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Non-transient luminance changes do not capture attention

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Abstract The processing of luminance change is a ubiquitous feature of the human visual system and provides the basis for the rapid orienting of attention to potentially important events (e.g., motion onset, object onset). However, despite its importance for attentional capture, it is not known whether a luminance change attracts attention solely because of its status as a sensory transient or can attract attention at a relatively high cognitive level. In a series of six experiments, we presented visual displays in which a single object underwent a luminance change that was either visible or obscured by a mask. A target then appeared either at the change location or elsewhere. The results showed that the luminance change attracted attention only in the visible condition. This was even observed with the largest change we could generate (> 75 cd/m^2). These data suggest that the importance of a luminance change is only in its status as a low-level sensory transient.

Keywords Vision · Attention · Motion · Luminance · Object onset

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An abundance of research has shown that the processing of luminance is a central feature of the human visual system. Behaviourally, the importance of luminance is shown in the findings that many visual functions are compromised when luminance differences are reduced or abolished. For instance, Cavanagh, Tyler, and Favreau (1984) asked observers to adjust the velocity of a moving luminance-modulated grating to match that of a chromatically modulated grating presented within the same display. The results showed that the absence of luminance information in the latter stimulus adversely affected the perception of motion (see also Lindsey & Teller, 1990; Ramachandran & Gregory, 1978). Other visual phenomena that have been shown to rely on luminance processing include accommodation (Wolfe & Owens, 1981), vernier acuity (Morgan & Aiba, 1985), spatial contrast sensitivity (Mullen, 1985), stereopsis (Kingdom, Simmons, & Rainville, 1999), phase discrimination (Troscianko & Harris, 1988), and object formation (Luiga & Bachmann, 2008).

The processing of luminance is particularly important for the rapid detection of sudden transient changes that can occur in the visual field. A familiar example is seen in the precueing paradigm (e.g., Posner & Cohen, 1984). In this procedure, a luminance change is presented at a location displaced from fixation and followed at some short interval by the appearance of a target. The important manipulation is the spatial relationship between the cue and target. When the cue and target are in close proximity to each other, response time (RT) is decreased relative to when the cue and target are displayed apart. The common explanation is that the luminance change rapidly summons attention, thus facilitating subsequent responses to stimuli at that location. Many other types of transient event associated with luminance change have been shown to attract attention. The onset of a dot (Nakayama & Mackeben, 1989; Pratt &

McAuliffe, 2001; Steinman, Steinman, & Lehmkuhle, 1995), a square (von Grünau & Faubert, 1994), a short horizontal line (Kröse & Julesz, 1989; Theeuwes, 1991), and a looming object (Skarratt, Cole, & Gellatly, 2009) will all result in beneficial effects on the processing of targets located adjacent to the transient. Furthermore, there is a certain degree of automaticity about capture by these types of events. For instance, Posner, Cohen, and Rafal (1982) showed that a luminance cue attracts attention even if the target appears at the cued location on only 20% of trials. Attentional capture by transient events can also give rise to other related phenomena, such as the perceived spatial displacement of a visual probe (the "attentional repulsion effect"; Suzuki & Cavanagh, 1997) or the apparent lengthening of a line from the location of a transient event ("polarized gamma motion"; Kanizsa, 1951; see also Hikosaka, Miyauchi, & Shimojo, 1993). The principle common to all these phenomena is the rapid shift of attention brought about by the luminance change. Because the majority of transient events invariably create a change in brightness at their location, a low-level luminance detection mechanism would be an efficient way of shifting attention to a location where a potentially life-threatening event is occurring. Indeed, Breitmeyer and Ganz (1976) suggested that the role of visual channels specialised for the detection of abrupt luminance change is to direct attention to behaviourally important events.

Similar to perceptual phenomena (e.g., vernier acuity; Morgan & Aiba, 1985), the capture of attention by certain visual events is also compromised if the inducing stimulus is not accompanied by a luminance change. For instance, employing a variant of the precueing paradigm discussed above, Cole, Kentridge, and Heywood (2005) presented a colour change to one of two objects located in a visual display. Importantly, both objects (and background) were composed of a number of small squares, each changing to a random luminance value every 40 ms. Thus, the colour transients were not accompanied by a change in luminance, because they were embedded within an array of random luminance noise. The results showed that the standard capture effect by a peripheral event was abolished when the cues were defined in this way. Similarly, the *preview benefit* effect (Watson & Humphreys, 1997), in which visual search can be facilitated when observers receive a preview of half of the search items, is abolished if the display items are isoluminant with the background (Donk & Theeuwes, 2001; but see Braithwaite, Hulleman, Watson, & Humphreys, 2006).

The importance of luminance change processing for capture has also been demonstrated via the finding that object appearance, which almost invariably coincides with a luminance change, is particularly effective in attracting attention. As with other capture paradigms, the standard procedure requires observers to make a speeded response to a target. The crucial manipulation is that the target either occurs at the location of a new item or of an item that has been present in the display for some time (e.g., for 500 ms). An abundance of evidence has shown that RTs are facilitated in the former condition relative to the latter (e.g., Cole & Kuhn, 2009; Franconeri, Hollingworth, & Simons, 2005; Jonides & Yantis, 1988; Yantis & Jonides, 1984). This effect occurs irrespective of whether the task requires a discrimination to be made (as in letter identification) or a simple detection (as in the precueing paradigm), and it holds irrespective of whether or not set size is manipulated, in order to assess search efficiency.

The central role that luminance change processing plays in object onset capture is additionally supported by the demonstration that onset capture is usually abolished, or at least attenuated, when the new item is no longer associated with a luminance transient. For instance, Gellatly, Cole, and Blurton (1999) showed that onset capture is reduced if the appearing item is defined by the direction of moving lines generating a second-order contour (see also Cole, Gellatly, & Blurton, 2001). Although some studies have suggested that luminance change is not a necessary condition for object capture (for debate of this point, see Cole & Kuhn, 2009, 2010a; Davoli, Suszko, & Abrams, 2007; Hollingworth, Simons, & Franconeri, 2010), the consensus view is that luminance plays a central role.

One of the most important developments in the attention capture literature over the past two decades has been the notion of contingent voluntary orienting (Folk, Remington, & Johnston, 1992). Folk et al. argued that the likelihood of a stimulus capturing attention is largely dependent upon an observer adopting a subtle, goal-directed attentional set. Specifically, the propensity for a visual property to attract attention is contingent on the stimulus sharing some property that is relevant to an observer's task. For example, a colour cue is more likely to attract attention if the target is defined by colour than if the target is defined by luminance. Conversely, a luminance cue is more likely to attract attention if the target is defined by luminance than if the target is defined by colour (Folk et al., 1992). Hence, a "bottom-up" capture effect by a particular stimulus may in fact be due to top-down orienting. Since Folk et al.'s initial findings, two central aspects of attentional control settings have been identified, namely *singleton detection mode* (Bacon & Egeth, 1994) and *display-wide contingent orienting* (Gibson & Kelsey, 1998). With respect to singleton detection mode, Bacon and Egeth showed that a unique element (i.e., a singleton) amongst homogeneous distractors is likely to attract attention if observers are required to look for a target that is also a singleton. Thus, for example, a square presented amongst a number of circles will attract attention if the target is a horizontal line amongst vertical line distractors. Because the target line is itself a singleton, capture will occur. By contrast, the same square will no longer attract attention if the target is not a singleton. This notion may even explain the capture effect seen in the standard cueing paradigm of Posner and colleagues. In their basic procedure, participants are cued by a singleton (i.e., the luminance increment) and are also set to look for a target that is a singleton (e.g., the onset of a luminance-defined probe dot). With respect to display-wide contingent orienting, Gibson and Kelsey showed that attention can be set by properties that signal the appearance of the whole display and not solely by properties that may only define a target. For instance, Atchley, Kramer, and Hillstrom (2000) observed capture by an onset when the whole search display appeared at the beginning of a trial. By contrast, the same stimulus failed to attract attention when the search display occurred as a result of figure 8 "placeholders" shedding segments to form letters (see Gellatly et al., 1999; Yantis & Jonides, 1984). The important difference is that in the latter procedure, the search display was not associated with onset, instead being defined by offset of the figure 8 segments. It is possible, therefore, that the many examples of capture via the processing of luminance change are due to top-down attentional sets rather than to bottom-up orienting. Indeed, Burnham (2007) carried out an exhaustive review of the capture literature and concluded that all of the published capture effects are due to top-down processing.

Irrespective of whether attentional orienting is ever truly stimulus driven, this brief review demonstrates the ubiquitous nature of brightness change and the associated processing of luminance. It is therefore reasonable to assume that luminance change processing has a special status within vision. However, despite the abundance of luminance change research, it is unknown whether the importance of luminance change is due solely to its association with low-level sensory change, as suggested in most of the studies reviewed above, or whether luminance change can be represented at a higher level. That is, will a change in luminance at a location in a visual scene attract attention if the change is not a visual transient? The central aim of the present work was to examine this question. Given the importance of luminance change to attentional capture, one might expect this to be the case.

Evidence from the change detection paradigm has provided some insight into this question. An abundance of work has clearly shown that changes to a visual scene typically go unnoticed when the transient associated with the change is masked by other display-wide transients (e.g., Simons, 1996; Simons & Rensink, 2005). This appears to suggest that nontransient luminance changes do not attract attention. However, one should be cautious in making this conclusion, because awareness and attention are considered to be two different processes (see Lamme, 2003). This is revealed in the many reports of visual cues orienting attention when observers are not aware of the cue (e.g., Cole & Kuhn, 2010b; Kentridge, Nijboer, & Heywood, 2008; Weiskrantz, 2009). Indeed, to preempt part of our results, our experiments showed the opposite effect: Participants were *perfectly aware* that a luminance change had occurred, even when it was not associated with a transient, but this change failed to attract attention. Furthermore, observers in the typical change detection paradigm are explicitly instructed to look for a change. By contrast, in the typical attention-cueing paradigm, observers are asked to look for a target that is not explicitly task relevant. Thus, the change detection paradigm on its own cannot address the issue of whether or not masked luminance changes attract attention.

In the present series of experiments, one of only two items in an otherwise uniform visual array changed luminance, a change that preceded the onset of a target. The target occurred at the location of either the changing or the nonchanging item. Importantly, the luminance change either was visible or was briefly occluded by an additional object in the display. If luminance change can attract attention above and beyond its status as a transient, the change should orient attention, irrespective of its visibility. It is worth noting that the presentation of only two objects in the displays provides an extremely liberal test of whether luminance change can attract attention.

Experiment 1

In Experiment 1, we presented two outline boxes, one to either side of a centrally located fixation point (cf. Posner & Cohen, 1984; see Fig. 1). One of these figures changed luminance before the onset of a target. Either the luminance change was visible (i.e., was a transient) or was briefly occluded. This was achieved by a technique developed by Franconeri, Hollingworth, and Simons (2005), in which a large object traverses the display, moving either in front of the display items or behind them. When the object moves in front, a change in the display occurs at the point when all items are occluded. When the object moves behind, the same change occurs, but this time it is fully visible. The important difference between our experiment and Franconeri et al.'s was that, whereas they presented a new object as the display change, in our study we presented a luminance change to an already present object. If a change in luminance can attract attention without an accompanying transient, we should observe a classic validity effect in the luminance-occluded condition (i.e., when the large object moves in front of the figures)—that is, shorter RTs on valid than on invalid trials. By contrast, if luminance changes rely on their status as a transient to attract attention, a validity effect should only be observed in the luminance-visible condition (i.e., when the large object moves behind the figures).

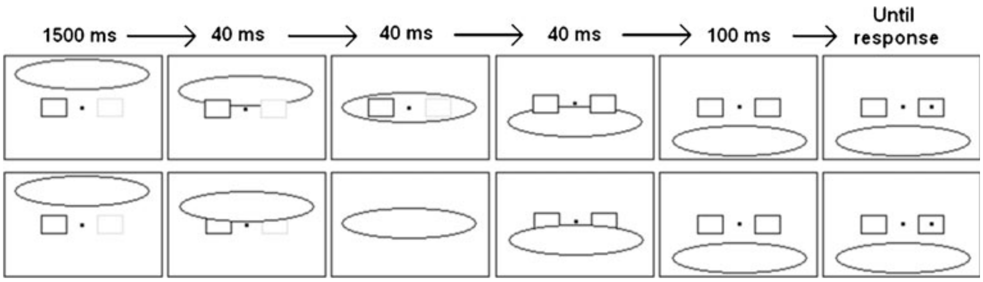

Fig. 1 Trial sequence for Experiment 1. The example shows a valid trial in which the cue and target both appear on the right side of fixation. The top row illustrates a luminance-visible trial, the bottom row a luminance-occluded trial

An additional aspect of our design was that participants were likely to be in singleton detection mode (Bacon & Egeth, 1994). As set out in the introduction, this top-down attention set is induced when participants are required to look for a target that is itself a singleton. This has the consequence of increasing the likelihood that a singleton cue will attract attention. In our first experiment, participants were set to look for the appearance of a singleton dot, with the cue also being a singleton. This, therefore, should increase the probability that the luminance change would attract attention.

Method

Participants A total of 18 undergraduate psychology students from the University of Durham participated in return for payment.

Stimuli and apparatus The two objects were outline squares measuring 3.8° in height and width. The thickness of the lines was 0.5°. The squares were located 4.2° to the left and right of the fixation point, measured to the nearest edge of the boxes. The luminance and x, y coordinates of the squares, measured in CIE colour space (using a Cambridge Research Systems ColorCal chromameter), were 0.3 cd/m^2 (.303, .284) for one of the squares and 17.8 cd/m^2 (.285, .325) for the other square. The luminance change cue was generated by changing the luminance of the lighter grey square to match the luminance of the darker square—that is, both became 0.3 cd/m^2 (.303, .284). This meant that the luminance values of the cued and noncued locations (i.e., the boxes) were the same when the target was presented, thus ensuring that target visibility was the same in both conditions. The moving disc was an outline figure measuring 7.6° in height and 21.8° in width. The thickness of its line was one pixel; its outline was 17.8 cd/m^2 (.285, .325) in luminance, and its inside was 42.5 cd/m^2 (.285, .326). The disc was initially located 3.1° above the fixation point, measured to its nearest edge. Its final resting position was 3.1° below the fixation point. The target was a small round disc (0.23° in diameter) measuring 17.8 cd/m^2 (.285, .325). All of the stimuli were presented against a light grey background measuring 42.5 cd/m^2 (.285, .326). The experiment was carried out in a single dimly lit room and was driven by a Pentium PC linked to an Eizo CRT monitor.

Design and procedure A within-participants 2 x 2 factorial design was used. The first factor was the location of the target with respect to the luminance change; targets appeared either inside the box that changed luminance (i.e., valid) or inside the nonchanging box (i.e., invalid). The second factor was whether the large disc moved in front of or behind the display items. The trial sequence is shown in Fig. 1. Each trial began with the presentation of a placeholder display containing the two squares and the occluder disc. After 1,500 ms, the disc moved quickly down the display in four successive steps, giving the appearance of a smooth motion sequence. In the luminance-occluded condition, the disc passed in front of the figures, whilst in the luminance-visible condition, the disc passed behind them. The target appeared 140 ms after the luminance changed occurred. The target display remained until the participant responded, and the beginning of a trial was initiated by the participant's response on the previous trial. Observers were seated approximately 70 cm from the display and were explicitly told to ignore the figures and events occurring in the "background," and simply to respond as soon as they detected the target. They were also instructed to maintain fixation for the entire duration of each trial and that although speed was paramount they should refrain from responding on "catch" trials. Two blocks of 192 trials were presented, equally divided amongst the four conditions. The targets and luminance changes occurred on the left or right with equal frequency. Additionally, a further 96 trials (20%) were presented in which no target appeared. These acted as catch trials and terminated automatically 2 s after the disc stopped. Hence, a total of 480 trials were presented in the experiment. A total of 24 practice trials were given following a demonstration trial. All trial types were presented in a random order.

Results and discussion

All RTs lying two standard deviations outside each participant's condition mean were omitted from the analysis. This resulted in the removal of approximately 5.1% of responses. The mean false alarm rate was 7.2%, and there were no misses. Mean RTs for the four conditions are shown in Fig. 2. A 2 × 2 ANOVA with luminance change (visible or occluded) and validity (valid or invalid) as the two factors found no significant main effect of luminance visibility, $F < 1$, and, at best, a small but nonsignificant effect of validity, $F(1,\ 17) = 2.5$, $p < .14$. There was, however, a significant interaction, $F(1,\ 17) = 5.5$, $p < .05$. Figure 2 suggests that the significant interaction is due to a validity effect in the luminance-visible condition but no such effect in the luminance-occluded condition. This was confirmed with additional analyses, showing a significant difference in the luminance-visible condition, $t(17) = 2.4$, $p < .05$, but no significant difference in the luminance-occluded condition, $t(17) < 1$ (95% confidence interval of the difference: lower = −3.7, upper = 5.2). In sum, the results from Experiment 1 clearly show that a luminance change attracted attention when it was visible but not when the same change was occluded. In other words, a luminance change was not able to marshal attention unless it was a sensory transient. Furthermore, the lack of capture in the luminance-occluded condition occurred despite the fact that participants were likely to be attentionally set for a singleton—that is, they were in singleton detection mode.

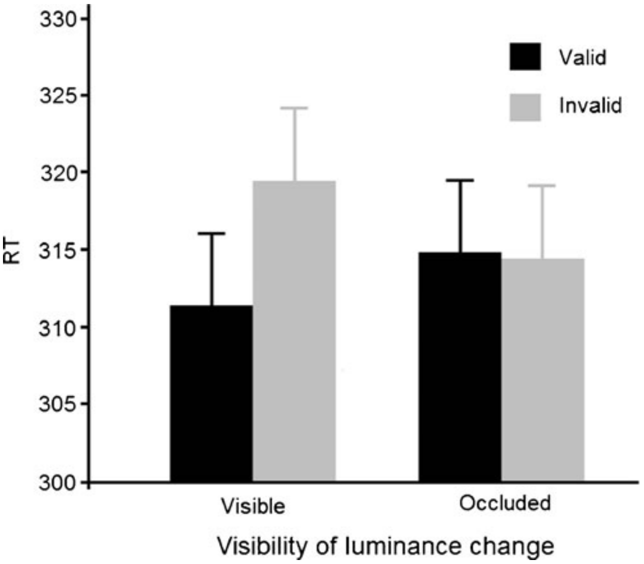

Fig. 2 Mean RTs for Experiment 1. Mean standard error bars are also included

Experiment 2

The results from Experiment 1 suggest that a luminance change cannot attract attention at a relatively high level of representation. Rather, such a change captures attention because of its status as a visual transient. However, it is possible that the luminance change failed to capture attention in the occluded condition because attention was shifted away from the figures to the large disc (in the upper part of the display) when it began to move. Although this would have also occurred for the luminance-visible condition, the saliency of the luminance transient in that condition may have been enough for it to attract attention, despite the competition for attention from the moving disc. A number of studies have shown that motion, and particularly the onset of motion, attracts attention. For example, Abrams and Christ (2003; see also Abrams & Christ, 2005; Franconeri & Simons, 2003, 2005; Skarratt et al., 2009; Zeki, 1974) presented observers with displays containing a number of block figure 8s. After approximately 3 s, segments of these figures disappeared to form letters, one of which was the target. Simultaneously, one of the items began to move whilst the others remained stationary. The results showed that when the target coincided with the moving item, RTs were independent of the display size. By contrast, when the target coincided with one of the stationary items, RTs increased as a function of display size. This showed that the motion item attracted attention. Abrams and Christ (2003) further argued that although motion per se does not capture attention, the *onset* of motion does. This was supported by an additional experiment in which a motion onset was compared directly against other kinds of motion (e.g., continuous motion and motion offset) within the same trial. The results showed that RTs for targets associated with the motion onset item produced the shortest RTs. In order to circumvent any potential confound induced by motion onset, the present Experiment 2 repeated the design of Experiment 1, with the exception that we occluded the luminance change with the use of a stationary pattern mask that briefly covered the middle of the display, including both squares (see Fig. 3). Thus, although the luminance change was again obscured, no motion occurred. Any capture effect was then compared with a condition in which no pattern mask was presented.

Method

Participants A total of 25 undergraduate psychology students from the University of Durham participated in return for payment. None had taken part in Experiment 1.

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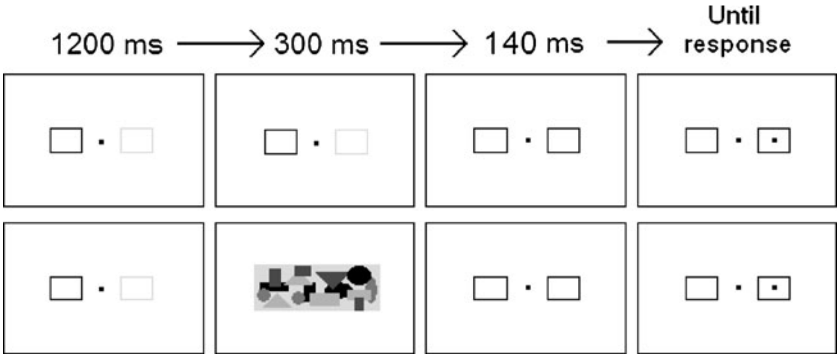

Fig. 3 Trial sequence for Experiment 2. The top row illustrates a luminance-visible trial, the bottom row a luminance-occluded trial

Stimuli and apparatus All aspects of the stimuli and apparatus were as described in Experiment 1, with the following exceptions. Instead of a moving disc, the stimulus that occluded the luminance change was a pattern mask that briefly overlaid both squares. This mask was rectangular (measuring 6.9° high and 20.0° wide) and comprised an array of many overlapping shapes and colours.

Design and procedure These were as described in Experiment 1. Thus, a within-participants 2 × 2 factorial design was used, with the location of the target with respect to the luminance change as the first factor (i.e., valid or invalid) and visibility of the luminance change as the second factor (i.e., visible or occluded). Each trial began with the presentation of a placeholder display containing the two squares, for 1200 ms. In the luminance-visible condition, one of the squares decreased in luminance, followed 140 ms later by the target. In the luminance-occluded condition, the procedure was identical, except that the pattern mask was presented for 300 ms before the luminance change. The luminance-visible and luminance-occluded conditions were blocked and counterbalanced. A total of 192 trials were presented, equally divided between the four conditions. Additionally, a further 48 catch trials (20%) were presented, in which no target appeared. Hence, a total of 240 trials (120 per block) were presented in the experiment.

Results and discussion

The removal of outliers resulted in the omission of approximately 4.1% of responses. The mean false alarm rate was 2.6%, and there were no misses. Mean RTs for the four conditions are shown in Fig. 4. The main effects of both luminance visibility and validity were significant, $F(1, 24) = 8.1$, $p < .01$, and $F(1, 24) = 10.2$, $p < .01$, respectively. There was also a significant interaction, $F(1, 24) = 5.7$, $p < .05$. Additional analyses showed that this interaction was due to a significant validity effect in the luminance-visible condition, $t(24) = 3.9$, $p < .001$, but not in the luminance-occluded condition, $t(24) < 1$ (95% confidence interval of the difference: lower = −7.5, upper = 5.4). In sum, these data concur with those from Experiment 1. A luminance change attracted attention only when it was visible, not when it occluded. Although it is not of central consideration, it is worth remarking on the main effect of visibility. Overall, RTs were significantly shorter in the luminance-occluded condition. This is likely due to an overall alerting effect generated by the onset of the mask prior to the appearance of the target (see, e.g., Fernandez-Duque & Posner, 1997; Skarratt et al., 2009; and the present General Discussion).

Experiment 3

Both Experiments 1 and 2 suggest that a luminance change is not able to attract attention unless it is a sensory transient. In Experiment 3, we examined whether attention could have been attracted to the luminance change in Experiment 2 using the phenomenon of *inhibition of return* (IOR; Posner

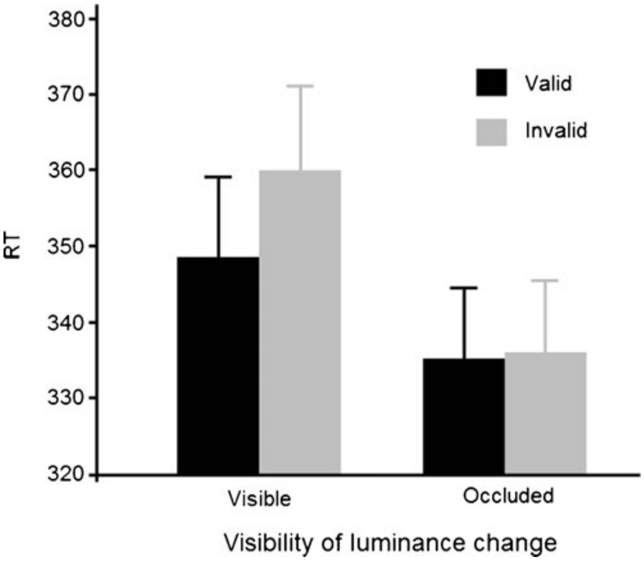

Fig. 4 Mean RTs for Experiment 2. Mean standard error bars are also shown

& Cohen, 1984). IOR is the slowing of responses to stimuli presented at a location that has been recently attended (see Klein, 2000, for a review). Importantly, it is now understood that facilitation and IOR are separable phenomena, rather than two parts of a unitary, biphasic process (Collie, Maruff, Yucel, Danckert, & Currie, 2000; Klein, 2000; McAuliffe & Pratt, 2005). This view is based on observations in which slight cue variations have brought about one effect without the other (e.g., Lambert, Spencer, & Hockey, 1991; Tassinari, Aglioti, Chelazzi, Peru, & Berlucchi, 1994; Tassinari & Berlucchi, 1993). Hence, the two effects are elicited independently by cue onset and coincide until the relatively brief facilitation effect has waned sufficiently, revealing the comparatively long-lasting IOR. Such findings therefore suggest that IOR can be used as an alternative to facilitation in determining whether a stimulus of interest has captured attention. Indeed, IOR has been used as an index of capture in a number of previous studies. For instance, Theeuwes and Godijn (2002) examined whether a unique colour presented amongst homogeneous distractors (i.e., a singleton) attracts attention (see the introduction above, and also Cole, Heywood, Kentridge, Fairholm, & Cowey, 2003; Cole, Kuhn, Heywood, & Kentridge, 2009; Gibson & Jiang, 1998; Johnson, Hutchison, & Neill, 2001; Jonides & Yantis, 1988). The results showed that a colour singleton did indeed generate IOR at its location. Theeuwes and Godijn concluded that the singleton must have initially captured spatial attention. In the present Experiment 3, we presented a luminance change at a display item, again either visible or occluded, and measured the degree of IOR induced.

Method

All aspects of the method were as described for Experiment 2, with the exception that the target appeared 800 ms after the luminance change occurred. Furthermore, 28 participants took part.

Results and discussion

All RTs lying two standard deviations outside each participant's mean were omitted from the analysis. This resulted in the removal of approximately 4.2% of responses. The mean false alarm rate was 1.7%, and there were no misses. Figure 5 shows the mean RTs for the four conditions. A 2 × 2 ANOVA showed no significant main effect of luminance visibility, $F(1, 27) < 1$, and no significant effect of validity, $F(1, 27) = 2.1$, $p < .2$. There was, however, a significant interaction, $F(1, 27) = 4.4$, $p < .05$. Additional analyses revealed that the interaction was due to an IOR effect in the luminance-visible condition, $t(27) = 2.1$, $p < .05$, but not in the luminance-occluded condition, $t(27) < 1$ (95% confidence interval of the difference: lower = −7.9, upper = 5.1). In sum, these results show that IOR was generated when the luminance change was visible, but not when it was occluded. Since inhibition did not occur in the latter condition, it is probable that the nonvisible luminance change did not attract attention. These data therefore support the findings from Experiments 1 and 2.

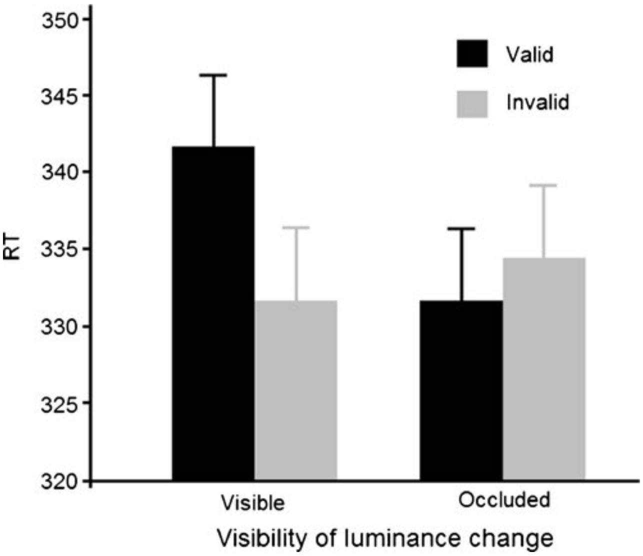

Fig. 5 Mean RTs for Experiment 3. Mean standard error bars are also shown

Experiment 4

In Experiments 1–3, participants were only required to indicate the presence of the dot probe. It is possible, however, that such a task is not sensitive enough to reveal an orienting effect of a masked luminance change. This issue concerns what effect attention has on a task in which observers merely report that an event has occurred (i.e., detection), as opposed to identifying some aspect of the event (i.e., discrimination). Early work suggested that spatial attention does not influence detection sensitivity. For instance, Bonnel, Stein, and Bertucci (1992) presented observers with two targets and instructed them to preferentially attend to one or the other. Bonnel et al. then assessed how attention influenced the participants' ability to either detect a luminance change to one of the targets or discriminate the polarity of the change. The results showed that whereas attention had no effect on the detection task, it did influence the discrimination judgement. Other work similarly failed to find an effect of attention on detection sensitivity (e.g., Davis, Kramer, & Graham, 1983; Graham, Kramer, & Haber, 1985; Shaw, 1984; Sperling, 1984;

Sperling & Dosher, 1986). Although the precueing paradigm (e.g., Posner & Cohen, 1984) and the present Experiments 1–3 have shown that spatial attention can improve (transient) luminance detection performance, the reported failures to show that attention increases detection sensitivity may suggest that detection tasks are less sensitive to the effects of attention than are discrimination tasks. This notion has received support from Brawn and Snowden (2000), who demonstrated that although spatial attention does increase detection performance, cueing effects are larger when observers are required to discriminate some aspect of a target. It is possible that attention has a greater effect on discrimination tasks due to greater task difficulty; clearly, a more difficult task is likely to benefit more from attention. However, Brawn and Snowden used signal detection analysis to equate their detection and discrimination tasks for difficulty, thus ruling out this explanation. Electrophysiological evidence has also provided support for the distinction between detection and discrimination with respect to attention. For instance, Mangun and Hillyard (1991) showed that whereas both P1 and N1 markers of a response are affected by a discrimination task, only the P1 component is affected by a detection task. In the present experiment, we replicated the procedure of Experiment 2, with the exception that observers were asked to discriminate a letter that could appear at one of the two locations rather than simply to detect a probe dot.

Method

All aspects of the method were as described for Experiment 2, with the following exceptions. Rather than a dot probe, the target was a letter S or H, 0.3 cd/m^2 (.303, .284), that measured 1.3° in height and 1.1° in width. Participants were asked to indicate as quickly as possible which of the two letters appeared by pressing a left-hand button for S and a right-hand button for H. No catch trials were presented. A total of 144 trials were presented in a single block and equally divided amongst all conditions. Furthermore, 18 psychology students from the University of Essex participated in return for payment.

Results and discussion

The mean RTs and numbers of errors for the four conditions are shown in Fig. 6. There was no difference in the error rates for valid and invalid trials in either of the visibility conditions, both ts(17) < 1.3, ps > .23. All RTs for correct responses lying two standard deviations outside each participant's mean were then omitted from the analysis. This resulted in the removal of approximately 4.4% of responses. A 2 × 2 ANOVA revealed a significant main effect of luminance visibility, $F(1, 17) = 7.2$, $p < .02$, and a significant effect of validity, $F(1, 17) = 6.5$, $p < .02$. There was also a significant interaction, $F(1, 17) = 10.2$, $p < .005$. Further analyses revealed that the interaction was due to a validity effect in the luminance-visible condition, $t(17) = 3.7$, $p < .002$, but not in the luminance-occluded condition, $t(17) < 1$ (95% confidence interval of the difference: lower = −10.2, upper = 10.4). In sum, these data closely replicate the results from Experiments 1–3. Whereas the transient luminance change oriented attention when it was visible, the nonvisible luminance change did not. This effect thus occurs irrespective of whether observers make a detection response or a discrimination judgement.

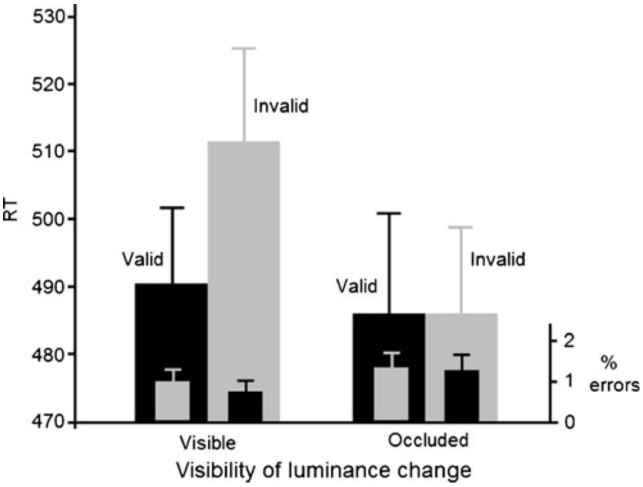

Fig. 6 Mean RTs and error rates for Experiment 4. Mean standard error bars are also shown

Experiment 5

Experiments 1–4 consistently demonstrated that the luminance change we presented is unable to attract attention unless it is a visual transient. It could be argued, however, that this degree of change (i.e., approximately 17.5 cd/m^2) is not great enough to reveal capture when it is obscured by a mask. Indeed, an abundance of work has revealed that capture by luminance cues is sensitive to the magnitude of the change. For instance, Rauschenberger (2003; see also Pashler & Badgio, 1985; Reynolds, Pasternak, & Desimone, 2000) examined whether a luminance change occurring at a 1,000-ms-"old" object could override an attentional control setting for new objects (see Folk et al., 1992, and the present introduction). Rauschenberger found this to be the case if the luminance change was sufficiently large; changes of approximately 50 cd/m^2 resulted in capture, whereas changes of approximately 10 cd/m^2 failed to do so. These findings partly motivated

Watson, Braithwaite, and Humphreys (2008) to assess whether the *preview benefit* effect (Watson & Humphreys, 1997), in which a preview of half of the items in a standard conjunction visual search task can facilitate search performance, is abolished if the preview items undergo a large luminance change simultaneous with target onset. Watson et al. found that the preview effect was resistant to a fourfold increase in absolute luminance (i.e., from 9.3 cd/m^2 to 38.8 cd/m^2). In the present Experiment 5, therefore, we repeated the procedure employed in Experiment 4, with the exception that the change in our luminance cue was much larger. Indeed, our luminance change was as great as we could generate (approximately 76 cd/m^2, as opposed to 17.5 cd/m^2), given the limitations of standard visual displays.

Additionally, unlike Experiments 1–4, Experiment 5 included a contrast polarity manipulation. With contrast polarity, display items can be brighter or dimmer than the background. On half of the trials, the luminance cue changed from black to white, whilst on the other half it changed from white to black, with both occurring against a mid-grey background. This manipulation was motivated by a number of studies that have shown an interaction between luminance contrast and luminance polarity (Aks & Enns, 1992; Enns, Austen, Di Lollo, Rauschenberger, & Yantis, 2001; Gilchrist, Humphreys, Riddoch, & Neumann, 1997; Sutter, Beck, & Graham, 1989). Specifically, these studies have revealed that sensitivity to differences in luminance contrast is increased when the change is accompanied by a reversal in polarity.

Method

Participants A total of 18 undergraduate psychology students from the University of Essex participated in return for payment.

Stimuli and apparatus All aspects of the stimuli and apparatus were as described for Experiment 4, with the following exceptions. Two placeholder squares appeared at the beginning of each trial, one of which was black, 0.2 cd/m^2 (.305, .281), and the other of which was white, 79.2 cd/m^2 (.287, .328). These appeared against a grey background 17.4 cd/m^2 (.289, .321) in luminance. The cue was generated by changing one of the squares from its original luminance value to the luminance of the other square—that is, from either black to white or white to black—resulting in both squares being black or white for the target display.

Design and procedure A within-participants 2 × 2 × 2 factorial design was used, with the location of the target with respect to the luminance change as the first factor (i.e., valid or invalid), visibility of the luminance change as the second factor (i.e., visible or occluded), and change direction as the third factor (i.e., from black to white or white to black). A total of 160 trials were presented within a single block, equally divided between the eight conditions. All other aspects of the procedure were as described for Experiment 4.

Results and discussion

Figure 7 shows the mean RTs and numbers of errors for the eight conditions. Only one significant difference in error rates for valid and invalid trials emerged: More errors were made in the invalid than in the valid conditions when the luminance change was visible and went from white to black, $t(17) = 3$, $p < .01$. All other ts < 1. With respect to RTs, all correct responses lying two standard deviations outside the participant's mean were omitted from further analysis. This resulted in the removal of approximately 5.3% of responses. A 2 × 2 × 2 ANOVA revealed significant main effects of luminance visibility, $F(1, 17) = 43.1$, $p < .01$, and validity, $F(1, 17) = 12.3$, $p < .001$, but no main effect of change direction, $F(1, 17) < 1$. Additionally, there was a significant validity x visibility interaction, $F(1, 17) = 10.1$, $p < .005$. The other three interactions were not significant, all Fs(1, 17) < 1.1, ps > .29. Further analyses revealed a significant validity effect for both luminance-visible conditions—that is, when the luminance change went from either black to white or white to black, $t(17) = 2.6$, $p < .02$, and $t(17) = 3.6$, $p < .002$, respectively. There was, however, no validity effect in either of the luminance-occluded conditions, ts(17) < 1 (95% confidence interval of the difference: for the black-to-white condition, lower = −11.1, upper = 13.4; for the white-to-black condition, lower = −17.9, upper = 8.1).

In sum, these results demonstrate that a luminance change failed to attract attention unless it was a visible transient. This occurred despite the fact that the change was the largest we could generate and included two types of luminance polarity changes (i.e., black to white, and vice versa).

Experiment 6

In Experiment 6, we assessed the possibility that the salience of the mask presented in Experiments 2–5 was such that it abolished any likelihood of the luminance change attracting attention. Put another way, a change in luminance might well have been able to attract attention, but the effects of our mask may have been too great to

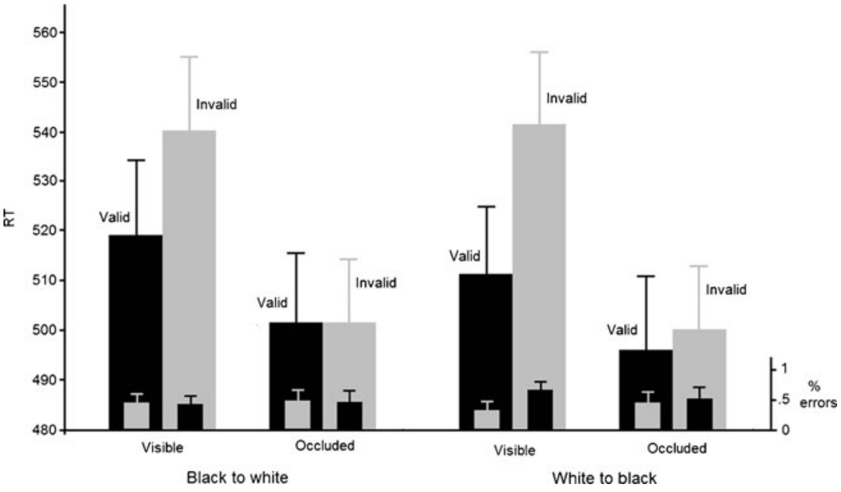

Fig. 7 Mean RTs and error rates for Experiment 5. Mean standard error bars are also shown

allow for capture to occur. If we can show that another type of change can overcome the effects of our mask, this will give us greater confidence that the failure of the luminance change to attract attention in Experiments 2–5 was not because the mask was too powerful.

In addition to luminance change, the appearance of a new object has been shown to be particularly effective in marshalling attention. One of the reasons for this is that new objects are invariably accompanied by a change in luminance at the onset location, and luminance change, as reviewed in the introduction, is itself an effective attention capture cue. However, following Yantis (1993), Cole and colleagues (e.g., Cole, Kentridge, Gellatly, & Heywood, 2003; Cole, Kuhn, & Liversedge, 2007; Cole & Liversedge, 2006; Gellatly & Cole, 2000) have argued that object onset has a special role in attention capture, beyond its accompanying luminance change. For instance, Cole, Kentridge, and Heywood (2004) showed that object onset is less susceptible to *change blindness* (Simons, 1996; Simons & Rensink, 2005) than are many other types of change that can occur in a visual display, such as colour change or object offset. In Experiment 6, a new object therefore acted as the cue. If a validity effect were to be observed using an onset cue, it would demonstrate that the salience of our mask was not too strong to allow for any kind of cue to attract attention.

Method

Participants A total of 18 undergraduate psychology students from the University of Durham participated in return for payment.

Stimuli and apparatus All aspects of the stimuli and apparatus were as described for Experiment 2, with the following exceptions.

Instead of a luminance change, the cue was the onset of a square (see Fig. 8). Two types of new onset were presented in two different blocks. The onset either was defined by colour, and the object was isoluminant with the background, or was accompanied by a change in luminance.[1] For the colour-defined trials, the background was red, measuring 29.7 cd/m^2 (.440, .392), and the objects (including the new onset) were green, measuring 29.6 cd/m^2 (.276, .441). Two target placeholders were present at the beginning of each trial, both 42.5 cd/m^2 (.285, .326), one of which changed to 0.3 cd/m^2 (.303, .284), denoting the target. For the luminance-defined trials, the background was grey, 17.8 cd/m^2 (.285, .325), and the objects were black, 0.3 cd/m^2 (.303, .284). The two target placeholders were 42.5 cd/m^2 (.285, .326), one of which changed to white, 77.7 cd/m^2 (.283, .325), denoting the target. Note that in the luminance-defined condition, the luminance change that occurred at the cue (i.e., as a result of the new object appearing) was identical to that of Experiments 1–4. Thus, any attention capture we observed as a result of the cue could not be due to the different magnitude of the luminance change.

Design and procedure A within-participants 2 × 2 factorial design was used with onset type (i.e., luminance- or colour-defined) and cue location with respect to the target (i.e., valid or invalid) as the two factors. Each trial began with the presentation of a placeholder display containing one square, for 1200 ms. The pattern mask was then presented for 300 ms. When this offset, two squares were present, (i.e., one new item appeared). A total of 192 trials were presented, equally divided amongst all conditions. Addi-

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[1] Although this new object has an accompanying luminance change, this condition cannot tell us anything regarding luminance change and attention capture. The luminance change was effectively confounded with the appearance of a new object representation, the formation of which might itself lead to capture.

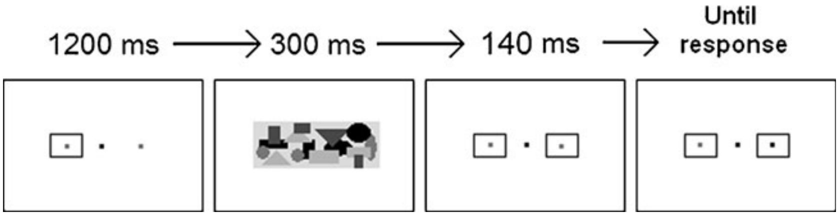

Fig. 8 Trial sequence for Experiment 6. This example shows the new object appearing on the right side of the display

tionally, a further 48 catch trials (20%) were presented in which no target appeared. This generated a total of 240 trials presented in the experiment. The luminance- and colour-defined trials were blocked and their presentation order counterbalanced across all participants. Note that, unlike Experiments 1–5, Experiment 6 did not present a luminance-visible condition.

Results and discussion

RTs lying outside two standard deviations from each participant's condition mean were omitted from the analysis. This resulted in the removal of approximately 4.6% of responses. The mean false alarm rate was 2.1%, and there were no misses. Mean RTs for the four conditions are shown in Fig. 9. A two-way ANOVA with onset type (luminance-or colour-defined) and validity (valid or invalid) as the two factors showed no significant main effect of onset type, $F(1, 17) < 1$, but a significant effect of validity $F(1, 17) = 14.6$, $p < .01$. There was no significant interaction, $F(1, 17) < 1$. Additional analyses revealed that the simple effects of validity were significant in both the colour-defined and luminance-defined conditions, $t(17) = 2.4$, $p < .05$, and $t(17) = 3.0$, $p < .01$, respectively. These data clearly show that the onsetting object attracted attention, even when its appearance was obscured by the mask.

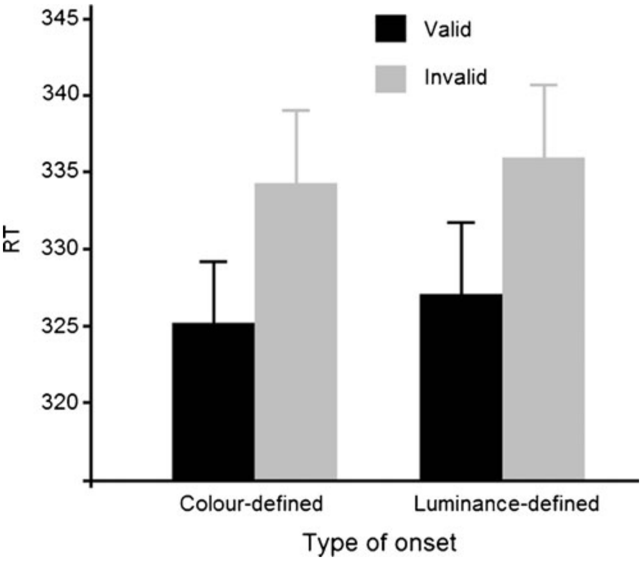

Fig. 9 Mean RTs for Experiment 6. Mean standard error bars are also shown

General discussion

The processing of differences in luminance underpins many visual phenomena, such as accommodation (Wolfe & Owens, 1981), spatial contrast sensitivity (Mullen, 1985), perception of motion (Lindsey & Teller, 1990), and stereopsis (Kingdom et al., 1999). Furthermore, a sudden change in luminance is particularly effective in attracting attention (e.g., Kröse & Julesz, 1989; Nakayama & Mackeben, 1989; Pratt & McAuliffe, 2001; Steinman et al., 1995; Theeuwes, 1991; von Grünau & Faubert, 1994). Given the importance of luminance change detection, the present series of experiments have addressed whether a luminance change can be represented at a relatively high level or whether luminance change detection is only effective as an attention-capturing cue when it is a sensory transient. Our results are consistent in showing that a luminance change is able to orient attention only when it is associated with a visual transient. When the transient was obscured by a larger additional event in the display, the luminance change failed to attract attention.

The importance of *transient* luminance change for the rapid orienting of attention makes sense from an evolutionary perspective. Although recognition of a stimulus is clearly important, this process is relatively complex, and hence slow. However, behaviourally important events that occur within a visual scene will almost always be associated with a transient change in luminance (e.g., motion onset and object looming), and evolution appears to have selected a fast-acting visual channel specifically dedicated to the processing of luminance. The magnocellular (M) visual pathway (e.g., Livingstone & Hubel, 1987) originates in the ganglion cells of the retina before projecting to the primary and secondary visual cortical areas via the lateral geniculate nucleus. It has long been established that this channel rapidly processes dynamic visual information associated with changes in luminance. Thus, the M pathway projects to area MT, well known for its central role in processing motion, the perception of which has its basis in luminance processing. Traditionally, therefore, the M channel has always been linked with luminance processing. However, other evidence has emphasised the involvement of additional pathways in the processing of transient information. For instance, Cavanagh and Anstis (1991) argued that the colour-opponent parvocellular (P) pathway may convey information concerning transient motion. Indeed, although motion discrimination thresholds are reduced when luminance cues are abolished, movement can still be perceived (Cavanagh, Tyler, & Favreau, 1984; Ramachandran & Gregory, 1978). Furthermore, many primate MT neurons have been shown to be sensitive to motion under conditions of isoluminance. More recently, the koniocellular (K) retinogeniculocortical pathway has also been identified as a possible transient-processing channel (see, e.g., Hendry & Reid, 2000). This projection is anatomically separate from the M and P pathways and, as with P cells, carries colour-opponent signals. However, whereas the P channel relays information concerning red–green opponency (i.e., information from long- and medium-wavelength selective cones), the K channel conveys blue-on signals via S-cone input (see Morand et al., 2000). Importantly, using an event-related potential mapping technique, Morand et al. showed that moving stimuli only visible to the K channel evoked relatively fast electrical fields (between 40 and 75 ms). This, the authors argued, suggests rapid activation of visual areas via K-channel input. Thus, the processing of potentially important transient information is not only conveyed by the M channel, but also by other fast-acting pathways.

The present findings provide evidence for the dissociation between attention and awareness. As we stated in the introduction, a wealth of research has shown that stimuli can orient attention even in the absence of awareness (e.g., Weiskrantz, 2009). The luminance-occluded conditions of our experiments additionally reveal that observers can be aware that an event has occurred (i.e., the luminance change) without orienting attention toward it. Awareness of the masked luminance change was confirmed in our Experiment 4, in which we asked participants after the experiment whether they had noticed what had changed when the stimuli reappeared subsequent to the offset of the mask. All reported that a luminance change had occurred. This is not surprising; the stimulus sequence in our luminance-occluded trials was analogous to a change detection procedure in which a single change occurs at one of only two objects presented against a uniform background. Change blindness is extremely unlikely to occur under such conditions. Indeed, the representation of our two objects is well within the capacity limits of visual working memory. For instance, observers are able to track four objects in a multiple-object tracking task (Alvarez & Cavanagh, 2004; Pylyshyn & Storm, 1988; Sears & Pylyshyn, 2000) and can hold approximately four objects in working memory in a change detection task (Luck & Vogel, 1997; Pashler, 1988; Vogel, Woodman, & Luck, 2001). In his review of the central findings in the field, Lamme (2003) posited a number of hypothetical models of how attention and awareness could interact. Although attention is usually assumed to gate or select what becomes conscious, Lamme's models don't always assume that attentional orienting is necessary for awareness to occur, as our results show. Instead, observers may be consciously aware of all incoming stimuli—most of which, however, are quickly forgotten.

It could be argued that one of the limitations of the present work is that our conclusions are effectively based on a null finding. That is, we have found no evidence for capture by a nontransient luminance change. However, Experiment 6 is particularly important in this respect. Recall that our final experiment examined whether the absence of a capture effect in Experiments 2–5 was due to the mask being too effective in obscuring the luminance transient. One can imagine a scenario in which a mask is so salient and long-lasting that any subtle change to a visual display would have little chance of attracting attention. However, the data from Experiment 6 showed that if the display change comprised an onsetting object, this change was able to attract attention. This gives us greater confidence in the absence of capture in Experiments 2–5. Furthermore, Experiment 5 presented the largest luminance change we could generate, and we have also consistently observed a robust capture effect with our transient luminance changes. Finally, as stated previously, the presentation of only two objects in our displays provided an extremely liberal test of whether luminance change can attract attention.

The present results provide further evidence for the notion that object appearance is particularly effective in attracting attention (e.g., Cole & Liversedge, 2006; Gellatly & Cole, 2000; Yantis, 1993). Although the magnitude of the (nonvisible) luminance change accompanying the cue (i.e., the new object) in Experiment 6 was equal to that of the cues used in Experiments 1–4, such a change was only able to attract attention when associated with a new object. This is therefore consistent with findings from, for example, the change detection paradigm, in which the types of change that are particularly resistant to change blindness have been examined. Cole et al. (2004) found that luminance changes occurring in a visual display resulted in relatively high levels of change blindness, as compared to object onsets. Although our methods were different, insofar that the changes in the present displays were not task relevant, the results from Cole et al. and from our Experiment 6 show that object appearance plays a particularly important role in attention capture.

One final aspect of the present results concerns a consistent alerting effect. *Alerting* is usually defined as improved performance immediately following a warning cue (Roberts, Summerfield, & Hall, 2006) and is often observed in attention studies, even though no shift in spatial attention has occurred (see Fernandez-Duque & Posner, 1997). Indeed, alerting and attention orienting are considered to arise from different neural systems, with the former being associated with the subcortical noradrenergic system, a system known to be involved in general arousal and modulated by behaviourally important stimuli (see, e.g., Aston-Jones, Foote, & Bloom, 1984). In Experiments 2–5, the luminance change was obscured by a large mask that appeared briefly. The mask is likely to have acted as a warning signal, thus resulting in relatively shorter RTs than when no mask was presented. This effect, however, did not occur in Experiment 3, where the interval between the mask and target was increased to 800 ms. It is likely that the facilitatory effect of the mask had waned by this point.

In summary, given the central importance of luminance change in vision, the present work has assessed whether such changes can be represented beyond the level of sensory processing. We found that luminance change has to be associated with a transient in order to attract attention.

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