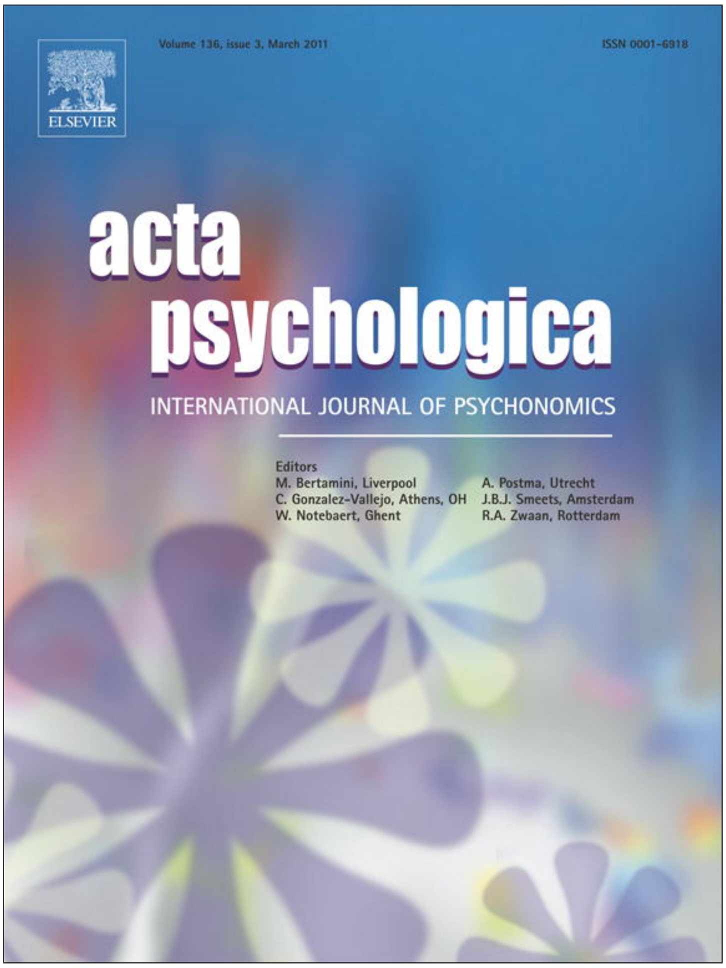
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Novelty and saliency in attentional capture by unannounced motion singletons

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ABSTRACT

The present study examined attentional capture by an unannounced motion singleton in a visual search task. The results showed that a motion singleton only captured attention on its first unannounced occurrence when the observers had not encountered moving items before in the experiment, whereas it failed to capture when observers were familiar with moving items. This indicates that motion can capture attention independently of top-down attentional control settings, but only when motion as a feature is unexpected and new. An additional experiment tested whether salient items can capture attention when all stimuli possess new and unexpected features, and novelty information cannot guide attention. The results showed that attention was shifted to the location of the salient item when all items were new and unexpected, reinforcing the view that salient items receive attentional priority. The implications of these results for current theories of attention are discussed.

We can only process and perceive a limited amount of information present in a visual scene. Attention prioritizes some objects in the visual scene for further processing while it de-prioritizes others. Given the importance of attention for conscious perception and action, researchers have taken great efforts to unravel the factors that can guide attention, and to describe the underlying mechanism.

It is well known that observers can voluntarily tune attention to particular features, for instance, when searching of an item with a known feature. Items that possess the same feature as a sought-for item can also capture attention involuntarily and instigate an involuntary shift of attention to a location (e.g., Folk, Remington, & Johnston, 1992, 1993; Folk & Remington, 1998; Wolfe, 1994). However, it is still unclear whether and to what extent certain stimulus characteristics can capture attention in a purely bottom-up fashion.

According to the saliency capture hypothesis, local feature contrasts guide attention in a purely bottom-up fashion, without or even against the intentions of the observers (e.g., Theeuwes, 1991, 1992). However, subsequent research called this view into question (see Burnham, 2007, for a recent review). Numerous studies have tested the attention-driving capacity of salient items from the luminance, colour or motion dimension. However, the results of these studies showed that salient items do not, as a general rule, capture attention when they constitute an additional, irrelevant item (i.e., a distractor). For instance, Yantis and Egeth (1999) tested capture by irrelevant colour, luminance and motion singletons when observers had to search for a vertical target bar among differently tilted nontarget bars. In separate blocks, they varied the probability that the target would coincide with the salient distractor, and measured search efficiency by varying the number of nontargets in the display (i.e., set size). The results showed that search was efficient (i.e., zero set size effect) only when the colour or motion singleton was 100% predictive of the target location. However, in blocks where the distractor coincided with the target at chance level, search remained inefficient — even on trials where the distractor validly indicated the target location (Yantis & Egeth, 1999). These results led Yantis and Egeth (1999) to conclude that colour and motion singletons do not capture attention against the observers' intentions, but can be used to guide attention in a top-down controlled fashion when the singleton is predictive of the target location (see also Folk, Remington, & Wright, 1994; Hillstrom & Yantis, 1994; Jonides & Yantis, 1988). Correspondingly, Yantis (2000) proposed that feature contrast acts as a passive bottom-up limitation for search efficiency, but does not actively guide attention.

However, it could be argued that the experiments did not test whether feature contrast can actively guide attention, but rather, whether such bottom-up effects can be overridden by top-down attentional control settings. Note that the distractor feature was

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always constant across a block of trials, and that observers knew that it would be located at one of the nontarget positions on the majority of trials. Hence, observers may have tried to actively suppress the salient distractor, to render it ineffective in the guidance of attention (e.g., Folk & Remington, 1998). In fact, subsequent studies showed that observers will inhibit the distractor feature when the distractor is never presented at the target location or when the distractor coincides with the target at chance level (Becker, 2007; Theeuwes & Burger, 1998; Pinto, Olivers, & Theeuwes, 2005).

The fact that top-down attentional control settings can override bottom-up effects of saliency makes it very difficult to assess whether saliency can guide attention independently of the observers' attentional control settings. This however would be necessary to assess whether it plays an active or passive role in the guidance of attention. This question probably cannot be assessed by repeatedly presenting a distractor, but requires assessing capture with respect to a novel stimulus when the observer does not expect it, that is, without briefing the observer about its occurrence, so that it can be examined whether the novel stimulus captures attention at the first, unannounced presentation. If the stimulus has never been presented in the course of the experiment, observers cannot create a mental set for or against paying attention to it, which allows gauging the capacity of the stimulus to capture attention in the absence of attentional biases (Horstmann, 2005; Gibson & Jiang, 1998; Horstmann & Ansorge, 2006). Thus, testing attentional capture at the first unannounced presentation can provide more straightforward evidence for or against the capacity of stimuli to capture attention independently of the top-down attentional control settings.

1. Attentional capture by novel and by familiar stimuli

Studies testing a salient stimulus on its unannounced first presentation have in fact revealed attentional capture, but only when the salient stimulus is novel. For instance, Horstmann (2005) found that a colour singleton such as a red item presented among green items captured attention at the unannounced first presentation only when red was unexpected and presented for the first time. By contrast, when observers were familiar with red items, because half or all of the stimuli on some of the previous trials had been red, then a red item presented among green items for the first time did not capture attention (Horstmann, 2005). Thus, the salient item has to possess an unexpected or novel feature to produce attentional capture, indicating that saliency alone is not sufficient to produce attentional capture.

According to the expectancy-mismatch hypothesis, stimuli that deviate from the range of expected stimuli can elicit an orienting of attention towards the mismatching stimulus (e.g., Horstmann, 2002, 2005). In particular it is assumed that feature expectancies build up as a result of exposure to the features encountered during an experiment. A new object that has a novel and expectancy-mismatching feature will then interrupt ongoing search processes guided by the attentional control settings, temporally pre-empt attentional control, and steer attention to the new object. Phenomenally, such expectation-discrepant stimuli will also frequently elicit surprise.

Note that not all surprising or unexpected characteristics of a new object can elicit attentional capture: the unexpected stimulus must mismatch an expectancy concerning a basic feature ("feature expectancy"), because only basic features are pre-attentively available, and can thus be used to guide attention. By contrast, expectancies concerning a specific combination of features or even conceptual properties ("object expectancies") cannot elicit surprise prior to deploying attention to the stimulus' position. This is because the conjunctions of features are usually not available pre-attentively, which in turn means that they cannot guide attention; stimuli deviating from object-expectancies may, however, evoke surprise when observers attend to the item during serial search (Horstmann, 2005).

2. Aims of the present study

In sum, previous research indicates that saliency alone is not sufficient to capture attention in a purely bottom-up fashion, and by implication, independently of an observer's intentions. Rather, salient stimuli must either match the top-down attentional control settings, or violate the observers' expectancies in order to capture, contrary to what has been suggested by the saliency capture view (e.g., Theeuwes, 1991, 1992).

However, with respect to capture by expectancy mismatching stimuli, this conclusion is based on experiments testing the effects of static colour singletons only. Correspondingly, a first aim of the present study was to test whether the results pattern found with colour singletons generalize to different feature dimensions. To that aim, the present study tested motion singletons in similar conditions as in Horstmann (2005).

Motion appeared to be an ideal candidate dimension, for a number of reasons, inter alias that (a) motion is subjectively highly salient, allowing immediate selection when the target is a motion singleton (e.g., Hillstrom & Yantis, 1994), (b) motion differs from colour in that it is a dynamic discontinuity while colour is a static discontinuity (e.g., Folk & Remington, 1998), and (c) motion seems to be a prime candidate to draw attention under conditions of unexpectedness, from an ecological perspective. Motion singletons have originally been suspected to be able to capture attention solely in virtue of their saliency or inherent behavioural relevance, of signalling potentially threatening objects (e.g., Abrams & Christ, 2003). The idea that dynamic objects can capture attention in a purely bottom-up fashion still has great appeal, presumably, because moving objects can interfere more directly with our goals and action plans, and so should receive attentional priority. Previous studies testing capture by expected and repeatedly presented motion singletons however yielded inconsistent results. The most widely embraced view today is perhaps that a subclass of motion singletons can capture attention but not all kinds of motion. Among the subtypes of motion singletons that have been reported to capture in visual search are looming but not receding stimuli (Franconeri & Simons, 2003), motion cues that segregate an element from a group of other objects (resulting in the percept of a suddenly appearing new object; e.g., Hillstrom & Yantis, 1994), and motion onsets, or suddenly accelerating objects suggestive of animal motion (Abrams & Christ, 2003; von Muehlenen, Rempel, & Enns, 2005).

In the present study, we tested attentional capture with rotational motion, when the motion onset was clearly visible. We chose rotational rather than translational motion to ensure that the target item could remain stationary and would not suddenly move itself, which could have interfered with the discrimination task. The first two experiments tested capture when motion was introduced as a completely new and unexpected feature on the critical trial (Experiment 1) versus when moving stimuli had been presented before and observers were familiar with motion (Experiment 2).

A second aim of the study was to revisit the role of saliency in attention capture. Although prior research already showed that saliency is not sufficient for capture, the role of saliency in the guidance of attention to new and unexpected stimuli is less clear. Previous results are open to two interpretations: first, we could assume with Yantis (2000) that feature contrast affects capture only passively, by determining whether a new stimulus is pre-attentively available, whereby attention is guided to new items by the mechanism that detects expectation-discrepant events. On the other hand, it is conceivable that saliency plays a more active role in guidance and guides attention to salient region once the pre-planned search pattern has been interrupted by the occurrence of an expectancy discrepant display change. Previous studies testing capture by a familiar singleton feature may have failed to find this effect, because the occurrence of a salient item alone was not sufficient to interrupt the pre-planned search pattern. Experiment 3 tested whether saliency can guide attention under these conditions, by unexpectedly presenting new features on all positions of the display, and presenting the target at the only salient location in the visual field. In this condition, the novel feature could not be used to guide attention to the target, because all items had new features that were unfamiliar and unexpected. The target was thus singled out only by its saliency. Hence, if attention can be guided by saliency when the ongoing search behaviour has been interrupted by new information, then the target should capture attention in these conditions.

3. Experiment 1

The aim of the first experiment was to test whether a motion singleton presented for the first time would capture attention when motion was unexpected. Experiment 1 was designed in the fashion of earlier studies (e.g., Horstmann, 2005). In the initial segment of the experiment – the pre-critical trials – observers had to perform a difficult search task of searching through an array of Landolt C's, that is, white rings with a gap, which were presented against the background of stationary black squares. The target Landolt C had a gap in the horizontal plane whereas the distractor Landolt C's all had different orientations, and observers had to indicate with a key press whether the gap of the target Landolt C was oriented to the left or right (see Fig. 1).

After 48 trials, the target was unexpectedly presented against the background of a fast rotating square, constituting a motion singleton. Importantly, participants were not informed about this occurrence, and had not encountered motion on any of the pre-critical trials, so that the 49th, critical trial constituted the first unannounced presentation of a motion singleton. The following post-critical trials of the experiment were designed in exactly the same way as the critical trial, so that the target Landolt C was always presented at the location of the motion singleton.

To assess attentional capture by the motion singleton, the number of items (i.e., the set size) was randomly varied. Since the target Landolt C was very difficult to discriminate from the nontarget Landolt C's, search should be inefficient on the pre-critical trials, and search times should correspondingly increase with increases in the increases in the set size (e.g., Treisman & Gelade, 1980; Wolfe, 1994, 1998). On the critical trial, however, the target Landolt C was validly cued by the rotating square: thus, if the motion singleton captures attention on the critical trial, the target should be found immediately and without scanning the nontargets first. Accordingly, search times should be independent of the set size, reflecting an efficient search (e.g., Yantis & Egeth, 1999). By contrast, if the motion singleton fails to capture attention, then observers should continue in the serial search mode, so that the critical trial does not show a reduction in set size effect (compared with the previous, pre-critical trials).

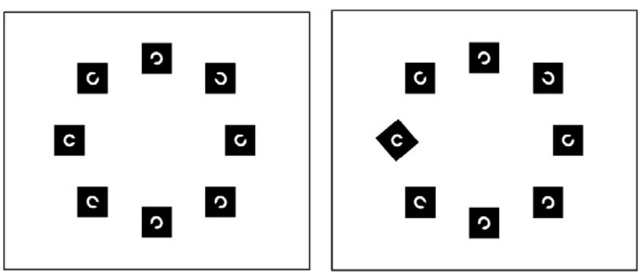

Fig. 1. Examples for displays in the pre-critical trials (left panel) and critical as well as post-critical trials (right panel). The target consisted of a ring that had its gap oriented in the horizontal plane. The critical trial comprised the first unannounced presentation of a singleton (with the diamond shape representing the rotating square). In the post-critical trials, the target was consistently presented against the background of the singleton item.

On the post-critical trials, the motion singleton was always presented at the location of the target Landolt C. Search is usually efficient on the post-critical trials. However, the zero set size effect does not necessarily reflect involuntary capture by the colour singleton, but may only reflect that observers had grasped that the target was always a singleton and tuned attention to the singleton feature in a goal-directed manner (e.g., Folk et al., 1992). Thus, efficient search on the post-critical trials can only be taken to reflect that the singleton was pre-attentively detectable, allowing attention to be guided to its location.

Because attentional capture is centrally assessed with respect to a single trial, set size is treated as a between-subjects variable, with the group of subjects completing the critical trial in the set size 4 condition providing the data for all set size 4 conditions, and subjects completing the critical trial in the set size 8 condition providing the data for all set size 8 conditions. Capture can then be assessed by comparing set size effects (1) between the pre-critical trials and the critical trials, and (2) between the critical trial and the post-critical trials.

Previous studies using colour singletons have reliably shown that the set size effect on the critical trial is significantly reduced, compared with the set size effect on the pre-critical trials, whereas the set size effects did not differ significantly between the critical trial and the post-critical trials. This result pattern has usually been taken to reflect that a colour singleton carrying a new and unfamiliar feature can capture attention at the unannounced first presentation (e.g., Horstmann, 2002, 2005).

However, this interpretation has been recently criticized by Burnham (2007), who speculated that averaging RT over the entire block could lead to an overestimation of the set size effect on the pre-critical trials. To address the possibility that significant differences in the set size effects on the pre-critical condition and the critical trial could reflect training, we collated the data in various different ways in the present experiments: first, as in previous studies, we compared the grand mean set size effects between the critical and pre-critical trials; for a second analysis, we restricted computations of the set size effect to the last 4 pre-critical trials prior to the critical trial, and for a third analysis, we used only the last trial before the critical trial. However, the differences in aggregating data did not change the results for any of the present experiments. For brevity's sake, we will thus report only the results from the second analysis.

On the basis of earlier studies, we also expected RTs to be generally slowed on the critical trial, by a fixed amount, compared to the post-critical trials. These generally elongated RT on the critical trial are characteristic when observers first encounter an unexpected display change. This delay occurs only after attention has been shifted to the location (Horstmann, 2006; Niepel, Rudolph, Schützwohl, & Meyer, 1994; see also Brockmole & Boot, 2009), and presumably reflects the time needed to process the new item, and possibly, to adapt expectancies and knowledge to the new contingencies. Previous studies have shown that these processes can produce delays between 700 ms and 1000 ms. These delays are however constant across different set size conditions and are strictly additive to the time needed to find the target, so that set size effects still accurately reflect differences in search efficiency (Horstmann, 2005, 2006; Meyer, Niepel, Rudolph, & Schützwohl, 1991; Niepel et al., 1994).

The predictions were as follows: if the motion singleton captures attention on its first unannounced occurrence, then the set size effect that usually accompanies inefficient search on the pre-critical trials should be significantly reduced on the critical trial, leading to a significant interaction between set size and search condition. Moreover, comparing the critical trial to the post-critical trials should not show any differences in the set size effect. However, due to the fixed delay which specifically occurs on the critical trial, we would expect RT to be generally inflated on the critical trial, compared to the post-critical trials, by about 700 to 1000 ms.

3.1. Method

3.1.1. Participants

These were 33 women and 23 men with a mean age of 23.5 (SD = 3.2) years. They participated voluntarily and without payment in the 5-min experiment.

3.1.2. Materials

All experiments reported in this article used a standard keyboard, a microcomputer with an Intel 80486/100 MHz CPU and a 17" computer monitor for stimulus presentation and response registration. Stimuli were presented with a resolution of 640 × 480 pixels and a refresh rate of 75 Hz. The arrow down and arrow left keys of the computer keyboard were used as right and left response buttons, respectively. For event scheduling and RT measurement the experimental runtime system ERTS (BeriSoft Cooperation) was used.

3.1.3. Stimuli

The stimuli consisted of 4 or 8 white Landolt C's with a diameter of 0.25°, which had their gap in the horizontal or diagonal plane. There were 2 Landolt C's which had their gap in the horizontal plane, i.e., on the right or left side, and 4 Landolt C's which had their gap in the diagonal plane (up-left, up-right, bottom-left, and bottom-right). Each Landolt C was located in the centre of a black square. At a head monitor distance of 114 cm, the squares measured 1.25° × 1.25° and were presented on a constantly white background (100 cd/m^2). All stimuli were equally spaced from each other and located on the outlines of an imaginary circle with a diameter of 8.5°. The task was to search for a Landolt C which had its gap in the horizontal plane.

In the set size 4 condition, the stimuli occupied the 0°, 90°, 180° and 270° positions, and in the set size 8 condition 4 stimuli were additionally positioned at the 45°, 135°, 225° and 315° positions. The set size was varied in order to distinguish between efficient and inefficient search strategies. Since eccentricity was kept constant across the different set sizes, the density of the stimuli varied: in the set size 4 condition the distance between two adjacent stimuli measured 6.0° centre to centre, in the set size 8 condition it was 3.3°.

3.1.4. Design

The experiment consisted of the conditions set size (4 vs. 8 search items) and trial type (pre-critical, critical, and post-critical). The set size was varied within participants in the pre-critical and post-critical trials, but had to be varied between participants on the single, critical trial (because there was only a single critical trial per participant). In the pre-critical trials, which comprised 48 experimental trials, all squares were identical. They were followed by 49 trials in which one square rotated. The rotating motion of the stimulus was produced by successively presenting 22.5° rotated images of the square at each monitor refresh rate (every 13 ms).

On the critical and post-critical trials, the rotating square always coincided with the position of the target stimulus. The first trial with a singleton square was the critical trial, with the following 48 trials constituting the post-critical trials. The experiment flowed continuously from one segment to another, and participants were not informed that one square would be moving or that it indicated the target position.

On the pre-critical and post-critical trials, the position and orientation of the target object were randomly determined such that each target type (left or right oriented) appeared equally often within each set size condition. The orientation of the distractor Landolt C's and their positions were equally randomly determined. The critical trial was construed such that between participants, equal numbers of combinations of target type × set size could be obtained. The experiment was preceded by a written instruction and two examples of the target stimuli in the different set size conditions.

3.1.5. Procedure

Each trial started with the presentation of a small black fixation cross located at the centre of the screen. After 500 ms, the stimulus display consisting of the black squares and the circles was presented and the fixation cross disappeared. Participants were required to search the display for a circle that had its gap in the horizontal plane: upon finding the target, they had to press the right key when the gap was located to the right and the left key if it was oriented to the left. The stimulus display remained on screen for 4000 ms or until response. Immediately after that, a feedback was provided consisting of the written words "correct" or "wrong" (in German) which were presented for 1000 ms. After an inter-trial interval of 500 ms, in which a blank white screen was presented, the next trial started with the presentation of the fixation cross. Participants were instructed to respond as fast as possible without making mistakes.

3.1.6. Analysis

Mean RTs for the pre-critical trials and the post-critical trial were computed so that they matched the conditions on the critical trial. That is, set size was either 4 or 8 (varied between participants) on the single critical trial and only trials of the same set size were used to collate data for the pre-critical trials and the post-critical trials. Because of the possibility that set size effects get smaller during the pre-critical trials (Burnham, 2007), only the final four pre-critical trials for either set size were used to compute mean RT for the pre-critical trials. For the post-critical trials, however, all correct RTs were used.

3.2. Results

For the RT-analysis, errors (2.3%) and RTs exceeding 4000 ms (2.7%) were excluded. This pertained to 11 critical trials, which reduced the sample size for the RT-analysis to 45. Mean RTs for the two set size conditions in the three types of trial are depicted in Fig. 2.

Separate 2 × 2 ANOVAs were conducted over the RTs, contrasting, first, the set size effects of the critical trial to the pre-critical trials, and second, the set size effects of the critical trial to the post-critical trials. The first 2 × 2 ANOVA comparing set size effects (4 vs. 8) across the different trial types of pre-critical trials vs. the critical trial revealed a significant main effect of set size only [set size: $F(1, 43) = 10.59$, $p = .002$; trial type: $F(1, 43) = 2.02$, $p = .162$]. Most importantly, a significant trial type × set size interaction could be observed, $F(1, 43) = 7.98$, $p = .007$. The significant interaction was due to the fact that the set size effect was greatly reduced in the critical trial (slope = 18 ms/item) when compared to the set size effect in the pre-critical condition (slope = 174 ms/item).

A corresponding 2 × 2 ANOVA comparing the set size effects between the critical trial and the post-critical trials (slope = 3 ms/item) revealed a main effect for trial type only, $F(1, 43) = 121.5$,

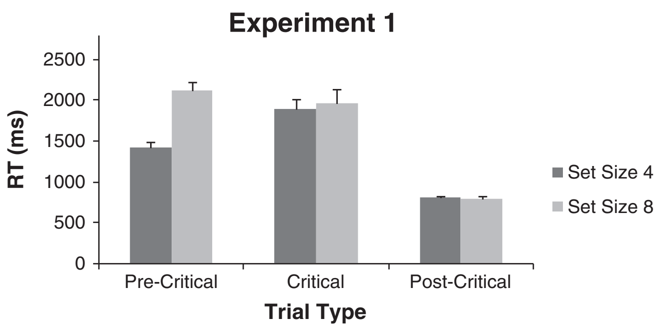

Fig. 2. Mean response times for Experiment 1, where all stimuli were presented on static squares on the pre-critical trials, and the target was a suddenly rotating square on the critical trials and the post-critical trials. Search performance is depicted as a function of trial type (pre-critical, critical and post-critical) and set size (4 vs. 8 items). The error bars depict one standard error of the mean.

Table 1
Error scores of Experiments 1–3 (in %).

		Pre-critical	Critical	Post-critical
Exp. 1	Set size 4	1.9	7.1	1.3
	Set size 8	3.1	10.7	2.8
Exp. 2	Set size 4	1.0	0.0	1.0
	Set size 8	2.3	0.0	0.7
Exp. 3	Set size 4	1.5	3.8	0.8
	Set size 8	1.9	0.0	1.4

$p<.001$ (all other effects, $F<1$). Neither a significant set size effect nor a set size × trial type interaction between the critical and post-critical condition was observed.

Corresponding analysis for the error scores revealed a marginally significant main effect for trial type when comparing the critical trial to the post-critical trials, $F(1, 54)=3.27$, $p=.076$, indicating more errors in the critical than in the post-critical trials (8.9% vs. 1.9%). The other effects were not significant (Fs<1.80, ps>.185) (Table 1).

3.3. Discussion

The results from Experiment 1 indicate that a motion singleton captured attention on its first unannounced occurrence: as can be seen in Fig. 2, RTs only increase with increasing set size on the pre-critical trials, but not on the critical or on the post-critical trials. Statistical comparisons confirmed that the set size effect was significantly reduced on the critical trial, compared with the pre-critical trials, as indicated by the significant Trial type × Set size interaction. Conversely, search efficiency did not differ significantly between the critical and the post-critical trials, indicating that the motion singleton was immediately attended both on the critical trials and on the post-critical trials, when observers knew that it validly indicated the target position. Efficient search on the post-critical trials cannot be taken as an evidence for involuntary capture, because participants might have already learned that the moving element is always at the target's location, and their attending to this element might therefore be strategic. However, on the critical trial, before attention was shifted to the singletons' location, observers could not know that the target would be at the singleton's location. Hence, these conditions satisfy Yantis (1993) criterion of involuntary attentional capture, insofar as the capturing feature (here: movement) is independent from the target-defining attribute (whether the gap is on the horizontal axis) and reported attribute (whether the gap is left or right).

The set size effects differed numerically on the critical and post-critical trials, with slightly more inefficient search on the critical trial (18 ms/item) than on the post-critical trials (3 ms/item). Such numerical differences are commonly observed with the present paradigm (e.g., Horstmann, 2005), and are probably due to the fact that capture by an unannounced singleton is slowed compared to top-down guided search. Horstmann (2006) systematically varied the SOA between the presentation of the unexpected singleton and a briefly presented target display, and found that it can take up to 300 ms to shift attention to unexpected items. This is considerably slower than the 100 ms proposed for bottom-up saliency capture (e.g., Kim & Cave, 1999), or the time needed to select a salient item in a top-down controlled manner (Ansorge & Horstmann, 2007; Horstmann, 2006). Accordingly, it is possible that observers have already selected another item on the critical trial prior to detecting the unexpected motion singleton. The trend for slightly shorter mean RT in the set size 4 condition could therefore be due to the fact that the a priori probability of selecting the target with the first attention shift is higher in the set size 4 condition (25%) than in the set size 8 condition (12.5%; for a more detailed discussion see Horstmann, 2005, 2006).

The significant main effect of trial-type reflects that baseline RT were overall delayed on the critical trial (see Fig. 2). Previous studies show that such delays can almost always be observed with the surprise presentation of a display change, probably reflecting the time needed to overcome the unexpectedness of the display changes (e.g., Gibson & Jiang, 1998; Horstmann, 2002). Importantly, the delay is an additive component, adding a fixed constant to the RT in the different set size conditions (cf. Sternberg, 1969). This implies that the source of the delay is different from the attentional deployment proper, occurring after the attention shift and before the selection of the response (see Horstmann, 2005, for a more detailed account). Since search was efficient on the critical trial, the magnitude of the delay has to be estimated by comparing the RT of the critical trial to the RT on the post-critical trials (not to the pre-critical trials, which can only serve as a reference when the singleton had not captured on the critical trial). In the present study, the delay measured about 1,100 ms. This is quite large compared to delays observed with unexpected colour singletons (delays of 700 ms to 1,000 ms), which could reflect that new motion violates expectations to a higher degree than stationary features such a new colours.

In sum, the results of Experiment 1 were consistent with the expectancy-mismatch account, which predicts that unexpected stimuli with new information content should involuntarily capture attention. However, it is also possible that a very salient motion singleton will always capture attention, regardless of whether it is expected or unexpected (saliency capture hypothesis; e.g., Theeuwes, 1992). The next experiment was designed to investigate this possibility.

4. Experiment 2

In Experiment 2, we eliminated the novelty of rotational motion, to see whether a very salient motion singleton might nevertheless capture attention in virtue of its saliency alone (saliency capture view). In Experiment 2, observers were made familiar with motion by including displays in the pre-critical condition where all squares rotated in unison. On half of all trials in the pre-critical condition, the squares all remained stationary, as in Experiment 1, whereas on the other half of the trials, all squares rotated. Thus, observers were acquainted with moving items, but motion did not help with the task because it never singled out the target. On the critical trial, only the target square rotated whereas the distractors were presented against the background of stationary squares.

Previous studies using the same design with colour singletons showed that an unexpected colour singleton (e.g., red item among green items) does not capture attention when observers are acquainted with the feature of the target (e.g., red) and it ceases to have new information content (Horstmann, 2005). If these results can be replicated with the salient motion singleton, then the motion singleton should similarly not capture attention on its first unannounced occurrence. This should result in a sizable set size effect on the critical trial, reflecting inefficient search. On the other hand, if singletons can involuntarily capture attention in virtue of their saliency alone, we would expect a large reduction in the set size effect on the critical trial, similar to Experiment 1, where motion constituted a novel feature.

4.1. Method

4.1.1. Participants

These were 25 women and 24 men with a mean age of 23.4 (SD = .6) years.

4.1.2. Stimuli, design, and procedure

Experiment 2 was identical to Experiment 1 with the exception that on half of all trials in the pre-critical condition, target and non-targets were all moving rotating squares. On the critical trial, the target was presented against the background of stationary distractors, replicating the conditions of Experiment 1.

4.2. Results

For the RT-analysis, errors (1.1%) and RTs exceeding 4000 ms (3.5%) were excluded. This pertained to 1 critical trial in the set size 8 condition. Mean RTs for the two set size conditions in the three types of trial are depicted in Fig. 3.

The first 2 × 2 mixed ANOVA comparing the set size effects in the pre-critical trials to the set size effect on the critical trial revealed a significant main effect of set size, $F(1, 41) = 42.24$, $p < .001$, but no main effect of trial type, $F(1, 41) < 1$, and the interaction was similarly non-significant, Trial type × Set size: $F < 1$. The significant main effect was due to a large set size effect of 227 ms/item.

A corresponding ANOVA involving comparisons of the critical trial with the post-critical trials revealed significant main effects of set size, $F(1, 41) = 15.72$, $p < .001$, and trial type, $F(1, 41) = 102.98$, $p < .001$. Most importantly, a significant trial type × set size interaction could also be observed, $F(1, 41) = 19.13$, $p < .001$. The significant interaction was due to the fact that the set size effect on the critical trial (slope = 241 ms/item) was significantly larger than the non-significant set size effect in the post-critical condition (slope = −8 ms/item).

Corresponding analysis for the error scores revealed only a significant main effect for trial type when the critical trial was compared to the post-critical trials, $F(1, 47) = 5.32$, $p = .026$, reflecting less errors in the critical than in the post-critical trials (0.0% vs. 0.8%). The other effects were not significant (Fs < 2.00, ps > .164 (Table 1)).

4.3. Discussion

The results show that when observers expect moving stimuli on at least some trials, a motion singleton does not capture attention on its first unannounced presentation. These results replicate earlier results with colour singletons (Horstmann, 2005) and thus show that even highly salient items cannot capture attention involuntarily when they are part of the set of expected events. Thus, the results support the view of the expectancy-mismatch hypothesis, that saliency is not sufficient for involuntary attentional capture (although it may still be necessary for capture).

It is also interesting to note that, in the absence of capture, there was also no delay of baseline RT on the critical trial. (Since the motion singleton did not capture, RT on the critical trial have to be compared to the pre-critical trials to estimate the delay.) Correspondingly, observers in Experiment 2 were more likely to respond within the time-window of 4000 ms on the critical trial, so that fewer participants had to be excluded in Experiment 2 than in Experiment 1 (where most errors on the critical trial were caused by observers not responding within 4000 ms). The observation that the delay often co-occurs with capture and is correspondingly often absent when a singleton fails to capture on the critical trial is consistent with previous observations, although delays have also been reported to occur in the absence of capture (Horstmann, 2002, 2005).

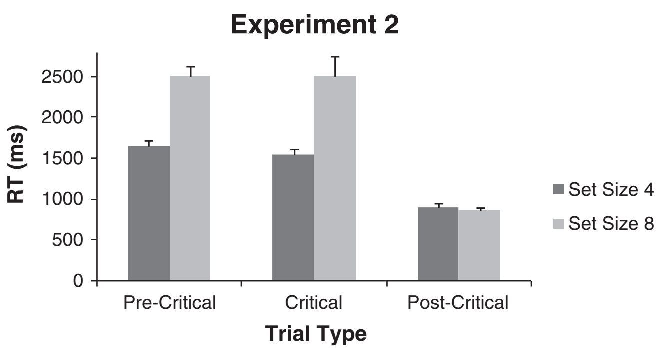

Fig. 3. Mean response times for Experiment 2, where the pre-critical trials included displays where all squares rotated. On the critical and post-critical trials, the target was presented on the background of a rotating square, among static distractors. Search performance is depicted as a function of trial type (pre-critical, critical and post-critical) and set size (4 vs. 8 items). The error bars are one standard error of the mean.

5. Experiment 3

Experiment 2 showed that an unexpected motion singleton does not capture attention when observers are familiar with motion and motion is thus not expectancy-discrepant. This result is consistent with the view that saliency does not actively guide attention, but merely serves as a passive, bottom-up limitation for search efficiency (e.g., Yantis, 2000): in fact, previous results have been explained by assuming that the saliency of the newly introduced feature determines only whether or not it is pre-attentively detectable by the expectation-mismatch mechanism, which then interrupts ongoing behaviour and instigates the attention shift to the expectation-discrepant item (Horstmann, 2005).

However, present and past results are also consistent with the view where the roles of saliency and novelty are reversed: it is still possible that saliency can actively guide attention, provided that some pre-conditions are fulfilled; in particular, (1) that there is no top-down attentional control setting against the feature of the salient item, and (2) that the normal (serial) search behaviour has been interrupted and suspended by the mechanism detecting unexpected features. According to this view, saliency can potentially guide attention, but saliency capture is rarely detected because commonly, studies violate either the first or the second pre-condition for saliency capture. With regard to the present study, it is clear that Experiment 2 violates the second requirement, because observers were familiar with motion, so that the motion singleton did not trigger the expectation-discrepant mechanism that interrupts ongoing search behaviour.

Experiment 3 tested this hypothesis, by presenting both the target and the distractors with novel features on the critical trial, whereby the target had a feature different from the distractors: after presenting only stationary squares on the pre-critical trials, the target was presented against the background of a stationary diamond among suddenly rotating distractors on the critical and the post-critical trials. On the critical trial, the target had a new shape and thus, was novel: however, all distractors had novel features, too, so that novelty could not be used to guide attention to the target. The target was only singled out by its saliency or feature contrast.

Thus, if saliency can guide attention in the absence of discriminating novelty information, then we would expect that the stationary target will draw attention to its location, leading to efficient search on the critical trial. If, on the other hand, saliency only determines the bottom-up limitations of detecting an expectation-discrepant feature, and attention would have to be guided to the target by the mechanism detecting expectation discrepancies, then search should remain inefficient on the critical trial, as in Experiment 2.

5.1. Method

5.1.1. Participants

These were 29 women and 26 men with a mean age of 23.5 (SD = 3.7) years. They participated voluntarily and without payment in the 5-min experiment.

5.1.2. Stimuli, design and procedure

The pre-critical trials were identical to those in Experiment 1, where all items were presented against the background of 4 or 8 stationary squares. In the critical and post-critical trials, the distractor stimuli (but not the target) were set into rotating motion (with the same speed as in Experiment 1). Simultaneously, the target was presented against the background of a black stationary diamond, which was obtained by rotating the square by 45°.

5.2. Results

For the RT-analysis, errors (1.4%) and RTs exceeding 4000 ms (2.2%) were excluded. This pertained to 13 critical trials (5 in the set size 4 condition, and 8 in the set size 8 condition), which reduced the sample size for the RT analysis to 42. Mean RTs for the two set size conditions in the three types of trial are depicted in Fig. 4.

The 2×2 ANOVA contrasting the pre-critical trials and the critical trial with respect to set size revealed significant or marginally significant main effects [set size: $F(1, 40) = 11.24$, $p = .002$; trial type: $F(1, 40) = 2.86$, $p = .098$], and a significant trial type×set size interaction, $F(1, 40) = 8.72$, $p = .005$. The interaction was due to the fact that the set size effect was much larger on the pre-critical trials (slope = 195 ms/item) than on the critical trial (slope = 22 ms/item).

A corresponding ANOVA involving the post-critical trials revealed significant main effect for trial type only, $F(1, 40) = 100.5$, $p < .001$, with the other two effects being not significant, $F < 1$. The absence of an interaction between the variables reflected that the set size effects on the critical and post-critical condition were very similar (22 ms/item and 25 ms/item, respectively).

Corresponding analyses of the error scores yielded no significant main effects or interactions, $Fs < 1.76$, $ps > .190$ (Table 1).

5.3. Discussion

The results from Experiment 3 showed that a novel static shape which was rendered salient by embedding it in an array of moving distractors can capture attention on its first unannounced occurrence. The finding that capture occurs even in the absence of discriminating novelty information indicates that attention can be guided by saliency, provided that pre-planned serial search behaviour is interrupted and suspended by the detection of unexpected features in the display.

6. General discussion

6.1. Methods of assessing capture

The results of the present study showed that a motion singleton can capture attention, but only when motion as a feature is new and observers have not encountered motion before (see Experiments 1 and 2). This replicates earlier findings with colour singletons (Horstmann, 2002, 2005). Interestingly, these results were obtained despite using a different method of aggregating data: in response to a criticism raised by Burnham, average RT in the pre-critical condition were computed in several different ways, viz., by including only the last trial, the four last trials, or all trials of a particular set size condition in computations of the mean. The results showed that these variations did not change the results pattern, which invalidates the concern that the set size effect of the pre-critical trials may be artificially inflated by including trials from the beginning of the experiment, because participants were not practiced.

Such concerns appear to be unfounded when we consider that (1) although practice usually greatly improves baseline RT, practice does not affect the slope of the RT×set size function much (e.g., Wolfe, 1998); (2) capture by unexpected singletons has been shown with methods that are not subject to the possible complications that accompany the computations of set size effects (e.g., Horstmann, 2002, Experiments 1 and 2; Horstmann & Becker, 2008; see also Gibson & Jiang, 1998), and that (3) the concern of practice effects is inconsistent with the finding that capture is absent when the target singleton possesses a familiar and expectancy-congruent feature (Horstmann, 2005 and the present Experiment 2).

6.2. Capture by motion and motion onset

A second interesting finding of the present study is that motion singletons do not capture attention solely in virtue of their saliency or inherent behavioural relevance (e.g., of signalling potentially threatening objects), but only when motion was unexpected. At a first glance, the finding that the rotating motion singleton in Experiment 2 did not capture attention when observers were familiar with motion may seem to contradict a recent finding of Al-Aidroos, Guo, and Pratt (2010). In their study, Al-Aidroos and colleagues found that a rotating singleton can capture attention, even when it is task-irrelevant, and attributed capture to the fact that the motion onset was clearly visible (e.g., Al-Aidroos et al., 2010). One possible differences between the present study and the study of Al-Aidroos that may account for the different outcome is that the target was a colour singleton in the study of Al-Aidroos et al., and therefore, the target could be found without the need to serially inspect items. Theeuwes (1993) argued that saliency can only affect attention in parallel search, when attention is widely distributed across the display, whereas serial search results in a narrowing of the attentional spotlight. This focused mode of attention can in turn prevent salient items from taking effect because salient items are then more likely to fall outside the boundaries of the attentional spotlight (see also zoom lens idea; Eriksen & St. James, 1986, and Yantis & Jonides, 1990). This hypothesis was also recently corroborated in a study of Belopolsky, Zwaan, Theeuwes, and Kramer (2007), who systematically manipulated the size of the attentional spotlight and demonstrated that an irrelevant colour singleton captures when attention is distributed across the field, but not when the attentional spotlight is narrowed in anticipation of serial search. With respect to the present study, it is noteworthy that the motion singleton captured attention despite the fact that observers were presumably set for serial search — but only when motion as a feature was expectancy-discrepant. This finding suggests that a possible role of the expectancy-discrepant detection mechanism is to interrupt the ongoing serial search, thereby breaking the narrow, focused mode of attention and forcing observers to adopt a more distributed mode of attention. This view would be consistent with the finding that attentional capture by unexpected new features is typically delayed by about 200 ms (e.g., Horstmann, 2006), and would render the present results consistent with previous studies that reported capture by motion onsets in a distributed mode of attention (e.g., Abrams & Christ, 2003; Al-Aidroos et al., 2010).

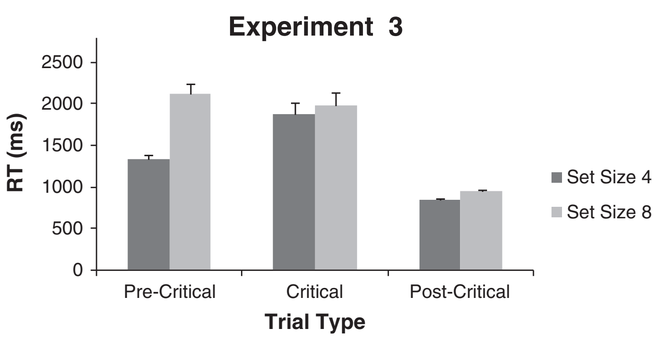

Fig. 4. Mean response times for Experiment 3, where all items were static squares in the pre-critical condition, and the target was a new diamond shape presented among unexpectedly rotating distractors on the critical trial. Search performance is depicted as a function of trial type (pre-critical, critical and post-critical) and set size (4 vs. 8 items). The error bars depict one standard error of the mean.

However, previous studies examining motion capture differ in other important aspects from the present study as well; for instance, in that almost all studies rendered motion (onsets) irrelevant by presenting them at chance level at the target location. Although motion (onset) singletons were hence uncorrelated with the target and observers had no incentive to tune attention to motion (onsets), they also did not have a strong incentive not to attend to motion singletons, either: since the target was as likely at the location of the singleton, attending to it did not harm search performance (whereas firmly inhibiting motion could have resulted in wrongfully excluding a possible target location; e.g. Becker, 2007). Hence, these studies tested whether and to what extent observers are able or willing to ignore irrelevant motion singletons. By contrast, the present study tested whether and to what extent motion singleton can capture attention when observers did not have a chance to create a mental set for or against attending to it.

Naturally, it could be asked whether presenting trials where all stimuli were moving in Experiments 2 did not provide an incentive to ignore motion in Experiment 2, so that the present results could be explained by top-down attentional control settings instead of a mechanism that detects expectancy-discrepant events. However, several observations would seem to argue against this possibility: first, the concept of top-down attentional control settings seems to be too narrow to replace the concept of expectations, because the attentional control settings contain only task-relevant or potentially relevant features, that are activated or inhibited for the guidance of attention (e.g. Folk et al., 1992; Wolfe, 1994). In the context of the present study, the attentional control settings should hence contain information that allows discriminating target Landolt C's from distractor Landolt C's. Rotating or stationary squares are only location markers that equally and indiscriminately indicate the possible target locations (because the display contained either all rotating or all stationary squares). Since search cannot possibly profit from either activating or inhibiting stationary versus rotating squares, neither stationary nor rotating squares can be presumed to form part of the attentional control settings. In addition, inhibiting rotating squares would seem a sub-optimal strategy, because rotational movement reliably indicated possible target locations, and inhibiting all possible target positions would have slowed search.

Secondly, previous studies showed that capture by unexpected items is much slower than the time-courses observed for top-down contingent capture. This would also appear to argue against the possibility that capture by unexpected and new features can be subsumed under the notion of top-down contingent capture (Horstmann, 2002, 2006). In sum, without a rather substantial modification and broadening of the concepts of top-down attentional control settings, the present results seem to be best accounted for by the expectancy-mismatch account.

6.3. The role of saliency in capture

Experiment 3 established that salient items can capture attention independently of the intentions and goals of the observers — provided that all stimuli in the display possess new and unfamiliar features. This is an important finding, because it suggests that salient items may indeed have an inherent attention-driving capacity. The assumption that saliency can potentially guide attention is the cornerstone of most current visual search theories, like the saliency-based model of Itti and Koch (2000) and the Guided Search model (Wolfe, 1994). According to these models, feature contrasts between all items are computed early on from the visual input, and the corresponding bottom-up activation signals are then weighted by top-down information about the likely target feature. Attention is then guided by the integrated activation signals originating from bottom-up and top-down computations.

Despite the fact that most models assume that saliency thus plays a very active role in the guidance of attention, there is surprisingly little evidence in support of this role. As mentioned in the Introduction, it is undisputed that a certain amount of feature contrast is necessary to detect features pre-attentively and to guide attention to the corresponding location. However, this view is also consistent with the assumption that feature contrasts play a purely passive role in the guidance of attention, without actively steering attention to particular locations. For instance, Yantis (1998, 2000) has proposed that sufficient feature contrasts can also be described as critical bottom-up limitations that permit or do not permit efficient selection of the target according to top-down goals and intentions.

To distinguish between these views, and to ascertain that saliency can actively guide attention, it has to be shown that items with a high feature contrast can capture attention even when they are irrelevant to the task (cf. Yantis, 1993). To date, there are several studies reporting attentional capture by irrelevant singletons. However, in our view, none of the studies to date have provided strong evidence for the view that feature contrasts can actively guide attention: first of all, it is well known that suddenly appearing onsets can involuntarily capture attention (e.g., Jonides, 1981). However, onsets certainly do not capture attention because of their feature contrasts. Hence, corresponding results cannot be taken as evidence for the singleton capture hypothesis or indeed the central tenets of current visual search theories that feature contrasts can potentially guide attention. Second, as mentioned in the introduction, there have been reports that, in specific instances, onsets of motion, or specific forms of motion such as looming stimuli may capture attention. Again, it is implausible to attribute capture in these instances to the feature contrast of the singleton, so that the results cannot be cited in support of singleton capture. Third, some studies purported to show attentional capture by an irrelevant colour singleton. For instance, Theeuwes (1991, 1992) showed that, in search for a shape singleton, an additional irrelevant colour singleton elongates RT, compared to a distractor-absent control condition. Similarly, it has been shown that RTs are shorter when an irrelevant colour singleton is presented at the same position as the target (e.g., shape or size singleton target) than when the colour singleton is presented away from the target (e.g., Becker, 2007; Yantis & Egeth, 1999). These results have initially been taken to show that irrelevant colour singletons can capture attention without or even against the intentions of the observers, solely in virtue of their feature contrast. However, there are two major problems with the design of these studies: first, the target in these experiments was regularly also a singleton from a different dimension, and therefore, it is plausible to assume that observers had voluntarily tuned attention to the discriminating feature of the target. Hence, it is possible that the irrelevant colour singleton did not capture attention in virtue of a bottom-up attentional system that computes the feature contrasts of all items and assigns attentional priorities, but because the singleton status of the distractor rendered it more similar to the target (e.g., Bacon & Egeth, 1994; Folk & Remington, 1998; Turatto & Galfano, 2001). A second problem of the aforementioned studies was that they did not use a spatially sensitive measure to assess capture, but inferred capture from the observation of elongated mean RT. It is entirely possible that presenting an additional unique feature (away from the target location) does not capture attention, but interferes with search at a different level: for instance, presenting an additional unique feature in the display could produce costs at the level of encoding different features in the display, or make it more difficult to select the target without eliciting involuntary attention shifts (e.g., by interfering with grouping), or it could interfere with decisional processes of deciding whether an already selected item is indeed the target (e.g., Palmer, 1995). Follow-up studies investigated these possibilities using stricter, space-based criteria to assess attentional capture by irrelevant colour singletons accordingly showed that irrelevant salient distractors do not involuntarily capture attention, but have to be related to the task or the intentions and goals of the observers in order to capture (e.g., Ansorge & Heumann, 2003; Becker, 2007, 2008a,b; Becker, Ansorge, & Horstmann, 2009; Folk et al., 1992, 1993; Folk & Remington, 1998; Hillstrom & Yantis, 1994). Fourth, some studies have shown that colour singletons can capture attention and the eyes when the features of the target and/or the distractor vary randomly across trials, so that, for instance, observers have to respond to a target that can either be a diamond among circles, or a circle among diamonds, whereby the salient distractor can be either a red item presented among all green items or vice versa (e.g., Theeuwes & Burger, 1998; Theeuwes, de Vries, & Godijn, 2003). This result pattern has usually been taken to show a lack of top-down knowledge about the exact features of the target and/or distractor renders observers more vulnerable to capture by salient items. However, follow-up studies analysing capture on a trial-by-trial basis showed that the salient distractor only captures on switch trials, when the features of the target and/or distractor switch, compared to the previous trial, but not when they are repeated (e.g., Becker, 2007, 2010; Pinto et al., 2005). The mechanism thought to underlie these intertrial priming effects is however feature-specific, and switch trials will misguide attention to irrelevant items even when these items are non-salient (e.g., Becker & Horstmann, 2009). Hence, it is doubtful whether these findings can be taken to reflect that salient items have an inherent bottom-up attention-driving capacity. In sum, the evidence that feature contrasts play an active, as opposed to merely passive, role in the guidance of attention is surprisingly weak, especially when we consider that this view is the centrepiece of most current visual search models.

In this respect, it is important to note that the present study has shown guidance by a salient item while avoiding the major problems of previous studies: first, deviating from previous studies, the target was not a singleton on the pre-critical trials, and observers had no information about the presence of the singleton on the critical trial. Hence, the finding that the salient item captured attention on the critical trial cannot be attributed to the top-down attentional control settings, but reflects truly intention-independent capture by a salient item. Secondly, the target on the critical trial was only singled out by its feature contrast, but not by inherent specific features that may automatically draw attention, as object onsets, or motion onsets: since only the distractors moved, whereas the target was presented against the background of a stationary diamond shape, capture by the target cannot be attributed to some additional specific features of the target. Third, capture was assessed by comparing set size effects, or search efficiency, across different conditions. The results showed that the set size effect on the critical trial was strongly reduced, which indicates that the target could be found without much scanning of the nontargets prior to selecting the target. This result pattern cannot be interpreted by an alternative, spatially non-specific process, but offers the most direct evidence that indeed, spatial attention was deployed to the singleton. Hence, the present results can be viewed as evidence for the view that items with a high feature contrast can indeed capture attention independent of the intentions and goals of the observers.

However, this conclusion is subject to some caveats: first, the results cannot be taken to show that feature contrasts guide attention in a completely stimulus-driven fashion. In the present study, capture was contingent on the display containing new and unfamiliar items. However, as long as saliency capture is contingent on other factors, we cannot declare that capture was purely stimulus-driven. Second, the finding that saliency can guide attention under the specific conditions of Experiment 3 should not be taken to show that attention cannot also be guided by novelty. Experiment 3 tested saliency capture when novelty information was insufficient to single out a likely target location, which probably does not allow generalisations to cases where novelty is in fact sufficient to single out a likely target location. Granted, the view that the mechanism detecting expectancy mismatching features only interrupts pre-planned search processes governed by attentional control settings, and that salience then guides attention to the novel feature (e.g., Experiment 1) is consistent with all previously published results, since previous studies examined only capture by unexpected items that were both novel and salient. However, we regard this two-step process atypical for surprise capture, for two reasons. First, our original assumption that an expectancy mismatching feature both interrupts pre-planned search and guides attention appears to be more parsimonious. Second, yet unpublished research presenting only two stimuli revealed attentional capture by a novel feature (Horstmann & Ansorge, in preparation). With only two stimuli on screen, neither is salient, so that attention must have been guided to the stimulus on the basis of the novel feature.

Even if saliency only guides attention when novelty information is insufficient, the present results show that salient items can capture attention without a relevant attentional set. Given the scarcity of positive empirical evidence for this view to date, the present results significantly extend on previous findings, and support the widely-held view that saliency can indeed play an active role in the guidance of attention.

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