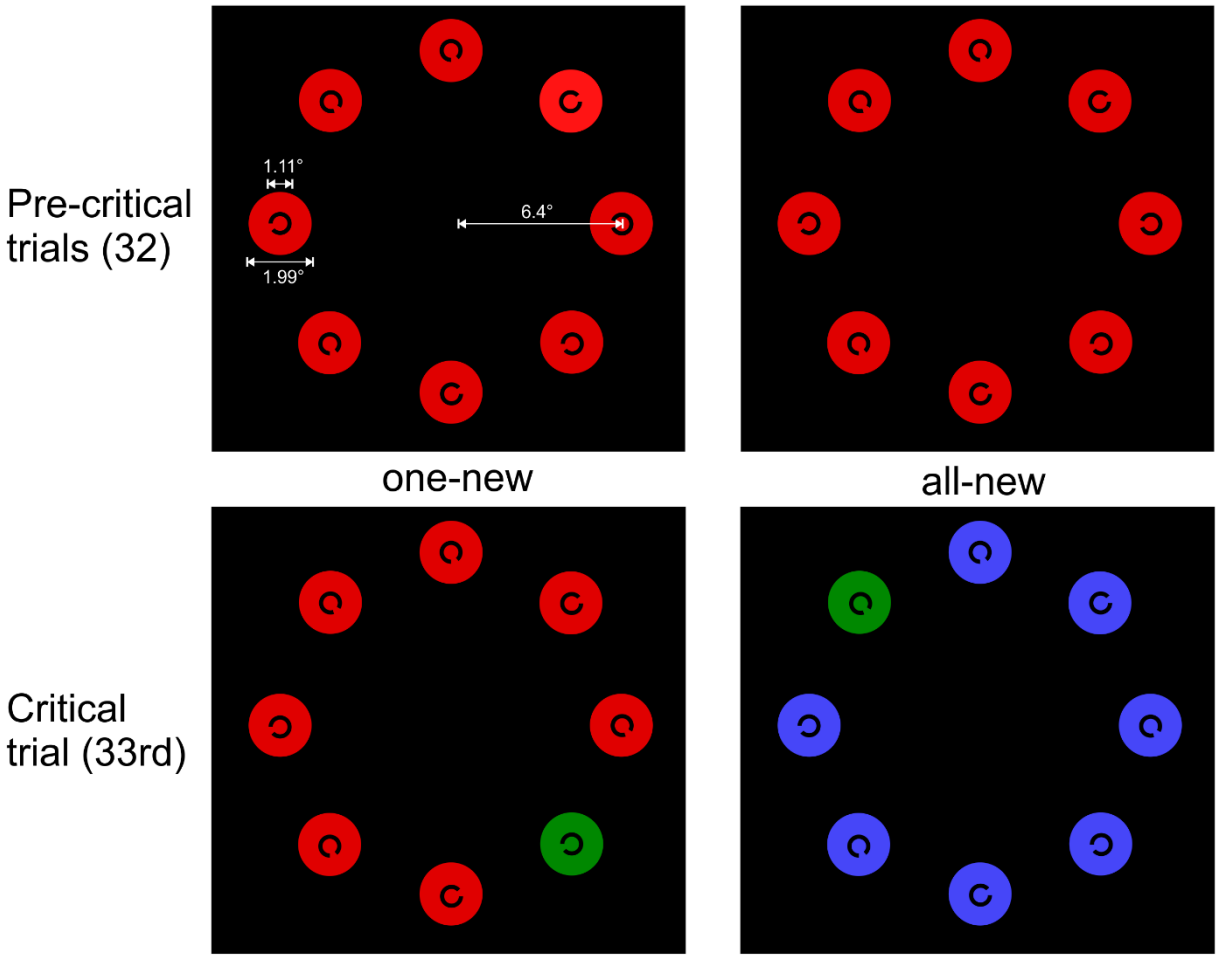

Figure 1. Exemplary displays of the pre-critical familiarization trials and the critical surprise trials for both groups.

Method

Participants

72 students or visitors of Bielefeld University (18 men and 54 women) participated in the 10-min experiment. The sample size was oriented on in a pilot study which mainly differed in that colors were not counterbalanced. Participants were approached in the central hall of the university main building, and asked to participate in a short experiment in return for 2€. Mean age was 22.17 (*SD* = 2.53). Participants gave written informed consent prior to participation. All were tested for normal or corrected-to-normal vision and for normal color vision. The study was approved by the Ethics Committee of University of Bielefeld (EUB), and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Apparatus

Stimuli were presented on a 19-in. display monitor (100-Hz refresh rate, resolution 1,024 x 768 pixels) at a distance of 71 cm. Before testing, the monitor was warmed for at least 30 minutes, to ensure temporal stability of luminance and color (Poth & Horstmann, 2017). A video-based eye-tracker (EyeLink 1000, SR Research, Ontario, Canada) with a sampling rate of 1 kHz was used for the recording of eye movements. The participants' head was stabilized by a chin rest, and the right eye was monitored in all participants.

Stimuli

The target was a 1.11° diameter ring with a line-width of 0.23° (viewing distance 71 cm). The distractors were identical to the target with the only difference of a small radial gap of 0.09° height. 16 different gap positions were evenly distributed between 22.5° and 360°. The rings

were black and presented on circular color patches of 1.99° diameter against a black background (RGB: 0, 0, 0; CIE: x = 0.280, y = 0.226; 0.114 cd/m^2). Possible patch colors were red (RGB: 224, 0, 0; CIE: x = 0.606, y = .329), green (RGB: 0, 136, 0; CIE: x = 0.282, y = .589), and blue (RGB: 70, 70, 248; CIE: x = 0.169, y = .100). With the exception of the black background, all colors had a matched physical luminance of 24 cd/m^2 (±1). Eight stimuli (color patches plus search stimuli) were presented in each search display. The stimuli were evenly distributed on an imaginary circle with a radius of 6.4°.

Design

The experiment comprised one single block of 33 trials; 32 pre-critical familiarization trials in which only homogenous color patches without a salient item were presented, and one critical surprise trial with an unannounced salient color singleton. Half of the displays in each group were target present trials, and half were target absent trials. On target present trials, the target position was determined randomly, with all possible target positions realized equally often. The singleton position in the critical trial was likewise random. Furthermore, the critical trial was always a target absent trial to allow measuring surprise effects unconfounded with the presence of the target (Ernst & Horstmann, 2018).

Participants were randomly assigned to one of two experimental groups, which had the same pre-critical trials with only homogenous color patches (e.g., all red) but differed in the critical trial (see Figure 1). For the all-new group, the search display in the critical trial consisted of a color singleton distractor with a novel color (e.g., green), while the remaining non-singleton distractors had another color that was likewise novel (e.g., blue). In the one-new group, the critical trial only had a singleton with a novel color (e.g., green) while the remaining non-

singleton distractors had the same color like in the pre-critical trials (e.g., red). All possible color combinations were counterbalanced between participants.

Procedure

The participants' task was to report the presence or absence of the target with a corresponding key press (arrow left and arrow down keys in the lower row of the keyboard, operated with the right index and middle fingers), and participants were instructed to perform the search task as fast as possible while avoiding any response errors. Each trial began with a drift correction where participants fixated on the middle of the screen and confirmed fixation with a key press (left hand).

The drift correction was followed by a fixation display with a central fixation cross for a variable period before the search display appeared. The durations of this pre-display were the sum of a) a randomly drawn value from an exponential distribution with an expectation value of 0.5s ($\lambda = 2$), b) a following period of 100ms, in which the eye tracker controlled for a central fixation, and c) possible additional time until the central fixation has been successful. To reduce variance between participants, within the fore-period of the critical trial we fixed the time at the exponential distribution's expectation value of 500ms. Afterwards the search display was presented until a key press was registered. An error sound occurred whenever an incorrect response had been recorded.

The exponential distribution of the "non-aging" (Näätänen, 1971) fore-periods is characterized by a constant hazard rate, rendering the onset of the search display less predictable by the time the fore-period already has elapsed. Thereby, we intended to reduce possible pre-planned eye movements at the onset of the search display.

Results

The first 16 trials were considered practice, leaving 16 pre-critical trials for the analysis plus the single critical trial. Raw gaze data were pre-processed using the EyeLink Data Viewer (2.3.22), which parses eye position data into saccades and fixations according to an acceleration threshold (8,000 degrees/sec^2), and a velocity threshold (30 degrees/sec). Fixations were classified as eye data that exceeded neither of these thresholds for a period of 20ms or more. Fixations were assigned to a stimulus when they fell within a circular region with a radius of 2.41° from the center of the stimulus. Further preprocessing and statistical analysis were done using R 3.4.3 (R Core Team, 2016). All reported *p*-values are two-tailed.

In order to adequately model binary dependent variables like fixations (our main dependent variable) and accuracy without violating the assumption of homoscedasticity (Warton & Hui, 2011), we used Generalized Estimation Equations (GEE, Liang & Zeger, 1986). GEEs allow for the use of a logit link function while they simultaneously control for correlated data (here, due to repeated measurements) in order to prevent underestimation of standard errors. To conduct GEEs, an initial working correlation structure must be specified. Due to its parsimony, we used an exchangeable working correlation structure that assumes equal correlations between any pair of measurements within a participant. GEEs yield robust estimates, however, even if the correlation structure is mis-specified, because the empirical correlations are also considered (Liang & Zeger, 1986). The basic output and interpretation of GEEs are analogue to those of regression models. Note that the raw slopes reported in the table of a logistic model are mainly interpretable with respect to their sign. The raw slopes, however, can be transformed into the

proportions of the predicted categories which are coded with 1 (vs. 0). For a better interpretability, we will report these proportions in the text.

Because of categorial factors of this experiment (trial type: pre-critical vs. critical; group: one-new vs. all-new), dummy coded GEE models were calculated which directly tested planned contrasts together with the interaction. In all GEE analyses, we set the critical trial of the all-new group as reference category, whose outcome is represented by the intercept of the model. Thus, the models tested the following comparisons to the reference category: First, the within group difference to the pre-critical trials; second, the between difference to the critical trial of the one-new group; and third, the interaction which tests whether the trial type difference differs between the groups. Note that these comparisons correspond to the ANOVA's interaction and post-hoc tests which are the meaningful comparisons within the present design.

As the critical trial was always a target absent trial, we only compared with pre-critical target absent trials. Target present trials we excluded from all analyses.

Accuracy

We recoded the response pattern of one participant who exchanged response keys and showed 0% correct answers before transformation. Overall, accuracy in pre-critical trials was 95%. By means of a dummy coded GEE model with a logit link function, we regressed responses (1= correct; 0= false) on the factors group (one-new vs. all-new) and trial type (pre-critical vs. critical), as well as on their interaction. However, there were no significant differences, *Wald* $\chi^2(1)$s < 1.59, *ps* > .207.

In the following analyses, only trials with correct answers were included. Two participants of the all-new group did not answer correctly in the critical trial and were excluded

from all following analyses. Furthermore, we completely removed one participant of the all-new group with an extremely long response time in the critical trial (18,377ms; $z_{included}$ = 14.74), reducing the sample size to 69.

Manual response times

An ANOVA for manual response times with the factors group (one new vs. all new) and trial type (pre-critical vs. critical) yielded a significant main effect for trial type with longer response times in the critical trial (M = 3,747ms) than in pre-critical trials (M = 2,531ms), $F(1,67) = 94.84$, $p < .001$, $\eta_G^2 = .33$, indicating that the surprising stimulus features disrupted the visual search process in both groups. The interaction just failed to reach significance, $F(1,67) = 3.61$, $p = .062$. The average response time difference between pre-critical trials and the critical trial tended to be somewhat more pronounced within the all-new group (2,462 vs 3,928ms) than in the one-new group (2,594 vs. 3,582ms). The main effect for group was not significant, $F(1,67) = 0.40$, $p = .531$, $\eta_G^2 < .01$.

Gaze data

For the analyses of the gaze data, we compared fixations on the singleton in the critical trial with the average gaze behavior on all distractors in all pre-critical target absent trials, whereas the distractors serve as a baseline for unbiased attention distribution. Where informative, also gaze behavior on non-singletons in the critical trial was analyzed. Note that we use the word "distractors" if we refer to stimuli in pre-critical trials, whereas we use the words "singleton" and "non-singletons" if we refer to stimuli in the critical trial (though on principle all stimuli in target absent trials are distractors). Overall, participants fixated 96% of the presented stimuli.

Stimulus fixation latencies

To assess the time course of the fixations on the different stimulus types, the latencies of their first fixation relative to the onset of the search display were examined (see Figure 2). Note that this is not necessarily the first fixation after the search display's onset. An ANOVA including the factors group (one new vs. all new) and stimulus type (distractors in pre-critical trials vs. singleton in the critical trial) yielded a significant main effect for stimulus type, $F(1,67) = 135.61$, $p < .001$, $\eta_G^2 = .49$, and a significant interaction, $F(1,67) = 4.91$, $p = .030$, $\eta_G^2 = .03$. The main effect for group was not significant, $F(1,67) = 3.46$, $p = .067$, $\eta_G^2 = .03$.

Pair-wise comparisons revealed that the singleton in the critical trial of the one-new group was fixated significantly earlier ($M = 433$ms) than in the all-new group ($M = 604$ms), $t(56.83) = 2.76$, $p = .034$, $d = .53$. Compared to distractors in pre-critical trials, the singleton was significantly prioritized both within the one-new group (433 vs. 996ms), $t(35) = 11.54$, $p < .001$, $d_z = 1.92$, and within the all-new group (604 vs. 987ms), $t(32) = 5.80$, $p < .001$, $d_z = 1.01$.

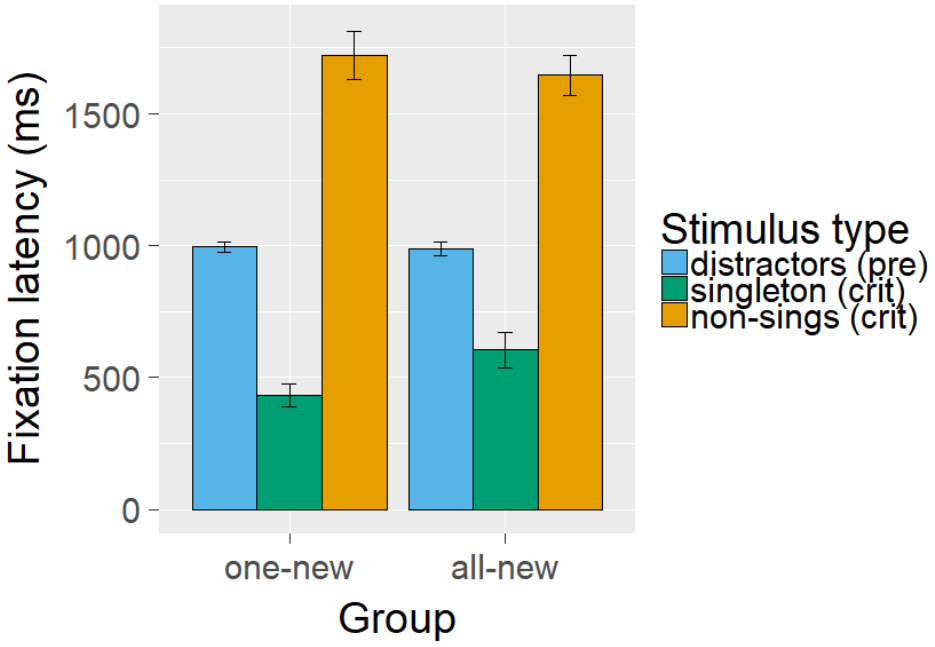

Figure 2. Mean latencies of the first fixation on distractors in pre-critical trials, singletons in the critical trial, and non-singletons in the critical trial, separately for the one-new and the all-new group. Error bars indicate standard error of the mean.

Early fixation destinations

In order to inspect the destinations of the very early fixations after search display's onset, we examined the cumulative proportions of at least one visit on a specific stimulus within the first three fixations by means of GEE models with a logit link function (see also Ernst & Horstmann, 2018; Horstmann et al., 2016). For instance, as shown in Figure 3, the proportion of at least one singleton visit in the one-new group within the first, first and second, and the first three fixations was .22, .75 and .90, respectively.

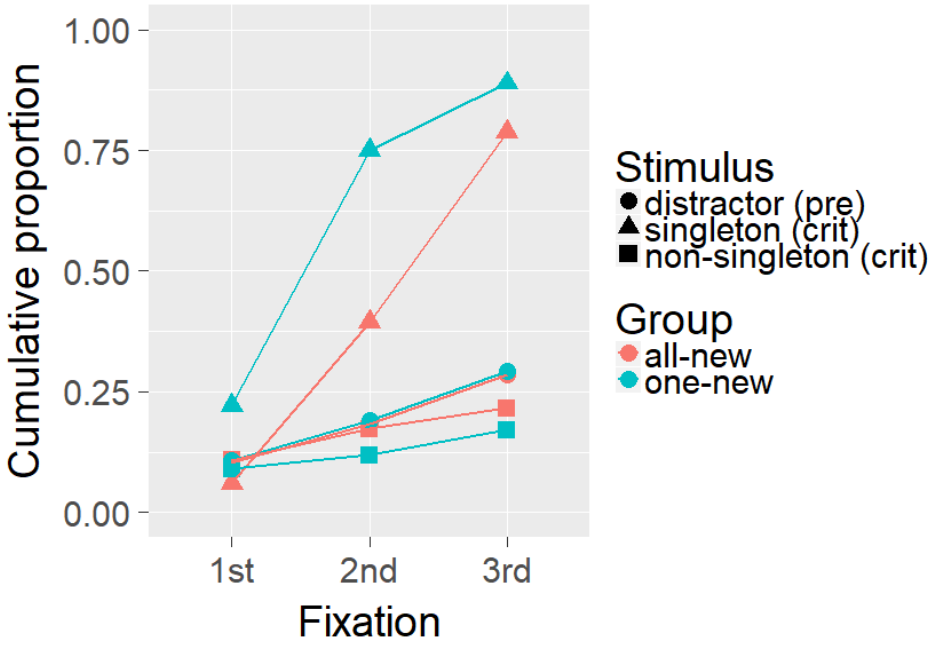

Figure 3. Proportions of at least one visit on the different stimulus types within the first, first and second, and within the first three fixations, separately for the one-new and all-new group.

In the following analyses, the fixations on the singleton in the critical trials of the all-new group served as reference category. The first GEE regressed stimulus fixations (1= fixated; 0= not fixated) on the factors stimulus type (distractor in pre-critical trials vs. singleton in the critical trial), group (one new vs. all new), and their interaction. However, there were no significant effects (see Table 1, upper model for detailed statistics).

If both first and second fixations were regressed on the same factors (Table 1, second model), there was a significantly higher proportion of at least one singleton fixation in the critical trial of the one-new group than in the all-new group (.75 vs. .39), *Wald* $\chi^2(1) = 8.50$, $p = .004$, as reflected in the significant positive slope for the singleton in the one-new group (see Table 1,

second model). Within the all new group, the probability of a singleton visit in the critical trial was significantly higher than the probability of a distractor visit in the pre-critical trials (.39 vs. .18), *Wald* $\chi^2(1) = 9.43$, $p = .002$. Within the one-new group, the analogue stimulus type difference was significantly more pronounced (.75 vs. .19), *Wald* $\chi^2(1) = 8.07$, $p = .005$, indicating a stronger singleton prioritization within the one-new group than in the all-new group.

The model for the first three fixations (Table 1, bottom model) only showed a significant difference between pre-critical distractors in the all-new condition (.29) compared to the singleton in the critical trial of this group (.79), *Wald* $\chi^2(1) = 27.29$, $p < .001$. The non-significant interaction suggests that the analogue stimulus type difference within the one-new group was comparable. Thus, the stronger singleton prioritization in the one-new group as compared to the all-new group mainly occurred within the first two fixations.

Table 1. GEE models for at least one visit on singletons in the critical trial and distractors in pre-critical trials within the first three fixations

Dependent variable		*b*	*Wald* $\chi^2(1)$	*p*
1st Fixation	Intercept: singleton (crit), all-new	- 2.74	14.11	< .001*
	Distractors (pre), all-new	+ 0.57	0.60	.437
	Singleton (crit), one-new	+ 1.49	3.20	.074
	Stimulus type × Group (one-new)	- 1.43	2.97	.085
1-2nd Fixations	Intercept: singleton (crit), all-new	- 0.43	1.46	.227
	Distractors (pre), all-new	- 1.06	9.43	.002*
	Singleton (crit), one-new	+ 1.53	8.50	.004*
	Stimulus type × Group (one-new)	- 1.49	8.07	.005*
1-3rd Fixations	Intercept: singleton (crit), all-new	+ 1.31	9.50	.002*
	Distractors (pre), all-new	- 2.23	27.29	< .001*
	Singleton (crit), one-new	+ 0.77	1.27	.259
	Stimulus type × Group (one-new)	- 0.74	1.16	.282

Note. GEEs comprised a logit link function. Singletons in the critical trials of the all-new group were set as reference category which is represented by the intercept. Signs of non-interaction slopes indicate whether fixation probability increases or decreases compared to the reference category. See text for further details. * $p < .05$.

To confirm that the lower proportion of singleton fixations in the critical trial of the all-new group was actually accompanied by an increased prioritization of the remaining non-singletons, we repeated the previous analyses for non-singleton fixations in the critical trial (instead of singleton fixations) and distractor fixations in pre-critical trials. Here, non-singletons in the critical trial of the all-new group served as the reference category (the detailed results of

the GEE model are depicted in Table 2, and the proportions of at least one fixation on non-singletons are depicted in Figure 3).

There were no significant effects at the first fixation (Table 2, upper model).

If both first and second fixations were analyzed, the all-new group showed a higher proportion of fixations on non-singletons than the one-new group (.17 vs .12), *Wald* $\chi^2(1) = 7.30$, $p = .007$, as reflected in the significant slope for non-singletons in the critical trial of the one-new group (see Table 2, second model). Within the all-new group, there was no reliable difference between fixations on non-singletons in the critical trial and fixations on distractors in pre-critical trials (.17 vs. .18), *Wald* $\chi^2(1) = 0.38$, $p = .539$. However, the analogue comparison was significantly different within the one-new group because of fewer fixations on non-singletons in the critical trial than on distractors in pre-critical trials (.12 vs. .19), *Wald* $\chi^2(1) = 8.02$, $p = .005$, as reflected in the significant interaction. Thus, there was a higher prioritization of non-singletons within the all-new group.

If the first three fixations were analyzed (Table 2, bottom model), within the all-new group there were significantly fewer fixations on non-singletons in the critical trial than on distractors in pre-critical trials (.22 vs .29), *Wald* $\chi^2(1) = 14.98$, $p < .001$. The significant interaction reflects that the analogue difference between both stimulus types was more pronounced within the one-new group with even fewer fixations on non-singletons (.17 vs .29), *Wald* $\chi^2(1) = 4.60$, $p = .032$. Lastly, the direct comparison between both groups reveals that there were more fixations on non-singletons in the critical trial of the all-new group than in the one-new group (.22 vs. .17), *Wald* $\chi^2(1) = 3.97$, $p = .046$, as indicated in the significant slope for non-singletons in the critical trial of the one-new group.

Table 2. GEE models for at least one visit on non-singletons in the critical trial and distractors in pre-critical trials within the first three fixations

Dependent variable		*b*	*Wald* $\chi^2(1)$	*p*
1st Fixation	Intercept: non-singleton (crit), all-new	- 2.11	364.78	< .001*
	Distractors (pre), all-new	- 0.07	0.32	.573
	Non-singleton (crit), one-new	- 0.19	1.15	.284
	Stimulus type × Group (one-new)	+ 0.25	1.78	.182
1-2nd Fixations	Intercept: non-singleton (crit), all-new	- 1.56	232.18	< .001*
	Distractors (pre), all-new	+ 0.07	0.38	.539
	Non-singleton (crit), one-new	- 0.44	7.30	.007*
	Stimulus type × Group (one-new)	+ 0.48	8.02	.005*
1-3rd Fixations	Intercept: non-singleton (crit), all-new	- 1.29	207.50	< .001*
	Distractors (pre), all-new	+ 0.37	14.98	< .001*
	Non-singleton (crit), one-new	- 0.29	3.97	.046*
	Stimulus type × Group (one-new)	+ 0.32	4.60	.032*

Note. GEEs comprised a logit link function. Non-singletons in the critical trials of the all-new group were set as reference category which is represented by the intercept. Signs of non-interaction slopes indicate whether fixation probability increases or decreases compared to the reference category. See text for further details. * $p < .05$.

Dwell times

As another component of surprise capture, we also examined dwell times, which are defined as the summed fixation durations of the first continuous visit on a stimulus (see Figure 4). Here, we also considered non-singleton distractors in the critical trial. As the repeated measurement factor now includes three levels, *p*-values were Greenhouse-Geisser corrected when the assumption of sphericity was violated (indicated by the Greenhouse-Geisser epsilon).

An ANOVA with the factors group (one-new vs. all-new) and stimulus type (distractors in pre-critical trials vs. singleton in critical trial vs. non-singletons in critical trial) revealed a significant main effect for group, $F(1,67) = 5.92$, $p = .018$, $\eta_G^2 = .03$, stimulus type, $F(2,134) = 88.94$, $\varepsilon = .06$, $p < .001$, $\eta_G^2 = .45$, and a significant interaction, $F(2,134) = 6.53$, $\varepsilon = .06$, $p = .012$, $\eta_G^2 = .06$. The main effect for stimulus type reflects that singletons in the critical trial of both groups were gazed at significantly longer ($M = 495$ms) than both distractors in pre-critical trials ($M = 222$ms) and non-singletons in the critical trial ($M = 231$ms), ts(68) > 9.22, ps < .001, d_zs > 1.10. Moreover, dwell times on non-singletons in the critical trial of both groups ($M = 231$ms) were significantly longer than on distractors in pre-critical trials ($M = 222$ms), $t(68) = 2.07$, $p = .043$, $d_z = 0.25$, (that is, irrespective of whether they had a novel color or not).

Dwell times on the singleton in the critical trial of the one-new group ($M = 566$ms) were significantly longer than on the singleton in the all-new group ($M = 418$ms), $t(51.18) = 2.64$, $p = .011$, $d = 0.62$, indicating that the novel color of the non-singletons may have shortened dwell times on the singleton in the all-new group.

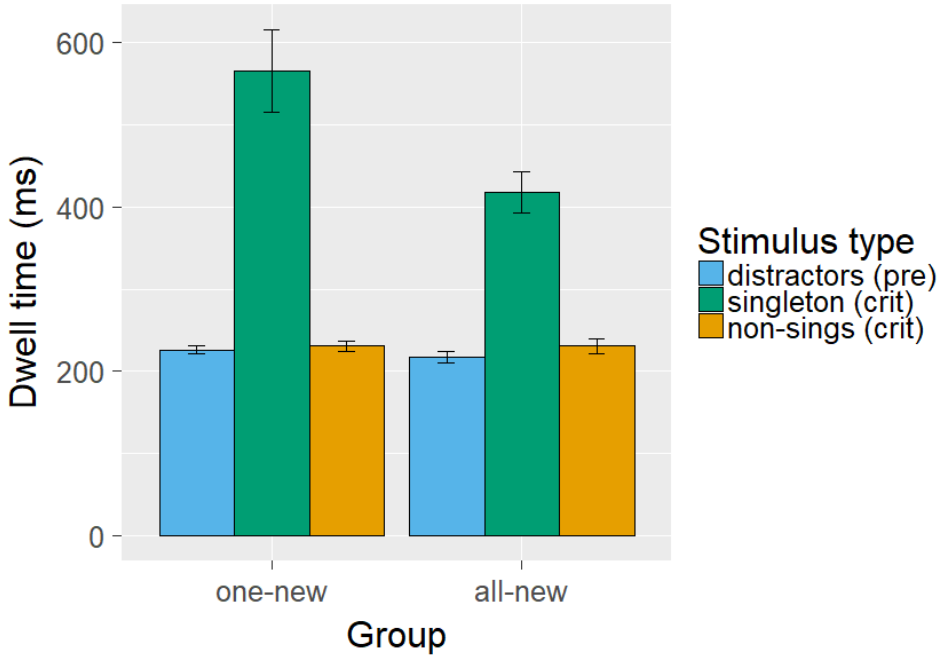

Figure 4. Mean dwell times of the first visit on distractors in pre-critical trials, the singleton in the critical trial, and non-singletons in the critical trial, separately for the one-new and the all-new group. Error bars indicate standard error of the mean.

Revisits

As an hitherto relatively unexplored component of surprise capture, we additionally examined the proportions of at least one revisit on the several stimulus types (Figure 5). Proportions were analyzed by means of GEEs with the same settings as previously for fixation proportions. The detailed results can be seen in Table 3. For simplicity, we run separate GEE models for singletons and non-singletons in which we compared them with distractors in pre-critical trials.

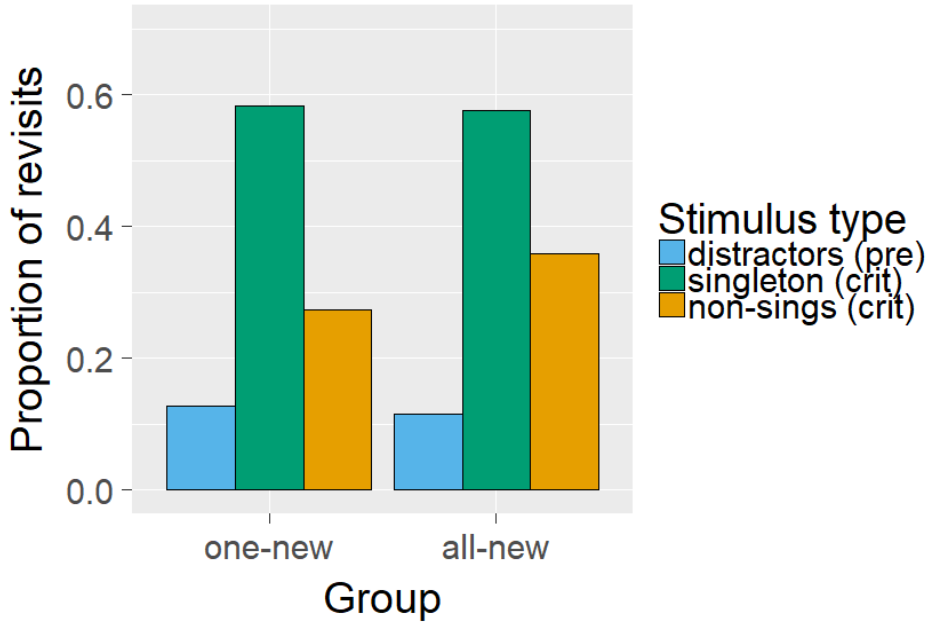

Figure 5. Proportions of at least one revisit on distractors in pre-critical trials, the singleton in the critical trial, and non-singletons in the critical trial, separately for the one-new and the all-new group.

The first GEE model (see Table 3, upper model) regressed the proportion of revisits on the factors stimulus type (distractor in pre-critical trials vs. singleton in the critical trial) and group (one new vs. all new) and their interaction. Within the all-new group, there was a significantly higher proportion of revisits on the singleton in the critical trial than on distractors in pre-critical trials (.58 vs. .12), *Wald* $\chi^2(1) = 37.65$, $p < .001$. The non-significant interaction indicates that the analogue stimulus type difference was comparable within the one-new condition (.58 vs. 13), *Wald* $\chi^2(1) = 0.02$, $p = .877$.

The second GEE model (see Table 3, bottom model) included non-singletons in the critical trial (instead of the singleton) and distractors in pre-critical trials as stimulus types, besides the group

factor. Within the all-new group, there was a higher proportion of revisits on non-singletons in the critical trial than on distractors in pre-critical trials (.36 vs. .12), *Wald* $\chi^2(1) = 56.48$, $p < .001$. The analogue stimulus type difference was, however, significantly less pronounced within the one-new group (.27 vs. 13), *Wald* $\chi^2(1) = 4.44$, $p < .035$.

Table 3. GEE models for at least one revisit on singletons in the critical trial and distractors in pre-critical trials (upper model) and on non-singletons in the critical trial and distractors in pre-critical trials (bottom model)

Stimulus types		*b*	*Wald* $\chi^2(1)$	*p*
Singleton vs. distractors	Intercept: singleton (crit), all-new	+ 0.31	0.75	.386
	Distractors (pre), all-new	- 2.34	37.65	< .001*
	Singleton (crit), one-new	+ 0.03	0.00	.949
	Stimulus type × Group (one-new)	+ 0.08	0.02	.877
Non-singletons vs. distractors	Intercept: non-singleton (crit), all-new	- 0.58	12.09	< .001*
	Distractors (pre), all-new	- 1.45	56.48	< .001*
	Non-singleton (crit), one-new	- 0.40	3.46	.063
	Stimulus type × Group (one-new)	+ 0.51	4.44	.035*

Note. GEEs comprised a logit link function. Singletons (upper model) and non-singletons (bottom model) in the critical trials of the all-new group were set as reference categories which are represented by the intercepts. Signs of non-interaction slopes indicate whether fixation probability increases or decreases compared to the reference category. See text for further details. * $p < .05$.

Discussion

In this study, it was tested whether novelty competes with saliency for visual attention. To that aim, we designed a visual search experiment where we manipulated the color novelty of the non-singleton stimuli by contrasting a “one-new” condition, in which only a surprising color singleton had a novel color, with an “all-new” condition, in which both a surprising color singleton and the remaining non-singleton distractors had a novel color. A competition between novelty and saliency within a priority map should result in attenuated capture of the singleton in the all-new group as compared to the one-new group because of an increased prioritization of the novel non-singleton stimuli in the all-new group. The results strongly supported this prediction.

Crucially, the analyses of the fixated stimulus types within the first three fixations after search display’s onset showed that there were fewer early fixations at the singleton in the all-new group than in the one-new group– mainly within the first two fixations. Accordingly, non-singletons with a novel color in the critical trial of the all-new group were fixated more often within the first three fixations than in the one-new group where non-singletons had a familiar color. Additional support for a reduced prioritization of the singleton in the all-new group comes from the mean singleton fixation latencies, which were shorter in the one-new group, and from singleton dwell times which were longer in the one-new group.

Overall, the results are completely in accordance with the framework of noisy working priority maps (Moran et al., 2013; Wolfe, 1994, 2007; Wolfe et al., 1989; Zelinsky & Bisley, 2015), and the additional assumption of novelty as a source of activity. The activation difference between singleton and non-singleton locations within the all-new group should be smaller as the color features of both stimulus types were novel and the activation increase of the singleton should only be due to its saliency. In the one-new group, however, the singleton position is

distinguished from all other locations because of both saliency and novelty, which lead to a larger difference in activation between both stimulus types than in the all-new group. Activation due to top-down priorities should have been rather constant and low across both groups because the pre-critical familiarization trials were designed such that a) they did not induce the need for an attentional set towards a specific color (Folk et al., 1992), and b) the novel colors in the surprise trial should have been completely unexpected and therefore were unlikely prioritized in a strategic manner (e.g., singleton detection mode; Bacon & Egeth, 1994).

Note that the singleton position in the critical trial of both groups is still expected to be marked by the highest fixation probability as compared to the remaining non-singleton distractors, which is also supported by the data within the first three fixations. However, a deterministic mapping of activation and selection ordering should always have led to the singleton being selected as the first item on the critical trial. Yet, the results of the present study showed that the first fixation after search display's onset was (just) not significantly affected by our manipulations. Because the most relevant or salient item does not always receive the first fixation, but only with a higher probability, it has been argued that the priority map is noisy (Noran et al., 2013; Wolfe, 1994, 2007; Zehetleitner, Koch, Goschy, & Müller, 2013). Likewise, with a noisy priority map, it is not necessarily the first saccade that is directed to the surprising color singleton in the present study. Moreover, it is immediately clear that a smaller activation difference between the singleton location and the non-singleton locations in the critical trial of the all-new group should also result in a smaller difference in the proportion of early fixations on both stimulus types as compared to the one-new group. This is also in line with previous studies which suggested that noise within a priority map occasionally caused attentional capture by less

salient distractor singletons than the target singleton (Koch, Müller, Zehetleitner, 2013; Zehetleitner et al., 2013).

One could argue that because search is assumed to be serial in this experiment, participants could also have adopted strategies like beginning search always at an idiosyncratically chosen position (e.g., the top position) which leads to pre-planned first saccades that are less susceptible to singleton capture. Yet, this argument could only explain why in general the first fixation was not significantly affected by the singleton but not the difference of the singleton effect between both experimental groups.

In line with the time course of surprise capture in previous studies, the surprising color singleton in the one-new group was first fixated with an average latency of 433ms (e.g., Ernst & Horstmann, 2018; Horstmann, 2006; Horstmann & Herwig, 2015). By contrast, the singleton in the all-new group was fixated on average with an increased latency of 604ms. Results in the one-new group also showed the distinctive pattern of the singleton prioritization emerging mainly with the second fixation. This appears to be different from gaze capture that has been attributed to pure saliency which is characterized by a latency of about 200-250ms (Theeuwes et al., 2003; Weichselbaum & Ansorge, 2018; van Zoest et al., 2004; but see Geyer, Müller, & Krummenacher, 2008). However, it should be kept in mind that in the present study, search difficulty was relatively high as compared to studies on saliency capture, where the target is often a salient stimulus (e.g., Theeuwes, 1991). We will discuss the relevance of search difficulty on attention capture in more detail at the following section.

Implications for the time course of surprise capture and saliency capture

While the main aim of this study was to test the effects of novelty, the all-new condition in the present experiment can also be discussed with respect to the question whether saliency is able to draw attention in a bottom-up manner, which has been questioned by several authors (e.g., Ansorge, Horstmann, & Scharlau, 2010; Bacon & Egeth; 1994; Burnham, 2007; Folk et al., 1992; Todd & Kramer, 1994). It is a general problem of experiments which attempt to induce saliency capture that the salient stimuli are completely expected because they are presented repeatedly. This renders a possible supporting result vulnerable to several alternative top-down explanations. Even prior exposure or expectedness per se have been postulated to change object processing (e.g., Bar, 2007; Bar et al., 2006; Di Lollo, 2018; Enns & Lleras, 2008; Herwig & Schneider, 2014; Köller, Poth, & Herwig, 2018; Poth, Petersen, Bundesen, & Schneider, 2014; Rao & Ballard, 1999; Waszak & Herwig, 2007; Weiß, Schneider, & Herwig, 2014). The surprise trial of the present all-new group, however, is a condition in which the color features of all items within the display are unexpected and only differ because of their saliency (see also Becker & Horstmann, 2011, Experiment 3; Horstmann et al., 2016). This would render a prioritization of the color singleton difficult to explain by top-down strategies– at least by those strategies which are not specific to surprise. Nevertheless, in the all-new group, the singleton was fixated on average after 604ms, and thus much later than in studies examining oculomotor capture by color singletons which was assumed to be elicited in a bottom-up manner (e.g., Theeuwes et al., 2003; van Zoest et al, 2004; Weichselbaum & Ansorge, 2018). This raises the question to which extent singleton prioritization in the all-new group is driven by saliency capture.

First, it must be considered that the singleton fixation latency in the all-new group was prolonged because of the demonstrated increased non-singleton prioritization. Second, although

the *average* latency of the first singleton fixation was 604ms within the all-new group, the analyses of the early fixation destinations shows that a prioritization already emerged within the first two fixations after search display's onset.

Yet, fixation latencies at surprising singletons in "standard one-new groups" of about 400ms (e.g., Horstmann, 2006; Ernst & Horstmann, 2018; Horstmann & Herwig, 2015; see also the one-new group of the present study) are still relatively late compared to fixation latencies of expected singletons (e.g., Theeuwes et al., 2003). The question remains why novel singletons do not capture the gaze earlier as they are still highly salient which should induce an early saliency capture effect (followed by a later surprise capture effect). One explanation could be that most surprise studies used a difficult search task. Theeuwes (2004, 2010) argues that saliency capture can hardly be induced in difficult searches because the size of the attentional window where stimuli can be processed in parallel is adjusted to be smaller (to allow fine-grained discriminations within the focus of attention; but see Barras & Kerzel, 2017a, 2017b). Further studies supported this hypothesis (Lu & Han, 2009; Proulx & Egeth, 2006).

Assuming that the participants of the present study actually had a focused attentional window and that this window was so narrow that it often did not include the singleton at the beginning of the search trial can explain why saliency capture had a lower probability to bias the *first* fixation. However, if search is exhaustive, the singleton must necessarily enter the attentional window at a random point in time (if not already at the beginning) and should induce saliency capture on the subsequent fixation. Otherwise, it would be at odds with the assumption that saliency capture cannot be completely suppressed by top-down control (Theeuwes, 2010). Actually, our data show that the singleton is prioritized in both groups, as compared to baselines. However, within the all-new group, the singleton only differs by saliency from the remaining

non-singleton stimuli. Thus, the singleton prioritization within the all-new group yields additional support for saliency driven oculomotor capture within difficult searches, which however could be delayed because of the difficult search paradigm. Accordingly, also recent experiments without surprise conditions suggest that saliency effects can be found at later fixations in difficult searches (de Vries, van der Stigchel, & Hooge, 2018; see also Martin & Becker, 2018).

With respect to surprise capture, one might likewise argue that the usually measured fixation latency of about 400ms when a singleton is presented for the first time (e.g., Horstmann & Herwig, 2015; or within the one-new group of the present study) is too late to dub this effect "surprise *capture*"; at least in relation to the fast nature of saliency and contingent capture. However, as already discussed before, considering that within a difficult search task the surprising singleton can also enter the attentional window or the functional view field (Hulleman & Olivers, 2017) at a later fixation and elicit oculomotor capture, suggests that the absolute fixation latency of the salient stimulus might be a doubtful criterion for attention capture in difficult searches. Though it is one reasonable method to test attention capture by focusing on the very first fixation after the display's onset in easy search, it necessarily curtails the range of fixation latencies that can be measured (usually about 200-250ms, Geyer, Müller, & Krummenacher, 2008; Theeuwes et al., 2003; van Zoest et al, 2004; Weichselbaum & Ansorge, 2018).

To conclude, attention capture effects must not necessarily occur at the very first fixation in an all or nothing fashion. Attention capture can still fulfil the criterion of being involuntary and automatic (e.g., Jonides, 1981) when it is not elicited at the first fixation.

Post-selective novelty effects

Our results revealed longer dwell times on any stimulus in the surprise trial of both groups. For non-singleton stimuli in the all-new group, increased dwell times are in line with previous studies which found similar effects on singletons with a novel color (Horstmann et al., 2016; Horstmann & Herwig, 2016). The non-singletons in the one-new group, however, had the same familiar color as they have had in pre-critical search trials and yet we observed an increase in dwell times (see also Ernst & Horstmann, 2018). From a cognitive-evolutionary perspective it has been argued that surprising events are analyzed with respect to validation of expectation discrepancy, causes of the surprising event, and action relevance (Meyer, Reisenzein, & Schützwohl, 1997; Reisenzein et al., 2017). Accordingly, participants in the surprise trial of the one-new condition could have inspected non-salient stimuli more thoroughly in order to check for other changes, less salient than the singleton, with potential relevance for the search task.

However, several studies suggest that dwell times increase with higher target-distractor similarity (Becker, 2011; Horstmann et al, 2017; Martin & Becker, 2018). The process of target-distractor discrimination could also be prolonged because of the surprise induced revision of expectations which requires cognitive capacity. Accordingly, Mandler (1984) assumed an immediate and conscious expectation revision, which is in line with experiments where surprise effects disappeared already in the first post-critical trials (Ernst & Horstmann, 2018; Horstmann & Herwig, 2015; Schützwohl, 1998). With respect to the postulated conscious expectation revision, it would be interesting to test whether increased dwell times in a surprise trial predict higher awareness rates for the surprising event and faster diminishing of novelty effects in post-critical trials (see Martin & Becker, 2018; for more on how target-distractor similarity, attention

capture, and gaze dwell times affect awareness). If so, increased dwell times could reflect that conscious expectation revision interferes with the target-distractor discrimination process.

Another yet relatively unexplored surprise effect is the increase of stimulus revisits. The present results show higher rates of revisits on any stimulus type in the surprise trial, and the increase is even more pronounced on non-singletons with a novel color compared to when they had a familiar color. As in the case of dwell times, this could reflect another component of a surprised induced exploratory search mode (also termed "check-after-surprise" mode; Foerster, 2016), but also to some extend impaired memory for the previously fixated stimulus locations (e.g., Woodman & Luck, 2004; but see also Woodman, Vogel, & Luck, 2001) due to more cognitive resources spent on expectation revision. It is assumed that three to four previously fixated locations can be kept in visual working memory (e.g., Hullemann & Olivers, 2016; McCarley, Wang, Kramer, Irwin, & Peterson, 2003). However, this span only appears to be reduced if location specific information occupies working memory (Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001). If the expectation's update process actually increases refixations because of impaired memory for previously fixated locations, this could imply that the location information of the surprising stimuli is part of the expectation's update process which involves working memory.

Overall, an exploratory search mode as indicated by increased dwell times and revisits on any stimulus in a surprise trial is likewise in line with a "novelty-bonus" that enhances dopamine signals when unfamiliar stimuli are encountered (Kakade & Dayan, 2002). The novelty-bonus has been described as a hard-wired mechanism that engages animals and humans to actively explore the environment for rewards (Barto et al., 2013; Knutson & Cooper, 2006; Krebs, Schott, Schütze, & Düzel, 2009; Schultz, 1998).

Conclusion

To sum up, the present study shows that novelty attracts attention, even when presented in a low-salient manner and at the cost of saliency effects. Furthermore, novelty can also add up with saliency to induce a strong attentional prioritization. We propose novelty (or expectation discrepancy) as an additional factor which contributes to activity in a priority map that influences gaze behavior.

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Disclosure statement

The authors report no conflicts of interest.

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Record of achievement

Study I: Ernst & Horstmann (2018):

Conceived by Ernst & Horstmann

Planned, programmed, and conducted by Ernst

Analyzed by Ernst

Written by Ernst & Horstmann

Revised by Ernst & Horstmann

Study II: Ernst & Horstmann (submitted):

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Study III: Ernst, Becker, & Horstmann (submitted):

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Declaration of dissertation authorship

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Hiermit versichere ich, dass die vorliegende Dissertation von mir selbständig verfasst wurde. Lag ein Beitrag von Dritten im weiteren oder engeren Sinne vor, wurde dieser unter „Records of achievement“ als solcher spezifiziert. Ich habe keine anderen als die in der Dissertation angegebenen Hilfsmittel benutzt. Alle Stellen, die wörtlich oder sinngemäß aus anderen Schriften entnommen sind, wurden als solche kenntlich gemacht. Die Dissertation hat in der gegenwärtigen oder in einer anderen Fassung keiner anderen Fakultät oder Universität vorgelegen.

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Daniel Ernst

German summary

Deutsche Zusammenfassung

Eine viel debattierte Frage innerhalb der Forschung zur visuellen Aufmerksamkeit ist, in welchem Ausmaß visuelle Aufmerksamkeit von Stimulus getriebenen Faktoren (bottom-up) und von zielgerichteter Aufmerksamkeitssteuerung (top-down) bestimmt wird. Die vorliegende Arbeit beschäftigt sich mit dem speziellen Faktor der Erwartungsdiskrepanz, welche ebenfalls die visuelle Aufmerksamkeit lenkt, die aber keiner der beiden Kategorien eindeutig zugeordnet werden kann. Häufig wird der Einfluss der Erwartungsdiskrepanz getestet, indem Versuchsteilnehmende wiederholt visuelle Suchdurchgänge mit farbhomogenen Reizen an einem Bildschirm absolvieren. Dabei findet eine Gewöhnung an die Suchreize und deren visuellen Eigenschaften statt, sodass zunehmend die wiederholte Darbietung in den folgenden Suchdurchgängen erwartet wird. Wenn nach einigen Durchgängen unangekündigter Weise ein einzelner Reiz mit einer neuen Farbe präsentiert wird (ein „Singleton“), zieht dieser automatisch die Aufmerksamkeit und den Blick auf sich. Die vorliegende Arbeit demonstriert anhand von drei Studien, dass erwartungsdiskrepante Reize nicht zwingend in Form eines neuen Singletons dargeboten werden müssen um die Aufmerksamkeit auf sich zu lenken; das heißt, die Neuheit einer visuellen Eigenschaft per se ist hinreichend. Die erste Studie zeigt, dass ein aufgabenirrelevantes Farbsingleton stark den Blick einfängt, wenn es überraschend mit einer neuen Farbe präsentiert wird. Des Weiteren wurde die Alternativerklärung geprüft, dass Erwartungsdiskrepanz die attentionale Kontrolle außer Kraft setzt, was zu einer verstärkten Priorisierung von salienten Reizen führt. Die Ergebnisse legen jedoch keinen ausschlaggebenden Einfluss eines solchen Effektes für unerwartete Reize nahe. Die zweite Studie demonstriert, dass die Intensität, mit der die Augen von einer neuen Farbe angezogen werden, davon abhängt, wie

eng die Erwartung bezüglich der bekannten Farbe ist. Angenommen wurde, dass die Erwartung einer Farbe enger wird, je weniger die wahrgenommene Farbe variiert, und je häufiger die Farbe wahrgenommen wurde. Somit sollte die Erwartungsdiskrepanz einer neuen Farbe bei einer engen Erwartung groß und bei einer breiten Erwartung gering sein. Experimente mit einem ähnlichen Design wie in Studie 1 zeigten, dass der Blick von einem irrelevanten Singleton mit einer neuen Farbe schwächer angezogen wird, wenn das Singleton zuvor bereits stärker seine Farbe variierte und je weniger Suchdurchgänge es gab. Es wurde ein Ansatz vorgeschlagen, mit dem das Ausbilden einer Erwartung mathematisch modelliert werden kann. Die dritte Studie zeigt, dass Neuheit mit Salienz um attentionale Priorisierung konkurrieren kann. Genauer gesagt wurde dargelegt, dass die Priorisierung eines neuen Singletons mit einer neuen Farbe in einem Überraschungsdurchgang abgeschwächt wird, wenn die verbleibenden Stimuli ebenfalls eine neue Farbe aufweisen. Letztere werden dabei verstärkt beachtet. Das Ergebnismuster ließ sich anhand von probabilistisch funktionierenden Prioritätskarten für Aufmerksamkeitszuweisung vorhersagen, indem angenommen wurde, dass Neuheit grundsätzlich zu einer erhöhten Aktivität führt. Zusammen tragen die drei Studien zu einer genaueren Spezifizierung des Zusammenhangs zwischen Erwartungsdiskrepanz und Aufmerksamkeit bei.