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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 of any color was unlikely. The results show that the singleton in the all-new group 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.

1. Introduction

An important part of the early theoretical and empirical development in visual attention research 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 selection. 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 and examine how it affects attention and eye movements. Note that in the following, the terms novelty and surprise (or unexpectedness) will be used synonymously, as the differences between the concepts are not the focus of the current study (but see Barto, Mirolli, & Baldassarre, 2013, for an overview) and can be neglected here for simplicity.

The attentional prioritization caused by unexpected simple features has been termed *surprise capture* (Horstmann, 2002, 2015). 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 previous 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 strategic prioritization of singletons (Bacon & Egeth, 1994; Gibson & Jiang, 1998). Actually, multiple studies showed that unexpected singletons capture attention and the gaze at their first 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 mechanism rather than to saliency-based mechanisms, because the time course of surprise capture seems to differ from the time course of saliency capture, which is assumed to be purely stimulus-driven (Theeuwes, 2010). Saliency capture has been postulated to occur after 60–150 ms for covert attention shifts (Kim & Cave, 1999; Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000), and after about 200–250 ms for overt attention shifts (i.e., oculomotor capture, Theeuwes, deVries, & Godijn, 2003; van Zoest, Donk, & Theeuwes, 2004; Weichselbaum & Ansorge, 2018). Surprise capture instead has

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been found to mainly occur after about 400 ms for covert attention shifts (Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Horstmann, 2006), and 400–500 ms 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, the 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 discrepancies, 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).

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 et al., 2015). However, recent studies suggest that surprise capture is not necessarily limited to the combination of novel features and singleton status. 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 (whereby capture may have been either due to the singleton's 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 singleton status 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 demonstrate that novelty prioritization can be integrated into the framework of priority maps for visual attention. 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, although not always perfectly, as there is noise either in the activation calculation (e.g., Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989) or in the process of following the activation gradient (e.g., Moran et al., 2013).

We propose novelty as an additional source of activation in 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, novelty and saliency can add up to induce a strong peak in activity within the priority map[1], 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. That is, although novelty and saliency are assumed to constitute independent sources of activation, within the priority map both can compete for attentional selection, if the corresponding stimuli are presented at different locations.

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 the deployment of visual attention (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 Fig. 1). Importantly, the color dimension was not discriminative for the target as participants had to detect the presence of a specific shape that was potentially located inside one of the color patches. In the surprise trial (which was always a target absent 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 differed with respect to the novelty of the non-singleton stimuli. Assuming that novelty contributes as an additional factor besides physical stimulus saliency to activity in a priority map has two implications for the predicted data pattern. First, 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. Second (and crucially), as novelty also contributes to activation in the priority map at the positions of non-singleton stimuli with a novel feature, the difference in activation between the singleton's position and the positions of the remaining stimuli should be smaller in the all-new condition. Here, all stimuli in the display are novel and hence, the activation difference should be solely due to saliency information. Thus, if fixation probability is a function of the activation in the priority map plus noise (e.g., Zelinsky, 2008), there should be fewer early fixations on the singleton in the all-new relative to the one-new condition. Accordingly, more early fixations should be directed on the non-singletons in the all-new condition (when the non-singletons have a novel feature) than in the one-new condition (when the non-singletons all have a familiar feature).

Note that by presenting only one critical surprise trial which is a target absent 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 the need for an attentional set towards any color, and the displays do not contain a target on the surprise trial. Thus, the present study allows for a relatively clear-cut discrimination between novelty and saliency effects of the colors.

[1] As mentioned before in the introduction, novelty prioritization has been found to peak somewhat delayed as compared to saliency capture (Horstmann, 2002, 2006). Stating that activity which is induced by novelty and saliency can add up to a strong peak within a priority map is actually a simplified depiction of two merged time course distributions that originally had shifted modes. In other words, we assume that novelty effects may occur as early as saliency effects but with a lower probability.

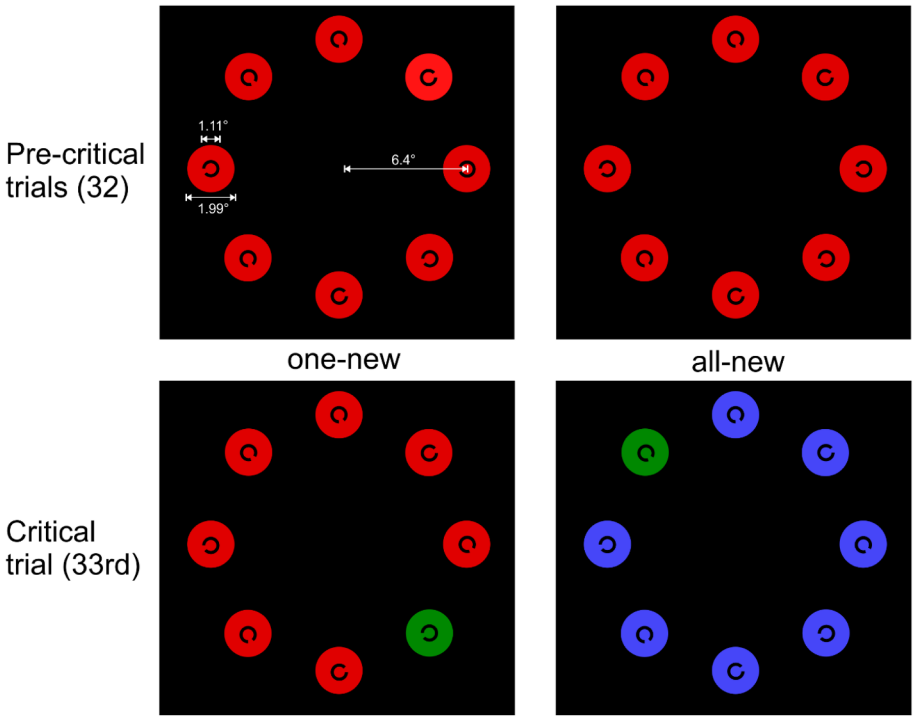

Fig. 1. Exemplary displays of the pre-critical familiarization trials and the critical surprise trials for both groups.

2. Method

2.1. Participants

72 students or visitors of Bielefeld University (18 men and 54 women) participated in the 10-min experiment. The sample size was based on a pilot study that already yielded significant effects for the early fixation destinations, which is the main dependent variable of interest for this study. The pilot study mainly differed from the present study 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).

2.2. Apparatus

Stimuli were presented on a 19-inch display monitor (100-Hz refresh rate, resolution 1024 × 768 pixels) at a distance of 71 cm. Before testing, the monitor was warmed for at least 30 min, 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.

2.3. 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 = 0.329), green (RGB: 0, 136, 0; CIE: x = 0.282, y = 0.589), and blue (RGB: 70, 70, 248; CIE: x = 0.169, y = 0.100). 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°.

2.4. 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 pre-critical trials 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) and differed only in the critical trial (see Fig. 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 as in the pre-critical trials (e.g., red). All possible color combinations were counterbalanced between participants.

2.5. 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 of a standard 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 0.5 s ($\lambda = 2$), b) a following period of 100 ms, in which the eye tracker controlled for a central fixation, and c) possible additional time until the central fixation has been successful. The exponential distribution of this "non-aging" (Näätänen, 1971) fore-period 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.

To reduce variance between participants, within the fore-period of the critical surprise trial we fixed the time at the exponential distribution's expectation value of 500 ms. Afterwards, the search display was presented until a key press was registered. An error sound occurred whenever an incorrect response had been recorded.

3. 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 (8000°/s^2), and a velocity threshold (30°/s). Fixations were classified as eye data that exceeded neither of these thresholds 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 center of the stimulus. Further preprocessing and statistical analysis used R 3.4.3 (R Core Team, 2016). All reported *p*-values are two-tailed using an alpha level of $\alpha = 0.05$.

In order to adequately model binary dependent variables like stimulus 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, because of repeated measurements) to prevent underestimation of standard errors. To conduct GEEs, an initial working correlation structure must be specified. Because of its parsimony, we used an exchangeable working correlation structure that assumes equal correlations between any pair of measurements within a participant. GEEs still 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 analogous 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 the categorial factors in 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 term. 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.

As the critical trial was always a target absent trial, we only compared performance in the critical trial with pre-critical trials that did not contain a target, either. Target present trials were excluded from all analyses.

3.1. Accuracy

We recoded the response pattern of one participant who exchanged response keys and showed 0% correct responses 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 (18377 ms; $z_{included} = 14.74$), reducing the sample size to 69.

3.2. 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 ($M = 3747$ ms) than in pre-critical trials ($M = 2531$ ms), $F(1,67) = 94.84$, $p < .001$, $\eta_G^2 = .33$, indicating that the surprising stimulus features disrupted the visual search process in both groups. The interaction just failed to reach significance, $F(1,67) = 3.61$, $p = .062$, $\eta_G^2 = .02$, reflecting that the average response time difference between pre-critical trials and the critical trial tended to be somewhat more pronounced within the all-new group (2462 vs. 3928 ms) than in the one-new group (2594 vs. 3582 ms). The main effect for group was not significant, $F(1,67) = 0.40$, $p = .531$, $\eta_G^2 < .01$.

3.3. Gaze data

For the analyses of the gaze data, we compared fixations on the singleton in the critical trial with gaze behavior on distractors in all pre-critical target absent trials, whereby the latter serves as a baseline for an unbiased attention distribution. Where informative, also gaze behavior on non-singletons in the critical trial was analyzed. Note that we use the word "distractors" when we refer to stimuli in pre-critical trials, while we use the words "singleton" and "non-singletons" when we refer to stimuli in the critical trial (although on principle all stimuli in target absent trials are distractors). Overall, participants fixated 96% of the presented stimuli in target absent trials, irrespective of stimulus type.

3.4. Stimulus fixation latencies

Fig. 2 shows the mean latencies for the first fixation on a specific item relative to the onset of the search display. Note that these are not necessarily the first fixations in a trial. For instance, a participant with a singleton fixation latency of 600 ms in the critical trial may have fixated a non-singleton beforehand. For distractors in pre-critical trials, the mean latency of their first visit is the average of all performed distractor fixations in pre-critical target absent trials (irrespective of fixation index and excluding revisits), which serves as a baseline. That is, the mean fixation latency of distractors in pre-critical trials (which is about 1000 ms) corresponds to the expected fixation latency of the singleton if it was selected at random, without any prioritization. In the statistical analyses, we did not include fixation latencies on non-singletons in the critical trial as they are necessarily negatively correlated with singleton

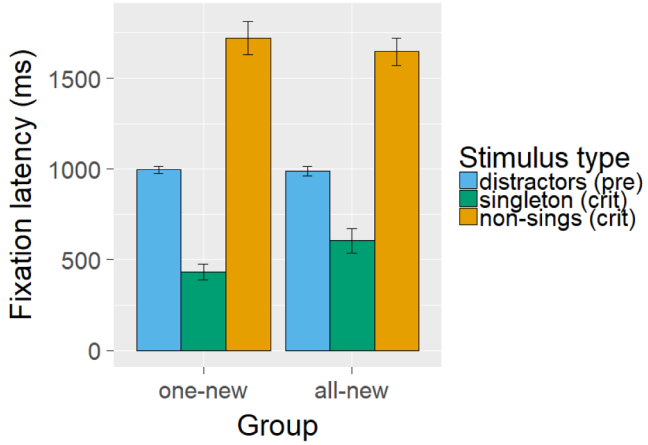

Fig. 2. Mean latencies of the first fixation on distractors in pre-critical trials, singletons in the critical trial, and non-singletons in the critical trial, separately for the one-new and the all-new group. Error bars indicate standard error of the mean.

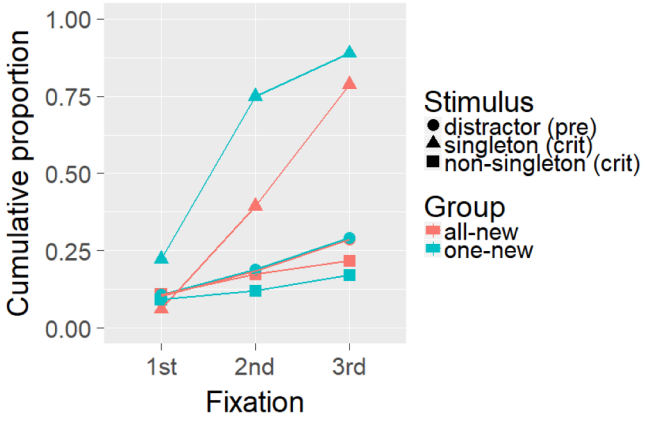

Fig. 3. Proportions of at least one visit on the different stimulus types within the first, first and second, and within the first three fixations, depicted separately for the one-new and all-new group.

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	−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	−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	−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. The signs of non-interaction slopes indicate whether fixation probability increases or decreases compared to the reference category. See text for further details.
* $p < .05$.

fixation latencies.

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 was fixated significantly earlier in the one-new group ($M = 433$ ms) than in the all-new group ($M = 604$ ms), $t(56.83) = 2.76$, $p = .034$, $d = 0.53$ (degrees of freedoms are Welch corrected here and in the following *t*-tests between groups). Compared to distractors in pre-critical trials, the singleton was significantly prioritized both within the one-new group (433 vs. 996 ms), $t(35) = 11.54$, $p < .001$, $d_z = 1.92$, and within the all-new group (604 vs. 987 ms), $t(32) = 5.80$, $p < .001$, $d_z = 1.01$.

3.5. Early fixation destinations

In order to inspect the destinations of very early fixations after search display's onset, we examined the cumulative proportions of at least one fixation on specific stimulus types within the first three fixations (excluding revisits) by means of GEE models with a logit link function (see also Ernst & Horstmann, 2018; Horstmann et al., 2016). For instance, as shown in Fig. 3, the proportion of at least one singleton fixation in the one-new group within the first, first and second, and the first three fixations was .22, .75 and .90, respectively. The graphs for distractors in pre-critical trials indicate that a proportion of .10 of all distractors in the pre-critical target absent trials was visited with the first fixation. Within the first two and the first three fixations, a proportion of .19, and .29, respectively, of all presented distractors was visited. Again, the proportions of distractor visits in pre-critical target absent trials serve as a baseline for an unbiased attention distribution.

In the following analyses, the fixations on the singleton in the critical trials of the all-new group served as reference category. With the first GEE model, stimulus fixations (1 = fixated; 0 = not fixated) were regressed 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).

When 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. Within the all-new group, the probability of a

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	+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	+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	+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.
* $p < .05$.

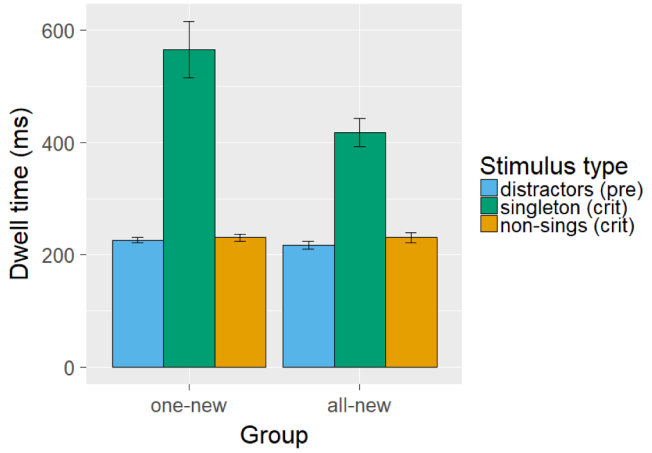

Fig. 4. Mean dwell times of the first visit on distractors in pre-critical trials, the singleton in the critical trial, and non-singletons in the critical trial, separately for the one-new and the all-new group. Error bars indicate standard error of the mean.

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 analogous difference between stimulus types was significantly more pronounced (.75 vs. .19), *Wald* $\chi^2(1) = 8.07$, $p = .005$, as reflected in the significant interaction, 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 analogous stimulus type difference within the one-new group was comparable. Thus, the predicted stronger singleton prioritization in the one-new group than in the all-new group mainly occurred within the first two fixations.

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 (see Table 2 for the detailed results of the GEE model, and Fig. 3 for the results relating to the proportions of at least one fixation on a specific stimulus type within the first, first and second, and first to third fixation).

The model showed no significant effects for the first fixation (see Table 2, upper model).

When 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 analogous comparison was significantly different within the one-new group, due to 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.

When 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 analogous 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.

Overall, the analyses confirm that there was a higher prioritization of non-singletons with a novel color in the all-new group than in the one-new group, where the non-singletons had a familiar color.

3.6. 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 Fig. 4). In this analysis, we included non-singleton distractors in the critical trial since dwell times on singleton and non-singleton stimuli are not expected to be negatively correlated (as opposed to fixation latencies). 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

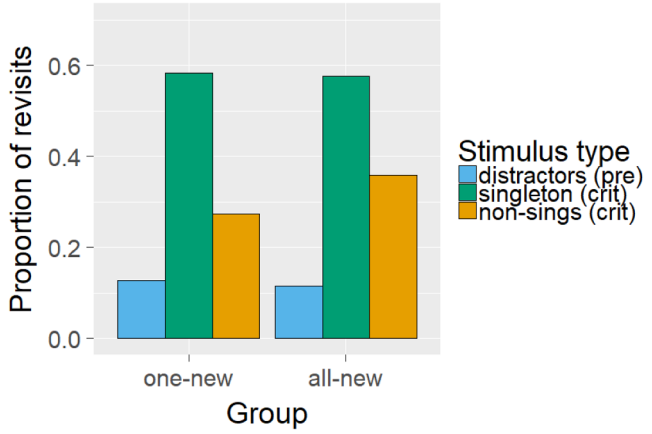

Fig. 5. Proportions of at least one revisit on distractors in pre-critical trials, the singleton in the critical trial, and non-singletons in the critical trial, separately for the one-new and the all-new group.

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.

3.7. Revisits

As a hitherto relatively unexplored component of surprise capture, we additionally examined the proportions of at least one revisit on the different stimulus types (Fig. 5). A revisit is defined here as the fixation of a previously fixated item with a visit on at least one different item in between. Proportions were analyzed by means of GEEs with the same settings as used previously for the proportions of fixations (although the present analyses were not restricted to the first three fixations in a trial). The detailed results can be seen in Table 3. For simplicity, we run separate GEE models for singletons and non-singletons, and compared them with the distractors in pre-critical trials.

In a first GEE model (see Table 3, upper model), the proportion of revisits was regressed 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. 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 analogous 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 analogous stimulus type difference was, however, significantly less pronounced within the one-new group (.27 vs. .13), *Wald* $\chi^2(1) = 4.44$, $p < .035$.

4. 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. Specifically, we contrasted 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.

Overall, the results are completely in accordance with the framework of noisy priority maps (Moran et al., 2013; Wolfe, 1994, 2007; Wolfe et al., 1989; Zelinsky & Bisley, 2015), and support the view that

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	+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	+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.

* $p < .05$.

novelty acts as an additional 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 leads to a larger difference in activation between both stimulus types than in the all-new group. Activation because of top-down prioritization of any color 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 to be prioritized in a strategic manner.

With respect to the familiar color of the non-singleton stimuli in the one-new group, it could be argued that this color has been strategically suppressed, which led to a de-prioritization relative to the non-singleton stimuli in the all-new group. For instance, according to the dimensional weighting account (DWA, Found & Müller, 1996), task irrelevant feature dimensions can strategically be down-weighted in order to accentuate salience signals of the task relevant feature dimension in the priority map. Within the color dimension, experiments show that it is also possible to down-weight specific color features (e.g., Müller, Reimann, & Krummenacher, 2003; Treisman & Sato, 1990). However, studies also suggest that such a strategic adjustment of attentional priorities is associated with costs and only occurs when participants have a strong incentive for feature suppression; that is, if a singleton-distractor is presented at least in a specific proportion of trials (cf. Folk & Remington, 2015; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). In the present study, however, the familiar color of the non-singletons in the surprise trial of the one-new group was previously presented only within displays that contained color homogeneous search stimuli. Down-weighting of this color would not result in any benefits in increasing the signal of the task relevant shape feature. Thus, a strategic down-weighting of any color in the present experiment was unlikely as the participants did not have an incentive to do so.

The singleton position in the critical trial of both groups is 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 (Moran et al., 2013; Wolfe, 1994, 2007; Zehetleitner, Koch, Goschy, & Müller, 2013). A noisy priority map can also explain why the first saccade was not deterministically 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 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 (cf. Treisman & Souther, 1985), 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 the following fixations.

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 433 ms (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 604 ms. 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 200–250 ms (Theeuwes et al., 2003; Weichselbaum & Ansorge, 2018; van Zoest, Donk, & Theeuwes, 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). The relevance of search difficulty on attention capture will be discussed in more detail in a later part of this discussion.

The differentiation between saliency capture and surprise capture also leads to the question of whether surprise capture should be interpreted as bottom-up or top-down driven. The prioritization of visual input that has been rendered unexpected in the previous course of an experiment appears to be another case of attentional phenomena whose emergence are bound to the conditions of prior search trials (e.g., intertrial priming, reward learning, and statistical learning; Maljkovic & Nakayama, 1994; Anderson & Yantis, 2012; Wang & Theeuwes, 2018). It has been proposed to categorize such effects as being specifically dependent on the selection history in order to circumvent the issue that these forms of attentional prioritization cannot unambiguously be assigned either to the bottom-up or to the top-down camp (see Awh, Belopolsky, & Theeuwes, 2012, for a detailed discussion). We would, however, follow the notion of Gaspelin and Luck (2018) to traditionally ascribe "selection history"-effects to the top-down category (see also Becker, 2007; Wolfe, Butcher, Lee, & Hyle, 2003), as they do not solely depend on the present stimulus but also on the past context of a task which has affected the current mental state– even if such effects are assumed to occur involuntary (but see Theeuwes, 2018, for a different view).

4.1. 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 salient items are able to involuntary capture attention in a bottom-up manner, which has been questioned by several authors (e.g., Ansorge, Horstmann, & Scharlau, 2010; Bacon & Egeth, 1994; Becker, 2007; 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). Also, the presence of a salient stimulus per se was unexpected. 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 604 ms, and thus much later than in studies examining oculomotor capture by color singletons, which was assumed to be elicited in a bottom-up manner (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 was 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 604 ms 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 400 ms (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 may 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). Further studies supported this hypothesis (Lu & Han, 2009; Proulx & Egeth, 2006; but see also Barras & Kerzel, 2017a,b).

Assuming that the participants of the present study with a difficult search task 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 and the attentional window covers more than one stimulus, the singleton must necessarily enter the attentional window at a random point in time 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 baseline. However, within the all-new group, the singleton only differs in saliency from the remaining non-singleton stimuli. Thus, the singleton prioritization within the all-new group yields additional support for saliency driven oculomotor capture in difficult searches, which however could be delayed because of the difficult search paradigm. Accordingly, recent experiments without surprise conditions also suggest that saliency effects can be found at later fixations in difficult searches (de Vries, van der Stigchel, Hooge, & Verstraten, 2018; see also Martin & Becker, 2018).

With respect to surprise capture, one might likewise argue that the usually measured fixation latency of about 400 ms 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 usually reported fast nature of saliency and contingent capture. However, as already discussed before, considering that in a difficult search task the surprising singleton can also enter the attentional window at a later fixation and elicit oculomotor capture, suggests that the absolute value of the singleton fixation latency might be a doubtful criterion for attention capture in difficult searches. Although 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 200–250 ms, Geyer et al., 2008; Theeuwes et al., 2003; van Zoest et al., 2004; Weichselbaum & Ansorge, 2018).

To conclude, we propose that 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.

4.2. Post-selective novelty effects

Our results revealed longer dwell times on any stimulus in the surprise trial of both groups. Note that the non-singletons in the one-new group had the same familiar color as in pre-critical search trials and yet we observed an increase in dwell times (see also Ernst & Horstmann, 2018, for a similar effect). 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 et al., 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.

Several studies suggest that dwell times are a function of target-distractor similarity (Becker, 2011; Horstmann, Becker, & Ernst, 2017; Horstmann, Ernst, & Becker, 2019; Martin & Becker, 2018). In a surprise trial, however, the process of target-distractor discrimination could 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). For future studies it would be interesting to test whether the postulated conscious expectation revision is reflected in awareness rates of the surprising singleton, which increase with prolonged dwell times 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).

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 as compared to when they have a familiar color. Similar to dwell times, this could reflect another component of a surprised induced exploratory search mode (also termed "check-after-surprise" mode by Foerster, 2016), but also to some extend impaired memory for the previously fixated stimulus locations (Woodman & Luck, 2004; but see also Woodman, Vogel, & Luck, 2001) because more cognitive resources are spent on expectation revision. It is often assumed that three to four previously fixated locations can be kept in visual working memory (e.g., Hulleman & Olivers, 2017; McCarley, Wang, Kramer, Irwin, & Peterson, 2003). However, this memory span appears to be reduced if location specific information occupies working memory (Woodman & Luck, 2004; Woodman et al., 2001). If the expectation's updating process actually increases refixations because of impaired memory for previously fixated locations, this would imply that location specific information of the surprising stimuli is part of the expectation's updating process which involves working memory. This hypothesis could likewise be tested with awareness ratings in future studies; there should be higher awareness rates of the surprising stimulus' location if more revisits occur in a surprise trial.

Overall, the idea of an exploratory search mode as indicated by increased dwell times and revisits on any stimulus in a surprise trial also seems to be 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).

5. 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.

CRediT authorship contribution statement

Daniel Ernst: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Stefanie Becker:** Methodology, Writing - review & editing, Funding acquisition. **Gernot Horstmann:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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