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# Stimulus-driven attentional capture: An empirical comparison of display-size and distance methods

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Four experiments examined attentional capture by colour as assessed by two different investigative methods. Subjects performed a visual search task for a vertical-target line embedded among tilted-distractor lines, presented inside 4, 8, or 12 coloured discs. Interestingly, when the colour singleton was task irrelevant, and data were analysed by means of the display-size method combined with the zero-slope criterion, no evidence for attentional capture by colour was found. However, when data were analysed by means of the distance method, which consists of monitoring the spatial relationship between the target and the singleton, results showed that the target was found faster and/or more accurately when it was inside the singleton than when it was in a nonsingleton location. This provided evidence for a stimulus-driven attentional capture. In addition, the application of signal detection methodology showed that attentional capture, as revealed by the distance method, resulted from a perceptual modulation at the singleton location, rather than from a criterion shift. We conclude that, at least with the kind of stimuli used here, the display-size method combined with the zero-slope criterion is less than ideal for investigating how static discontinuities can affect the automatic deployment of visual attention.

One of the most debated issues in the mainstream of attention research concerns the way in which attention is deployed in the visual field. Since the seminal work of Posner and his colleagues (Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980) it has been recognized that attention can be directed either exogenously or endogenously. The first experiments investigating attentional capture mechanisms were primarily based on a *spatial*-

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*cueing* paradigm, in which the likely position for the target to appear was signalled either by a "peripheral" cue (e.g., a sudden onset to the right or to the left of fixation) or by a "central" cue (e.g., a directional arrow above the fixation point). One of the most important notions that emerged from these and other studies is that sudden onsets appear to be able to summon attention to their position in a mandatory manner (e.g., Jonides & Yantis, 1988; but see Yantis & Jonides, 1990), producing what has been defined an *implicit* or *stimulus-driven attentional capture*. This phenomenon has been characterized as the interruption and redirection of the ongoing behaviour by items in the visual field that are irrelevant to the task at hand (see, e.g., Simons, 2000; Yantis, 1993a).

## Assessing attentional capture in visual search: The display-size method

In the early 80s, Treisman and her colleagues (e.g., Treisman & Gelade, 1980) made popular a different method for studying visual attention mechanisms. Whereas the spatial cueing paradigm was basically aimed at exploring the role of position in the deployment of attention, the *display-size* method, originally devised by Neisser (1967; also see Egeth, Jonides, & Wall, 1972; Shiffrin & Gardner, 1972), turned out to be a useful tool for addressing when a stimulus defined by certain features requires focused attention in order to be identified. In a typical experiment relying on the display-size method, observers are requested to detect the presence or absence of a target item embedded among distractors. By varying the number of distractors, it is possible to assess whether target search is accomplished either by a parallel or by a serial search (but see Townsend, 1972). According to Treisman and Gelade (1980), parallel search can be used when the target differs from distractors on the basis of a single feature, or in other words when the target is a singleton (e.g., a red item among green items). In this case, response times (RTs) for target detection do not significantly increase as display size increases—namely, the target pops out from the distractors, which has been interpreted as evidence for preattentive processing (Treisman & Gelade, 1980; but see, Di Lollo, Kawahara, Zuvic, & Visser, 2001; Joseph, Chun, & Nakayama, 1997; Wolfe, 1998b). By contrast, when the target is defined by two or more features (e.g., a red square among red circles, green squares, and green circles), a serial search is adopted to perform the task. In this kind of search, focused attention is thought to explore one item at a time, until the target is found or all items are visited. Accordingly, RTs for target detection increase as display size increases, and the slope for target-absent trials is steeper than the slope for target-present trials (Wolfe, 1998a).

Understanding the way in which attention is deployed in the visual field is a central topic for both empirical and theoretical reasons, as testified by many current models of visual attention (e.g., Cave, 1999; Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Itti & Koch, 2000; Niebur & Koch, 1998; Wolfe, 1994). From the original work of Treisman (e.g., Treisman & Gelade, 1980) to date, the display-size method has also been used as the most popular method for addressing which stimulus features are able to grab attention automatically (e.g., Folk & Annett, 1994; Jonides & Yantis, 1988; Todd & Kramer, 1994; Yantis & Egeth, 1999). In these kinds of experiment, observers are presented with a set of stimuli, and the task consists of detecting the presence of a given target, whose search ought to be performed in a very inefficient way (Galfano & Turatto, 2002; Turatto & Galfano, 2001; Yantis, 1993b). For example, a set of 4, 8, or 12 elements can be displayed circularly arranged around a fixation point. One element among the others is a singleton in a given dimension (say colour, form, luminance, or sudden onset presentation), but the possibility that it can be the target is only $1/n$ of the total elements, where $n$ is the number of elements in the display. To address whether a given feature captures attention, the logic behind the use of the display-size method is the following: If RTs for target detection do not increase as display size increases when the target is the singleton, then it entails that the singleton element is the first visited by attention (zero-slope criterion). Since this happens despite the observers having no reason to deliberately attend to the singleton, it means that attention is automatically grabbed to the singleton position (Yantis, 1993b).

Results from display-size method experiments indicated that only an onset singleton is able to grab attention automatically. Other singletons defined by static discontinuities, such as those produced by the manipulation of colour, form, and luminance, would not elicit such involuntary capture of attention (Folk & Annett, 1994; Jonides & Yantis, 1988; Todd & Kramer, 1994; Yantis & Egeth, 1999). It should be noted, however, that the zero-slope criterion is a very restrictive way to establish the conditions under which attention capture occurs. Even according to the classic visual search studies devoted to the investigation of attentive and preattentive processing, pop-out targets defined by simple features do not always exhibit the expected flat slopes (e.g., Cave & Wolfe, 1990; Wolfe, 1998a). In other words, if the zero-slope criterion does not always hold even for task-relevant features, there is no reason to expect that the same features meet this criterion when they are task irrelevant.

Other methods for assessing attentional capture, relying on different criteria, have been used in a variety of studies (see Simons, 2000, for a review). A paradigmatic example is provided by those studies that employ a spatial-cueing procedure (e.g., Folk, Remington, & Johnston, 1992; Jonides, 1981; Posner, 1980), where attentional capture is evaluated by comparing RTs for target detection when the target is presented in the same location as the cue (valid trials) with RTs for when the target appears in a different location (invalid trials).

Moreover, as Turatto and Galfano (2001) observed (also see Todd & Kramer, 1994), although quite clear, the findings based on the application of the zero-slope criterion are at odds with the predictions made by many contemporary models of visual attention, which posit that a singleton in any dimension should grab attention as a mere consequence of its saliency (see, e.g., Cave, 1999; Duncan & Humphreys, 1989; Itti & Koch, 2000; Koch & Ullman, 1985; Treisman & Sato, 1990). In addition, recent converging empirical evidence obtained by means of different techniques emerged, supporting the notion that a salient task-irrelevant singleton is able to produce an involuntary shift of spatial attention (e.g., Kim & Cave, 2001, Exp. 1; Schmidt, 2000; Scholl, 2000; Theeuwes & Burger, 1998). For instance, Schmidt (2000) has reported evidence that static discontinuities, such as irrelevant luminance and orientation singletons, are able to produce a stimulus-driven attentional capture by using a very different methodology, primarily based on the *illusory line motion* phenomenon (Hirosaka, Miyauchi, & Shimojo, 1991), also known as the motion induction effect (see, e.g., Faubert & Von Grünau, 1995). Schmidt showed that illusory line motion was sensitive to the presence of singletons in the display when the singleton was unpredictive of the location where line probe will be presented. Finally, Scholl (2000) recently demonstrated that, in a flicker paradigm, observers showed an attenuated *change blindness* for exogenously attended elements characterized as colour singletons—that is to say, elements that were irrelevant for the change detection task, being not correlated with the loci of the changes. According to these studies, singletons that vary over space but not over time are indeed able to produce a stimulus-driven attentional capture, though the phenomenon seems to be less strong if compared to that elicited by dynamic discontinuities (Schmidt, 2000; Von Grünau, Faubert, Iordanova, & Rajska, 1999; Yantis & Johnson, 1990).

## Assessing attentional capture in visual search: The distance method

In the attempt of reconciling diverging position on attentional capture by static discontinuities, we developed the *distance method* (Turatto & Galfano, 2000, 2001), which was modelled after the procedure used by Cave and Zimmerman (1997) and consists of presenting a display of elements all at once, just as in standard visual search. The crucial difference is that only one fixed display size is required. As in standard visual search, the subject has to report the presence or absence of a predefined target (alternatively, which of two possible targets was present in the array), embedded between distractor elements in a circular array centred on the fixation point. One of the elements in the array is always a singleton in a feature dimension not correlated to the target-defining attributes. This means that on target-present trials the target is also the singleton of the task-irrelevant feature in $1/n$ of the trials. Attentional capture can be measured by monitoring target–singleton distance in the array. In fact, we define *p0* (p zero) as those trials in which target position coincides with that of the singleton. Likewise, *p1* identifies those trials in which the target is a flanker of the singleton element (either to the right or to the left side), whereas *p2* identifies those trials in which the target is a flanker of the element flanking the irrelevant singleton, and so on (the number of positions depending on the display size). In this method, evidence for attentional capture is observed when RTs for p0 are significantly faster (or percentage correct is significantly higher) than RTs (or percentage correct) of the fastest (or most accurate) nonsingleton position. It should be noted that this is a very conservative standard for observing attentional capture, since one could have decided to compare RTs (or accuracy) for p0 with the RT mean of all the nonsingleton positions.

As we have already pointed out (Turatto & Galfano, 2000, 2001) there are reasons to suspect that the display-size method could be less than ideal to address stimulus-driven attentional capture by singletons different from sudden onset. We reasoned that, when the singleton and distractors are presented, a global transient (or many local transients) is generated by the onset of the whole set of elements. This signal might swamp the local signal produced by the singleton, which otherwise should ensure that attention is attracted to its position. This delocalizing effect produced by the distractors is evident in the change blindness phenomenon when the mudsplashes paradigm is used (O'Regan, Rensink, & Clark, 1999). What is observed is that the change is often missed because the corresponding transient signal is attenuated by, and must compete with, many transient signals caused by mudsplashes. The relevant point to note is that, with the display-size method, the distracting effect suffered by the local signal generated by the feature singleton, which by itself might be able to draw attention, increases as display size increases. In fact, in a signal/noise ratio perspective, the activation signal coming from the colour singleton is progressively overwhelmed, at larger display size, by the noise signals from distractors (for a similar position also see the "interrupt threshold hypothesis", Martin-Emerson & Kramer, 1997). By contrast, the use of a single display size ensures that the signal/noise ratio is kept constant.

In order to start shedding light on the controversial issue of attentional capture by colour, we decided to make a first direct empirical comparison between the display-size method and the distance method. To this purpose, in Experiments 1 and 2 we used a paradigm similar to that used by Turatto and Galfano (2000), in which accuracy, instead of RTs, was the measured dependent variable. That was motivated by the fact that, as Gibson and Jiang (1998) have pointed out, RTs might be less sensitive than accuracy to detect this kind of phenomenon. However, since in a more recent study (Turatto & Galfano, 2001) we have found evidence in favour of stimulus-driven attentional capture also by focusing on RTs, Experiment 3 was aimed at replicating Experiment 1 results with RTs. Finally, Experiment 4 was aimed at exploring whether any processing advantage for the singleton location resulted from the modulation of either sensitivity or bias.

We decided to focus our experiments on colour, since a colour singleton could probably be seen as more phenomenally salient if compared to a form or an orientation singleton, and because colour is probably the most studied feature in the attentional capture literature.

## EXPERIMENT 1

The aim of this experiment was to carry out a direct empirical comparison between the classic display-size method and the distance method as diagnostic tools for investigating attentional capture by an irrelevant colour singleton in a visual search task. To this purpose we devised an experimental procedure that combined the characteristics of the two methods. This was achieved by presenting a red-coloured singleton disc among three different display sizes of distractors, thus reproducing the typical display-size method measurement (e.g., Jonides & Yantis, 1988). On the other hand, within each display size, we also monitored subjects' performance as a function of target singleton distance, as defined by the distance method (e.g., Turatto & Galfano, 2000). Thus, at any given trial, we had the possibility of obtaining two distinct measures of the subjects' search behaviour with two separate and independent methods. In so doing, we could compare the two methods in their sensitivity to any possible form of attentional capture elicited by an irrelevant, although salient, colour singleton. By using the distance method with the type of stimuli employed here, we already found evidence for stimulus-driven attentional capture by colour (and other static discontinuities; Turatto & Galfano, 2000). Therefore, our prediction was to replicate, for each display size, our previous results, with subjects showing the best visual search performance at the singleton location. However, if we were right in retaining the display-size method as being less than ideal or inadequate for exploring attentional capture by static discontinuities, then when subjects performance is analysed by this method we would expect attentional capture to be absent, thus replicating the results of those studies that manipulated display size (e.g., Jonides & Yantis, 1988). A second possibility was that we might find evidence for a stimulus-driven attentional capture by colour with both methods, which in turn would indicate that it was the kind of stimuli we used that mattered, or also that subjects, for some reason, adopted an attentional set for the singleton.

## Method

### Subjects

A total of 28 subjects (6 male and 22 female) from the University of Padua served as subjects (age range 20–29 years). All had normal or corrected-to-normal visual acuity and were unaware of the purpose of the experiment.

### Apparatus

Stimuli were presented on a 17-inch NEC colour monitor, driven by a Digital Venturis 575 PC, equipped with a 640 × 480 (60-Hz) graphic board. The subjects sat with the head positioned on a headrest, so that the distance between the eyes and the screen was approximately 57 cm. The task required subjects to respond by pressing two keys on a keyboard, and it was performed in a dimly lit room (about 1 cd/m$^2$).

### Stimuli

The display consisted of 4, 8, or 12 coloured discs, equally spaced and arranged in an imaginary circle around a fixation point at the centre of the screen (see Figure 1). Each disc covered 1.6° of visual angle, whereas the circular array of discs covered 9°. All the discs but one were of the same colour and appeared on a dark background (0.15 cd/m$^2$). Discs might be green with a red-singleton disc, or red with a green-singleton disc. Red and green colours were matched for luminance.[1]

The target was a vertical line segment embedded among distractors composed of randomly tilted lines, either to the left or to the right side. Target and distractor lines appeared at the centre of the disc elements and were white lines (24.8 cd/m$^2$) covering approximately 1.2°. The degree of orientation of the distractors was adjusted according to an adaptive staircase procedure based on subjects' performance in order to keep overall performance at 75% correct. The maximum level of orientation the distractors could reach was 85° from horizontal plane (maximal similarity with the target), whereas the minimum was 45° (minimal similarity with the target). Subjects' performance was monitored on-line every four trials. The following staircase rule was used: If performance was 100% correct, lines orientation was

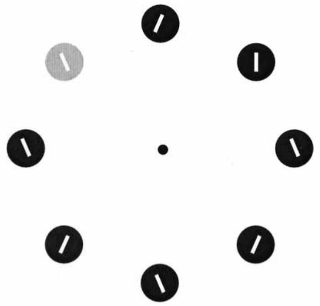

**Figure 1.** Example of the stimuli used for Experiments 1, 2, and 3. Differences in colour are represented as differences in grey level (light grey corresponds to green; black corresponds to red). The background was black. In this example, representing the display size 8, the vertical-target line is in p2.

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[1] The photometric and colorimetric measurements were carried out by means of a Minolta chromameter CS-100. The green (CIE $x, y$ chromaticity coordinates of .302/.576; RGB palette value set at 0, 29, 0) and red elements (CIE $x$, $y$ chromaticity coordinates of .610/.432; RGB palette value set at 45, 0, 0) had a luminance of 4.3 cd/m$^2$.

increased by 10°; if it was 50% or below, lines orientation was decreased by 5°; finally, if performance was 75%, lines orientation remained unchanged. As we have already demonstrated (Turatto & Galfano, 2000), this procedure should ensure that the vertical-target line did not pop out from the distractors and that the task was performed reasonably inefficiently.

### *Design*

Within each display size, target position in the array was random. Hence, on target-present trials, the target appeared inside the colour singleton in only 1/4, 1/8, or 1/12 of the total trials for display size 4, 8, or 12, respectively. As far as the display-size method is concerned, the factor considered was display size (4, 8, and 12), and the crucial condition was represented by those trials in which the target appeared inside the colour singleton disc. With regard to the distance method, for each display size the factor considered was target–singleton distance. We labelled p0 the trials in which the target was inside the colour singleton, p1 the condition in which the target flanked the singleton (to either the right or the left side), and so on. Hence, the levels of the target–singleton distance factor were 3 (p0, p1, and p2) for display size 4; 5 (from p0 to p4) for display size 8; and 7 (from p0 to p6) for display size 12. Each subject was submitted to 576 trials divided into four blocks of 144 trials each. Within a block, each display size was presented for 48 trials (24 trials for target present and 24 trials for target absent).

### *Procedure*

Trials began with a fixation point presented for 500 ms, then the visual search display was turned on and displayed only for 180 ms, rendering any eye movements useless. From visual-search display onset, subjects had 2500 ms for responding. Half of the subjects responded to target present with the left hand ("Q" key), and to target absent with the right hand ("P" key), and the remainders vice versa. The feedback for the incorrect responses was a 500-ms, 500-Hz tone, presented together with the message "error". If a response was not produced within 2500 ms, the same sound signal, along with the display message "missed response", was presented. Subjects were told to be as accurate as possible in making their responses.

## Results

Data analyses were concentrated on accuracy (proportions correct) for the target present condition only and were carried out separately for the two methods.

### *Display-size method*

With this method the crucial condition is subjects' performance when the target position coincides with that of the colour singleton. The typical signature for attentional capture is a flat slope of subjects' performance as a function of display size (zero-slope criterion), which is an index that the singleton was the first position visited by attention in searching for the target (e.g., Jonides & Yantis, 1988). Hence, accuracy data analysis was restricted to those trials in which the target was inside the singleton. Proportions correct were entered into a one-way repeated measures analysis of variance (ANOVA), in which the factor was display size (three levels: 4, 8, or 12). The factor was significant, $F(2, 54) = 6.797$, $p < .002$, with subjects' performance decreasing as display size increased (display size 4, $M = 0.828$, $SD = 0.091$; display size 8, $M = 0.726$, $SD = 0.148$; display size 12, $M = 0.687$, $SD = 0.190$). Planned comparisons showed that proportion correct for display size 4 was significantly higher than those for

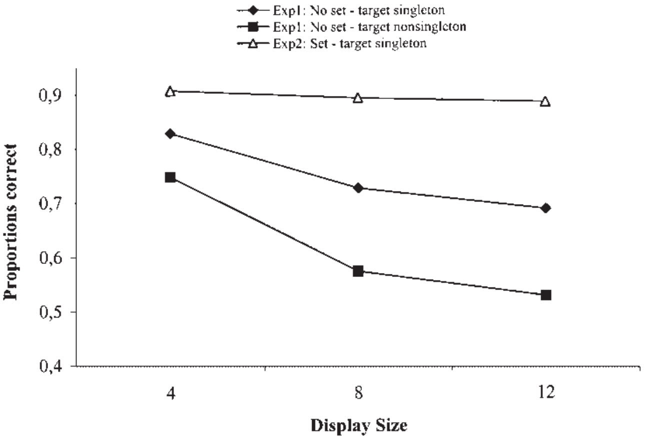

**Figure 2.** Mean accuracy (proportions correct) as a function of display size. Filled diamonds represent the condition in which the target and the colour singleton had the same spatial position in Experiment 1 (irrelevant singleton). Filled squares represent the condition in which the target did not appear in the colour singleton in Experiment 1 (irrelevant singleton). Open triangles represent the condition in which the target and the colour singleton had the same spatial position in Experiment 2 (relevant singleton).

display sizes 8 and 12 (all *p*s < .005). This pattern of results clearly indicated that, with the display-size method, we failed to detect evidence for an attentional capture by the odd-coloured item (see Figure 2).

### *Distance method*

Subjects' performance is evaluated by monitoring target–singleton distance. Hence, because the number of elements—that is to say, the number of distances from the target and the singleton—is different for each display size, data analyses were performed separately. Proportions correct were entered into a one-way repeated measures ANOVA in which the factor was target–singleton distance.

*Display size 4.* The factor was significant, *F*(2, 54) = 11.543, *p* < .0001. Planned comparisons showed that proportion correct in p0 (*M* = 0.828, *SD* = 0.091) was significantly higher (*p* < .001) than proportion correct in p2 (*M* = 0.750, *SD* = 0.123), namely the most accurate of the nonsingleton position (see Figure 3).

*Display size 8.* The factor target–singleton distance was significant, *F*(4, 108) = 10.793, *p* < .0001. Planned comparisons showed that proportion correct in p0 (*M* = 0.726, *SD* = 0.148) was significantly higher (*p* < .0001) than proportion correct in p1 (*M* = 0.595, *SD* = 0.110), namely the most accurate of the nonsingleton positions (see Figure 3).

*Display size 12.* The factor target–singleton distance was significant, *F*(6, 162) = 6.719, *p* < .0001. Planned comparisons showed that proportion correct in p0 (*M* = 0.687, *SD* = 0.190) was significantly higher (*p* < .003) than proportion correct in p4 (*M* = 0.570, *SD* = 0.114), namely the most accurate of the nonsingleton position (see Figure 3).

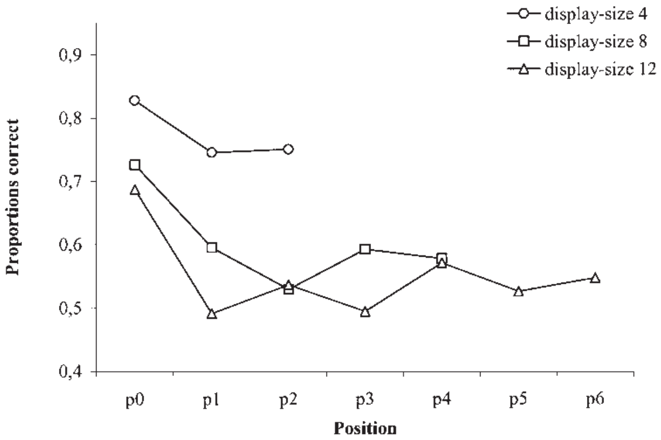

**Figure 3.** Mean accuracy (proportions correct) as a function of target–singleton distance in Experiment 1, in which the singleton was task irrelevant. For each display size, the most accurate position was the singleton location (p0). Note, however, that in p0 accuracy decreased as display size increased.

Confirming what we showed in a previous study (Turatto & Galfano, 2000), the results that emerged by analysing subjects' performance by means of the distance method revealed that, within each display size, the most accurate position was that of the colour singleton, thus providing evidence for a stimulus-driven attentional capture by colour.

## Discussion

This experiment had the purpose of making a direct comparison between the display-size method and the distance method in their capability to reveal a stimulus-driven attentional capture by a colour singleton. In this regard, the results were very interesting, revealing that if subjects' performance was monitored by means of the display-size method, no evidence of attentional capture emerged (see Figure 2). This result apparently confirms previous work, which posits that an irrelevant colour singleton does not capture attention automatically (e.g., Folk & Annett, 1994; Jonides & Yantis, 1988; Todd & Kramer, 1994; Yantis & Egeth, 1999). However, because from our standpoint this method might be insensitive for revealing attentional capture by stimulus properties different from onset (i.e., static discontinuities), we also monitored subjects' performance using the distance method. Confirming the results of a previous study (Turatto & Galfano, 2000), we found evidence that the colour singleton indeed summoned attention, as testified by the fact that, for each display size, the most accurate position for target detection was the one occupied by the singleton (see Figure 3).

It should be noted that, with the display-size method, the crucial condition to observe attentional capture is defined by those trials in which target position coincides with that of the colour singleton. Hence, subjects' performance, measured by RTs or accuracy, is computed for this position as a function of the number of elements in the display (i.e., the display size). Attentional capture is said to occur when no RT increment, or accuracy decrement, is observed as display size increases. However, this criterion allows the analysis of only a part of the whole data, whereas a more complete and detailed analysis is accomplished by using the distance method (see Figure 3). Basically, with the display-size method, the only data considered are those represented by the condition in which the target and the singleton share the same spatial position, which, in turn, in the distance method terminology is the condition labelled as p0. If one considers only this subset of data, the distance method also reveals a decrement in performance (here represented by a decreased proportion of correct responses) in p0 as display size increases (see p0 data in Figure 3). However, the fundamental point advocated here is that, for each display size considered, accuracy in p0 is higher than that in the most accurate of the remaining positions, which is a clear indication that the irrelevant colour singleton showed a substantial processing advantage.

Although we interpreted the present accuracy pattern as evidence of a stimulus-driven capture elicited by the odd-coloured disc, one may observe that we cannot exclude the possibility that subjects adopted a set for colour despite the singleton being task irrelevant. This might have happened because the task was very difficult, and the array was visible for a very short time, and therefore subjects might have decided to use the singleton as the starting point during the visual search (see Todd & Kramer, 1994). If this were the case, the capture that emerged should not be considered as a pure stimulus-driven shift of attention, but instead as a "contingent capture" (Folk et al., 1992; see Ruz & Lupiáñez, 2002, for a similar argument). The next experiment will explore this issue more consistently.

## EXPERIMENT 2

The hypothesis that subjects, despite instructions, deliberately adopted a set for the odd-coloured disc can be reasonably discarded for two reasons.

First, if the reason for adopting a set for colour was task difficulty, one would expect such a set to be more useful in the most task-demanding condition. In other words, the probability that a subject was set on the odd-coloured disc should increase when task difficulty was increased—that is to say, for a larger display size rather than for a smaller display size. It follows that, as far as p0 is concerned, the most accurate performance should have been observed for display size 12 rather than for display size 4, but clearly this was not the case (see Figure 3). The second reason to dismiss the contingent-capture hypothesis is even simpler. If subjects had a set for colour, attentional capture should also have emerged with the display-size method. Yet, previous findings failed to show such capture when data were analysed by means of the display-size method.

However, in order to further explore the possibility that previous findings were due to the adoption of an attentional set, in the present experiment we explicitly invited subjects to adopt a set for the colour singleton. That was achieved by rendering the singleton the most likely position for the target to appear, thus inducing subjects to attend to it. If a set was used in Experiment 1, we expected the same pattern of results.

### Method

#### *Subjects*

A total of 28 subjects (13 male and 15 female) from University of Padua served as subjects (age range 23–29 years). All had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

### Apparatus and stimuli

These were the same as those in Experiment 1.

### Design

The design was identical to that of Experiment 1 except that on target-present trials (50% of the total trials) the target appeared on about 70% of the total trials within the coloured disc. Each subject was submitted to 588 trials divided into three blocks of 196 trials each. Within each block, on target-present trials, the display size 4 had the target inside the singleton on 21 out of 30 trials (70%), the display size 8 had the target inside the singleton on 23 out of 33 trials (69%), and the display size 12 had the target inside the singleton on 24 out of 35 trials (68%).

### Procedure

This was the same as that in Experiment 1.

## Results

As in Experiment 1 data analysis was concentrated on accuracy (proportions correct) for the target present condition only and were carried out separately for the two methods.

### Display-size method

Accuracy data analysis was restricted to those trials in which the target was inside the singleton. Proportions correct were entered into a one-way repeated measures ANOVA. The only factor considered was display size (three levels: 4, 8, or 12), which was not significant, $F(2, 54) = 2.129$, $p > .12$. Subjects' performance did not show a significant decrement as display size increased (display size 4, $M = 0.907$, $SD = 0.065$; display size 8, $M = 0.893$, $SD = 0.080$; display size 12, $M = 0.885$, $SD = 0.065$). The results indicated that attentional allocation was biased toward the colour singleton. As expected, the adoption of a set had the consequence of producing the same performance for the three display sizes (see Figure 2).

### Distance method

Proportions correct were entered into a one-way repeated measures ANOVA. Again the factor was target–singleton distance.

*Display size 4.* The factor was significant, $F(2, 54) = 77.608$, $p < .0001$. Planned comparisons showed that proportion correct in p0 ($M = 0.907$, $SD = 0.065$) was significantly higher ($p < .001$) than proportion correct in p2 ($M = 0.558$, $SD = 0.158$), namely the most accurate of the non singleton position (see Figure 4).

*Display size 8.* The factor target–singleton distance was significant, $F(4, 108) = 46.059$, $p < .0001$. Planned comparisons showed that proportion correct in p0 ($M = 0.893$, $SD = 0.080$) was significantly higher ($p < .0001$) than proportion correct in p1 ($M = 0.413$, $SD = 0.186$), the most accurate of the nonsingleton positions (see Figure 4).

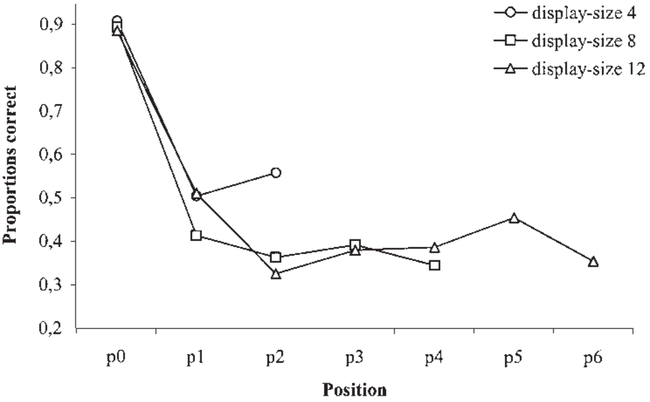

**Figure 4.** Mean accuracy (proportions correct) as a function of target–singleton distance in Experiment 2, in which the singleton was task relevant. For each display size, the most accurate position was the singleton location (p0). Subjects' performance in p0 did not vary as a function of display size.

*Display size 12.* The factor target–singleton distance was significant, $F(6, 162) = 23.700$, $p < .0001$. Planned comparisons showed that proportion correct in p0 ($M = 0.885$, $SD = 0.065$) was significantly higher ($p < .0001$) than proportion correct in p1 ($M = 0.510$, $SD = 0.224$), the most accurate of the nonsingleton positions (see Figure 4). Hence, the distance method, for each display size, also showed that attention was deliberately allocated to the singleton.

## Discussion

Although in Experiment 1 subjects had no reason to adopt a set for the colour singleton, and even though we have already discussed the reasons for it being reasonable to rule out this possibility on the basis of Experiment 1 findings, the present experiment was devised for addressing subjects' performance when the colour singleton was made useful for the task. To this purpose, we rendered the colour singleton position the most likely position for the target to appear. This manipulation led subjects effectively to attend to the odd-coloured disc, which, in turn, produced a very different accuracy pattern from that of Experiment 1. When data were analysed by means of the display-size method, as expected, accuracy in the colour singleton position did not differ as a function of display size (see Figure 2), which, according to zero-slope criterion, is an index that attention was strategically deployed to the singleton. Needless to say, for each display size, the distance method also revealed a similar effect (see Figure 4). In addition, two more aspects of the results show the effect of the adoption of an attentional set in the present experiment as compared to Experiment 1. First, for all display sizes, accuracy in the colour singleton position was higher in Experiment 2 than in Experiment 1. Second, the use of a relevant set for colour produced a global decrement of performance in all the remaining locations, as testified by the fact that overall accuracy for the nonsingleton position was lower in Experiment 2 than in Experiment 1.

In sum, when an attentional set was effectively adopted for colour (Experiment 2), the pattern of results was very different from that of Experiment 1, which is further converging evidence that in Experiment 1 no relevant set was adopted for the odd-coloured disc. In the next experiment we sought to replicate Experiment 1 findings using RTs as the crucial dependent variable.

## EXPERIMENT 3

Since traditionally the display-size method has been used with RT data, we set up an experiment in which RTs, instead of accuracy, were the main dependent variable. A possible replication of Experiment 1 results obtained with RTs would strengthen the claim that the display-size method combined with the zero-slope criterion might be overly strict for assessing stimulus-driven attentional capture by static discontinuities.

A critical condition to be met is that search for the target ought to be inefficient, in order to avoid subjects to be engaged in a singleton-detection mode when searching for the target (Galfano & Turatto, 2002). Wolfe, Friedman-Hill, Stewart, and O'Connell (1992) showed that seeking for a vertical target among tilted distractors engage subjects in an inefficient visual search, producing very steep slopes as a function of target–distractors similarity. Hence, for the purpose of the present study, we have chosen to fix distractors orientation to either 20° or –20° from vertical (0°) target alignment.

### Method

#### *Subjects*

A total of 14 subjects (6 male and 8 female) from the University of Padua served as subjects (age range 21–28 years). All had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

#### *Apparatus and stimuli*

These were the same as those in Experiment 2, with the exception that distractors' orientation did not vary as a function of subjects' performance. Instead they were randomly tilted to 20° and –20°.

#### *Design*

The design was identical to that of Experiment 1. Each subject was submitted to 576 trials divided into four blocks of 144 trials each (plus a first block of 30 training trials). Within each block, on target-present trials (72), the display size 4 had the target inside the singleton on 6 out of 24 trials, the display size 8 had the target inside the singleton on 3 out of 24 trials, and the display size 12 had the target inside the singleton on 2 out of 24 trials. This way, for each display size the probability for the target to appear inside the singleton was $1/n$, where $n$ is the display size. Therefore, subjects had no incentive to adopt a relevant set for the singleton (Yantis, 1993b).

#### *Procedure*

This was the same as that in previous experiments, with the following exceptions. Since emphasis was on RTs, stimuli were displayed until subjects responded or 3000 ms elapsed. Also, eye movements were allowed, as in the vast majority of visual search studies hinging on RTs (Palmer, 1998; Wolfe, 1998a).

## Results

Before analyses were carried out, RTs were trimmed by computing outliers following the method proposed by Van Selst and Jolicoeur (1994).

### *Display-size method*

*RT data.* As a consequence of the outlier latency criterion, fewer than 2% of the data were trimmed. Data were initially entered into a within-subjects repeated measures ANOVA, in which the factors were display size (4, 8, and 12) and target (present and absent). Both the main effects of display size, $F(2, 26) = 142.025$, $p < .001$, and target, $F(1, 13) = 262.896$, $p < .001$, were significant. The Display Size × Target interaction was also highly significant, $F(2, 26) = 53.335$, $p < .001$. This interaction indicates that there is a difference between the slopes of the two target conditions (see Figure 5). Target-present trials showed a slope of 67 ms/item, whereas target-absent trials showed a slope of 144 ms/item. The ratio between the two slopes is approximately 2:1, a typical value for a very inefficient search (Wolfe, 1998a). This indicates that subjects, on target-present trials, ought to search through an average of half the elements of the display, whereas on target-absent trials they have to explore all items. This result allowed us to safely assume that subjects were not engaged in a singleton detection mode (Bacon & Egeth, 1994) when searching for the target.

Data were further analysed for target-present condition only. RTs were entered into a within-subjects repeated measures ANOVA, with display size (4, 8, and 12) and target (singleton and nonsingleton) as factors. Both the main effects of display size, $F(2, 26) = 142.025$, $p < .001$, and target, $F(1, 13) = 262.896$, $p < .001$, were significant. The Display Size × Target interaction was also highly significant, $F(2, 26) = 53.335$, $p < .001$.

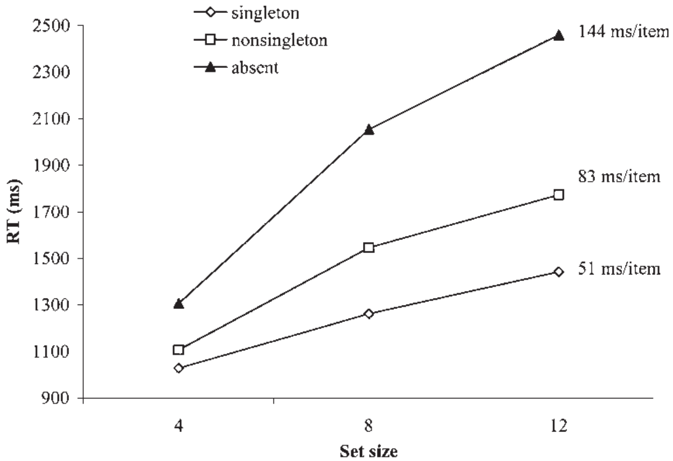

**Figure 5.** Mean RTs in Experiment 3 as a function of display size and target condition. Open diamonds represent the condition in which the target and the colour singleton had the same spatial position. Open squares represent the condition in which the target did not appear in the colour singleton. Filled triangles represent the target-absent condition.

TABLE 1
Proportion of target seen by target condition and display size in Experiment 3

| | *Target condition* | | |
|---|---|---|---|
| *Display size* | *Present singleton* | *Present nonsingleton* | *Absent* |
| 4 | .936 | .910 | .980 |
| 8 | .929 | .807 | .974 |
| 12 | .902 | .734 | .962 |

Planned comparisons showed that when the target was inside the singleton RTs were faster for display size 4 than for display size 8 (RT difference 234 ms; $p < .001$), and faster for display size 8 than for display size 12 (RT difference 179 ms; $p < .02$) On average, in the target–singleton condition the slope was 51 ms/item, which, according to the display size method, would indicate that the colour singleton did not capture attention. By contrast, in the target–nonsingleton condition the slope was 83 ms/item. The slope difference (32 ms/item) was significant ($p < .001$), indicating a processing advantage for the target–singleton condition over the target–nonsingleton condition.

In addition, comparisons between the condition in which the target was inside the singleton and the condition in which it was not showed that the target, within each display size, was detected faster when it was inside the singleton (display size 4, RT difference 79 ms, $p < .01$; display size 8, RT difference 284 ms, $p < .001$; display size 12, RT difference 331 ms, $p < .002$).

*Accuracy data.* Proportions correct were entered into a two-way repeated measures ANOVA. The two factors considered were display size (three levels: 4, 8, and 12), and target (three levels: singleton, nonsingleton, and absent). Both the main effects of display size, $F(2, 26) = 11.437$, $p < .001$, and target, $F(2, 26) = 22.174$, $p < .001$, were significant. The interaction was also significant, $F(4, 52) = 11.017$, $p < .001$, due to the fact that accuracy slope of the target–nonsingleton condition was statistically different from the slopes of the target–singleton and the target-absent conditions (see Table 1). However, this result is not particularly informative since slopes might differ simply because in these latter conditions accuracy was above 90%, and the correspondent psychophysical curves tend to flatten out.

### Distance method

*RT data.* It is worth reiterating that, with this method, it is crucial to compare RTs when target was inside the singleton (p0) with RTs when the target was in the fastest of the nonsingleton position within each display size. Three distinct one-way repeated measures ANOVAs in which the factor was target–singleton distance were performed for each display size.

*Display size 4.* The factor was significant, $F(2, 26) = 4.674$, $p < .02$. Planned comparison showed that RTs in p0 ($M = 1027$, $SD = 88$) were significantly faster ($p < .05$) than RTs in p2 ($M = 1094$, $SD = 124$), namely the fastest of the nonsingleton positions (see Figure 6).

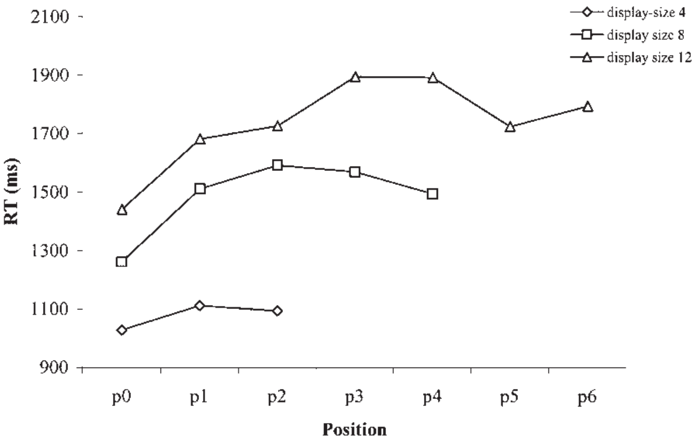

**Figure 6.** Mean RTs as a function of target–singleton distance in Experiment 3, in which the singleton was task irrelevant. For each display size, the most accurate position was the singleton location (p0). Note, however, that in p0 RTs increased as display size increased.

*Display size 8.* The factor was significant, $F(4, 52) = 8.378, p < .001$. Planned comparison showed that RTs in p0 ($M = 1262, SD = 195$) were significantly faster ($p < .015$) than RTs in p4 ($M = 1494, SD = 221$).

*Display size 12.* The factor was significant, $F(6,78) = 4.444, p < .001$. Planned comparison showed that RTs in p0 ($M = 1441, SD = 335$) were significantly faster ($p < .02$) than RTs in p1 ($M = 1681, SD = 173$).

In summary, the results indicated that, within each display size, the target was detected faster when inside the singleton than when inside any of the other positions.

*Accuracy data.* Three distinct one-way repeated measures ANOVAs with target–singleton distance as factor were performed for each display size.

*Display size 4.* The factor was not significant.

*Display size 8.* The factor was significant, $F(4, 52) = 5.897, p < .002$. Planned comparison showed that accuracy in p0 ($M = 0.929, SD = 0.134$) was significantly higher ($p < .01$) than accuracy in p4 ($M = 0.827, SD = 0.165$).

*Display size 12.* The factor was significant, $F(6, 78) = 3.613, p < .004$. Planned comparison showed that accuracy in p0 ($M = 0.902, SD = 0.121$) was significantly higher ($p < .01$) than accuracy in p2 ($M = 0.764, SD = 0.144$). Overall, accuracy data that were analysed considering target–singleton distance replicated RT data, showing a significant processing advantage for the colour singleton.

## Discussion

Let us first discuss the main results that emerged when RTs were analysed according to the display-size method. First, data showed that, when searching for the vertical target among tilted distractors, subjects were not engaged in a singleton detection mode. As already pointed out, this is a crucial condition that needs to be satisfied in order to interpret a possible attentional capture by an irrelevant singleton as purely stimulus driven (Galfano & Turatto, 2002; Turatto & Galfano, 2001). Second, with regard to the attentional capture issue, the RT pattern suggests a processing-speed advantage when the target and singleton shared the same position than when they did not (also see Todd & Kramer, 1994). Yet, because the search slope when the target was inside the singleton was not flat, one should conclude that the singleton did not capture attention (Jonides & Yantis, 1988; Todd & Kramer, 1994).

However, when RTs were analysed separately for each display size as a function of target–singleton distance, evidence for a stimulus-driven attentional capture by the irrelevant singleton emerged. The present results, obtained with RTs, confirmed and extended those of Experiment 1, where accuracy was the only dependent variable considered. Overall, the results of Experiment 3 suggest that the zero-slope criterion might be overly strict to assess attentional capture by static discontinuities. In fact, data showed that capture can take place even when the slope for the Target–Singleton × RT function is not flat. This conclusion is also supported when data are analysed according to the distance method.

So far, we have explained the advantage for the singleton location observed with the distance method invoking stimulus-driven attentional capture. However, one might argue that a similar pattern of data could be interpreted as the consequence of a response bias instead of an increase in sensitivity resulting from attentional capture by the singleton object. Importantly, the methodology employed in our previous experiments provides no means of applying the signal detection theory (e.g., Macmillan & Creelman, 1991) to the data in order to ascertain whether the increase in hit rate (correct detection of the vertical line segment when present) at the singleton location was determined by either an increase in sensitivity or a strategic response bias. In order to rule out the response bias account, we performed an additional experiment based on an experimental task similar to that employed by Handy, Jha, and Mangun (1999) in the context of inhibition of return (IOR; Posner & Cohen, 1984). Specifically, Handy et al. (1999) were interested in investigating the nature of IOR, and they used signal detection measures to demonstrate that inhibition of return has a clear perceptual/attentional component. In fact, they observed that the classic behavioural IOR pattern (better performance in invalid than in valid trials at long stimulus onset asynchronies) is accompanied by a significant modulation in $d'$ and not in beta. In the following experiment we adopted the same rationale: If the advantage for the singleton location is the consequence of a mechanism (attentional capture) that operates at perceptual-level stages of processing, then we predicted $d'$ scores to be significantly higher for the singleton location than for the nonsingleton locations at each display size. Moreover, in order to rule out any response bias account, no significant variation in beta should emerge as a function of target–singleton distance at each display size.

# EXPERIMENT 4

In the present experiment we kept the methodology that combined the characteristics of both the distance method and the display-size method. However, we modified the experimental task in order to allow the application of signal detection theory to the data. To this purpose, we had subjects performing a go/no-go task. The visual search target was present on each trial, and subjects were presented with two possible targets. Specifically, half of the subjects were to press a response key if the target was a vertical line segment (go trials) and to refrain from responding if the target was a horizontal line segment (no-go trials). The remaining subjects received the opposite instructions. Go and no-go trials occurred with the same probability. Such a task makes it possible to analyse what happens when noise (the horizontal line segment) appears at both the singleton and the nonsingleton locations. As in Experiments 1 and 2, accuracy was the only dependent variable considered. Subjects were instructed to respond as accurately as possible, with the only temporal constraint being that a response had to be made within 2500 ms from the onset of the search display.

Our prediction was to replicate, for each display size, the results of Experiment 1, with subjects showing the highest visual search performance at the singleton location. In addition, performance at the singleton location was expected to show the highest $d'$ score, which would be evidence for a modulation of sensitivity. As far as beta is concerned, no significant difference was expected to be observed, which would be evidence that the singleton advantage that emerged in Experiments 1 and 3 is bias free.

## Method

### *Subjects*

A total of 12 subjects (2 male and 10 female) from the University of Padua served as subjects (age range 19–26 years). All had normal or corrected-to-normal visual acuity and were unaware of the purpose of the experiment. None of them had participated in the previous experiments.

### *Apparatus*

This was the same as that in previous experiments.

### *Stimuli*

The target was either a vertical or a horizontal line segment embedded among distractors composed of randomly tilted lines, either to the left or to the right side. The degree of orientation of the distractors was adjusted according to an adaptive staircase procedure based on subjects' performance in order to keep overall performance at 75% correct. The maximum level of orientation that the distractors could reach was 85° from either the vertical or the horizontal plane (maximal similarity with the targets), whereas the minimum was 45° (minimal similarity with the targets). Subjects' performance was monitored on-line every four trials. The same staircase rule as that employed in Experiments 1 and 2 was used.

### *Design*

As in Experiments 1 and 3, target position in the array was random within each display size. Each subject was submitted to 432 trials divided into three blocks of 144 trials each. Within a block, each display size was presented for 48 trials.

### Procedure

As in the previous experiments, trials began with a fixation point presented for 500 ms, then the visual search display was turned on and displayed only for 150 ms, in order to prevent eye movements. From visual-search display onset, subjects had 2500 ms for responding. Subjects were required to make a discrimination judgement of the target line's orientation and to respond only to targets of a prespecified orientation (which was counterbalanced across subjects). Subjects responded to the designated target by pressing the "Q" key with the right hand. The feedback for the incorrect responses was a 500-ms, 500-Hz tone, presented together with the message "error". If a response was not produced within 2500 ms, the same sound signal, along with the display message "missed response", was presented. Subjects were told to be as accurate as possible in responding. Hits were defined as responses on trials with the designated target orientation present (go trials). False alarms were defined as responses on trials with the designated target orientation absent (no-go trials). Half trials were go trials, and the remainders were no-go trials.

## Results

Data analysis was focused on accuracy (proportions correct) for both the target-orientation-present and the target-orientation-absent conditions and was carried out separately for the two methods.

### Display-size method

Accuracy data analysis was performed on go and no-go trials in which the target (in both its designated and nondesignated orientation) appeared inside the singleton. Hits and false alarms were used to compute $d'$ and beta scores (see Macmillan & Creelman, 1991). First, a one-way repeated measures ANOVA was performed on $d'$ scores. The only factor considered was display size (three levels: 4, 8, or 12), which yielded a significant main effect, $F(2, 22) = 3.632$, $p < .05$, showing that $d'$ scores significantly decreased as display size increased (display size 4, $M = 2.567$, $SD = 0.955$; display size 8, $M = 1.860$, $SD = 1.086$; display size 12, $M = 1.531$, $SD = 1.142$). Another one-way repeated measures ANOVA was performed on beta scores, with display size as factor. No significant main effect emerged ($F < 1$). These results are consistent with those obtained in Experiments 1 and 3, and they show that the display-size method is not able to show any attentional capture by colour effect. The lack of significance for the ANOVA performed on beta scores, speaks in favour of the fact that it is implausible that subjects used different strategies to perform the task depending on the different numerosity of the display size.

### Distance method

The $d'$ and beta scores were entered into two different one-way repeated measures ANOVAs. As in all the previous experiments, the factor was target–singleton distance.

*Display size 4.* In the ANOVA performed on $d'$ scores, the factor was not significant, $F(2, 22) = 2.286$, $p = .125$. The same result was observed in the ANOVA performed on beta scores, $F(2, 22) = 1.928$, $p = .169$. According to this pattern of results we should conclude that no evidence for attentional capture emerged with the distance method either. However, in order to check whether the pattern of results emerged at this display size was significantly different from the one that we observed in Experiment 1, where the distance factor yielded a significant effect, we performed another ANOVA on proportions correct of the present experiment and those of Experiment 1, with a between-subjects factor. Crucially, the Distance × Experiment interaction was far from significant ($F < 1$). We conclude that the observed lack of attentional capture on $d'$ scores at the display size 4 in the present experiment might be due to a ceiling effect, the task being much easier than the one to be performed in Experiment 1, as also attested by the overall higher scores in the present experiment (see Figure 7).

*Display size 8.* The ANOVA on $d'$ scores showed a significant main effect of target–singleton distance, $F(4, 44) = 4.781, p < .004$. Planned comparisons showed that $d'$ scores in p0 ($M = 1.860, SD = 1.086$) were significantly higher ($p < .05$) than $d'$ scores in p3 ($M = 1.003, SD = 0.514$), namely the most accurate of the nonsingleton positions. In contrast, target–singleton distance was not significant in the ANOVA performed on beta scores ($F < 1$). This pattern of results shows that the processing advantage at the singleton location (p0) is the consequence of a modulation of sensitivity and not the result of a strategic response bias.

*Display size 12.* The ANOVA on $d'$ scores yielded a significant main effect of target–singleton distance, $F(6, 66) = 2.940, p < .02$. Planned comparisons showed that $d'$ scores in p0 ($M = 1.531, SD = 1.142$) were significantly higher ($p < .05$) than $d'$ scores in p6 ($M = 0.732, SD = 0.965$), the most accurate of the nonsingleton positions. No significant main effect emerged in the ANOVA on beta scores ($p = .172$). These results parallel those reported for the display size 8, and, once again, argue for a perceptual/attentional interpretation of the singleton advantage observed with the distance method in both Experiments 1 and 3.

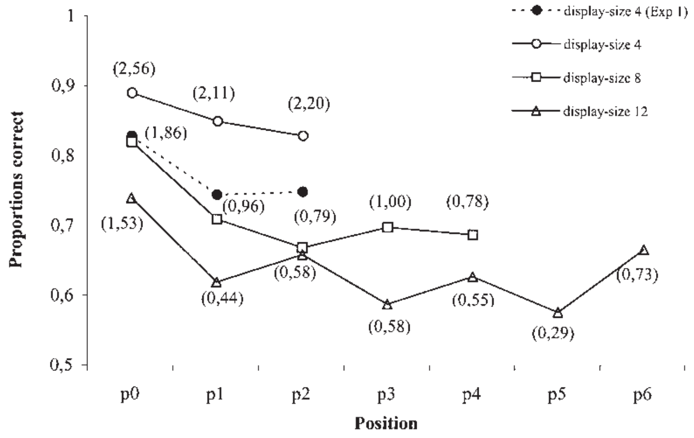

**Figure 7.** Mean accuracy (proportions correct) as a function of target–singleton distance in Experiment 4, in which the singleton was task irrelevant. For each display size, the most accurate position was, as in Experiment 1, the singleton location (p0). Values of $d'$ are reported in parentheses. Display size 4 data from Experiment 1 are also shown (filled circles).

## Discussion

The results of the present experiment were clear-cut in favour of a perceptual/attentional interpretation of the singleton advantage that emerged in Experiments 1 and 3 with the distance method. In fact, there was no evidence that a strategic bias (as indexed by variations in beta scores) was implicated in either the display-size or the distance method. In particular, $d'$ scores for the singleton location analysed by means of the display-size method showed a significant decrease, with increasing display size, thus replicating the pattern of results that emerged in Experiments 1 and 3. We interpret this finding as evidence that varying the signal/noise ratio has a significant impact on sensitivity and does not affect response-related stages of processing. More important to our hypotheses, when analysed by means of the distance method, $d'$ scores revealed a significant increase for the singleton location compared to the nonsingleton locations at both the display size 8 and the display size 12, which is a clear sign that the processing advantage influenced perceptual-level processing. The lack of significance observed at display size 4 has been interpreted as due to a ceiling effect.

# GENERAL DISCUSSION

In a previous study (Turatto & Galfano, 2000), based on accuracy as the primary dependent variable, we found evidence that an irrelevant colour, form, or luminance singleton was able to grab attention automatically in a visual search task for a vertical-line target among tilted-line distractors. In a more recent study (Turatto & Galfano, 2001), in which RTs were the main dependent variable, data pointing to a stimulus-driven attentional capture by colour were also found when subjects performed a very inefficient-search task, in which the target consisted of a randomly rotated *T* among randomly rotated *L*s.

As already pointed out, however, data from many visual-search tasks suggested that an irrelevant colour singleton does not capture attention in a stimulus-driven manner (e.g., Folk & Annett, 1994; Jonides & Yantis, 1988; Todd & Kramer, 1994; Yantis & Egeth, 1999). These results emerged from studies in which a display-size manipulation was used to assess attentional capture. In order to reconcile our data with those apparently contradictory obtained by manipulating display size, we decided to compare the efficiency of the display-size method and the efficiency of the distance method, in revealing attentional capture by colour. In so doing, we designed four experiments in which we varied the display size, while also keeping track of subjects' performance as a function of the target–singleton distance within each display size. In Experiment 1 our manipulation ensured that the singleton was not useful for performing the task, whereas in Experiment 2, which was basically a control experiment, the colour singleton was a valid predictor of target position. However, because Experiments 1 and 2 used only accuracy, whereas the display-size method has been traditionally used with RT data, in Experiment 3, which had the same rationale of Experiment 1, we used RTs as the main dependent variable. Finally, Experiment 4 was devised in order to apply signal detection theory to the data, thus allowing us to verify whether the bottom-up singleton advantage that emerged in previous experiments was due to a genuine attentional effect (revealed by a variation in $d'$), or, by contrast, to a strategic response bias (revealed by a variation in beta).

To reiterate, if in evaluating attentional capture by static discontinuities using the display-size method one strictly conforms to the zero-slope criterion, our main prediction was that evidence for a stimulus-driven attentional capture by an irrelevant colour singleton might be detected only when data are collected, and analysed, using the distance method. In the present experiments three different display sizes were used, which is tantamount to saying that data were analysed as a function of the target–singleton distance for each display size. Note that one might be tempted to conclude that the display-size method and the distance method are not different methods, but only different ways of looking at the same data. We want to point out that this is simply not true. In fact, it is only for the purpose of the present study that display size and target–singleton distance were manipulated concurrently. In our view, the distance method is a method in itself, in that, when adopted properly to assess attentional capture in visual search, it relies exclusively on a fixed set size. As a matter of fact, for evaluating attentional capture, a visual search task *does not* necessarily need a manipulation of display size.

The results of Experiments 1, 3, and 4 demonstrated indeed that the distance method was able to reveal attentional capture, whereas the display-size method combined with the zero-slope criterion was not. When accuracy was the main dependent variable (Experiment 1) it emerged that, according to the display-size method, when the target was inside the singleton (p0), subjects' performance decreased as display size increased, revealing a great proportion of errors at larger display sizes. Experiment 4 replicated and extended this finding, showing that the bottom-up singleton advantage was due to a modulation of $d'$, but not of beta. This pattern of data is not in line with the flat slope expected if the singleton had captured attention (e.g., Jonides & Yantis, 1988).

However, the conclusion is quite different if data are analysed according to the distance method. In fact, regardless of the display size considered, when target–singleton distance is monitored, it clearly emerged that accuracy was higher in the singleton position than in any other position. This is exactly what one would predict if the singleton was the first position inspected (at least in the vast majority of trials), namely if it had captured attention.[2] Note that, by simply using the display-size method, comparisons between trials in which the target was inside the singleton and trials in which the target was in one of the nonsingleton positions seem to reveal an accuracy-processing advantage for the singleton condition over the nonsingleton condition (see Figure 3). This result was also replicated using RTs in Experiment 3, whose possible relation with the attentional capture phenomenon is discussed in detail below. As already pointed out, the main goal of Experiment 3 was to replicate Experiment 1 findings using RTs, in order to strengthen our conclusion about the hypothesized superiority of the distance method in revealing attention capture by static discontinuities and, conversely, the insensitivity of the zero-slope criterion in the display-size method to this phenomenon.

With regard to the possibility that accuracy data from Experiment 1 showed attentional capture, an alternative account should be considered. Because we presented stimuli for a short period of time (180 ms), one might argue that subjects might have realized that they were unlikely to be able to search the entire display before it disappeared. For this reason, subjects might have chosen to adopt a strategy in which they deliberately selected the colour singleton on some trials simply because it was unique and served as an "anchor point" from which to

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[2] As we have already discussed (Turatto & Galfano, 2001), it is not strictly necessary that the colour singleton is the first position visited by attention on every trial (as an obligatory process would predict) to claim that the singleton automatically captures attention. Attentional capture need not be mandatory in order to be interpreted as automatic, in that neither onset meets this criterion (Yantis & Jonides, 1990).

start the search. Thus, in Experiment 3, the display was visible until subjects' response, as usually happens in experiments in which visual search is investigated using RTs (see Palmer, 1998; Wolfe, 1998a). By increasing stimuli exposure time up to a maximum of 3000 ms, we were also able to rule out the "anchor point" account. If the brief exposure time was the reason for the subjects to strategically attend to the singleton, then we should have failed to find evidence for attentional capture in Experiment 3, even when capture was assessed by the distance method. In fact, subjects had plenty of time to search for the singleton before the display was turned off, which very likely rendered useless the adoption of an anchor point strategy, advocated as a possible explanation when the display time was very brief (see Experiment 1). The results of Experiment 3 confirmed that attentional capture by colour is still detectable with the distance method, thus undermining the anchor point hypothesis. Basically, the results replicated those of Experiment 1 based on accuracy. When data were analysed according to the display-size method, RTs obtained when the target was inside the singleton did not conform to the zero-slope criterion, commonly assumed as the index of attentional capture (e.g., Jonides & Yantis, 1988), with such a method.

## Zero-slope criterion, saliency, attentional misguidance, and attentional capture

It is acknowledged that if the display-size method is used, evidence for attentional capture by an irrelevant singleton is said to occur *if and only if* the "gold standard" of the zero-slope criterion is met. Alternatively, even when the display-size method is used, one could argue that any slope benefit for singleton–targets relative to nonsingleton–targets might be taken as evidence for attentional capture, though this phenomenon might reflect a weaker or probabilistic form of attentional capture. In other words, if capture does not occur in every trial, but instead only on the majority of trials, this could be viewed as a form of imperfect capture. Why should the slope for target–singleton trials not conform to the zero-slope criterion? From our standpoint, the problem could be that when attentional capture by static discontinuities is investigated, the display-size method presents some potential methodological flaws.

In fact, when display size is manipulated, the local signal produced by the static singleton has to compete with the stronger transient signals generated by the global onset of the whole array of elements, an effect that is magnified as display size increases. As we pointed out in our previous work (Turatto & Galfano, 2000, 2001), manipulating the display size implies varying the signal-to-noise ratio between the local signal coming from the irrelevant singleton and the signal coming from the onset of the whole display configuration (i.e., singleton plus the nonsingleton items). We suspect that attentional capture due to the singleton saliency might be significantly attenuated by the delocalizing effect caused by the onset of the display items. Thus, increasing the display size will result in a greater distracting effect, which is reflected by a global slowing down of RTs at larger display sizes, and specifically affecting the condition in which the target appeared inside the singleton. This would account for the non-flat slope of the target–singleton condition when manipulating display size (see Experiment 3). As already stated, this problem is avoided when using the distance method, where a fixed number of items in the display is used (e.g., Turatto & Galfano, 2000, 2001) or considered (as in the present work), thus allowing attentional capture to be detected in a visual search task.

Moreover, it should be noted that the only case where the zero-slope gold standard of a flat RT × Display Size function is met, is when the irrelevant singleton item is an abrupt onset (see e.g., Jonides & Yantis, 1988). However, in the experimental setting typically used in abrupt-onset studies, the local transient signal produced by the singleton item does not have to compete with the transients produced by the global onset of the display, as the procedure for investigating abrupt onset capture consists of presenting a display of masked elements (the so called "no-onset" items, Todd & Van Gelder, 1979) *before* the appearance of the onset singleton. Therefore, the signal coming from the onset singleton only needs to compete with weaker transients caused by the decamouflaging of the no-onset items. Crucially, Martin-Emerson and Kramer (1997) have shown that increasing the number of offset transients produced by the decamouflaging of the no-onset items causes attentional capture by the onset singleton, as assessed by the display-size method, to disappear. This result, in our view, represents clear-cut evidence that the increase in noise strength (i.e., the number of transients with which the onset singleton has to compete) has an impact even on onset capture, according to the display-size method gold standard. The distance method we have proposed has the merit of not suffering from an unbalanced number of transients, in that the total number of transients is kept constant given the use of a fixed display size in visual search. This is the reason that we believe this method is completely independent of the display-size method.

Beside the amplification of the delocalizing effect discussed previously (that becomes manifest only in the display-size method), increasing the number of elements, by keeping eccentricity constant, decreases the interitem distance in the display, which in turn should concur in magnifying the saliency of the singleton (see Sagi & Julesz, 1987; Todd & Kramer, 1994; Wolfe, Cave, & Franzel, 1989). Hence, because the singleton would be more salient at larger display sizes, as display size increases the difference in RTs between the condition in which the target is inside the singleton and the condition in which the target is inside one of the nonsingleton positions should also increase. In order to correctly test this hypothesis we compared data from positions subtending the same retinal eccentricity in each display size (see Figure 8).

The following positions were considered: display size 4, p0 and p1 (90°), p0 and p2 (180°); display size 8, p0 and p2 (90°), p0 and p4 (180°); display size 12, p0 and p3 (90°), p0 and p6 (180°). Planned comparisons were applied to the data. For the 90°-retinal-distance condition,

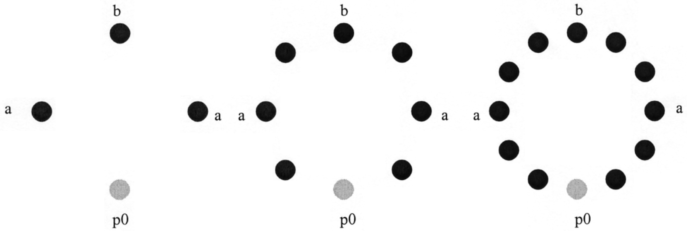

**Figure 8.** Schematic drawing of the positions considered in the estimation of the speed–processing advantage when the target appeared inside the singleton (p0), compared to when the target appeared in a nonsingleton position. The nonsingleton positions were chosen in order to share the same retinal distance across display sizes. Note that, as display size increases, saliency also increases as a consequence of the decreased interitem distance (Sagi & Julesz, 1987). Positions labelled "a" were those whose retinal distance from p0 corresponded to 90° in each display size. Positions labelled "b" were those whose retinal distance from p0 corresponded to 180° in each display size.

the RT difference between p0 and p1 for display size 4 (85 ms) was significantly smaller than the RT difference between p0 and p2 for display size 8 (329 ms, $p < .001$) and between p0 and p3 for display size 12 (453 ms, $p > .02$). For the 180°-retinal-distance condition, the RT difference between p0 and p2 for display size 4 (66 ms) was significantly smaller than the RT difference between p0 and p4 for display size 8 (232 ms, $p < .03$), and between p0 and p6 for display size 12 (352 ms, $p < .02$). In addition, further analysis showed that the effect of the singleton across display sizes showed a significant linear component $F(1,13) = 9.521$, $p < .01$, which shows that the increase in RT difference between p0 and the nonsingleton positions with the same eccentricity for both the 90° and the 180° retinal distance increased linearly. Overall, the RT pattern that emerged supports the notion that saliency is increased when density increases. Data analysis at each display size by means of the distance method crucially highlights the effects due to increasing the number of elements in the display. On the one hand, by increasing the display size, the delocalizing effect is also increased, which is reflected by the fact that when data are plotted according to the distance method, RTs for the target–singleton condition increased significantly as a function of display size. On the other hand, the stronger RT advantage for the singleton position over the nonsingleton positions was magnified as display size increased, an effect that was probably due to the augmented saliency of the singleton.

In order to further ascertain whether in Experiment 1 subjects were deliberately attending to the singleton, Experiment 2 was designed, in which subjects effectively adopted a relevant attentional set for the singleton. The prediction under this condition was that both methods should reveal a processing advantage for the singleton, which was due, however, to a contingent capture. Results were consistent with our hypotheses. The comparison of the results from Experiments 1 and 2 allowed us to provide further converging evidence that, in the former, participants did not adopt a "default set" for the colour singleton, which might prioritize novelty and/or discontinuities. Note that, in Experiment 3, RT data inspection by means of the display-size method revealed a speed–processing advantage for target detection in the singleton condition compared to the nonsingleton condition. This RT advantage for the singleton condition was already observed by Todd and Kramer (1994). The authors interpreted the lack of zero slope in the singleton condition and the advantage of the singleton trials over the nonsingleton trials as evidence that the irrelevant singleton did not capture attention in a stimulus-driven manner, but suggested that the singleton had an increased probability of being processed compared to the nonsingleton items, causing what they called an "attentional misguidance". According to Todd and Kramer, the attentional misguidance phenomenon would be the result of the interaction between bottom-up and top-down components of attentional control. That is, subjects on some proportion of trials would deliberately search for the target starting from the singleton. In other words, the attentional misguidance phenomenon would be mainly the consequence of an endogenous process. However, following the arguments presented above, if one assumes the zero-slope criterion to be too strict for assessing attentional capture by colour, the significant difference between the singleton and nonsingleton slopes observed might be taken as evidence for attentional capture. The reason for considering this phenomenon as purely stimulus driven and not related to an endogenously driven misguidance is that, as we have shown in Experiment 2, when a set is clearly induced by making the singleton task relevant, this results in a contingent attentional capture-like pattern in both the display size and the distance method.

In summary, although on the one hand we want to make clear that the display-size method is a very useful tool for investigating whether a given stimulus feature can be searched efficiently or not, on the other hand, our results suggest that, when used in association with the zero-slope criterion, it could be less than ideal for assessing stimulus-driven attentional capture by static discontinuities. The reason for this weakness is still not completely clear, and further investigation might possibly clarify this issue. However, our general view is that the problem with the display-size method in assessing attentional capture by singletons other than onsets is that increasing the number of distractors also entails increasing the total number of the transients accompanying the whole display onset.

To our knowledge, the only study reporting negative evidence for stimulus-driven attentional capture by colour using a method different from that based on the manipulation of display size is the one of Gibson and Jiang (1998). They used a visual search task with a fixed number of elements, in which attentional capture was estimated by comparing the percentage of correct responses on the first trial, in which an unexpected irrelevant colour singleton appeared as the target (the "surprise" trial), with the percentage of correct responses on previous trials, in which no irrelevant singleton was present. Accuracy on the surprise trial was not significantly higher than that on previous trials, which was interpreted as a lack of attentional capture by the colour singleton. However, a recent study by Horstmann (2002), in which the same surprise paradigm was used, showed that when some temporal parameters in the experimental procedure are slightly modified, attentional capture by colour singletons becomes manifest.

To conclude, at least for the sort of stimuli used here, our experiments showed that the display-size method combined with the zero-slope criterion is insensitive or might be too strict for revealing stimulus-driven attentional capture by colour. By contrast, the distance method is able to detect such an effect, and since previous evidence claiming that an irrelevant colour singleton does not grab attention automatically is based on null results, the distance method is a more appropriate and powerful tool for investigating the attentional capture phenomenon.

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