The Prioritization of Feature Singletons in the Change Detection Paradigm

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Abstract. Six experiments are reported investigating whether a discontinuity in colour can accrue attentional priority. In addition to a standard visual search paradigm, we examined the degree to which colour singletons and nonsingletons are susceptible to change blindness. Results showed that changes occurring at colour singletons were relatively more resistant to change blindness. Although suggestive of bottom-up marshalling of attention, no prioritization of the singleton occurred when the most stringent test of stimulus-driven attentional attraction was employed, that is, when attending to the singleton was detrimental to the task. We conclude that a discontinuity in colour will attract attention unless an attentional set is contrary to singletons.

Keywords: attention, colour, vision, change blindness

General Introduction

The deployment of attention across the visual scene is often characterised as being the result of either goal-driven or stimulus-driven processes. Goal-driven, or top-down, selection is said to occur when an observer uses goals, beliefs or intentions, to guide their attention to an object of interest. Stimulus-driven, or bottom-up, selection by contrast, occurs when an external event automatically elicits attention independently of the observer's goals. Research over the past two decades has been concerned with identifying which of the two processes is the larger determinant of attentional prioritization, and under what circumstances each operates.

The notion that selection is primarily based on bottom-up processes assumes that attention will automatically be attracted to a unique property in a visual array. Indeed, this is a core assumption of a number of influential attention theories (e.g., Cave & Wolfe, 1990; Itti & Koch, 2000; Koch & Ullman, 1985; Wolfe, 1994, 1998). It follows therefore that an object possessing a unique colour should capture an observer's attention in a stimulus-driven manner. Supporting evidence for bottom-up capture by discontinuities in colour originally came from visual search studies which demonstrated that an irrelevant "colour singleton", present in the search display, slows reaction time (RT) compared to when the singleton is not present. Theeuwes (1991, 1992), for example, presented observers with an array of circles together with a single diamond. Line segments of different orientations appeared inside each shape and the observer's task was to determine the orientation of the line segment inside the diamond. Crucially, on one half of the trials one of the circles was a colour singleton, for example, an irrelevant red circle presented amongst green circles and the (green) diamond. Results showed that RT was elevated on those trials in which the colour singleton was present. The interference caused by the colour distractor suggested that selection occurs in a stimulus-driven manner since the participants were not able to ignore the singleton despite it being irrelevant to the task. Indeed, Theeuwes has posited that virtually *all* selection is stimulus-driven, with little or no contribution from top-down processes.

Bacon and Egeth (1994), however, argued that the results of Theeuwes (1991, 1992) could be attributed to the subtle working of a top-down mechanism. In a modification of Theeuwes' procedure, observers were presented with an array of circles and, crucially, other unique shapes in addition to the diamond. Bacon and Egeth found that search under these conditions abolished the colour singleton capture effect. The important difference is that observers could not have adopted the strategy of searching for a discontinuity (i.e., singleton) in order to find the target. Put another way, when the participants were set to search for a (shape) singleton, as in Theeuwes design, the colour singleton captured their attention. When, by contrast, the participants were not set to search for a singleton, as in Bacon and Egeth's variation, no capture by the colour singleton occurred. The authors argued that when the participants are in this so-called "singleton detection mode", *any* type of singleton will capture attention. In other words, attentional capture by colour singletons is contingent upon the observer adopting an attentional set for singletons.

This form of goal-driven attentional modulation is a specific version of *contingent voluntary orienting* (Folk, Remington, & Johnston, 1992). Folk et al. argued that the deployment of attention is solely dependent upon an observer's goal-directed attentional set, or their "attentional

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control settings". This is supported by data showing that the propensity with which a visual property is able to modulate attention is contingent on the stimulus sharing a feature that is relevant to an observer's current task. For example, in a variation of a standard visual search experiment, a colour cue was shown not to capture attention when the target was defined by a property other than colour. Folk and Remington (1998) further showed that attentional control settings can be specific such that a colour cue may only capture attention if it shares the same colour as the target.

The findings of Bacon and Egeth (1994) and Folk et al. (1992) thus suggest that any bottom-up attentional modulation by colour singletons can be overridden by top-down contingencies. Indeed, little evidence exists for capture by colour singletons in the absence of a relevant attentional set. For instance, in the seminal work of Jonides and Yantis (1988), observers searched for a target letter that appeared amongst distracting (nontarget) letters. One of the search elements was a colour singleton, but importantly was no more likely to be the target as it was any of the nontargets. Thus, there was no incentive for the participants to bias their attention towards the colour discontinuity. Additionally, since the target could not be found on the basis of searching for any feature discontinuity (i.e., the target was not itself a singleton) observers were not in singleton detection mode. Jonides and Yantis had therefore set up a critical test of whether a discontinuity in colour can elicit stimulus-driven attentional capture. Results however showed that RT increased as a function of display size both when the target coincided with the colour singleton and when it coincided with one of the nonsingletons. In other words, no capture occurred. The absence of a purely stimulus-driven colour singleton capture effect has been replicated by many authors (e.g., Folk & Annett, 1994 Folk & Remington, 1998; Franconeri & Simons, 2003; Gibson & Jiang, 1998; Lamy & Egeth, 2003; Lamy & Tsal, 1999; Lamy, Tsal, & Egeth, 2003; Mounts, 2000; Todd & Kramer, 1994; Yantis & Egeth, 1999). As Pashler, Johnston, and Ruthruff (2001) have stated, "In the absence of any top down influence, feature singletons simply do not capture attention".

Only one group of researchers have found an RT benefit for targets associated with colour singletons. In the study of Turatto and Galfano (2001; see also Horstmann, 2002; Turatto & Galfano, 2000; Turatto, Galfano, Gardini, & Mascetti, 2004), the participants performed a standard visual search task in which they were required to detect a rotated letter T amongst rotated letter Ls. Each of the (eight) letters appeared inside a circle, one of which was unique in colour. For example, one red circle appeared amongst seven green circles. As is usual, the target was no more likely to occur inside the colour singleton as it was any of the other circles. Additionally, since a rotated T amongst Ls does not "pop-out" there would have been no attentional control settings to search for the most discrepant item. That is, the T was not itself a singleton. As with Jonides and Yantis (1988), Turatto et al. had therefore set up a stringent test of whether colour singletons can capture attention in a purely stimulus-driven manner. However, unlike Jonides and Yantis, Turatto et al. found that RT *was* facilitated when the target and colour singleton corresponded.

Given the theoretical importance of how colour may modulate attention, and the number of studies suggesting no role for singletons, the central aim of the present work was to investigate whether colour singletons do indeed receive attentional priority. Importantly, we assessed this issue using a relatively new approach. In addition to employing a standard visual search procedure we used the *change blindness* paradigm. Change blindness refers to the phenomenon whereby observers often fail to notice a change to a visual scene if the change is accompanied by other simultaneous visual transients (e.g., Simons & Rensink, 2005). For example, change blindness can occur if a uniformly blank image is presented for a brief period between the original and subsequent scene containing the change (Simons, 1996). The rationale for our use of the procedure is based on the link between attention and the degree to which change blindness is induced (e.g., Rensink, O'Regan, & Clark, 1997). If a particular visual property (e.g., discontinuity in colour) receives attentional primacy, one should expect that property to be relatively less susceptible to change blindness (see for instance, Cole, Kentridge, Gellatly, & Heywood, 2003; Cole, Kentridge, & Heywood, 2004; Cole & Liversedge, 2006; Pisella, Berberovic, & Mattingly 2004; Ro, Russell, & Lavie, 2001; Scholl, 2000). Although this approach contrasts with the more traditional method of inferring attentional prioritization from visual search studies, the method is not unlike all other experimental paradigms in the sense that *relative performance* across different conditions of a given task is used to make inferences about cognitive processes such as attention.

In four of six experiments reported here (Experiments 2–5; Experiments 1 and 6 employed two variants of a standard visual search task) we presented observers with a change detection task in which a number of items appeared briefly, disappeared and reappeared (i.e., "flickered"). When the items reappeared, one of them had changed (e.g., changed in letter identity) and the task was to determine the location of the changing element. Crucially, one of the items was a colour singleton but the changing item was no more likely to be the singleton as any of the other (nonsingleton) items. Accuracy of detection for changes occurring at the singleton location was then compared with accuracy for changes occurring at nonsingleton locations. If singletons do indeed receive attentional priority, we should expect change detection performance to be greater for changes occurring at singleton locations than changes occurring elsewhere. This rationale was similarly employed by Scholl (2000) who also examined the degree to which colour singletons attenuate change blindness. In his experiment, one of twelve images of everyday objects changed orientation, and observers were required to locate the changing item. Scholl found that RT was reduced when the changing item happened to be a colour singleton. However, since Scholl was primarily concerned with the issue of whether change blindness is attenuated by regions of "central interest", his singletons were constructed to be highly salient on the basis of luminance. For this reason, Scholl's singletons were brighter (or dimmer) than the nonsingletons. Hence, Scholl's study was not directly concerned with the issue of *colour* and attention.

The present experiments examine the issue of how attention is modulated by colour *as a high level representation*. Colour, by definition, is a higher order construction of the brain. Thus, in order to examine the question of how colour modulates attention, one must necessarily control for lower level sensory aspects of the stimuli. This is illustrated by recent work reporting the paradoxical finding that attention can be modulated by colour in patients with cortical colour blindness, or cerebral achromatopsia. For instance, Cole, Heywood, & Kentridge (2005) reported a colour-modulated flanker compatibility effect (Baylis & Driver, 1992; Eriksen & Eriksen, 1974) in one such patient (see also Cole, Heywood, Kentridge, Fairholm, & Cowey, 2003). This "colour"-dependent attentional effect was in fact due to earlier intact mechanisms that process chromatic-contrast; on trials in which chromatic-contrast was absent, no colour flanker effect occurred. The need to control for low-level attributes of stimuli when examining colour and attention is relevant to other previous work that has examined the issue using the colour singleton paradigm. For instance, as with Scholl (2000), Johnson, Hutchinson, and Neill (2001) employed colour singletons that were not isoluminant with respect to the nonsingletons or the background. Any singleton effect using nonisoluminant stimuli may therefore be due to differences in luminance rather than colour.

The use of the change blindness method also circumvents problems of response end processes associated with RT measurement, problems that are not apparent with perceptual measurements. The dissociation between perception and response in experimental paradigms was noted by Milliken and Tipper (1998) who suggested that experimentalists often assume that the dependent measures employed to index an effect do not influence the effect itself. The authors stated that "We often make the assumption that cognitive machinery sits still while we measure it . . . behaviors studied in the laboratory, such as the speed of response to a probe event, are often assumed to be determined before the point in time at which we introduce our measuring instrument . . . we ought to be aware that the act of measurement may contaminate the measurement itself" (Milliken & Tipper, 1998, p. 216). Because the change detection method involves the participants making a purely perceptual decision, rather than emitting a speeded motor response, one can surmise that since our "measuring instrument" is introduced earlier in the system the measurement is less contaminated by additional (response) noise. The use of accuracy as a possibly superior measurement compared with RT has previously been noted by Gellatly, Cole, Fox, and Johnson (2003) and Rafal, Smith, Krantz, Cohen, and Brennan (1990).

Experiment 1

In Experiment 1, we employed a search task in order to assess, using this traditional technique, whether a discontinuity in colour can accrue bottom-up attentional prioritization. One of the central issues of attentional capture concerns which experimental tasks index goal-driven processes and which index stimulus-driven processes. As suggested in the Introduction section, for attention to be attracted in a purely stimulus-driven manner, the experimental paradigm should have no attentional control settings component such as singleton detection mode. One such task is the detection of a target letter presented amongst other (distracting) letters. This task is known to require focal attention since the target and distractors all comprise combinations of vertical and horizontal line segments (Wolfe, 1998). Hence, the target cannot be found on the basis of any featural discontinuity. In our first experiment, observers were presented with four letters, two on either side of fixation, and asked to decide as quickly as possible whether a target letter occurred on the left or right side. One of the letters was a different colour to the other three (i.e., a colour singleton) and there was a one in four chance that the target letter would coincide with the singleton.

The experiment was therefore similar to that of Jonides and Yantis (1988). One major difference however was that we did not manipulate set-size. Turatto and Galfano (2000) have argued that varying set-size in a singleton experiment introduces a confound which reduces the sensitivity of the experiment to any colour singleton effect. They reasoned that the singleton can be considered as the signal and the onset of the distractors as noise. With a relatively small number of search items, there is a relatively high signal to noise ratio. This is due to the singleton only having to compete with maybe two other items also appearing. As the number of search items increases, the signal to noise ratio decreases because of the larger noise generated by more onsets. The result is that any capture effect of the singleton is reduced as set-size increases thus producing a serial search pattern. Turatto et al. (2004) systematically assessed whether set-size manipulations were indeed less sensitive to singleton effects. The authors found that when data were analysed based on the set-size method no prioritization for singletons was observed. When however, data were analysed by assessing each set-size independently, priority for singletons was found. Therefore, the present Experiment 1 adopted the nonset-size method as an attempt to increase sensitivity. With a constant set-size of four, the validity of the colour singleton cue and target was varied such that the target either coincided with the singleton (i.e., valid trials) or coincided with one of the three nonsingletons (i.e., invalid trials).

Method

Participants

Twelve undergraduate psychology students took part.

Stimuli and Apparatus

Four letters were presented each measuring 1.8° in height and 1.4° in width (see Figure 1). The centre of each item was positioned on the outside of an imaginary circle whose radius measured 2.6°. The letters were either red or green against an isoluminant grey background measuring approximately 32.2 cd/m^2. The coordinates of the three colours, measured in CIE colour space (using a Cambridge Research Systems ColourCal chromameter), were $x = 0.436$ and $y = 0.331$ for

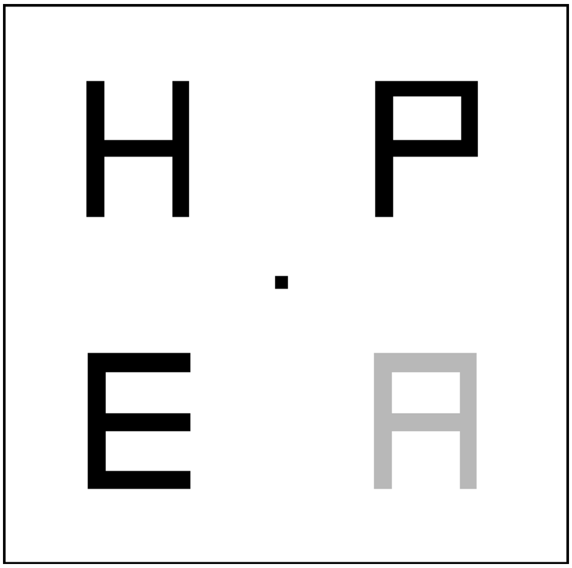

Figure 1. The type of stimulus display used in Experiment 1. The figures in the actual experiment were red and green, rather than black and grey as shown here.

red, $x = 0.287$ and $y = 0.590$ for green and $x = 0.283$ and $y = 0.329$ for grey. The target was the letter H whilst the three distractors were chosen randomly from the letters A, C, E, F, L, O, P, S and U. The experiment was carried out in a dimly lit room and was driven by a Pentium PC linked to a standard colour monitor running at 60 Hz.

Design and Procedure

A within-participant, single-variable two-alternative forced choice procedure was used. The target could either appear at the location of the colour singleton (i.e., a valid trial) or else appear at one of the nonsingleton locations (i.e., an invalid trial). Each trial began with the presentation of a fixation point for 1,000 ms before the appearance of the search display. The participants were asked to indicate whether the letter H was on the left or right side of fixation by pressing a right hand or left hand button. An emphasis was placed on speed whilst maintaining accuracy. The participants were also asked to remain fixated on the point located in the centre of the screen. The beginning of a trial was initiated by participant's response on the previous trial. Observers were seated approximately 80 cm from the display. On one half of the trials, a single red item appeared amongst three green items and on the other half, a single green item appeared amongst three red items. Thirty-six practice trials were given. One hundred and sixty trials were presented in the experiment. All trial types were presented randomly.

Results and Discussion

For each participant, outliers and incorrect responses were excluded from analysis. The criterion for an outlier was an RT more than two standard deviations above or below the mean for each condition for each participant. This resulted in the removal of approximately 6% of all responses. RT to localise a target coinciding with the colour singleton was 560 ms ($SD = 61$) compared with 568 ms ($SD = 80$) to localise a target located at a nonsingleton. This difference did not prove to be significant, $t(11) < 1$, $d = 0.24$ (Lower 95% CI = −13.3; Upper 95% CI = 29.1). These data clearly show that RT was not facilitated when the target occurred at the location of a colour singleton. That is, the colour discontinuity did not attract attention. Thus, when a strict criterion for bottom-up attentional prioritization is applied, i.e., when observers do not have an attentional set for singletons, no singleton prioritization occurs. These findings therefore support Jonides and Yantis' (1988) original assertion, and the numerous other studies demonstrating the absence of a colour singleton capture effect (e.g., Franconeri & Simons, 2003; Gibson & Jiang, 1998; Lamy & Egeth, 2003; Lamy & Tsal, 1999; Lamy et al., 2003; Mounts, 2000; Yantis & Egeth, 1999).

Experiment 2

In Experiment 2, we introduce the change blindness method to provide a further assessment of whether task irrelevant colour singletons can accrue bottom-up attentional prioritization. We noted earlier that if a particular visual property is thought to accrue attentional priority this might be expected to manifest itself in terms of facilitated change detection performance. Hence, if a colour singleton receives enhanced processing compared with nonsingletons we should expect that a singleton undergoing some form of change will be more resistant to change blindness compared with a change occurring elsewhere.

Experiment 2 used a variant of the "one-shot" change detection procedure whereby observers are required to indicate where a change occurred after only one presentation of the change (Rensink, 2000). This contrasts the more usual "continual alternation" method where the two critical images are continually repeated until the observer detects the change. As with Experiment 1, observers were presented with four letters, one of which was a colour singleton. The letters appeared briefly before disappearing and reappearing again. When they reappeared one of them had changed identity and the participant was required to indicate whether the change occurred at one of the two letters on the left side of fixation or at one of the two letters on the right side (see Figure 2). Importantly, the changing item was no more likely to be the singleton as it was any of the nonsingletons. Additionally, one can also argue that the target cannot be found on the basis of its saliency. Recall that a salient target (Theeuwes, 1991, 1992) induces the observer to adopt the strategy of searching for the most discrepant item, which results in capture by a salient singleton. Despite the singleton being nominally irrelevant, a subtle form of top-down processing will have modulated the capture effect. Clearly, the target (i.e., change) in a change detection trial cannot be found efficiently, hence the term change blindness. Therefore, because observers in Experiment 2 are unlikely to have adopted a relevant

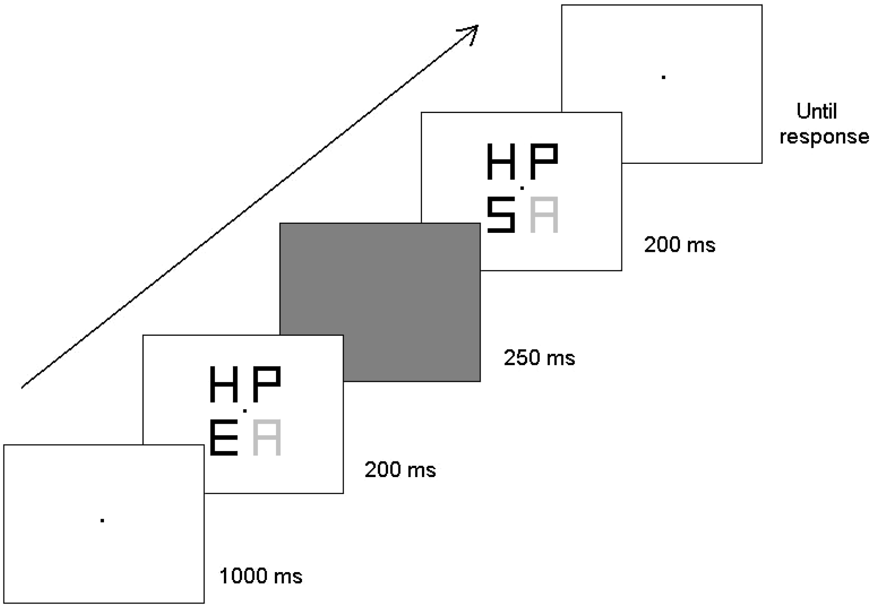

Figure 2. Trial sequence for Experiments 2, 4 and 5. In the example shown, the letter E is replaced by the letter S after the flicker. Note that the letters were chromatic and the figures are not drawn to scale.

attentional set, any prioritization of the singleton can be assumed to occur in a stimulus-driven manner.

Method

Participants

Fifteen undergraduate psychology students took part. None of the participants took part in Experiment 1.

Stimuli and Apparatus

All aspects of these were identical to those reported for Experiment 1 with the exception that the target was a change to the display when it reappeared. Additionally, the blank ("flicker") frame between the two images was uniformly black (0 cd/m^2).

Design and Procedure

A within-participant, single-variable (valid cue vs. invalid cue), two-alternative forced choice procedure was used. Figure 2 shows the trial sequence. A fixation point appeared for 1,000 ms before the appearance of the first image for 200 ms. A blank frame of 250 ms then followed before the onset of the second image for 200 ms. The initial frame then reappeared until the participant responded. The participants were asked to indicate whether they detected a letter change on the right or left side of fixation by pressing a right hand or left hand button. An emphasis was placed on accuracy rather than speed. If the change was not detected the participants were asked to guess. The beginning of a trial was initiated by participant's response on the previous trial. The participants were also instructed to maintain fixation for the entire duration of each trial and were seated approximately 80 cm from the display. On one half of the trials, a single red item appeared amongst three green items and on the other half, a single green item appeared amongst three red items. Twenty-four practice trials were given following a demonstration trial. One hundred and sixty trials were presented in the experiment. All trial types were presented randomly.

Results and Discussion

On average, the participants correctly localised the changing item on 88.1% (*SD* = 7.4) of valid trials (i.e., when cue and target occurred at the same location) and on 83.1% (*SD* = 9.3) of invalid trials. Each observer's correct detection score for valid and invalid trials was entered into a within-participant *t* test. The difference in detection rates proved to be significant, $t(14) = 2.27$, $p < .05$, $d = 0.58$. These data clearly show that when the changing item coincided with the colour singleton detection performance was increased compared with when the changing item coincided with one of the nonsingletons. This suggests that the discontinuity in colour received processing prioritization. Crucially, because the target could not be detected efficiently due to its lack of saliency, it is reasonable to assume that this prioritization occurred in the absence of any attentional set for singletons. This, together with the fact that the change was no more likely to occur at the singleton than at any of the other items, suggests that priority for the colour discontinuity was stimulus-driven.

It is possible, however, that the participants' increased change detection performance at the singleton resulted from a response bias independent of whether the change was detected or not. If observers simply chose the side where the singleton appeared, either consciously or unconsciously, we could expect a similar pattern of results. One way to assess this is to compare detection accuracy for changes occurring at the singleton with changes occurring at the nonsingleton that appears on the same side. If the participants' enhanced performance at the singleton was merely due to a bias of responses to the side containing the singleton, there should be no difference in performance between these two conditions. By contrast, if the singleton was genuinely attracting attention, accuracy should be greater at the singleton location. Results from this analysis showed that the mean detection rate for the singleton and nonsingleton conditions was 88.1% ($SD = 7.4$) and 83.2% ($SD = 9.1$), respectively. This difference proved to be significant, $t(14) = 2.51, p < .02, d = 0.65$. Thus, reduced change blindness at the singleton cannot be explained by a response bias.

Experiment 3

The aim of Experiment 3 was to investigate whether the singleton effect reported in Experiment 2 induces one of the many reported consequences that follow from attentional prioritization. If one of these effects is shown to occur, we can have greater confidence that the singleton effect is due to an attentional mechanism. Indeed, a more compelling demonstration of colour singleton priority would be one in which the phenomenon induces an accompanying effect that follows from a redistribution of spatial attention. A number of studies have shown that when attention is attracted to a given location, there exists a region of facilitated processing in the surrounding area (e.g., Downing & Pinker, 1985; Eriksen & St. James, 1986; LaBerge, 1983). Although disagreement revolves around the precise nature of this "attentional field", all studies assume some form of facilitation near the locus of a "precue" which then decreases as a function of distance. Eriksen and Hoffman (1973), for instance, found that the interference created by distractors in a response competition paradigm decreased as target-flanker distance increased. This "attentional gradient" disappeared at a distance of approximately 2°. The notion that spatial attention is organised in a graded manner has received support from many authors (Anderson, 1990; Egly & Homa, 1991; Eriksen & Hoffman, 1973; Henderson, 1991; Klein & McCormick, 1989; Mangun & Hillyard, 1988). Indeed, as Handy, Kingstone, and Mangun (1996) have pointed out, gradient-like patterns have been observed in studies that do not specifically address the issue of attentional distribution (e.g., Miller, 1991).

If the prioritization of the singleton observed in Experiment 2 is due to the marshalling of spatial attention, one might expect a similar pattern of data whereby items located adjacent to the singleton accrue a processing benefit relative to those located further away. We carried out a variation of the change detection procedure used in Experiment 2 that enabled us to examine any singleton-target distance effect. Rather than using letter stimuli, we presented observers with an array of six squares, one of which shifted location after the blank (i.e., "flicker") frame (see Figure 3). The six squares were arranged such that they were located on the edge of an approximate circle around the fixation point.[1] As with Experiment 2, one of the display items was a colour singleton and the participants were asked to decide the side on which the change occurred. Additionally, the change was no more likely to occur at the singleton element than it was at any of the other elements. We then assessed change detection performance for changes occurring at, (1) the location of the colour singleton, (2) items adjacent to the singleton ("singleton-plus-one"), (3) items two positions away from the singleton ("singleton-plus-two") and (4) items three positions away from the singleton ("singleton-plus-three"). The three nonsingleton positions equated to an approximate singleton-target distance of 1.1°, 2.6° and 3.5°, respectively. Since Experiment 3 used different stimuli from those of Experiment 2, we were also able to assess the reliability of the change detection method in demonstrating the colour singleton effect.

Method

Participants

Twelve new undergraduate psychology students took part.

Stimuli and Apparatus

Six squares were presented, each measuring 0.86° in height and width. Three were located on each side of the fixation point and formed an approximate circle. Distance between the singleton and nonsingleton items were measured from the nearest edges of the two squares. All other aspects of the stimuli (e.g., colour and luminance values) and apparatus were as described previously.

Design and Procedure

There were four within-participant levels of a single factor. The four levels were the distance between the singleton item and the nonsingleton items (target at singleton, singleton-plus-one, singleton-plus-two and singleton-plus-three). The trial sequence is shown in Figure 3. The centrally located fixation point appeared for 1,000 ms before the onset of the first image for 117 ms. A blank frame then appeared for 84 ms followed by the onset of the second image for 117 ms. The blank frame then reappeared until

[1] If the squares had been located on the edge of a perfect circle, participants could have performed the task by simply noting which of the squares lay outside of the circle gestalt.

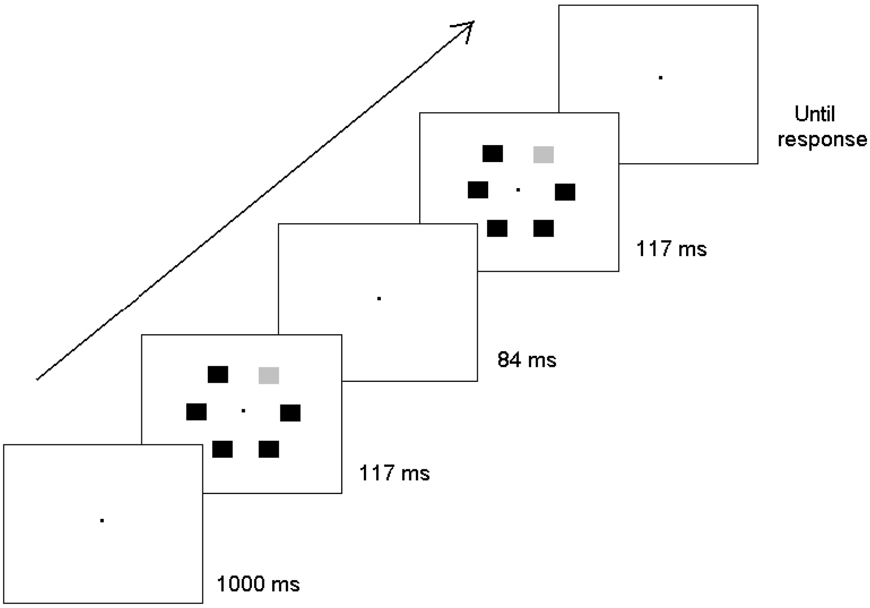

Figure 3. Trial sequence for Experiment 3. In this example, the left middle square has shifted to the right after the flicker. The squares in the actual experiment were red and green. The figures are not to scale.

the participant responded. When the squares reappeared, one of the squares had moved either to the left or to the right by a distance of 0.29°. There was a one-in-six chance that this occurred at the singleton item. All other aspects of the design and procedure were as described for Experiment 2 with the exception that 216 trials were presented in the experiment. Hence, there were 36 valid trials and 180 invalid trials.

Results and Discussion

Mean change detection rates for the target-at-singleton, singleton-plus-one, singleton-plus-two and singleton-plus-three conditions were 74.0% (*SD* = 8.2), 64.6% (*SD* = 10.5), 57.4% (*SD* = 9.8) and 58.4% (*SD* = 12.6), respectively. Each observer's correct detection score for the four conditions was entered into a within-participant ANOVA. The difference in detection rates was significant, $F(3, 33) = 19.3$, $p < .001$, $\eta^2 = 0.637$. We then carried out three planned comparisons, using Bonferroni's correction in order to guard against Type I error. Detection at the singleton item was significantly better than at the singleton-plus-one location, $t(11) = 3.73$, $p < .01$, $d = 1.08$, and the difference between the singleton-plus-one and singleton-plus-two conditions was also significant, $t(11) = 3.27$, $p < .01$, $d = 0.94$. There was however no difference between the singleton-plus-two and singleton-plus-three conditions, $t(11) < 1$, $d = 0.16$. These data therefore reveal that a change occurring at the colour singleton item resulted in reduced change blindness relative to changes at the nonsingleton items. Additionally, squares located adjacent to the singleton also accrued enhanced performance. Squares located further away did not accrue any such facilitation. As with Experiment 2, we examined the possible influence of response bias on the singleton effect by comparing accuracy for changes occurring at the singleton with changes occurring at the nonsingleton items located on the same side. The observed differences of 74.0% (*SD* = 8.2) and 66.3% (*SD* = 10.5) proved to be significant, $t(11) = 3.0$, $p < .02$, $d = 0.863$. Hence, a response bias cannot account for the singleton effect.

The first important finding from Experiment 3 is that the colour singleton suffered less change blindness relative to the nonsingleton elements, thus replicating the basic effect observed in Experiment 2. This provides further evidence that a discontinuity in colour does indeed receive processing primacy. Additionally, the effect has been shown to induce one of the many phenomena that follow from attentional prioritization, that is, enhanced performance for the detection of targets in the region immediately surrounding the attended area. This attentional field was characteristic of the classic "gradient" whereby facilitation was maximal at the locus of attention and decreased in the immediate surround (e.g., Eriksen & Hoffman, 1973). Moreover, the size of this region, extending up to approximately 3.0°, is consistent with many other reports (e.g., Steinman, Steinman, & Lehmkuhle, 1995). Because the singleton effect induced this common phenomenon, this suggests that the mechanism responsible for the singleton priority effect is an attentional mechanism concerned with the redistribution of resources.

Experiment 4

Experiments 2 and 3 suggest that attentional prioritization for colour singletons occurred in the absence of a relevant attentional set for singletons. One might say that participants' attentional control settings (Folk et al., 1992) were set at neutral with respect to the target. Additionally, attentional control settings operate extremely subtly. So subtly in fact that the participants are usually unaware that they are employing a particular contingency with respect to the cue as well as the target. Indeed, paradoxically attentional control settings appear to operate automatically. Thus, a singleton red cue will virtually guarantee attentional capture by a singleton red target. The aim of Experiment 4 was to assess the colour singleton priority effect when observers' control settings were explicitly biased against the singleton. This was achieved by having the target (i.e., change) correlate negatively with the singleton (see Turatto & Galfano, 2001, for a similar manipulation). Specifically, we replicated Experiment 2 with the sole exception that the target was half as likely to occur at the singleton location as it was at the (three) nonsingleton locations, and observers were informed of this. Thus, rather than having a *neutral* attentional set with respect to the colour singleton, our design meant that observers had an attentional set overtly concerned with the singleton in the sense that attending to it was detrimental to the task. This therefore is explicitly top-down, as opposed to the subtle form characteristic of attentional control settings. The crucial point is that this design enables bottom-up colour singleton priority to be tested under the strictest circumstances. As Schneider and Shiffrin's (1977) classic work argues, a process can only truly be considered to be automatic if the phenomenon occurs independently of the observer's goals.

Method

All aspects of the method were identical to that reported for Experiment 2 with the following exceptions. Fifteen new participants took part in the experiment which occurred in a different laboratory (but with the same equipment). For the experiment, 20 trials were presented in which the change occurred at the singleton location and 120 trials in which the change occurred at the three nonsingleton locations. This made a total of 140 trials. Additionally, observers were informed that although the change could occur at any of the four locations it was half as likely to occur at the odd coloured item.

Results and Discussion

Observers correctly localised the changing item on 83.3% ($SD = 9.6$) of valid trials and on 82.1% ($SD = 7.8$) of invalid trials. Each observer's correct detection score for the two conditions was entered into a within-participant t test. The difference in detection rates was not significant, $t(14) < 1$, $d = 0.18$ (Lower 95% CI = −2.33, Upper 95% CI = 4.86). Thus, when the changing item coincided with the colour singleton detection performance was not facilitated; detection was as efficient when the change occurred at one of the nonsingletons. This clearly implies that the singleton did not receive prioritization and is therefore in direct contrast to Experiments 2 and 3. The critical difference between the present experiment and Experiments 2 and 3 is that it paid observers not to attend to the colour singleton in the current task. This was because there was less chance of the target occurring at that location. Recall that strict *automatic* processing is usually considered to have occurred if an effect is observed independently of the observer's intentions (Schneider & Shiffrin, 1977). Hence, when this most stringent of criteria is applied, even a singleton that is able to attract attention in the absence of a relevant attentional set (i.e., Experiments 2 and 3) does not *automatically* attract attention.

We posit that a discontinuity in colour will attract attention when attentional control settings are set at neutral. When, by contrast, control settings are contrary to singletons the same discontinuity in colour will no longer attract attention. It is possible however that the singleton did automatically attract attention but the fact that the target was unlikely to occur at this location lead to rapid disengagement from the singleton. It is also worthy of note that changes coinciding with the colour singleton in Experiment 4 were *not detected less frequently* than changes that occurred elsewhere. If selection was completed under top-down control one should have expected the singleton to be inhibited because observers were aware that the target was less likely to occur at that location.

Experiment 5

On the basis of Experiments 2–4, we have suggested that a discontinuity in colour attracts attention unless attentional control settings are contrary to singletons. It follows therefore that if the target correlates negatively with the singleton, as in Experiment 4, the singleton should still accrue attentional priority if observers are unaware of the target-singleton correlation. The aim of Experiment 5 was to assess this. Specifically, we replicated Experiment 4 with the sole exception that observers were not informed that the target was half as likely to occur at the singleton location. We predict that the colour singleton will receive processing priority because observers will not have an attentional set contrary to singletons, this despite the fact that attending to the singleton is detrimental to the task.

Method

All aspects of the method were identical to that of Experiment 4 with two exceptions. Ten new participants took part in the experiment and observers were not informed of the target-singleton contingency.

Results and Discussion

Observers correctly localised the changing item on 87.0% ($SD = 4.8$) of valid trials and 79.2% ($SD = 10.5$) of invalid trials. Each observer's correct detection score for the two conditions was entered into a within-participant t test. This difference was significant, $t(9) = 2.59$, $p < .05$, $d = 0.82$. Additionally, when we include only the trials where the change occurred on the singleton side, participants' change detection at the singleton location (87.0%, $SD = 4.8$) was significantly better than when the change occurred at the nonsingleton location (77.5%, $SD = 11.2$), $t(9) = 3.38$, $p < .01$, $d = 1.06$. This rules out the possibility of any response bias accounting for the effect.

As with Experiments 2 and 3, but unlike Experiment 4, we have again observed attenuated change blindness for a change that coincided with a colour singleton. Since observers were not informed that attending to the singleton was detrimental to the task, they would not therefore have adopted an attentional set biased against the singleton. As hypothesised, a discontinuity in colour will accrue attentional priority unless a contrary attentional set is adopted. This therefore supports the findings of Turatto and Galfano (2001) who used a similar logic and manipulation.

Experiment 6

We have suggested throughout that our use of the change detection method indexes stimulus-driven priority for colour singletons. No relevant attentional set for saliency was assumed because the target (i.e., change) in a change blindness task is not, by definition, salient. However, an alternative interpretation might also explain the results. In order to detect the change in a change blindness trial, the observers necessarily have to compare a representation of the initial display with the subsequent display. This comparison could encompass an attentional set for a featural discrepancy, such as a sole motion transient or changed figural effect, which could be conceived as a form of singleton attentional set. In other words, there was something unique at the target location not apparent at the other (nontarget) locations. Thus, singleton detection mode was possible even though the letters required attention to identify. Experiment 6 therefore investigated whether colour singleton primacy could be obtained using a different technique from the change detection method, one in which singleton detection mode is unlikely to be employed. If singleton prioritization can be shown using two converging dependent measures, we can have greater confidence that the phenomenon is not due to any particular characteristics of the change detection method.

We employed a variation of the standard search paradigm used in Experiment 1 whereby observers are required to detect a target letter in a display of distractor letters, a task known to require focal attention (Wolfe, 1998). The crucial difference was that the search display occurred for a brief period only and percentage correct (i.e., accuracy) performance was calculated for the different conditions. In Experiment 2 we posited that tasks associated with perceptual measurement have the potential to be more sensitive to any colour singleton effect compared with RT measurement. Similar to the change detection method, Experiment 6 involved observers making a perceptual decision, rather than performing a speeded response. Four letters, two located either side of fixation, were presented for 150 ms, followed by a mask, and observers were asked to decide on which side the target occurred. As with Experiments 1–5, one of the display items was a different colour to the other and there was a one in four chance that the target letter would coincide with the singleton. If a discontinuity in colour receives attentional facilitation, targets coinciding with the singleton should be detected more frequently than targets coinciding with one of the nonsingleton items.

Method

Participants

Sixteen new observers took part.

Stimuli and Apparatus

All aspects of these were as reported for Experiment 1 with the exception of the mask. The mask was generated by overlaying (i.e., replacing) the letters with black (0 cd/m^2) block figure 8s.

Design and Procedure

A within-participant, two-alternative forced choice procedure was used. The target could appear either at the colour singleton or at one of the three nonsingletons. Each trial began with the appearance of a fixation point for 1,000 ms followed by the onset of the search display for 150 ms and then the mask. The participants were asked to indicate whether the letter H occurred on the left or right side of fixation. Responses were made by pressing a right hand or left hand button and an emphasis was placed on accuracy rather than speed. Thirty-six practice trials were given before the experiment proper. A total of 160 trials occurred in the experiment. All other aspects of the design and procedure were as described for Experiment 1.

Results and Discussion

The participants correctly localised the target on 88.4% ($SD = 6.41$) of valid trials and on 77.6% ($SD = 7.18$) of invalid trials. Each observer's correct detection score for both conditions was entered into a within-participant t test. The difference in accuracy was significant, $t(15) = 6.18$, $p < .001$, $d = 1.54$. Hence, when the target coincided with the colour singleton, detection performance was greater than when the target occurred at one of the nonsingletons. Based on the findings from Experiment 3 we then carried out additional analysis in order to investigate whether any gradient of attention occurred around the prioritized element. Detection accuracy was calculated for changes occurring at the colour singleton, at the singleton-plus-one location (i.e., changes at the items adjacent to the singleton), and at the singleton-plus-two location (i.e., opposite). Mean detection accuracy for these three conditions were 88.4% ($SD = 6.41$), 80.6% ($SD = 7.2$) and 72.4% ($SD = 9.5$), respectively. Detection at the singleton item was significantly better than at the singleton-plus-one location, $t(15) = 4.8$, $p < .001$, $d = 1.23$ and the difference between the singleton-plus-one and singleton-plus-two conditions was also significant, $t(15) = 5.9$, $p < .001$, $d = 1.99$. This replicates the effect observed in Experiment 3; targets positioned near to the colour singleton were detected more effectively compared with those located further away. We again examined any possible response bias by comparing trials in which the target appeared at the singleton with trials in which the target appeared at the nonsingleton on the same side. Means for these two conditions were 88.4% ($SD = 6.4$) and 80.8% ($SD = 8.2$), respectively. This difference again proved to be significant, $t(15) = 3.5$, $p < .03$, $d = 0.87$ and thus rules out any response bias explanation.

These data reveal that under degraded viewing conditions (i.e., during brief display presentations) targets that coincided with a discontinuity in colour were more effectively detected than targets located elsewhere. This clearly suggests that the colour singleton accrued preferential processing relative to nonsingleton items. Importantly, we have observed a colour singleton effect when using a different measure in addition to the change detection procedure employed in Experiments 2–5.

The results from Experiment 6 are also consistent with the notion that a "graded" attentional field surrounds the locus of attention (e.g., Downing & Pinker, 1985; Eriksen & St. James, 1986; LaBerge, 1983). An item located immediately adjacent to the colour singleton was more effectively detected than an item located further away.

General Discussion

It is well established that when an observer is required to detect a single coloured item amongst homogenous distractors, search time is relatively unaffected by the number of distractors (Treisman & Gelade, 1980). This finding, however, is distinct from the question of whether a uniquely coloured item attracts attention when an observer is not set to search for the salient element (Jonides & Yantis, 1988). Examining whether phenomenally salient items are prioritized in a bottom-up manner was the primary concern of the present paper. Specifically, we assessed whether a discontinuity in colour (i.e., a colour singleton) can accrue processing priority in the absence of a relevant attention set. Attenuated change blindness was observed for changes that occurred at colour singletons relative to changes occurring elsewhere. This concurs with the notion that if a particular visual attribute accrues processing prioritization that property should be relatively more resistant to change blindness (e.g., Cole et al., 2003, 2004). Additionally, priority for the singleton induced an area of facilitated processing surrounding the item characteristic of a spatially distributed "attentional field". Finally, we also observed facilitated detection performance for targets associated with a colour singleton when search displays were presented for a brief period followed by a mask.

These findings represent only one of few reports showing feature singleton priority in the absence of an appropriate attentional set (e.g., Turatto & Galfano, 2000). If observers are set to search for a salient item in one feature dimension (e.g., form), a salient feature in another feature dimension (e.g., colour) will automatically attract attention (Theeuwes, 1991, 1992). Since the target in the present series of experiments cannot be viewed as being salient (hence the name "change blindness"), singleton priority is unlikely to be due to observers searching for the most salient item. These findings are thus contrary to the many observations suggesting that colour singletons do not elicit bottom-up prioritization (e.g., Franconeri & Simons, 2003; Gibson & Jiang, 1998; Jonides & Yantis, 1988; Lamy & Egeth, 2003; Lamy & Tsal, 1999; Lamy et al., 2003; Mounts, 2000; Yantis & Egeth, 1999).

One of the primary motivations for investigating whether a discontinuity in colour can attract attention in a stimulus-driven manner is that many theories of attention assume bottom-up prioritization for this type of salient stimuli (e.g., Cave & Wolfe, 1990; Koch & Ullman, 1985; Wolfe, 1994). Indeed, salience is a primary determinant of attentional allocation in all variants of the model put forward by Koch and colleagues (e.g., Itti & Koch, 2000). In Koch and Ullman's (1985) original model, preattentive processing of early visual attributes, such as luminance, orientation and colour, results in a "salience map", represented at a neural level, which guides focal attention to the location of the stimulus with the greatest difference in signal, that is, salience. Hence, a discontinuity in colour, as presented in the current experiments, should automatically attract attention. Our data however only provide partial support for this assertion. Experiments 2, 3, 5 and 6, demonstrated priority for feature singletons when a relevant attentional set for singletons was unlikely to be operating. Such an observation would usually be considered as a demonstration of bottom-up prioritization and hence provide support for salience-based attention theories. However, it is Experiment 4 that provides the strictest test of whether discontinuities in colour can accrue priority in a purely stimulus-driven manner. In this experiment, the target was half as likely to occur at the colour singleton as it was at the nonsingletons. Hence, attending to the singleton was detrimental to the task and the participants were informed of this target-singleton contingency. Observers therefore had an attentional set biased against the singleton, not simply a neutral attentional set. Results showed that the colour singleton did not receive priority. It is commonly assumed that a process is only automatic, i.e., truly stimulus-driven, if it occurs independently of participants' goals and intentions (Schneider & Shiffrin, 1977). Hence, when the strictest criterion for automatic attentional attraction is employed, that is, facilitation independent of an observers intentions, no automatic prioritisation of the singleton occurred.[2] We posit therefore that a discontinuity in colour will attract attention, even in the absence of an attentional set for such a discontinuity, unless an attentional set is contrary to singletons.

[2] Turratto and Galfano (2000) do, however, argue that an effect need not be completely obligatory to be considered automatic.

The results clearly pose the question of why the standard visual search procedure failed to show colour singleton priority (Experiment 1), whereas the change detection (Experiments 2, 3 and 5) and brief display (Experiment 6) techniques revealed the effect. We suggested that perceptual measurement tasks are potentially more sensitive to colour singleton effects compared with RT tasks. As Santee and Egeth (1982) noted, RT and accuracy cannot always be viewed as equivalent measures. They suggested that under the "data limited" conditions (Norman & Bobrow, 1975) of briefly presented displays, as used here, accuracy measures are more sensitive to perceptual processes. It may be worthy of note that virtually all the studies that have failed to find a colour singleton effect have employed RT as the dependent measure rather than accuracy (e.g., Franconeri & Simons, 2003; Jonides & Yantis, 1988; Yantis & Egeth, 1999). There is however an alternative explanation for the RT/accuracy disparity associated with differences in the level of difficulty of the two tasks and thus strategies employed. The change detection and brief display methods both involved displays being presented for a very brief duration, thus making the tasks relatively difficult. As a consequence, observers may have adopted a particular strategy for detecting the target, a strategy not required when the search display was present indefinitely (as in Experiment 1). They may have chosen to bias their attention towards the singleton because it is the most clearly marked item and is no less likely to contain the target than any of the other items. A clear starting point, or "landmark" (see Todd & Kramer, 1994), would allow more items to be examined in the short time available. Given that this explanation suggests that observers adopted the strategy of starting their search at the most discrepant item, this account necessarily challenges the notion that the participants' attentional set was not biased towards the singleton. In other words, priority for the singleton may not have occurred in the absence of a relevant attentional set.

A further question that the results pose concerns the nature of the prioritization for the colour singleton. We have assumed that the singleton attracted attention based on the evidence for the link between attention and change blindness (e.g., Rensink et al., 1997). However, less is known about this link to be sure that our findings are indeed due to a redistribution of attention. For instance, salience might be important for change detection but not for attentional prioritization. Furthermore, in an extensive review of the attentional capture literature, Rauschenberger (2003) distinguishes between the involuntary diversion of spatial attention (i.e., attentional capture) and the prioritization of an item in a processing queue. Rauschenberger states that although an item may have high priority in visual search, the same item may fail to automatically attract attention. In other words, because an item is processed first – due to, for instance, it serving as a landmark for search (see above; Todd & Kramer, 1994) – this does not mean it forcibly attracts attention to itself.

Additionally, our findings also implicate the involvement of visual short-term memory mechanisms. The extent to which change detection tasks primarily engage attention or memory processes is not entirely apparent. The two processes are evidently linked. The fact that change blindness can be modulated by attentional factors (Rensink et al., 1997) clearly demonstrates the involvement of attentional processes. At the same time, the task of comparing one image with a subsequent image obviously requires memory. Moreover, fMRI work has revealed cortical areas involved with both attention and working memory (LaBar, Gitelman, Parrish, & Mesulam, 1999). It is possible that the colour singleton attracted attention to its location which then resulted in a better representation of the item in visual short-term memory. As has always been assumed, information that enters short-term memory must have been preferentially attended. Although there may be potential issues concerning inference, our use of the change detection procedure represents one of a growing number of studies that have used relative levels of induced change blindness as a metric for investigating various aspects of cognition (e.g., Cole, Kuhn, & Liversedge, 2007; Ro et al., 2001; Scholl, 2000). For instance, Pisella, Berberovic, and Mattingly (2004) examined which visual events are least likely to go unnoticed in neglect patients.

In conclusion, the present work examined whether a discontinuity in colour can accrue attentional priority in a bottom-up manner, as suggested by many models of visual attention. Results have shown this to be the case; colour singletons attract attention unless a top-down set is contrary to singletons.

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