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An effective attentional set for a specific colour does not prevent capture by infrequently presented motion distractors

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An organism's survival depends on the ability to rapidly orient attention to unanticipated events in the world. Yet, the conditions needed to elicit such involuntary capture remain in doubt. Especially puzzling are spatial cueing experiments, which have consistently shown that involuntary shifts of attention to highly salient distractors are not determined by stimulus properties, but instead are contingent on attentional control settings induced by task demands. Do we always need to be set for an event to be captured by it, or is there a class of events that draw attention involuntarily even when unconnected to task goals? Recent results suggest that a task-irrelevant event will capture attention on first presentation, suggesting that salient stimuli that violate contextual expectations might automatically capture attention. Here, we investigated the role of contextual expectation by examining whether an irrelevant motion cue that was presented only rarely (~3–6% of trials) would capture attention when observers had an active set for a specific target colour. The motion cue had no effect when presented frequently, but when rare produced a pattern of interference consistent with attentional capture. The critical dependence on the frequency with which the irrelevant motion singleton was presented is consistent with early theories of involuntary orienting to novel stimuli. We suggest that attention will be captured by salient stimuli that violate expectations, whereas top-down goals appear to modulate capture by stimuli that broadly conform to contextual expectations.

Keywords: Spatial attention; Attentional capture; Surprise capture; Rare singleton capture; Spatial cueing.

Lower layers of our visual system receive far more stimulation from the external world than is possible for our cognitive system to fully process. To compensate, mechanisms of selective attention allow us to focus cognitive processing on a small number of events or objects in the world. As a result, our conscious awareness consists primarily of those objects and events to which we have attended, and attended objects come to have a much greater force in determining our behaviour than do unattended items. It is not surprising then that psychologists have devoted much effort to understand how attention is controlled and what determines the events in the visual world to which we orient and attend.

Modern theories of attention recognize two forms of attentional control: *endogenous control*

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that allows us to voluntarily direct our attention to task-relevant objects and events, and *exogenous control* that directs attention involuntarily toward objects and events of possible importance that are not necessarily related to the ongoing task (Posner, 1980; Remington, Johnston, & Yantis, 1992; Theeuwes, 1991; Yantis & Jonides, 1984, 1990). The control mechanisms by which attention is involuntarily directed to objects and events have been the topic of much debate, particularly the degree to which involuntary orienting (attentional capture) can be modulated by top-down mechanisms (Yantis, 1993). Theories positing *stimulus-driven (bottom-up) attentional capture* argue that salient stimuli can automatically draw attention to their corresponding locations, in virtue of their bottom-up saliency and independent of the goals and intentions of the observer (Theeuwes, 1992, 1994, 2004; Theeuwes & Burger, 1998). Any modulation of attention by top-down mechanisms is presumed to occur late in processing, *after* attention has been shifted towards a stimulus ("de-allocation hypothesis"; see Belopolsky, Schreij, & Theeuwes, 2010; van Zoest, Donk, & Theeuwes, 2004). In contrast, theories positing top-down modulation of attentional capture, such as *contingent attentional capture* (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994), posit that involuntary attention shifts are contingent on the task demands and the goals of the observer. A salient, task-irrelevant item ("distractor") is presumed to capture attention only when it shares the task-relevant feature(s) of the search target. For example, Folk et al. (1992) showed that when the target was defined by an abrupt onset, an abrupt-onset cue but *not* a salient colour cue captured attention. In contrast, in search for a colour target, only a colour cue with the same colour as the target but *not* an abrupt-onset cue captured attention. Subsequent studies showed that a red cue captured attention when observers were searching for a red target, but not when they searched for a green target, and vice versa for the green cue (Folk & Remington, 1998; see also Ansorge & Heumann, 2003), indicating that attention can be set for specific feature values within a stimulus dimension. Subsequent work has shown that this effect is also reflected in eye-movement patterns (e.g., Becker, Ansorge, & Horstmann, 2009; Ludwig & Gilchrist, 2002; Wu & Remington, 2003) and specific event-related potential (ERP) components (e.g., Eimer, Kiss, Press, & Sauter, 2009; Lien, Ruthruff, Goodin, & Remington, 2008).

Evidence for bottom-up saliency capture

The evidence for top-down modulation of capture raises the question of how we become aware of events that are not tightly bound to ongoing task goals. The need for an interrupt system to protect us against predation, at the very least, suggests that some property of external events should be capable of triggering a purely stimulus-driven shift of attention. Such a claim has been made for stimuli presented with an abrupt luminance onset (Jonides & Yantis, 1988; Lamy & Egeth, 2003; Ludwig & Gilchrist, 2002; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Yantis & Jonides 1984, 1990), for the presentation of a new object (Hillstrom & Yantis, 1994), for motion onset (Abrams & Christ, 2003; Pratt, Radulescu, Guo, & Abrams, 2010), and for stimuli that have a high feature contrast in other dimensions, such as colour (Itti & Koch, 2000; Theeuwes, 1991, 1992). However, the evidence for stimulus-driven capture by all of these has been disputed.

Capture is often inferred when the presence of an irrelevant distractor results in elevated visual search times compared to no-distractor studies. It has been shown that such increases can be associated with a broadly defined target template that included the distractor attributes and can be eliminated when care is taken to ensure a precise feature set (see Bacon & Egeth, 1994; Wu & Remington, 2003). For example, Bacon and Egeth (1994) found that irrelevant colour singletons only interfered in a visual search paradigm when the task encouraged a strategy of searching for a singleton. When the task required that observers search for a specific feature (form), irrelevant colour singletons no longer interfered with search performance. In addition to such strategic biases that arise from explicit task demands, search performance can also be influenced by more subtle incentives of the method that can go unnoticed. Gibson and Kelsey (1998) demonstrated that apparent stimulus-driven effects in visual search paradigms can be explained by a match between the visual characteristics of distractors and display-wide attentional settings.

Interference by task-irrelevant distractors in visual search has also been shown to arise from general, nonspatial forms of interference without eliciting an attention shift ("filtering hypothesis"; e.g., Folk & Remington, 1998; see also Becker, 2007). Critically, these studies identify an issue with inferring attentional capture solely from a general slowing of response times to the presence of a task-irrelevant distractor. The possibility of nonspatial interference not associated with attention highlights the need for a measure that more clearly reflects the spatial locus of attention. In spatial cueing studies, for example, cues that cause a spatial reallocation of attention will lead to faster response times in conditions in which the cue occurs at the subsequent location of the target (valid) than in those that occur at a nontarget location (invalid).

Novel and unexpected stimuli

A characteristic of virtually all disputed findings is that distractors, like targets and nontargets, occurred regularly and could be said to conform to contextual expectations. That is, even though distractors do not occur on every trial, nor is their location predictable, they occur frequently enough to be part of the contextual expectancies of the sequence of events. This raises the possibility that top-down control might be restricted to stimuli conforming to contextual expectancies and, correspondingly, that stimulus-driven capture may be a product of stimulus expectations, rather than a stimulus's specific physical properties.

Indeed, the view that the human perceptual system has an appetite for the unexpected and novel dates back to the early psychological literature and even before (Darwin, 1965/1965; Descartes, 1984/1984; Wilcocks, 1928) and is expressed by models of perception and cognition that emphasize the role played by expectations in determining our conscious percept of the world (Horstmann, 2005; Meyer, Niepel, Rudolph, & Schützwohl, 1991; Sokolov, 1963). One of the earliest theoretical accounts of human orienting behaviour was proposed by Sokolov (1963) who described the behaviour as a reflex that is triggered by objects and events in the world that violate a set of contextually specific expectations labelled the *neuronal model*. According to Sokolov (1963), a stimulus or event will continue to capture attention and demand the resources of the perceptual system until the neuronal model is updated—a process that occurs over repeated exposure to a novel input. Whether it is accurate to describe attentional orienting as a reflex is perhaps debatable; however, the broader notion of an orienting mechanism that directs processing resources toward stimuli that do not "fit" with some internal predictive model of the world, whether this be nervous or otherwise, is also central to many schematic theories of cognition and perception (Meyer et al., 1991; Neisser, 1976; Rumelhart, 1984; Rumelhart, Smolensky, McClelland, & Hinton, 1986).

One plausible inference from models that emphasize the role of expectation and prediction in attention selection and conscious perception is that contingent capture only extends to events within a given schema or set of task-expectancies. That is, our ability to ignore irrelevant salient distractors could depend on contextual expectations that describe the characteristics of distractors to be inhibited (e.g., Becker, 2007; Folk & Remington, 1998; Treisman & Sato, 1990). Indeed, a number of authors have made the observation that unexpected stimuli evoke distinct patterns of neural activity (Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Näätänen, 1992; Yamaguchi, Hale, D'esposito, & Knight, 2004; for a review, see Ranganath & Rainer, 2003) and are associated with numerous perceptual and behavioural phenomena (Czigler, Weisz, & Winkler, 2006; Horstmann, 2005; Meyer et al., 1991). Within the visual search literature, unexpected stimuli have been associated with increased memory recall (Meyer et al., 1991; Meyer, Reisenzein, & Schützwohl, 1997; Niepel, Rudolph, Schützwohl, & Meyer, 1994; Schützwohl, 1998), behavioural interference (Asplund et al., 2010; Geyer, Müller, & Krummenacher, 2008; Horstmann, 2005; Neo & Chua, 2006; Schützwohl, 1998), and increases in discrimination accuracy when an unexpected stimulus coincides with the target location (Horstmann, 2002, 2005, 2006).

Interestingly, Neo and Chua (2006) showed that an infrequently presented onset distractor can interfere with search even when participants know in advance *where* the search target will appear. Using a spatial cueing paradigm, Neo and Chua (2006) had participants report the identity of a target (E or U) that appeared at a prespecified location in the search array. Prior to the target onset, an onset distractor could appear at a nontarget location on either 75% of trials or just 19% of trials. When the onset distractor was frequent (75% condition) they replicated the results of Yantis and Jonides (1990) by showing that the onset distractor did not slow response times (RTs) when participants knew with certainty the location of the target. However, when the distractor was infrequent (19% condition), RTs on the distractor trials were significantly elevated relative to the no-distractor trials. This result is important because it demonstrates that presentation frequency can influence search efficiency even when participants are able to shift spatial attention in advance to the location of the target; whether this is also true when observers have a top-down set for nonspatial features (e.g., red) is less clear.

Geyer et al. (2008) have shown that distractor presentation frequency has an effect on the number of erroneous first saccades to distractors during search for a shape singleton. Geyer et al. monitored observers' fixation pattern as they searched for a shape singleton (diamond embedded amongst circle nontargets; see also Theeuwes, 1991) in distractor and no-distractor conditions. The proportion of first saccades to a colour singleton distractor was greatest when the distractor was presented on 20% of the trials than in conditions in which the same distractor was presented on 50% and 80% of trials. This result is important because it suggests that an attentional set for a specific feature may be insufficient to prevent distraction from salient unexpected stimuli. However, a consequence of varying the distractor presentation frequency in separate blocks was to also vary the percentage of trials in which the target was a singleton in each block. When the distractor was presented on 20% of trials, the target was a singleton on the remaining 80% of trials, and vice versa. Therefore, it is possible, if not probable, that observers' task-set varied across conditions, such that in the low-frequency condition observers adopted a strategy to search for any singleton item (e.g., singleton detection mode; Bacon & Egeth, 1994) rather than to adopt a feature-specific set. Thus, the colour singleton may have captured in the low-frequency condition because participants adapted a strategy of searching for the most salient singleton in the display (e.g., Bacon & Egeth, 1994; Theeuwes, 1991). When the distractor was presented frequently, participants had more incentive to adopt a strategy of searching for the specific target feature. Thus, it is not clear where the frequency effect reported by Geyer et al. (2008) reflects an example of attentional capture that is truly independent of the search goals.

Aim of the present study

The studies of Neo and Chua (2006) and Geyer et al. (2008) support the principal assertion of the orienting reflex of Sokolov (1963) that attention will be involuntarily captured by salient events that violate contextual expectations. However, to demonstrate that a stimulus attribute, even its novelty, is sufficient to produce stimulus-driven involuntary capture, it is necessary to satisfy two conditions: (a) that attention is in fact reallocated to the location of the stimulus, and (b) that there are no incentives in the design that could have led subjects to adopt strategies for singletons or properties other than the desired set for the target feature. As discussed above, the existing demonstrations of the effects of infrequent distractors are open to criticism in failing to satisfy one or both of these two conditions. In particular, the Geyer et al. study, which does show spatial reallocation, leaves open the possibility of a singleton detection mode strategy.

The aim of the present study was to examine the ability of unexpected events to involuntarily capture attention under conditions that satisfy both the requirement of spatial reallocation and the requirement that subjects are set for a specific feature property. To do this we used the modified spatial cueing paradigm of Folk et al. (1992), in which an irrelevant distractor ("cue") is presented prior to the target display. If the cue captures attention, RTs will be faster when the target is presented at the cued location (valid trials) than when it is presented at a noncued location (invalid trials), as on valid trials attention will already be at the target location. In our spatial cueing paradigm, participants searched for a red target embedded among three white nontargets and were instructed to ignore irrelevant red and green cues presented prior to the target frame. Cue location was independent of target location and was, thus, uninformative as to target location. Previous studies have shown a cueing effect for red cues—faster RTs to valid than invalid red cues—but not for green cues when participants search for a *red* target and vice versa (e.g., Ansorge & Heumann, 2003; Folk & Remington, 1998). An effect of cue validity to cues that match the target, but not those that do not, suggests an active set for the target property. If a corresponding pattern can be observed in the present study, we can infer that attention was biased to the target feature value (red), not to other attributes of the target or search display (e.g., singleton status or display-wide features; Bacon & Egeth, 1994; Gibson & Kelsey, 1998). By showing such an effect, we can ensure that any capture associated with infrequent cues takes place in the presence of an active set for the target property.

To examine the effects of contextual expectations we included a motion cue that was presented frequently (Experiment 1) or infrequently (Experiment 2–4). The motion cue was created by rotating four white dots around a placeholder box in a clockwise fashion. Motion cues have been shown to capture attention in the spatial cueing paradigm when they are similar to the target but not when they are dissimilar to the target (e.g., Folk, Remington, & Wright, 1994; Remington, Folk, & McLean, 2001). In Experiment 1, we presented the red, green, and motion cue equally often, on a third of all trials. To examine contextual expectations, subsequent experiments limited the presentation of the motion cue to a small fraction of trials. The underlying logic is that frequently presented motion cues should be incorporated into the general experimental context and thus not constitute a violation of expectations, whereas rarely presented motion cues should violate expectations. Involuntary capture by salient stimuli that violate contextual expectations predicts two important outcomes: (a) a cueing effect for red cues, but not for green cues, and (b) a cueing effect for infrequent motion cues, but not for frequently presented motion cues.

EXPERIMENT 1

Before a claim can be made about the role of stimulus novelty in driving shifts of spatial attention, it is necessary to establish that the same stimulus presented regularly does not capture attention. In Experiment 1, subjects responded to a red target in the search display. A cue frame preceding the target frame consisted of a red, green, or motion cue presented with three white noncues at the other locations. According to contingent orienting (Folk & Remington, 1998) the red cue should capture attention, but not the green or motion cues. This should be reflected in the presence of a *cueing effect* for the red cue, but not for the green or motion cues (Folk et al., 1992; Folk et al., 1994).

Method

Participants

Fifteen participants (9 female) aged 17–24 years ($M = 19.6$, $SD = 2.3$) from the introductory psychology course at the University of Queensland participated for course credit. All reported normal or corrected-to-normal vision.

Apparatus

Experiments 1–4 were conducted using the computer software package Presentation (Neurobehavioural Systems). Stimuli were presented on a 19″ CRT monitor attached to a (Pentium 4) personal computer. Responses were recorded using a two-button mouse.

Stimuli

Each trial consisted of a fixation display, a cueing display, and a target display. All stimuli were presented on a black (RGB = 0, 0, 0) background. The fixation display was composed of a central white fixation cross (0.4° × 0.4°) surrounded by four peripheral boxes (2.1° × 2.1°) with white borders positioned (3.3°) above, below, to the left, and to the right of fixation. The cueing display was composed of the same stimuli as the fixation display with the addition of four white filled circles (0.4°) in a diamond configuration surrounding each location ("four-dot cue"; e.g., Folk et al., 1992). On every trial the four-dot cue was coloured either red (RGB = 255, 0, 0) or green (RGB = 0, 255, 0) or rotated clockwise around the box to create the perception of motion. The motion cue consisted of a 90° rotation of the diamond in three 30° clockwise increments at 40-ms intervals. The circles comprising the motion singleton were coloured white (RGB = 255, 255, 255), as were all dots surrounding placeholders at noncued locations.

The target display was composed of the same stimuli as the fixation display with the addition of a tilted bar presented in each of the four peripheral boxes (see Figure 1). The bars were tilted either 45° to the left or to the right and subtended 0.7° of visual angle vertically and 0.7° of visual angle horizontally. On every trial three of the titled bars were white while one, the target, was coloured red (RGB = 255, 0, 0). All stimuli were presented against a black (RGB = 0, 0, 0) background.

Design

Presentation of the cues (red, green, and motion) was randomized across the experiment with each cue occurring an equal number of times. The location of the cue was not correlated with the location of the target. On valid trials (25%), the target and the cue were presented at the same location. On invalid trials (75%), they were presented in different locations. Participants were informed of the three cue types prior to commencing the experiment and were instructed to do their best to ignore the cueing frame as the cue was uncorrelated with the target location. The target and the cue occurred at each location equally often. The orientations of the nontarget tilted bars that appeared at the three nontarget locations were randomized.

Procedure

Each trial began with the presentation of the fixation display for 500 ms. Following this, the fixation cross offset for 50 ms (see Figure 1). Then the fixation display reappeared for a randomly determined interval of 500, 600, 700, 800, or 900 ms. The cueing display was then presented for 160 ms followed by the fixation display again for 50 ms (interstimulus interval, ISI) and then the target display for 50 ms. Following the target display, the fixation display was presented and remained on screen until a response was made. After each response, participants were given feedback in the form of a tone. If the response was correct an 800-Hz tone sounded for 100 ms, followed by a 900-Hz tone for 100 ms, followed by a 1000-Hz tone for 100 ms. Alternatively if the response was incorrect a 600-Hz tone sounded for 150 ms, followed by a 400-Hz tone for 150 ms. The next trial began 1,000 ms after a response had been recorded

Prior to the experiment, participants were instructed to search for the red target bar and to respond to its orientation by pressing one of two response buttons (left tilted target: left mouse button; right tilted target: right mouse button). Moreover, participants were told that the cues were nonpredictive of the target location and were instructed to ignore the cues. Participants were told to respond as quickly as possible whilst minimizing errors. It was emphasized that they should remain fixated on the central fixation cross during the entire trial and that eye movements would be detrimental to their performance.

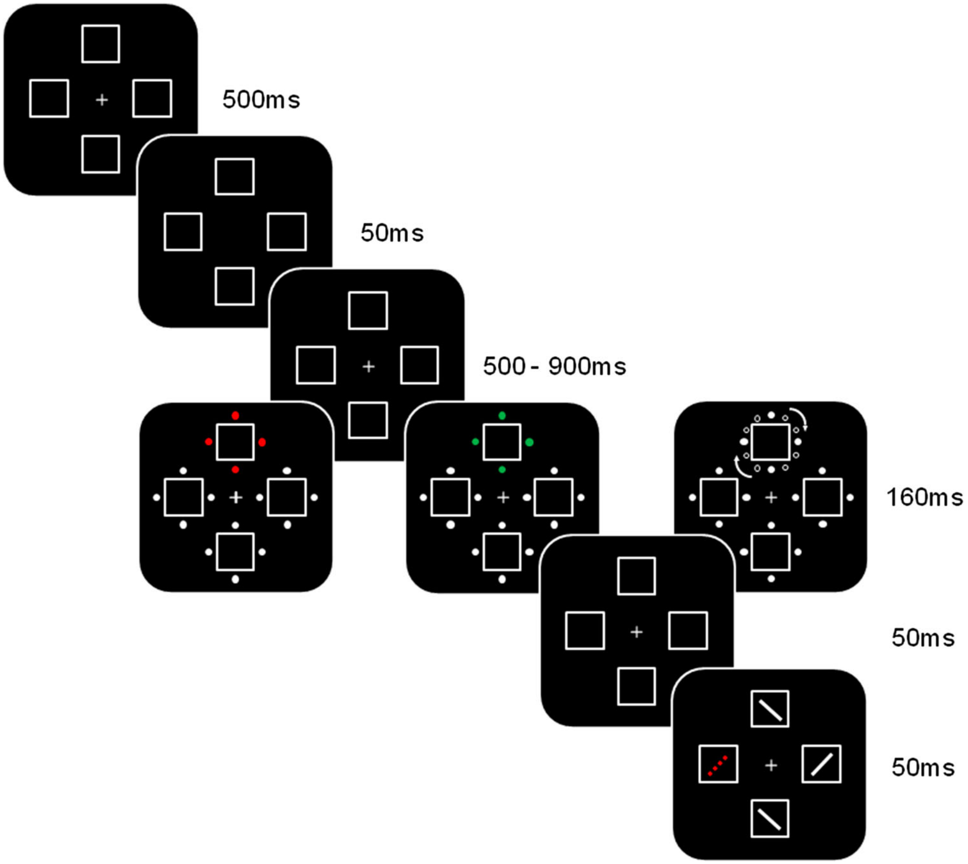

Figure 1. *Example trial sequence from Experiment 1. All cues were nonpredictive of the target location. The target is denoted by the dashed tilted bar. Note that the target did not appear as a dashed line in the experiment. To view this figure in colour, please visit the online version of this Journal.*

Participants completed 12 practice trials, followed by 384 experimental trials. The experiment was divided into four blocks of 96 trials, and between blocks participants were given the opportunity to rest. See Figure 1 for an illustration of a trial.

Results

Mean RTs and error rates for Experiment 1 are shown in Figure 2 and Table 1 respectively. RTs exceeding 1200 ms and errors were excluded from the RT analysis.[1] One participant was excluded from all analyses due to an unacceptably high average error rate of 19.8%. Across the remaining 14 subjects, the exclusion criteria resulted in a loss of 3.8% of experimental trials. To summarize the results: In Experiment 1 we found *no* effect of the frequently presented motion cue and a strong effect of the task-relevant red cue (see Figure 2).

RT analysis

A 2 (cue validity: valid, invalid) × 3 (cue type: red, green, motion) repeated measures analysis of variance (ANOVA) of RTs revealed a main effect of cue type, $F(2, 13) = 5.52$, $p = .020$, $\eta_p^2 = .48$ as

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[1] The reasoning behind our RT exclusion criteria is outlined in the Results section of Experiment 2.

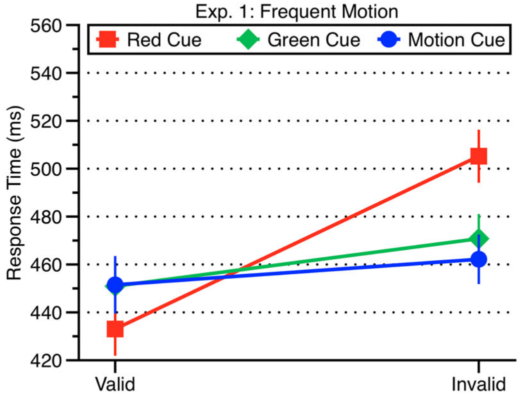

Figure 2. *Mean response time (RT) as a function of cue type and cue validity for Experiment 1. Error bars depict ±1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

well as a main effect of cue validity, $F(1, 13) = 73.33$, $p < .001$, $\eta_p^2 = .85$. Both main effects were qualified by a two-way interaction between cue type and cue validity, $F(2, 13) = 67.94$, $p < .001$, $\eta_p^2 = .92$. This interaction was due to the fact that the red (target- matching) cue captured attention more strongly than green (target-nonmatching) cue, $F(1, 13) = 146.94$, $p < .001$, $\eta_p^2 = .91$, or motion cue, $F(1, 13) = 57.99$, $p < .001$, $\eta_p^2 = .87$. Importantly, a pairwise comparison revealed no cueing effect for motion cues, with the difference between RTs associated with valid and invalid motion cues failing to reach significance, $t(13) = 1.59$, $p = .14$. However, there was a small but significant cueing effect associated with the green cue, $t(13) = 4.48$, $p = .003$, $d = 0.53$, suggesting perhaps a broad set for colour on some trials (see, e.g., Folk & Anderson, 2010).

Error analysis

The results of an error analysis were consistent with the pattern of results observed for RTs. The same 2 × 3 ANOVA on error rates revealed a main effect cue validity, $F(1, 13) = 27.40$, $p < .001$, $\eta_p^2 = .68$, and a two-way interaction between cue type and cue validity, $F(1, 13) = 6.52$, $p = .012$, $\eta_p^2 = .52$. Pairwise comparisons revealed a significant validity effect for the red cue, $t(13) = 4.60$, $p < .001$, $d = 1.55$, though not the green cue, $t(13) = 1.30$, $p = 0.44$, and importantly, not the motion cue, $t(13) = 1.20$, $p = .25$.

Discussion

The results of Experiment 1 were consistent with contingent capture in showing a significant cueing effect for target-matching red cues, less for green cues, and no significant effect for motion cues (e.g., Folk et al., 1992, 1994). Similarly, as shown in Figure 2, the motion cue also did not produce elevated baseline RT that would be indicative of filtering costs or other forms of spatially nonspecific interference (e.g., Folk & Remington, 1998). The cueing effect for green is consistent with previous studies showing capture by target nonmatching colours, which has been attributed to the adoption of a broader attentional set for the task-relevant dimension on a proportion of trials (dimension-specific setting, e.g., Folk & Anderson, 2010; Muller, Heller, & Ziegler, 1995). Nonetheless, the results clearly indicate that the motion cue produced no discernible evidence of capture.

EXPERIMENT 2

Experiment 2 tested the role of contextual expectations by presenting the motion cue on only ~3% of all trials. To increase the likelihood that the motion cue would not be part of the contextual expectations, subjects were not informed about its occurrence. To provide the maximum opportunity to adapt to the validity of the infrequent motion cue, one group of participants was always presented with a valid motion cue while another group of participants was always presented with an invalid motion cue. Involuntary capture by stimuli violating contextual expectations would predict a cueing effect for the infrequent motion cues, but not for the green (non-target colour) cue (Folk & Remington, 1998), or at least a significantly reduced cueing effect for the green cue relative to the red cue, as was observed in Experiment 1. Because motion-cue validity is between subjects we assessed two measures: the group difference for valid and invalid motion normalized for group differences in overall RT, and

Table 1. *Percentage of errors in each of the conditions in Experiments 1–4*

	Red cue		*Green cue*		*Motion cue*	
Experiment	*Valid*	*Invalid*	*Valid*	*Invalid*	*Valid*	*Invalid*
Experiment 1	0.89	6.03	2.90	3.79	2.01	2.83
Experiment 2	1.32	6.86	2.64	3.68	3.13	3.75
Experiment 3	1.16	5.69	4.03	4.15	3.13	2.73
Experiment 4	6.29	9.15	2.46	7.36	5.80	10.90

comparisons of valid and invalid motion cues with invalid nontarget colour cues. If the infrequent motion cue captured attention, then RTs for invalid motion cues would be expected to be *slower* than those for invalid nontarget colour cues while valid motion cues would be expected to be *faster* than invalid nontarget colour cues.

Method

Participants

Forty-three participants (31 female) aged between 17 and 36 years ($M = 20.4$, $SD = 2.3$) were recruited from introductory psychology classes at the University of Queensland and received course credit for participation. None of them had participated in Experiment 1, and all participants reported normal or corrected-to-normal vision.

Apparatus

The apparatus and stimuli used in Experiment 2 were identical to those used in Experiment 1.

Stimuli, design, and procedure

The stimuli, design, and procedure of Experiment 2 were identical to those of Experiment 1, with the following exceptions: First, the motion cue was presented on only eight trials (~3%), and, second, the validity of the motion cue varied between subjects. Participants completed 12 practice trials followed by nine blocks of 32 trials. No motion cue was presented in the first block. In each of the subsequent eight blocks the motion cue occurred once with its position in the block determined randomly, with the limitation that it could not occur within five trials of the preceding motion cue. Across the experiment the motion singleton was presented twice at each location and replaced an equal number of red and green cues—that is, four red and four green. Participants were not informed of the motion cue prior to the experiment. All other aspects of the design and procedure were identical to those of Experiment 1.

Results

Mean RTs for the valid-motion and invalid-motion groups are shown in Figures 3a and 3b, respectively. Error rates are shown in Table 1. Response times exceeding 1200 ms and errors were excluded from the RT analysis. A hard RT cut-off was chosen in favour of one based on standard deviations as we have good reason to suspect that RTs associated with the rare motion cue will cluster towards the top (slow) end of the RT distribution. Given the very small number of motion cue presentations, we want to avoid excluding these trials. Three participants' data were excluded from all analyses due to unacceptably high average error rates of 18% or greater in one or multiple conditions. Across the remaining 20 subjects the exclusion criteria resulted in a loss of 4.7% of experimental trials. To preview the results: in Experiment 2 we found an effect of the *infrequent* motion cue on performance. Though the effect is somewhat more nuanced than we predicted, there is a clear effect of motion presentation frequency on search performance (see Figure 3).

RT analysis

Colour cues. A 2 (motion-cue group: valid motion, invalid motion) × 2 (cue type: red, green) × 2

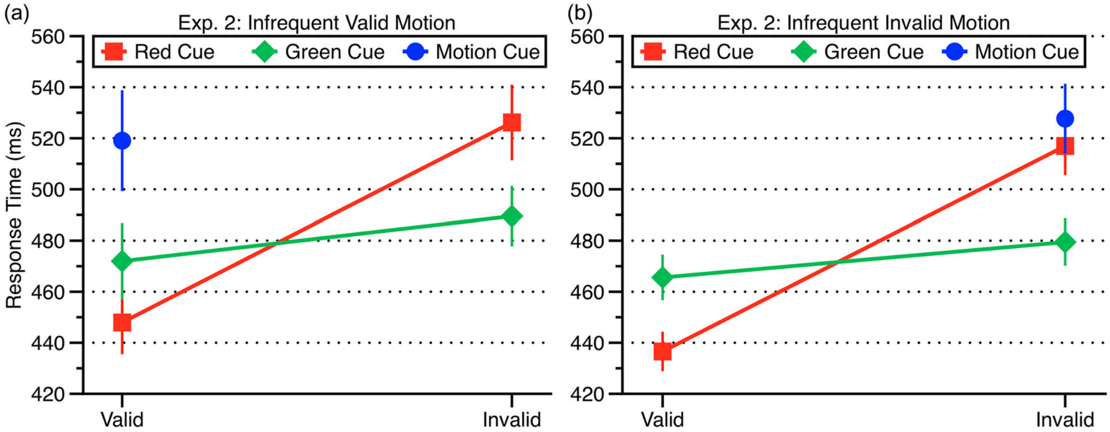

Figure 3. *Mean response time (RT) as a function of cue type and cue validity for (a) the valid-motion condition and (b) the invalid-motion condition in Experiment 2. Error bars depict ± 1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

(cue validity: valid, invalid) mixed-model ANOVA (motion-cue group entered as a between-subjects factor) on mean RTs revealed a main effect of cue type, $F(1, 39) = 4.42$, $p < .042$, $\eta_p^2 = .10$, as well as a main effect of cue validity, $F(1, 39) = 164.00$, $p < .001$, $\eta_p^2 = .81$. There was no main effect of motion-cue group, nor were there any interactions with motion-cue group. As such, we collapsed across motion-cue group when computing planned follow-up comparisons. Pairwise comparisons revealed that validly cued targets were responded to faster than invalidly cued targets for both red cues, $t(39) = 12.65$, $p < .001$, $d = 1.51$, and green cues, $t(39) = 6.59$, $p = .03$, $d = 0.31$. However, this validity effect was significantly larger for the red cue than for the green cue, as reflected by a two-way interaction between cue validity and cue type, $F(1, 39) = 62.92$, $p < .001$, $\eta_p^2 = .62$. These results replicate the findings of Experiment 1 and indicate that participants largely adopted a feature-specific setting in search for the red target (see Figure 3).

Motion cue. We asked two questions regarding the effect of the infrequent motion cue: first, whether RTs on trials with a motion cue differed from RTs associated with invalid nontarget (green) colour cues, and, second, whether subjects with valid motion cues produced faster RTs than those with invalid motion cues. Unexpectedly, *both* valid and invalid motion cue RTs were significantly elevated relative to invalid-green RTs [$t(19) = 2.50$, $p = .022$, $d = 0.41$; $t(19) = 5.43$, $p < .001$, $d = 0.92$, respectively]. Furthermore, there was no significant difference between valid and invalid motion cue RTs, $t(38) = 0.72$, $p = .33$ (see Figure 3).

The elevation of RTs for the invalid rare motion cue is consistent with the hypothesis that novel events capture attention; however, elevated *valid* motion RTs and the failure to find a validity effect associated with the motion cues challenge the claim that the elevated RTs are due to the reallocation of attention to the location of the motion cue. In his treatment of "surprise capture", Horstmann (2005) identifies the first presentation of a novel event as the trigger for surprise and notes the habituation of surprise capture over presentations. It is possible, therefore, that the failure to find a validity effect for the rare motion cue arises because our results reflect two convolved effects, surprise and reallocation. In Figure 4 we plot the effect of each of the eight presentations separately for the valid-motion and invalid-motion cue. Rather than depict raw RTs, we compensate for possible temporal effects (e.g., practice, fatigue) and baseline RT differences between the groups by computing the difference between the RT on motion cue trials and the mean of

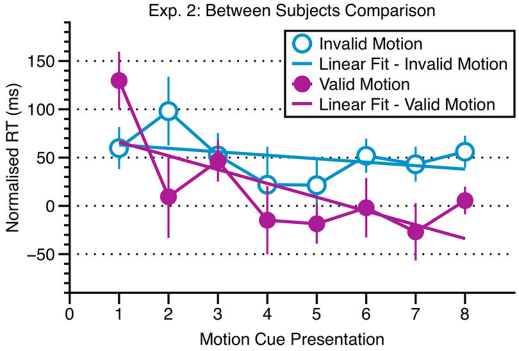

Figure 4. *Response time (RT) difference scores reflect a comparison of motion cue RTs to the RT average of valid and invalid green cue trials that preceded the presentation of a given motion cue. The results are depicted separately for valid and invalid motion cue trials, together with a linear function fitted to each data set. Error bars depict* ±*1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

temporally nearby green cues. The green cues in this case serve as a proxy for a neutral baseline. For each participant we computed the motion effect by subtracting the average RT for (valid and invalid) green cue trials in the 32 trials prior to each presentation of the motion cue from its respective motion cue. That is, we normalized the motion cue RTs to the respective green cue (valid and invalid) RTs. An independent-samples *t*-test revealed no difference between RTs associated with the first presentation of a valid and invalid motion cue, $t(36) = 0.86$, $p = .40$.

Two further analyses were conducted to determine whether a cueing effect emerged with repeated presentation of the motion cue as Figure 4 might suggest. First, we computed the average effect in Figure 4 separately for the first and second halves of the experiment (Presentations 1–4, and 5–8). An independent-samples *t*-test revealed a significant effect of cue validity for Presentations 5–8, $t(38) = 2.41$, $p = .021$, $d = 0.82$, but not for Presentations 1–4, $t(38) = 0.08$, $p = .94$. Second, we fitted linear functions to the data in Figure 4 separately for the valid and invalid motion cue. Consistent with the split half analysis above, a linear trends analysis revealed a significant linear decrease of the normalized RT for valid motion cue trials, $F(1, 16) = 15.83$, $p = .001$, $\eta_p^2 = .51$, but not for the invalid motion cue trials, $F(1, 15) = 1.99$, $p = .18$, $\eta_p^2 = .12$.

Inspection of Figure 4 shows that the RT elevation on valid motion cue trials dropped to the level of performance seen with the green cue, whereas this was not the case with the invalid rare motion cue. A pairwise comparison between the last four occurrences of the invalid motion cue and the average RT to green cues (valid and invalid) from the second half of the experiment revealed a significant interference effect associated with the invalid motion cue, $t(19) = 4.68$, $p = .001$, $d = 0.82$. These results indicate that the invalid rare motion cue continued to interfere with search throughout the experiment, whereas the valid motion cue showed substantial reduction in RT.

Error analysis

The results of an error analysis were consistent with the pattern of results seen for RTs (see Table 1). A 2 (motion-cue group: valid motion, invalid motion) × 2 (cue type: red, green) × 2 (cue validity: valid, invalid) mixed-model ANOVA (motion-cue group entered as a between-subjects factor) on error rates revealed a main effect of cue type, $F(1, 39) = 4.88$, $p = .033$, $\eta_p^2 = .12$, and of cue validity, $F(1, 39) = 29.68$, $p < .001$, $\eta_p^2 = .43$, and a significant two-way interaction between cue validity and cue type, $F(1, 30) = 32.59$, $p < .001$, $\eta_p^2 = .45$. There was no main effect of motion-cue group, nor were there any interactions with motion-cue group. Pairwise comparisons revealed that only when the cue was red did it have an effect on response accuracy, $t(39) = 6.54$, $p < .001$, $d = 1.54$. There was no effect of validity on error rates when the cue was green, $t(39) = 1.73$, $p = .09$. Given the pattern of errors across all conditions, the differences in response times reported above are not attributable to any speed–accuracy trade-offs. An independent-groups *t*-test revealed no significant difference in error rates associated with valid and invalid rare motion singletons, $t(38) = 0.31$, $p = .76$.

Discussion

In Experiment 2, observers adopted top-down settings for red, as evidenced by the significantly larger cueing effect for red than for green cues (see Figure 3). Despite this set, RTs were significantly elevated by the presentation of an unexpected, irrelevant motion singleton cue. Across the second half of the experiment, RTs associated with valid motion cues were significantly faster than RTs associated with invalid motion cues, consistent with the motion cue having captured attention. It is clear from a comparison of Experiments 1 and 2 that the frequency of presentation of the motion cue modulated target RTs, as in all other respects the motion cue was the same as that in Experiment 1. This observation is consistent with previous research demonstrating that frequency of presentation modulates distractor inference (Geyer et al., 2008; Horstmann, 2002, 2005; Neo & Chua, 2006) and extends the previous studies by demonstrating that this phenomenon occurs even when participants have an active top-down attentional setting for a specific colour.

Our analyses of the individual presentations revealed significant costs for both valid and invalid motion cues in the first half of the experiment, which did not differ significantly from each other. Across presentations, valid RTs declined linearly, whereas invalid RTs remained relatively flat and elevated, leading to a significant validity effect in the second half of the experiment. We argue that this pattern cannot be easily explained by either the spatial reallocation of attention or surprise alone. If attention were simply being captured by the motion cue then a validity effect should have been present in all presentations. Conversely, if the interference were due solely to surprise, with no reallocation of attention, then valid and invalid RTs should have shown a similar pattern of habituation from surprise over presentations, which does not appear to be the case. Instead, our data suggest that the first few presentations of the motion cue gave rise to surprise. As surprise habituated, the motion cue retained its ability to capture attention, and the cueing effect emerged. We deal further with the relationship of surprise to reallocation in subsequent experiments and discuss it in the General Discussion.

In Experiment 2 we manipulated the validity of the motion cue between subjects. It is possible that the observed differences between the valid and invalid motion cue in Figure 4 are due to the development of different strategies specific to the valid and invalid conditions. Specifically, in the case of the valid condition, participants may have learnt, either explicitly or implicitly, the relationship between the motion cue and the target location and biased their attention toward motion, consequently rendering motion task-relevant. Under either of these scenarios it would be a mistake to conclude that shifts of attention to the motion cue were involuntary and independent of the task goals. In Experiment 3 we use a within-subjects manipulation of cue validity to limit the development of differential strategies for attending to the motion cue. This should provide a more stringent test of whether the validity effect of the motion cue reflects attentional capture.

EXPERIMENT 3

In Experiment 3, each participant saw both valid and invalid motion cues. Given the small number of motion cues, we reasoned that the law of small numbers would make it possible that a random order of valid and invalid cues would produce sequences that differed significantly between subjects. To avoid this we alternated the presentation of valid and invalid motion cues and assigned each participant to one of two presentation orders that differed in whether the first motion cue was valid or invalid. The alternating pattern also controlled for position within the sequence so that both valid and invalid cues would be presented at equivalent practice levels. Since observers have no incentive to actively attend to or actively inhibit motion, better performance on valid than on invalid motion cue trials can be safely attributed to involuntary capture by the rare motion singleton. If the motion cue captures attention then we expect to see RTs to valid cues faster than to invalid cues.

Method

Participants

An independent sample of 32 participants (21 female) aged 17–25 years ($M = 19.3$, $SD = 2.1$)

from the introductory psychology course at the University of Queensland participated for course credit. All reported normal or corrected-to-normal vision.

Apparatus

The apparatus was identical to the one used in the experiments reported above.

Stimuli, design, and procedure

The stimuli, design, and procedure of Experiment 3 were identical to those of Experiment 2, with the exception that valid and invalid cues alternated within subjects. To obtain sufficient observations for a comparison between initial and latter presentations of the rare motion cues, the frequency of rare motion cues was increased to ~6% of trials. Eight valid and eight invalid motion cues were presented either in the order valid–invalid–valid–invalid, and so on, or vice versa, in the order invalid–valid–invalid–valid, and so on. The order of presentation was counterbalanced across participants. The experiment was divided into nine blocks of 32 trials. No motion cues occurred within the first 32 trials. Each of the eight subsequent blocks contained one valid and one invalid presentation of the motion cue.

After the experiment, participants were probed as to whether they had been aware of any pattern regarding the presentation of the motion cue with the following question: "Did you notice any pattern with respect to where the motion stimulus occurred in the display?" None of the participants reported being aware of an alternating valid–invalid order.

Results

Mean response times and error rates for Experiment 3 are shown in Figures 5 and 6 and Table 1, respectively. RTs exceeding 1200 ms and errors were excluded from the RT analysis. Participant 5 was excluded from all analyses due to an unacceptably high average error rate of 20.8%. Across the remaining 31 participants the exclusion criteria resulted in a loss of 4.8% of experimental trials. Experiment 3 produced a pattern of results consistent with those observed in Experiment 2. Again we again observed a clear effect of the infrequent motion cue when participants had a clear top-down set for the target feature (red; see Figures 5 and 6).

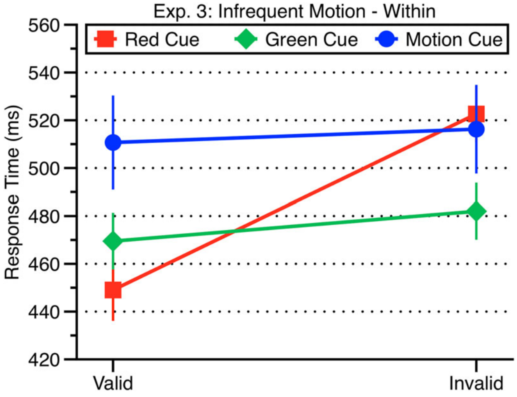

Figure 5. *Mean response time (RT) as a function of cue type and cue validity for Experiment 3. Error bars depict ±1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

RT analysis

A 3 (cue type: red, green, motion) × 2 (cue validity: valid, invalid) repeated measures of RTs revealed a main effect of cue type, $F(2, 29) = 13.94$, $p < .001$, $\eta_p^2 = .49$, and of cue validity, $F(1, 30) = 54.47$,

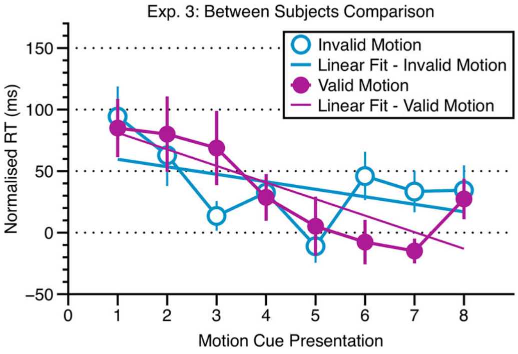

Figure 6. *Normalized response time (RT) for each presentation of the motion cue in Experiment 3. The data have been treated consistent with Experiment 2. Error bars depict ±1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

$p < .001$, $\eta_p^2 = .65$, and a significant two-way interaction between cue validity and cue type, $F(2, 29) = 38.28$, $p < .001$, $\eta_p^2 = .73$. The two-way interaction of cue validity and cue type reflected a significantly greater validity effect for the red cue, $t(30) = 12.66$, $p < .001$, $d = 1.14$, than for the green cue, which also showed a significant validity effect, $t(30) = 2.90$, $p = .018$, $d = 0.19$ (see Figure 5). Follow-up analyses for the motion cue are presented in the next section.

Motion cues. In Experiment 3 we again asked whether RTs were elevated on trials with a motion cue, and, secondly, whether there was a validity effect associated with the motion cue. Planned pairwise comparison confirmed that RT on both valid and invalid motion cue trials were elevated relative to the target nonmatching cue (green) [$t(30) = 2.59$, $p = .015$, $d = 0.32$; $t(30) = 3.96$, $p < .001$, $d = 0.39$, respectively] (see Figure 5). Consistent with Experiment 2, an analysis of mean RT across all presentations of the motion cue revealed no cueing effect associated with the motion, $t(30) = 0.52$, $p = .60$. As was done in Experiment 2, we conducted two further analyses to determine whether a cueing effect emerged with repeated presentation of the motion cue. Again we performed these analyses on normalized data to compensate for possible temporal effects (e.g., practice, fatigue) and baseline RT differences between the groups—the data were normalized according to the procedure outlined in Experiment 2. First, we computed the cueing effect associated with the motion cue separately for the first and second halves of the experiment (Presentations 1–4 and 5–8). A 2 (exposure: first half vs. second half) × 2 (cue validity: valid vs. invalid) repeated measures ANOVA comparing RT on valid versus invalid trials in the first and second halves of the experiment revealed a main effect of exposure, $F(1, 29) = 13.68$, $p < .001$, $\eta_p^2 = .35$, and a significant two-way interaction between cue validity and exposure, $F(1, 29) = 5.20$, $p = .033$, $\eta_p^2 = .15$. The interaction was due to the fact that the motion cue did not produce a significant validity effect in the first half of the experiment, $t(30) = -1.06$, $p = .30$. However, in the second half of the experiment, valid cue RTs were significantly faster than invalid cue RTs, $t(30) = 2.56$, $p = .015$, $d = 0.48$, consistent with attentional capture by the motion cue in the second half of the experiment.[2]

Secondly, we fitted linear functions to the data in Figure 6 separately for the valid and invalid motion cue. Consistent with the split-half analysis above, the linear trends analysis revealed a significant linear component to the decrease in RT associated with the valid rare motion cue, $F(1, 22) = 7.64$, $p = .011$, $\eta_p^2 = .26$, but not the invalid rare motion cue, $F(1, 20) = 1.81$, $p = .19$, $\eta_p^2 = .083$. This result replicates the effect found in Experiment 2.

Errors. The results of an error analysis conformed to the pattern of results observed for RTs. A 3 (cue type: red, green, motion) × 2 (cue validity: valid, invalid) repeated measures ANOVA on error rates revealed a main effect of cue validity, $F(1, 29) = 7.34$, $p = .011$, $\eta_p^2 = .20$, and a significant two-way interaction between cue validity and cue type, $F(2, 28) = 12.61$, $p < .001$, $\eta_p^2 = .47$. Pairwise comparisons revealed a significant validity effect for the red cue, $t(29) = 6.75$, $p < .001$, $d = 1.29$, but not for the green cue, $t(29) = 0.16$, $p = .99$.

A separate ANOVA of the error rates associated with the motion cue condition revealed no main effects or interactions. Given the pattern of errors across all conditions, the differences in response times reported here are not attributable to any speed–accuracy trade-offs.

Discussion

The elevated RTs associated with the rare motion cue in Experiment 3 provide further evidence of interference that was not observed in Experiment 1 when the motion cue was presented frequently.

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[2] This spatial validity effect held when the comparison between valid and invalid cues was expanded to include the last 10 presentations (Presentations 4–8) of the rare motion cue, $t(30) = 2.17$, $p = .035$, as well as when it was restricted to the last six presentations (presentations 6–8) of the rare motion cue, $t(30) = 3.24$, $p = .003$.

Moreover, in Experiment 3, the spatial validity effect associated with the motion cue emerged under conditions that precluded the development of different strategies to attend to motion, evidence of the involuntary capture of attention by rare motion cues. This result supports the contention that frequency of presentation is a contributing factor in producing capture from a transient (motion) stimulus.

Interestingly, in Experiment 3 we again observed the absence of a cueing effect for initial presentation of the motion cue. While this appears to conflict with the standard cueing effect observed robustly in spatial cueing studies, it is important to emphasize that our results reflect performance on the first presentation of a new stimulus. In a typical spatial cueing experiment, subjects are given several trials of practice on the exact stimuli they will encounter in the experimental session, or alternatively the first few trials are excluded from analysis. Even if included, the contribution of the first presentations is negligible when data from the entire experiment, or even over a block, are averaged. Our results are showing a new and apparently robust pattern in which initial *valid* motion cues produce large RT costs.

This underadditive result pattern is at odds with results showing additive effects of cue validity and surprise in visual search (Gibson & Jiang, 1998; Horstmann, 2002, 2005; Horstmann & Becker, 2008). Since we have argued that the initial presentations of the motion cue elicit surprise, we investigate the source of this underadditivity in Experiment 4 to better understand why our results differ from those of previous surprise capture studies.

EXPERIMENT 4

According to current models of surprise capture, surprise-induced costs should be additive with capture (Gibson & Jiang, 1998; Horstmann, 2002, 2005; Horstmann & Becker, 2008), because the RT delay that characterizes surprise is thought to reflect a disruption of decision-level processes that are separate from processes responsible for controlling orienting (Horstmann, 2005; Sternberg, 1967). How then can we explain the absence of a validity effect for the initial presentations of motion cue?

One notable difference between the experiments reported here and previous studies is that in the present experiments the target was always a colour singleton. The presence of a significant cueing effect for colour cues indicates that participants were set for the target colour. Thus, for invalid motion cues the feature for which attention was set was always present in a location other than that of the motion cue. If, as our evidence suggests, the motion cue captures attention, then on invalid trials the presence of the target feature provides a perceptual cue to facilitate disengaging from the motion cue. That is, perceptual processing of the target properties can proceed in parallel with disengagement from the motion cue. For valid trials, on the other hand, there is no spatially distinct perceptual signal to facilitate disengagement. If the process of disengaging from the surprise stimulus involves inhibition of the interfering distractor then it is easy to see this would interfere with parallel perceptual processing of the target, and how the cost could be very high for a valid surprise stimulus.

In contrast, previous studies of surprise capture have used predominately a conjunction search in which the target was not marked by a unique feature (Horstmann, 2002, 2005; Horstmann & Becker, 2008, 2011). Feature singletons are preattentively available, whereas conjunctions of features are not and mostly require an effortful serial search (e.g., Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994). In conjunction, the target would not compete as strongly for attention with the unexpected singleton as in the target feature in the present study.

We examined this in Experiment 4 by defining the target to be a conjunction of colour and orientation, more closely mirroring previous studies of surprise capture that observed additive effects of surprise and cue validity. A target defined by a conjunction of features should not facilitate disengagement from the motion cue. If our reasoning is sound, then in Experiment 4 we ought to find an RT elevation that is now additive with attentional capture (as indexed by the cueing effect).

To increase the difficulty of the search task, the number of possible search stimuli was increased to six, and participants were instructed to search for a red bar that could be either horizontal or vertical, among differently coloured bars that were oriented horizontally or vertically, or tiled left or right by 45°. Each display contained two red bars, two green bars, and two blue bars. Targets could only appear on four out of the six possible positions. Eye position was monitored to ensure that participants maintained fixation on the central fixation cross during the entire trial.

Method

Participants

A new sample of 70 participants (53 female) aged 17–47 years ($M = 20.7$, $SD = 2.7$) from the introductory psychology course at the University of Queensland participated for course credit. All reported normal or corrected-to-normal vision.

Apparatus

Experiment 4 was conducted using the computer software package Matlab (2010a) and the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). Participants' eye movements were measured using a video-based infrared eye-tracking system (Eyelink 1000, SR Research, Ontario, Canada) with a spatial resolution of 0.1 and a temporal resolution of 500 Hz.

Stimuli

The fixation display and target display contained six boxes positioned in a circular array around fixation. The size of each box and distance of each from fixation were the same as in the previous experiments. The cueing display consisted of a set of four dots around all six boxes. On colour cue trials, one set of four dots around one location was always coloured either red or green (four-dot cue). The motion cue was rendered by a 90° rotation of the diamond cue configuration in six 15° clockwise increments at 22-ms intervals.

The target display consisted of an oriented, coloured line in each of the six peripheral boxes. The bars could be oriented horizontally, vertically, or rotated 45° to either the left or right. Three of the bars were oriented either horizontally or vertically, and three were oriented either 45° to the left or 45° to the right. Two of the bars in the display were red (RGB = 255, 0, 0), two were green (RGB = 0, 255, 0), and two were blue (RGB = 0, 0, 255). The distribution of colours was such that each orientation (horizontal/vertical and 45° left/right) appeared in each colour. That is, the bars in the display varied across two features, orientation and colour, and no single bar in the display could be differentiated from the other bars by a single feature alone.

Design and procedure

As in Experiment 2, subjects were randomly assigned either to the group that received valid motion cues, or to the invalid motion group. Target and singleton cues never appeared at the position directly above or below fixation (see Figure 7), only at the remaining four locations. Participants were required to respond with the left and right arrow key when they saw either a red horizontal or a red vertical bar, respectively. The experiment was divided into six blocks of 32 trials and one block of 32 practice trials. Neither the practice block nor the first block of experimental trials contained a motion cue. Each of the five subsequent blocks contained either one valid or one invalid presentation of the motion cue. Incorrect responses resulted in the word "wrong!" being displayed on the screen for 1000 ms.

Results

Mean RTs and error rates for Experiment 4 are shown in Figures 8 and 9 and Table 1, respectively. RT exclusion criteria were relaxed to compensate for the increased difficulty of the search task. RTs exceeding 1500 ms and errors were excluded from the RT analysis. Six participants' (two from the invalid condition) data were excluded from all analyses due to unacceptably high average error rate of 20% or greater in one or multiple conditions.

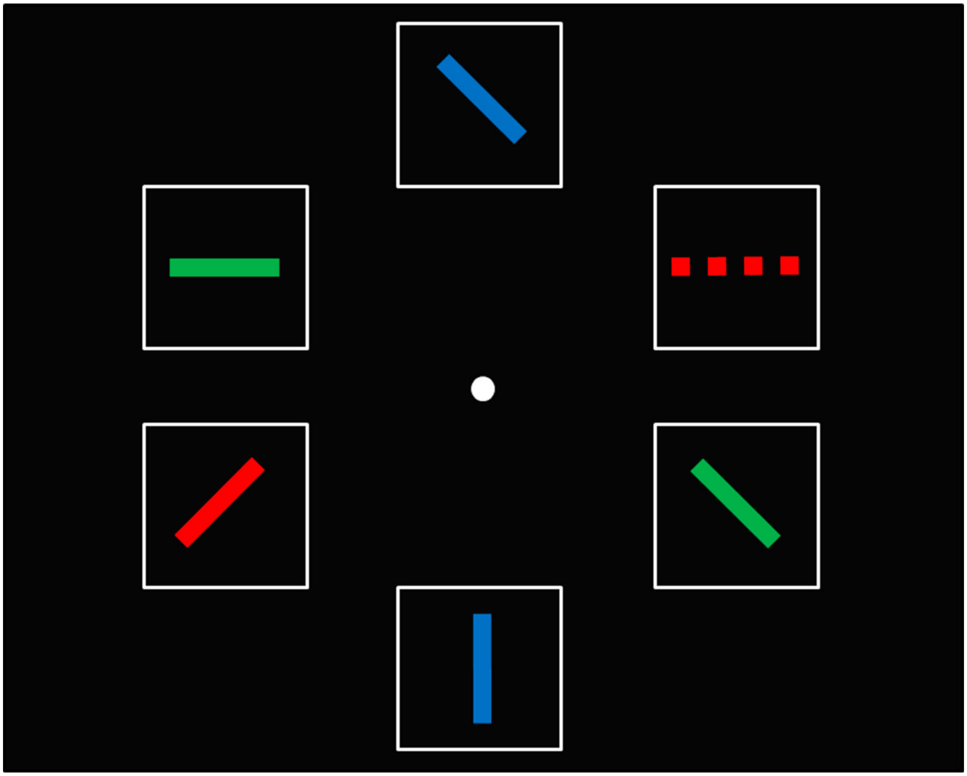

Figure 7. *Example target display from Experiment 4. The target in this example is the dashed horizontal red bar. Note that the target did not appear as a dashed line in the experiment. To view this figure in colour, please visit the online version of this Journal.*

Across the remaining 64 participants the exclusion criteria resulted in a loss of 8.6% of experimental trials.

Eye movement data were analysed online, and trials were aborted if participants did not remain fixated throughout the trial. Participants were deemed to be fixating if their gaze fell within a region of 1.3° of visual angle from the centre of the fixation cross. To summarize the results: In Experiment 4 we found a significant cueing effect associated with the rare motion cue. Importantly, this effect was found to be additive with surprised induced RT costs. That is, unlike Experiments 2 and 3, but consistent with our prediction, the cueing effect associated with the infrequent motion cue was present for initial presentations of the motion cue (see Figure 9).

RT analysis

Colour cues. A 2 (motion-cue group: valid motion, invalid motion) × 2 (cue type: red, green) × 2 (cue validity: valid, invalid) mixed-model ANOVA (motion-cue group entered as a between-subjects factor) on mean RTs revealed a main effect of cue validity, $F(1, 62) = 29.30$, $p < .001$, $\eta_p^2 = .32$, and a significant two-way interaction between cue validity and cue type, $F(1, 61) = 46.92$, $p < .001$, $\eta_p^2 = .43$. There was no two-way interaction between motion-cue group and cue type, $p = .23$, or motion-cue group and cue validity, $p = .52$. There was also no three-way interaction between motion-cue group, cue type, and cue validity, $p = .43$. As such, we collapsed across motion-cue group when computing planned follow-up comparisons. Pairwise

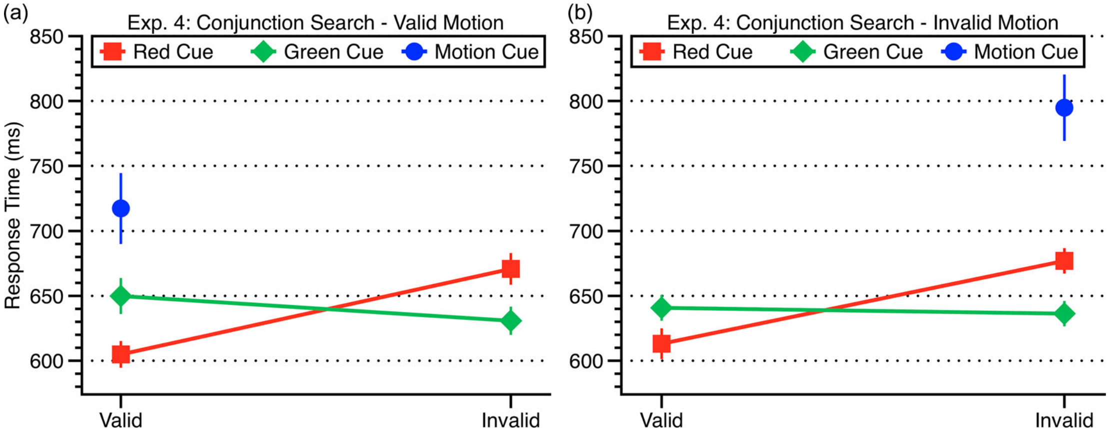

Figure 8. *Mean response time (RT) as a function of cue type and cue validity for (a) the valid-motion condition and (b) the invalid-motion condition in Experiment 4. Error bars depict ± 1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

comparisons revealed a significant validity effect associated with the red cue, $t(62) = 9.49$, $p < .001$, and a small but significant inverse validity effect associated with the green cue, $t(62) = -3.75$, $p < .001$ (see Figure 8).

Motion cues. To assess the effect of the motion cue we first compared RTs associated with the motion cue to the nontarget invalid green cue. Pairwise comparisons revealed that both valid and invalid motion cue RTs were significantly elevated relative to green cue RTs [$t(29) = 3.04$, $p = .007$, $d = 0.65$; $t(31) = 6.81$, $p < .001$, $d = 1.31$, respectively]. To test for between-subject differences in RT between valid and invalid motion cue trials, we first normalized data for valid and invalid motion cues. Normalization of the motion cue data was computed as before by subtracting RTs from surrounding green cues from the RT to the motion cue. An independent-samples t-test revealed that invalid motion RTs were significantly elevated relative to valid, $t(60) = 2.96$, $p = .004$, $d = 0.52$.

As with previous experiments, we looked at the effect of the motion cue across repeated presentations by computing the cueing effect associated with the motion cue separately for the first and second halves of the experiment (Presentations 1–2 and 4–5). Independent-samples t-tests revealed a significant effect of cue validity for Presentations 1–2, $t(60) = 2.76$, $p = .008$, $d = 0.71$, but not for Presentations 4–5, though the effect approached significance, $t(60) = 1.97$, $p = .054$, $d = 0.50$. Furthermore, mean RT on the first unannounced presentation of the motion cue was significantly faster for valid than for invalid cues, $t(55) = 2.28$, $p = .027$, $d = 0.60$. Note that this pattern of results is in stark contrast to those observed in Experiments 2–3.

Figure 9 shows the normalized RT data for each presentation of the motion cue. Linear functions fitted to both the valid and invalid data sets showed a linear trend towards decreasing RT with repeated presentations for both valid and invalid cues. Due to an increase in the number of errors on motion trials, a linear trend analysis on the RT data was not appropriate for either of the rare motion cue conditions. However, comparing RTs across the first two (1st and 2nd) presentations of the motion cue with RTs on the last two (4th and 5th) presentations of the rare motion cue within each condition revealed that RTs were significantly slower across the first two presentations of the motion cue than the last two presentations for invalid motion cues, $t(30) = 3.22$, $p < .004$, $d = 0.60$, and marginally significant for the valid motion cue condition, $t(28) = 1.90$, $p = .067$, $d = 0.81$.

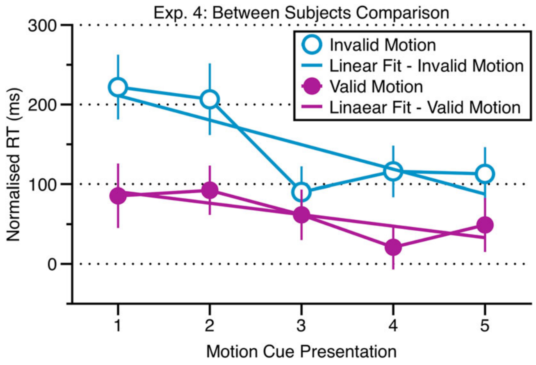

Figure 9. *Normalized response time (RT) for each presentation of the motion cue in Experiment 4. The data have been treated consistent with Experiments 2 and 3. Error bars depict ±1 standard error of the mean. To view this figure in colour, please visit the online version of this Journal.*

Error analysis

Error rates across the different conditions were largely consistent with the pattern of results seen for RTs. A 2 (motion-cue group: valid motion, invalid motion) × 2 (cue type: red, green) × 2 (cue validity: valid, invalid) mixed-model ANOVA (motion-cue group entered as a between-subjects factor) on error rates revealed a main effect of cue validity, $F(1, 62) = 7.44$, $p < .008$, $\eta_p^2 = .11$, such that more errors were associated with invalid than valid cues. A significant two-way interaction between cue type and cue validity, $F(1, 63) = 8.19$, $p = .006$, $\eta_p^2 = .12$, reflects that there was a validity effect associated with the red cue, $t(63) = 3.65$, $p < .001$, $d = 0.54$, but not the green cue ($p = .65$). A cue type by motion-cue group interaction revealed that error rates for the red cue condition were slightly high in the invalid motion condition compared to the valid motion condition, $F(1, 62) = 11.59$, $p = .001$, $\eta_p^2 = .16$ (see Table 1). There was no difference in error rates between the valid and invalid motion cues, $t(62) = 1.41$, $p = .16$.

Discussion

Experiment 4 provides the first decisive evidence for the hypothesis that top-down guided search for a preattentively available feature markedly changes the dynamics of capture by unexpected and rare stimuli. Standard cueing effects were observed on all presentations. Unlike Experiments 2 and 3, Experiment 4 showed significantly elevated RT for the initial presentations of the invalid motion cue that decreased linearly over repeated presentations. The validity effect was observed across repeated presentations of the motion cue, with consistently faster RT for the valid than for the invalid cues. This pattern of attentional capture and surprise-related RT elevation is consistent with the two effects having combined in an additive manner.

These results support our hypothesis that the failure to observe additive effects in the previous experiments was due to the fact that the target competed more strongly for attention with the unexpected motion cue, which facilitated disengagement from the motion cue and led to a fast reallocation of attention to the target. We argue that this reallocation prevented the propagation of surprise to higher, decision-related processes, reducing its impact on invalid RTs. The additive effects of surprise and spatial cueing observed in Experiment 4 conform to the pattern of results predicted by current models of surprise capture (Gibson & Jiang, 1998; Horstmann, 2002, 2005; Horstmann & Becker, 2008, 2011). The discrepancy between the results of Experiments 2 and 3 and previous reports of surprise hinges on the presence versus absence of a preattentively available signal in the target display to guide attention away from the location rare motion cue. According to this explanation, the absence of readily available information to match the top-down controlled attentional settings appears to be critical for the (full) manifestation of surprise. In the absence of strong competition by a preattentive feature and/or an effective bias that draws attention away, the unexpected item is then processed in sufficient depth to modulate decision- and response-related processes.

GENERAL DISCUSSION

The influence of top-down mechanisms on the orienting of attention has been well documented, with the general conclusion that the capture of attention by salient events is modulated by their relevance to ongoing task goals (Bacon & Egeth, 1994; Eimer & Kiss, 2008; Eimer et al., 2009; Folk & Remington, 1998; Folk et al., 1992, 1994; Wu & Remington, 2003). In the present series of experiments, we tested whether unexpected stimuli would capture attention even when attention is demonstrably set for a specific colour. The present series of experiments found that a rare task-irrelevant motion signal captured attention even when observers had adopted a top-down setting for a particular colour (red). As shown by Experiment 1, this effect was not due to the bottom-up saliency of the motion stimulus, as it could be successfully ignored when it was presented frequently. These findings support the view that novelty can override the top-down attentional control settings and prompt an attention shift toward rare and unexpected events. Importantly, these results were obtained in the modified spatial cueing paradigm used by Folk et al. (1992), which allowed us to confirm that participants had indeed adopted a feature-specific attentional bias for the target colour, and not a broader search for a discontinuity in the displays (e.g., singleton search mode or display-wide features; Bacon & Egeth, 1994; Gibson & Kelsey, 1998). In our experiments, the presence of a feature set (red) was demonstrated by the consistently larger cueing effect for the cue of the target colour (red) than for the nontarget colour (green), as well as by a frequently presented motion singleton. The observation of capture by infrequent events under conditions of an active top-down set for a specific target feature provides strong support for capture by novel stimuli and extends previous research showing attentional capture by infrequent task-irrelevant abrupt-transients (Neo & Chua, 2006).

Top-down control of attention

Our claim that attentional capture is sensitive to frequency of presentation, not the onset transient itself, is supported by the presence of interference from rare motion cues (Experiments 2, 3, and 4) compared to the absence of capture to the same motion cue presented more frequently in Experiment 1. This failure to find capture by motion cues in Experiment 1 is consistent with the results of other spatial cueing studies that have failed to find evidence of capture by onsets or motion cues when attention was set for a specific colour (Folk et al., 1992, 1994). Capture by the same motion cue when it was presented on only a small number of trials is strong evidence that the salient transient of the motion cue per se was not instrumental in capturing attention, as has previously been maintained (Abrams & Christ, 2003, 2006; Belopolsky et al., 2010; Franconeri, Simons, & Junge, 2004; Lamy & Egeth, 2003; Theeuwes & Van der Burg, 2007). Evidence supporting theories of stimulus-driven capture by salient onsets or motion come largely from visual search or irrelevant singletons (Schreij, Owens, & Theeuwes, 2008; Theeuwes, 1991, 1994) in which both targets and distractors are presented simultaneously. The simultaneous presentation pits the sensory processing of targets against that of distractors and, as a result, is more sensitive to physical attributes, such as intensity or salience. Evidence supporting the role of top-down modulation has come instead from spatial cueing studies, like ours, in which the distracting stimulus (cue) is presented in isolation prior to the target. The sequential presentation minimizes that perceptual interaction of cue and target, thus allowing more scope for top-down control. In this respect, our finding of capture by unexpected motion stimuli in a spatial cueing paradigm is strong support for the ability of novel events to generate stimulus-driven capture.

According to a strong version of contingent capture, a positive setting for a stimulus property would be necessary for it to capture attention. This cannot be the case in our experiments as subjects could not have a positive set for a stimulus they did not know would be presented. Even after the first presentation the motion cue continued to capture when presented infrequently, suggesting that whatever expectation was generated by each presentation was no longer active on the next presentation. How is it then that top-down control can prevent capture by frequently presented events, but not novel events?

One way to account for the range of findings is to consider the neural model posited by Sokolov (1963) to explain the orienting response. According to Sokolov, the brain maintains a model of the world that incorporates the recent history of processing. The orienting response is triggered by stimuli that fall outside that model. This suggests that the rare motion cue captured attention because its frequency of presentation did not support incorporation into this world model. When presented frequently, however, the same stimulus was updated regularly and incorporated into the model. This leads to a view of top-down control that is more than simply a positive set for the relevant target feature. Instead, it suggests that effective top-down control is the result of general contextual expectation for the properties of both targets and distractors (see Theeuwes, 1996). This is consistent with classical theories of attention that assume that salient irrelevant stimuli have to be filtered out or inhibited (Becker, 2007; Folk & Remington, 1998; Treisman & Sato, 1990). Such filtering or inhibition of irrelevant features would depend on prior exposure to these stimuli and implicit learning about their relevance. The effectiveness of inhibition or filtering would depend on an active set for distractor properties maintained by repeated occurrence and the probability that it indicates the target location or misguides attention to a non-target location (e.g., Geyer et al., 2008; Yantis & Egeth, 1999). In fact, Vatterott and Vecera (2012) found that, in search for a shape target, an irrelevant colour singleton interfered with search only in the first half of a block, but not in the second half. This pattern was observed for all blocks in which the colour of the singleton was changed from the previous block. These results show that top-down control included suppression of irrelevant salient stimuli, not just a positive setting for a target feature (which did not change in the study of Vatterott & Vecera, 2012).

Predictivity of colour cues versus motion cue

In Experiment 1, the red and green colour cues and the motion cue were all nonpredictive of the target location, as they coincided with the target on 25% of all trials. In the subsequent experiments, the colour cues remained nonpredictive; however, the motion cue was correlated—to varying degrees—with the target (Experiments 2–4). Yantis and Egeth (1999) showed that the amount of attention allocated to a nominally irrelevant singleton depends on its predictiveness of the target location: Is it possible that a similar mechanism guided attention to the motion singleton in the present experiments? We consider this unlikely, for the following reasons: In Experiments 2 and 3, participants were probed directly after the experiment regarding whether they had noticed any regularities associated with the presentations of the motion cue, and none of the participants correctly reported that the motion cue had been presented in a regular foreseeable sequence (i.e., of AAAA … or ABAB …). This negative result would seem to rule out that participants developed an *explicit* strategy in response to the predictiveness of the motion cue.

With respect to any *implicit* learning that may have occurred, we cannot rule this out. However, previous work using the spatial cueing paradigm has shown that presenting always valid cues and always invalid cues in different blocks yields very similar results patterns to those from presenting valid and invalid cues mixed within a block of trials (e.g., Folk et al., 1992). Finally, and importantly, any learning account cannot explain the cueing effect seen at the outset of Experiment 4. Possibly, the predictiveness of the distractor only has an effect in visual search tasks where the distractor feature (e.g., colour) is an attribute of the target itself and a more salient attribute than the target-defining feature, so that it can aid search when it is predictive (e.g., Yantis & Egeth, 1999).

Surprise

In discussing the experiments we made the point that our results appear to reflect the presence of both a standard cueing effect and surprise. There was clearly something about the initial presentations of a *valid* motion cue that elevated RTs and masked the spatial-cueing effect. In Experiments 2 and 3, RTs for valid motion cue trials decreased linearly over presentations, whereas RTs for invalid trials remained relatively constant. A standard cueing effect emerged around the third or fourth presentation and was significant in the second half of all experiments. We hypothesized that RTs for the first few presentations reflected both an orienting of attention to the cue and an initial surprise effect, which resulted in attention dwelling at the location and engaging response selection mechanisms for the cue. As surprise diminished over presentations, the orienting of attention remained, and a cueing effect emerged. Further, in Experiment 4 we provided evidence that the greater elevation with valid motion cue RTs resulted from the presence of a feature singleton with invalid cues that facilitated disengagement from the motion cue. In the absence of a singleton target feature in Experiment 4, RTs for both were elevated on first presentation, with valid RTs faster than invalid, as expected. The effect of surprise was additive with the cueing effect as has been previously found. Our results are also consistent with the hypothesis that the effect of surprise is not only to draw attention to the cue, but to engage response and decision mechanisms as well (Horstmann, 2005; Meyer et al., 1991; Schützwohl, 1998).

Theoretical implications

The principal theoretical implication of the present study is that a top-down setting for a particular colour does not prevent the capture of attention by a novel or rare salient stimulus. The present study provides the first evidence that unexpected stimuli can capture attention even when attention is firmly biased to the target feature value. This finding is inconsistent with the original contingent capture hypothesis that a stimulus has to be similar to task-relevant features in order to capture attention (Folk et al., 1992). We conclude that salient (transient) novel stimuli, by which we mean stimuli outside the current neural model of the world, will capture attention regardless of top-down attentional control settings. A second implication is that top-down modulation of capture is not accomplished simply by setting for a target property. In our account, both target and distractor properties must be actively in mind. Together with the study of Vatterott and Vecera (2012), the present study provides the compelling evidence that top-down control involves both target and distractor modulation.

The present results also extend on our knowledge of capture by unexpected and rare stimuli. Here we show, for the first time, that surprise capture and a surprise-induced RT elevation can also be obtained in the spatial cueing paradigm, in a task similar to Folk and Remington (1998), where the target is identified by a unique, constant feature. Although the present experiments yielded results similar to those found previously in difficult visual search tasks, they also showed some deviations from previous results: specifically, the nonadditivity of RTs for the first (few) presentation(s) of the unannounced motion cue. This results pattern deviates from previous reports where surprise-induced RT elevation has been reported to be additive with capture effects (e.g., Horstmann, 2005). Naturally, it is possible that the invalid motion cue did not capture attention and therefore did not lead to a surprise-induced RT-elevation. However, this hypothesis is difficult to reconcile with the fact that we found capture by motion in the second halves of Experiments 2 and 3.

We noted in Experiment 4 that a key feature distinguishing our displays in Experiments 2 and 3 from earlier studies of surprise is that on invalid trials the critical target feature is visible at an uncued location immediately following the briefly presented cue. Indeed when the target was defined as a conjunction of features and consequently rendered less distinguishable from the nontargets in Experiment 4, the observed RT costs appeared to combine with attentional capture in an additive manner. We have suggested that the underadditivity observed in Experiments 2 and 3 is the result of an ability to disengage with the motion cue when it was *invalid* due to the presence of the feature singleton (the target) in the subsequent target display. Such an account is consistent with previous reports showing a slowed time-course of surprise. A signature of *surprise capture*, at least with respect to colour singletons, is that surprise does not appear to propagate in the system until at least ~300 ms after stimulus onset, with pronounced effects found for targets 400 and 600 ms following the surprise stimulus (Horstmann, 2002, 2005, 2006). Furthermore, surprise capture has not been observed at stimulus onset asynchronies (SOAs) of 200 ms or less (Horstmann, 2006; Horstmann & Becker, 2008). As we employed an SOA of 210 ms, it may be that in the case of the invalid rare motion cue, attention was not held at the location of the unexpected stimulus long enough for surprise to manifest. In Experiment 4, spatial attention was able to linger at the location of an invalid rare motion cue due to the attenuated target signal in the subsequent target frame. This additional time may have been sufficient for surprise to propagate through the system. In the case of the *valid* rare motion cue, attention is drawn to the location of the motion cue and is held at that location by the presentation of the target. The time for which attention is focused at the location of a valid rare motion cue is thus lengthened sufficiently to allow for further processing of the motion cue, which interferes with the task. Note that an implication of this interpretation is that surprise not only requires just "time" to manifest but some sustained period of spatial attention directed at the location of a surprising stimulus. There is some evidence to suggest that this is indeed the case (see Horstmann & Becker, 2008).

Although our disengagement hypothesis certainly warrants further investigation, it is clear that the involvement of effective top-down attentional guidance significantly alters the results for unexpected and rare irrelevant singletons. Specifically, the ability to quickly locate the target in the spatial cueing paradigm interrupts further processing of the motion singleton, which in turn causes these costs to combine with capture effects in an underadditive manner. These results are important, in that they show that top-down controlled processes can dominate attention and alter our response to the unexpected.

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