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Attentional capture by color without any relevant attentional set

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The aim of the present study was to investigate mechanisms underlying attentional capture by color. Previous work has shown that a color singleton is able to summon attention only in the presence of a relevant attentional set, whereas when a color singleton is not useful for a task, evidence for purely stimulus-driven attentional capture is controversial. Three visual search experiments (T–L task) were conducted using a method different from that based on set sizes, consisting of monitoring target–singleton distance in a unique display size. In Experiment 1, we demonstrated that attention can be summoned in a real stimulus-driven manner by an irrelevant color singleton. Experiment 2A extended this observation, showing that the color singleton attracted attention even when capture was detrimental. However, Experiment 2B showed that such capture can be strategically prevented. Finally, in Experiment 3, we examined whether such a capture was due to a spatial shift or to a filtering cost, providing evidence supporting the shift hypothesis. Stimulus-driven capture was observed when color was neither the defining nor the reported target attribute (Yantis, 1993) and when subjects naive of visual search tasks were used. The present results give experimental support to many contemporary models of visual attention.

The natural visual environment provides a great number of stimuli that a human observer has to deal with. The question is whether the deployment of attention to the visual scene is under endogenous or exogenous control. In the last 10 years, many studies have investigated this issue, and the most frequent paradigm has been the visual search task (e.g., Jonides & Yantis, 1988; Pashler, 1988; Theeuwes, 1991, 1992). The fundamental notion that has emerged is that selection of information from the visual field can be affected either by stimulus properties (i.e., onset, color, luminance, or movement) or by the goal of the observer (Folk, Remington, & Johnston, 1992; Warner, Juola, & Koshino, 1990; Yantis & Jonides, 1990). This evidence led to the conclusion that visual selective attention can be controlled in two different manners: by *stimulus-driven* selection, also referred to as bottom-up or exogenous, and by *goal-directed* selection, also called top-down or endogenous. The issue regarding the interaction of bottom-up and top-down factors has also been addressed in many models of visual attention (Bundesen, 1990; Cave, 1999; Cave & Wolfe, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Grossberg, Mingolla, & Ross, 1994; Koch & Ullman, 1985; Wolfe, 1994, 1996; Wolfe, Cave, & Franzel, 1989). Almost all the models predict that a salient element—namely, an element that differs from the others in at least one feature (e.g., color, orientation, luminance)—should attract attention in a stimulus-driven fashion. This is because the visual system is thought to be equipped with feature-contrast detector mechanisms that are designed to extract salient elements by computation, ensuring that the most relevant location(s) will summon attention. Thus, saliency per se should guarantee that a singleton will draw attention regardless of any strategic factors, such as the subjects' goals and intentions (Cave, 1999; Nothdurft, 1993; Theeuwes, 1992).

Nonetheless, quite surprisingly, there is little or no evidence supporting this prediction in the literature. In fact, since the seminal work of Jonides and Yantis (1988), it has been shown that attentional capture is unique to stimuli characterized by abrupt visual onset, whereas discontinuities in other dimensions, such as color or brightness, cannot summon attention automatically. Specifically, many studies have failed to demonstrate that a color singleton grabs attention in a purely bottom-up fashion (e.g., Folk & Annett, 1994; Gibson & Jiang, 1998; Todd & Kramer, 1994). However, intuitively it seems quite reasonable that a color singleton should attract attention, in that, for example, a red element among green elements is a very salient object. Indeed, a study by Nothdurft (1993) seemed to provide evidence that a singleton element in the color dimension was able to attract attention merely by its saliency. Hence, the aim of the present study was to address this issue more thoroughly.

A factor that may have played a significant role in producing seemingly inconsistent data is the conditions under

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which attention is directed to the elements in a scene. One of the major disputes among researchers concerns when an attentional capture should be considered to be purely stimulus driven and when it should not (e.g., Folk, Remington, & Johnston, 1993; Yantis, 1993). We believe that, besides the divergent theoretical positions, the different procedures used to investigate attentional capture could also explain this disagreement (e.g., Folk et al., 1992; Jonides & Yantis, 1988). We interpret attentional capture as a matter of degree, rather than as an all-or-none phenomenon.

Folk et al. (1992) introduced a new conceptual framework (*contingent capture hypothesis*) on the basis of experiments conducted with a mixed paradigm, which combined a spatial cuing procedure with a visual search task. They demonstrated that the ability of abrupt stimulus onset to capture attention depends on what a subject is looking for in the visual search task. The most important finding of their study is that, given a relevant attentional set, a color singleton can also capture attention.

From the attentional control settings perspective, Bacon and Egeth (1994) proposed the distinction between two modes of processing visual information. They suggested that an observer can identify a unique element that differs from background elements, either by using the *feature search* mode (FSM), or by using the *singleton detection* mode (SDM). In a display of visual elements, if only one singleton is present, both strategies can be used efficiently in detecting the unique item. In contrast, if two or more singletons are present, the two strategies can lead to distinct results. Whereas the SDM can determine an involuntary attentional capture by a distractor singleton, the FSM should prevent this phenomenon.

Hence, in order to distinguish attentional capture contingent on the establishment of an attentional control setting (e.g., Folk & Remington, 1998; Folk et al., 1992, 1993) from a real stimulus-driven capture in which attentional allocation is due entirely to bottom-up factors (i.e., the stimulus properties), it is useful to provide a clear definition of what an attentional set is. From our standpoint, this is particularly relevant because, in the following experiments, we hope to demonstrate that an irrelevant color singleton can receive involuntarily attentional priority only on the basis of its features (Nothdurft, 1993). In doing so, we followed Yantis's (1993) criteria. The core of his theoretical position was the clear distinction between *defining attributes* and *reported attributes* of a target in a visual search task (Duncan, 1985). Defining attributes are those features of the target that are critical for the task. As Yantis (1993, p. 677) pointed out, defining attributes are "what the observer is 'looking for' during search," whereas reported attributes are what the observer reports in the response.

At this point, it should be clear that the first step in establishing whether a feature singleton can summon attention in a real stimulus-driven fashion is to rule out any top-down effects.[1] This aspect has not always been considered in previous work. Therefore, we completely agree with Yantis in claiming that the defining attributes determine the observer's attentional control setting, so that an effective stimulus-driven attentional capture is given only when attention is summoned independently of defining attributes or top-down factors. The distinction between SDM and FSM (Bacon & Egeth, 1994) is also useful in defining when an attentional capture should be considered really stimulus driven. In our opinion (but see Bacon & Egeth, 1994, for a different interpretation), such attentional capture is observed only when subjects adopt an FSM strategy for target detection—that is, a narrow attentional set limited to target-defining attributes (see the General Discussion section for a more detailed debate). Thus, an effective bottom-up capture should not depend on a subject's expectancy or strategy, which, in turn, seems to be clearly present when an SDM is used to perform a visual search task. In fact, whereas an FSM is comparable with a narrow attentional set (based on a specific feature value—i.e., the color red), an SDM is comparable with a broad attentional set. That is, the strategy adopted by the subjects could be *search for the discrepant element, whatever it is*. Hence, although SDM implies a less precise set, this is always a set (therefore, a strategy) that exerts a top-down influence in the visual search task (for a similar interpretation, see also Folk & Remington, 1998). It follows, by definition, that the attentional capture observed, if any, cannot be purely bottom-up. Therefore, an effective attentional capture for a particular feature should emerge with subjects' performing an FSM for a different stimulus property.

For example, Theeuwes (1992) discovered that a color singleton distractor captured attention, finding that "selectivity primarily depends on bottom-up processing" (p. 602). Bacon and Egeth (1994), however, argue that this statement is not fully justified on the basis of the results. In fact, in Theeuwes's form condition (1992, Experiment 1A), the target line segment was always inside a green circle surrounded by green squares, with or without a red square distractor. As was shown by Bacon and Egeth, these conditions did not ensure that subjects performed the task by using an FSM for the green circle; rather, subjects might have used an SDM to find the target. In fact, when an SDM was made ineffective by presenting more than one target shape, forcing subjects to adopt an FSM, attentional capture by a color singleton disappeared (Bacon & Egeth, 1994, Experiments 2 and 3).

Hence, to investigate attentional capture by an irrelevant color singleton, we used a task in which subjects looked for a rotated *T* among rotated *L*s, a typical task that is performed serially, in which the target does not pop out (see, e.g., Egeth & Dagenbach, 1991; Julesz & Bergen, 1983; Kwak, Dagenbach, & Egeth, 1991; Wolfe, 1998; Wolfe et al., 1989) and which, therefore, cannot be performed by means of an SDM.

EXPERIMENT 1

The purpose of the present experiment was to provide evidence that color can elicit a real bottom-up attentional capture when it is task irrelevant. An early study of Jonides

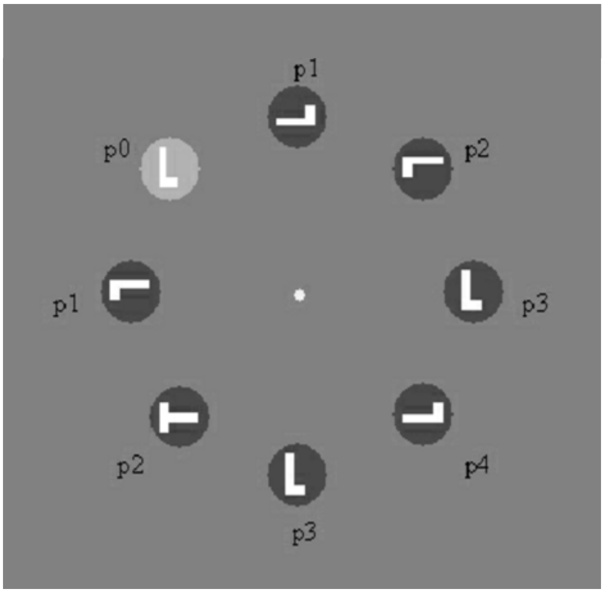

Figure 1. Sample stimulus display for Experiment 1. Differences in color are represented as differences in gray level (bright gray corresponds to green, dark gray corresponds to red). The background was black. Target–singleton distance is indicated by p_0, p_1, p_2, p_3, and p_4 (they were not present in the display). In this example, the target (T) is inside the element, at 90º from the color singleton.

and Yantis (1988) showed that color did not summon attention (see also Gibson & Jiang, 1998). It should be noted that in that study, color was not useful for finding the target and that target and distractor elements were all different letters, thus rendering an SDM inapplicable. As we mentioned above, these should be considered the correct experimental conditions to observe a possible bottom-up capture by color.

However, on the basis of the Guided Search model (Cave & Wolfe, 1990; Wolfe, 1994, 1996), as well as the FeatureGate model (Cave, 1999), the activation level of the bottom-up map (for a specific feature) is computed from the difference between the value for a feature at specific location and the value for the same feature at neighboring locations in the display (see also Koch & Ullman, 1985). It follows that there is no reason why a singleton in the color dimension should not produce a bottom-up activation—that is, a stimulus-driven capture (for a similar position, see also Todd & Kramer, 1994). Therefore, if attentional capture by color was not observed in previous studies, perhaps the subjects used a strategy that consisted of ignoring or inhibiting the bottom-up feature map activation. Jonides and Yantis's (1988) subjects might have been influenced by previous experience with similar tasks and/or might have developed a specific ability to suppress or neglect task-irrelevant information. Hence, because it is possible that the ability to discard this kind of information is related to experience, our experiment is designed to limit the role of top-down experience. We expected that subjects who had no previous experience with visual search tasks would be less likely to ignore the color singleton, even when they were clearly informed that such a singleton was not relevant for the task.

In addition, to test attentional capture by color, we devised a procedure different from set sizes but similar to the one developed by Cave and Zimmerman (1997), in which target–color-singleton distance is the critical independent variable. We termed this procedure the *distance* method. We also were interested in directly testing practice effects in capture. In fact, we believe that an irrelevant odd-colored item embedded in a homogeneous display should usually produce an involuntary shift of attention. However, if subjects are allowed to become familiar with such displays, they can perhaps learn to ignore the useless color information. We examined this prediction by submitting naive subjects to two experimental sessions, expecting that a reliable change in capture should emerge over sessions.

Method

Subjects. Fifteen students at the University of Padua (10 males and 5 females), all right-handed and with normal or corrected-to-normal vision, served as naive subjects. They had neither practice with visual search tasks nor any knowledge about cognitive psychology. They were ignorant of the purpose of the experiment and were recruited from faculties different from psychology or were naive of psychology.

Apparatus. Stimulus displays were presented on a Philips DM778C 19-in. color monitor driven by a personal computer equipped with a graphics board (640 × 480, 60 Hz). Stimuli were built using Micro Experimental Laboratory (MEL; Schneider, 1988). The monitor was placed at eye level on a table in front of the subject. The subject sat with the head positioned on a headrest, so that the distance between the eyes and the screen was approximately 50 cm. The subject responded by pressing keys on a keyboard, and the task was performed in a dimly lighted room (about 1 cd/m^2).

Stimuli. The stimulus field consisted of eight disk elements (1.6º in diameter), equally spaced around a fixation point on an imaginary circle whose radius was 4.5º. For each display element, there was one color singleton disk (e.g., green) among seven disks of the same color (e.g., red). The disks appeared colored on a dark monitor (background illumination of 0.15 cd/m^2). The red and green colors were matched for luminance.[2] When the target letter (*T*) was present (on 50% of the trials), it was inside one of the eight disks. The target could be presented at any of four rotations (0º, 90º, 180º, or 270º). Each of the seven remaining disks contained an *L* at any of the same four rotations. The color of the singleton and the color of the other disks were reversed randomly within each block of trials (on half of the trials, there was a red disk among green disks; the reverse happened on the remainder). The target and distractors covered 1.2º of visual angle (see Figure 1).

Target position was random, so that, when present, the target appeared inside the color singleton on only one eighth of the total trials.

Design. Three within-subjects factors—target position (five levels: p0, p1, p2, p3, and p4), session (two levels: first and second), and target presence (two levels: present or absent)—were used. The position p0 is defined as the position of the target inside the singleton, p1 is the position of the target inside the adjacent disc, and so forth. Each subject performed in two sessions, consisting of four blocks of 128 trials each, on 2 different days. In addition, because previous research had shown that the T–L task is very difficult, before the experiment began, the subjects performed in a 60-trial

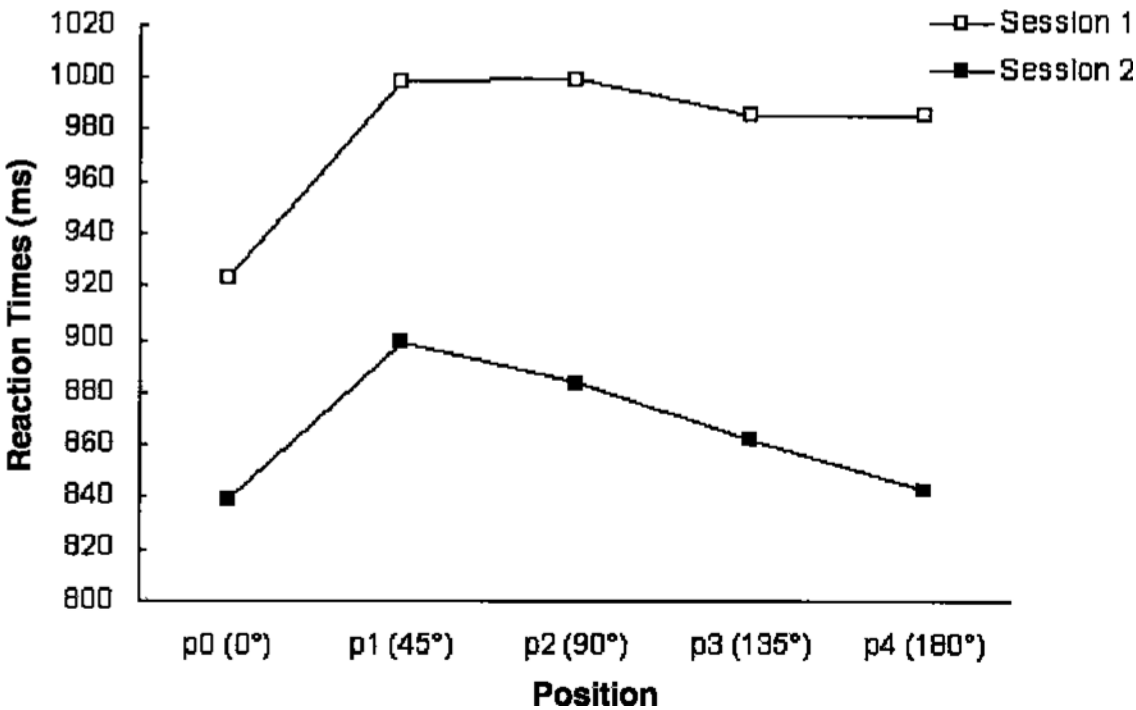

Figure 2. Mean response times in Experiment 1 as a function of target–singleton distance and session. In Session 1, even though the color singleton was not predictive of target position, the subjects exhibited an attentional capture by the odd-colored disk. In Session 2, this phenomenon slightly diminished, probably because subjects were able to ignore the irrelevant color singleton.

training session. In the training trials, which were not analyzed, no odd-colored item was presented.

Procedure. The subjects were given an oral and a written description of the stimuli and task. They responded by pressing one of two keys: Q for target absent and P for target present (right and left hands were counterbalanced across subjects). Also, they were told to respond as quickly as possible, while maintaining accuracy. The subjects were fully informed that the color singleton was not predictive of the target position. The stimulus display remained visible until the subject responded (Wolfe et al., 1989). This was necessary because a pilot study in which the display lasted for only 180 msec revealed that the task was very hard and many errors were made (about 40%). It was emphasized to the subjects that they should fixate the central point and not move their eyes at any time during stimulus presentation. Eye movements were monitored on line by means of an infrared ray device throughout the trial. Those trials in which an eye movement was detected were discarded and not replaced. However, the subjects made very few eye movements (fewer than 2%), maintaining fixation as required.

The sequence of events began with fixation point presentation for 500 msec, followed by the visual search display. From stimulus occurrence, the subjects were given 2,500 msec to respond by pressing one of the two keys. The feedback for an incorrect response was a 500-msec, 500-Hz tone, presented together with a display message, "error." If a response was not given within 2,500 msec, the subjects received the same sound signal, along with a display message, "missed response."

Results and Discussion

In this and all the subsequent experiments, outliers were discarded from the data sets before the analyses were carried out. Outliers were defined as response times (RTs) faster than 150 msec or more than 2.5 standard deviations above the mean. This resulted in the removal of approximately 3% of all the observations.

For target-present trials only, data were explored by considering target position and session factors. Mean correct RTs were entered into a two-way repeated measures analysis of variance (ANOVA). The main effects of target position [$F(4,56) = 6.548, p < .001$] and session [$F(1,14) = 54.729, p < .001$] were significant. The target position × session interaction was significant [$F(4,56) = 2.552, p < .05$]. Pairwise comparisons (*t* tests) of target position data revealed that, in Session 1, RTs at p0 ($M = 923$ msec, $SD = 156$) were significantly faster than RTs at p4 ($M = 986$ msec, $SD = 156$)—that is, at the fastest of the nonsingleton positions (RT difference, 30 msec, $p < .05$). By contrast, in Session 2, p0 was not significantly different from either p3 or p4 (see Figure 2).

Error rates (see Figure 3) were entered into a two-way repeated measures ANOVA, with target position and session as factors. Only the main effect of target position was significant [$F(4,60) = 17.805, p < .001$]. Pairwise comparisons revealed that the error rate at p0 ($M = 10\%$) was significantly lower than the error rate at p3 ($M = 16\%$)—that is, at the most accurate of the nonsingleton positions ($p < .01$).

The error rate pattern paralleled the RT data, providing additional evidence that attention improved speed as well

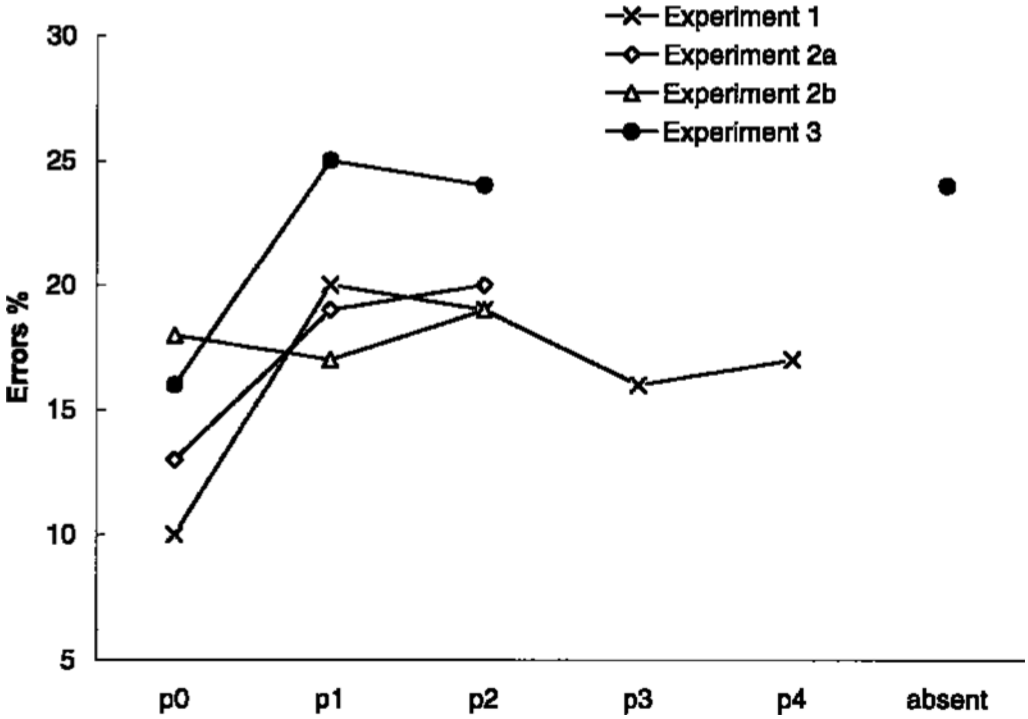

Figure 3. Error rate (%) in Experiments 1, 2A, 2B, and 3 as a function of target–singleton distance and session. In every experiment but Experiment 2B, the error rate at p0 was significantly smaller than the error rate at the most accurate of the nonsingleton positions. The patterns were very similar to those for response times, thus excluding any speed–accuracy tradeoff.

as accuracy for target discrimination, thus excluding any speed–accuracy tradeoff.

In addition, to provide evidence that the task was performed strictly serially, the data were further analyzed by considering only the target presence (present or absent) factor, regardless of target position or session. Mean correct RTs were entered into a one-way repeated measures ANOVA, which was significant [$F(1,15) = 44.088$, $p < .001$]. The subjects responded more rapidly when the target was present ($M = 923$ msec, $SD = 176$) than when the target was absent ($M = 1{,}114$ msec, $SD = 262$). Because many experiments have shown that the T–L task engages subjects in a serial and self-terminating search (e.g., Wolfe, 1998; Wolfe et al., 1989), we can reasonably assume that the same occurred in the present experiment. Hence, by dividing the RT difference (191 msec) between the absent and the present conditions by half the number of elements (eight) in the array, we estimate that the time required for processing each item was about 48 msec. This value is very similar to those found in previous studies using the T–L task, strongly suggesting that the present task was performed serially.

In sum, the present results provide evidence that a salient element in the color dimension produced a signal that clearly had an impact on the deployment of attention. Since the experimental conditions reasonably exclude the possibility that any attentional set for color might be implicated, the singleton evoked a stimulus-driven attentional capture. In fact, this experiment showed that the salient color singleton attracted attention to an item that had no higher probability of being the target than any other item in the display. Note that these are exactly the conditions that were met in Jonides and Yantis's (1988) experiments for demonstrating attentional capture for onset. This is direct behavioral proof that a task-irrelevant color singleton can elicit an automatic attentional capture in the absence of any set (cf. Folk et al., 1993).

Although we interpreted the RT difference between p0 and p4 as being due to an involuntary shift of attention elicited entirely by the saliency of the color singleton, one may observe that the same results could also be explained simply on the basis of the filtering cost hypothesis, without involving any shift of attention (Folk & Remington, 1998). This alternative interpretation would state that, in searching for the target, the display was explored by attention's starting from a disk at chance. If the target was found outside the color singleton, an inhibitory process that filtered out the distractor singleton was initiated. Clearly, the closer the target was to the colored item, the greater were the resources required for inhibiting it, thus lengthening RTs for target detection. This account would explain the RT difference between p1 and p4. However, when the target was inside the singleton, no salient distractor had to be filtered out, and therefore, RTs at p0 were faster than RTs at p4. In Experiment 3, we explored this hypothesis in a more direct manner.

In addition, the data suggested that practice had some effect on the subjects' performance in that, in the second session, attentional capture by color was sensibly reduced. As we argued previously, it is possible that subjects can learn to counteract attentional deployment to a singleton.

We also conducted an ANOVA on RTs, considering only the nonsingleton positions (p1, p2, p3, and p4). The main effect of target position was significant [$F(3,45) = 4.300, p < .01$], showing an RT pattern in which the distance of the target from the singleton was inversely related to the speed of response in discriminating the target. Pairwise comparisons showed that RTs at p1 were significantly slower than RTs at p3 and p4 ($p < .05$). This RT pattern was similar to that found by Cave and Zimmerman (1997). They showed that when attention selects an object in the visual field, a suppressive surround centered on the object location is initiated, providing the first behavioral evidence of the flanking inhibition phenomenon (see also Carr & Dagenbach, 1990). Likewise, Walley and Weiden (1973) had originally proposed that, to avoid information overload, a lateral inhibition mechanism is involved in attentional selection. They suggested that the inhibitory effect, termed *cognitive masking*, varies as a function of distance, so that with respect to the object selected, neighboring units would be more suppressed.

EXPERIMENT 2A

On the basis of the results of Experiment 1, it seems reasonable to conclude that onset is not unique in eliciting a stimulus-driven attentional capture but, rather, that even color attracts attention in a bottom-up fashion. At this point, it is worth remembering that a shift of attention is said to be automatic when it occurs independent of the observer's will—that is to say, when it is a mandatory process (Hasher & Zacks, 1979; Posner & Snyder, 1975; Schneider & Shiffrin, 1977). However, as has already been demonstrated by several studies, if one should use this constraint to define automatic attentional capture, neither onset meets this criterion (e.g., Warner et al., 1990; Yantis & Jonides, 1990). Thus, we do not expect exogenous orienting by color to be completely obligatory to be considered automatic. However, since one could argue that in Experiment 1, the subjects might have spontaneously deployed attention to the singleton because it did not carry any cost, we decided to run a new experiment in which the position of the color singleton was negatively correlated with target position. Hence, we established an experimental condition in which any involuntary strategic attentional deployment to the odd-colored item was detrimental. However, the subjects were not explicitly informed that the color singleton was the less likely position for the appearance of the target; rather, we allowed the subjects to exhibit unbiased behavior about the observed display. This, as will be discussed later (see the General Discussion section), was motivated by the fact that we maintain that color is able to grab attention unless the observer has a set contrary to the singleton. In our view, it is not strictly necessary that color elicit a completely involuntary shift of attention to claim that it can affect subjects' searching behavior—that is, attentional allocation. Note that, in this regard, neither onset would attract attention automatically if a strong orthogonal set is adopted (see, e.g., Warner et al., 1990; Yantis & Jonides, 1990). Attentional capture by color should not be held to a higher standard than attentional capture by abrupt onset. If attention goes to a stimulus just because of the saliency of its color, then it captures, for the purposes of this paper.

Method

Subjects. Twelve students at the University of Padua (2 males and 10 females), all right-handed and with normal or corrected-to-normal vision, served as naive subjects. They had neither practice with visual search tasks nor any knowledge about cognitive psychology. They were recruited according to the criteria of Experiment 1.

Apparatus and Stimuli. The apparatus and stimuli were the same as those in Experiment 1, except that the stimuli were four disks. This choice was motivated by the fact that, with four elements, we can reach a sufficient number of trials for the detrimental singleton, while also maintaining the same overall number of trials as that in previous experiments.

Design and Procedure. The design and procedure were the same as those in the previous experiment, with few exceptions. The subjects performed a single experimental session consisting of four blocks of 124 trials each, and the target was present on 61.3% (304/496) of the trials. Across blocks, the target appeared in the singleton position in 64 trials, whereas each of the nonsingleton positions accommodated the target in 80 trials. This means that the probability of the target's appearing in the singleton position was 21%, whereas the probability of the target's appearing in each of the nonsingleton positions was 25%. In order to avoid any voluntary set contrary to the singleton, the subjects were only told, as in Experiment 1, that it was not predictive of the target's position. In addition, by having only four target positions, the subjects were able to perform the task with a shorter display time. So, although we emphasized the need for the subject to keep his/her eyes fixed on the center point, the fact that the stimulus display appeared on the screen for a short time (180 msec) made any eye movements useless.

Results and Discussion

In this experiment, fewer than 3% of all the observations were discarded because of the outlier-latency criterion. Mean correct RTs were entered into a two-way repeated measures ANOVA, in which the factors were target position and blocks. The only factor that was significant was target position [$F(2,22) = 13.253, p < .001$]. Neither the main effect of blocks nor the target position × blocks interaction was significant. Pairwise comparisons of target position data revealed that RTs at p0 (M = 762 msec, SD = 97) were significantly faster than RTs at p2 (M = 810 msec, SD = 101)—that is, at the fastest of the nonsingleton positions (RT difference, 48 msec, $p < .01$; see Figure 4).

Error rates (see Figure 3) were entered into a two-way repeated measures ANOVA, with target position and blocks as factors. Only the main effect of target position was significant [$F(2,22) = 5.279, p < .02$]. Pairwise

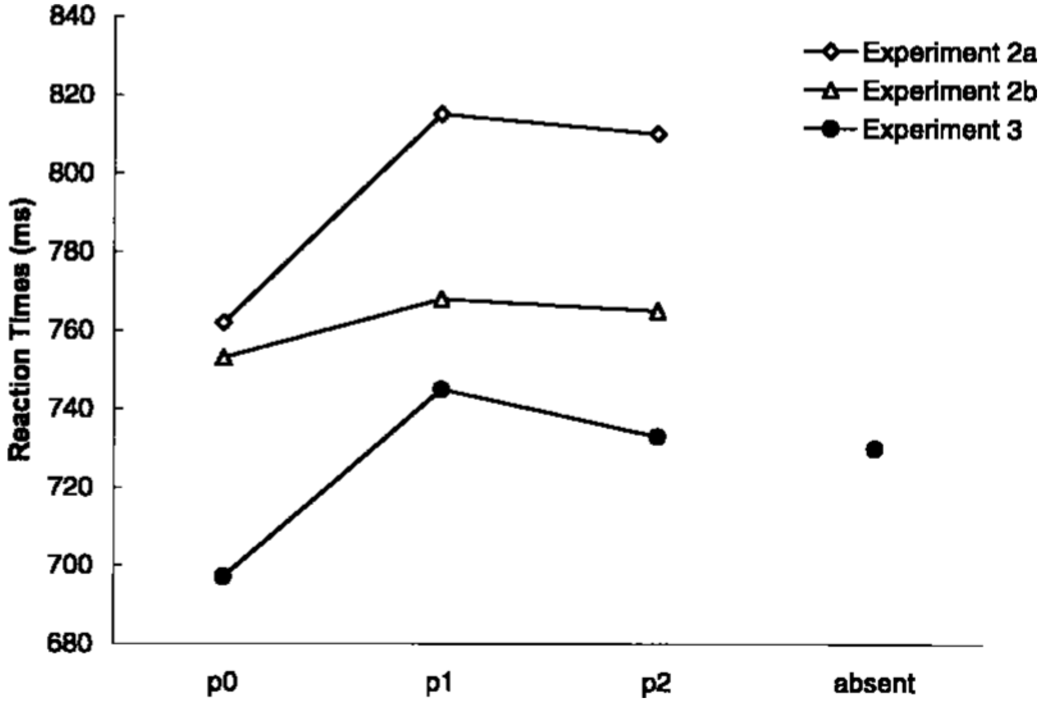

Figure 4. Mean response times in Experiments 2A, 2B, and 3 as a function of target–singleton distance. In Experiment 2A, the color singleton summoned attention even though it was negatively correlated with target position. Such an effect disappeared (Experiment 2B) when the subjects were informed about color validity. In Experiment 3, target detection was faster for the color singleton position than when the singleton was absent in the display. This result is at odds with a filtering cost interpretation; rather, it likely reflects a spatial shift of attention.

comparisons revealed that the error rate at p0 ($M = 13\%$) was significantly lower than error rate at p1 ($M = 19\%$)—that is, at the most accurate of the nonsingleton positions ($p < .02$).

As in Experiment 1, the error rate pattern paralleled the RT data, thus confirming that attention improved speed as well as accuracy for target discrimination.

By respecting the criteria used by Jonides and Yantis (1988) to show the uniqueness of abrupt visual onset in capturing attention, Experiment 1 provided evidence that a local feature discontinuity in the color dimension could attract bottom-up attention. However, as was pointed out previously, one could argue that attention was deployed to the singleton because it was salient and, critically, because attention to the singleton did not carry any cost. We have three responses to this hypothesis. First, if this were the case, the subjects could have attended to the color singleton in Jonides and Yantis' study as well. Second, this account could be applied to all the results claiming singleton attentional capture and could be seen as an explanation of such capture. Third and most important, it seems to us that the singleton captured attention exactly because it was the salient item, and saliency is thought to be a useful tool for the visual system, exogenously directing attention to the location(s) that differs from the rest, because a conspicuous position often provides interesting information (Cave, 1999; Nothdurft, 1993).

Nevertheless, in order to meet a more stringent definition of attentional capture by color, we devised an experimental condition in which the colored item in the display was the less likely position for the target. In other words, we rendered the color singleton not only useless for the task but, rather, detrimental, since it was negatively correlated with target position.

Even in this condition, the data showed that the detection of the target was faster and more accurate when it occurred at the singleton's location than when it occurred at other positions. This, in our view, is evidence of a purely stimulus-driven attentional capture by a salient color element in the visual field, as has been predicted by many models of visual attention (e.g., Cave, 1999; Cave & Wolfe, 1990).

EXPERIMENT 2B

The aim of this experiment was to address attentional capture by color when the subjects were explicitly informed that the singleton was negatively correlated with target position. As has already been pointed out, we expected that, in this condition, the attentional capture by color that emerged in Experiments 1 and 2A could be prevented voluntarily.

Method

Subjects. Twelve students of the University of Padua (2 males and 10 females), all right-handed and with normal or corrected-to-normal vision, served as naive subjects. They were recruited in accordance with the same criteria as those in the previous experiments.

Apparatus, Stimuli, Design, and Procedure. The apparatus, stimuli, design, and procedure were the same as those in Experiment 2A, with the exception that the subjects were fully informed that the singleton position was the less likely location for the appearance of the target.

Results and Discussion

In this experiment, fewer than 2% of all the observations were discarded because of the outlier-latency criterion. Mean correct RTs were entered into a two-way repeated measures ANOVA, in which the factors were target position and blocks. Neither the main effects nor the interaction was significant (all *p*s $< .4$). An analysis of the error rates showed only a main effect of blocks, with subjects' performance improving over blocks [$F(3,33) = 10.894, p < .001$]. However, the overall results (see Figures 3 and 4) showed that when explicitly informed that the salient element was the less likely position for the target, the subjects were able not to pay attention to the color singleton or, more precisely, they were able to prevent attentional capture otherwise elicited by color in Experiment 2A.This result does not undermine our finding that color is able to draw attention automatically, in the sense of occurring by default whenever there is no intent to prevent such capture.

EXPERIMENT 3

The goal of the third experiment was to investigate the nature of the attentional capture that emerged from Experiments 1 and 2A. That is, we addressed the question of whether the benefits for the color singleton found in the previous experiments were due to a real shift of spatial attention or to a filtering cost (Folk & Remington, 1998). Although we interpreted faster RTs for the color singleton position as being the consequence of a spatial attentional capture evoked by the salient color element, one could argue that the same pattern of results could have been obtained even if we assume that color did not attract attention but, rather, that the target was found by allocating attention randomly throughout the display elements. Hence, when the colored element was not coincident with target position, the singleton acted as a distractor and then had to be filtered out. By contrast, when the target was presented inside the color element, the singleton did not carry any cost. It would follow that faster RTs for the color singleton reflected the absence of a filtering cost that, in contrast, was required when the color singleton and the target did not coincide.

Therefore, we used the same experimental conditions as those in the previous experiment, except that target position was random—namely, the target appeared inside the color singleton in one fourth of the trials that included a singleton. However, the singleton was presented only on two thirds of the total trials. We reasoned that if attention is attracted by the singleton, target detection should be faster when it is coincident with the odd-colored item than when the singleton is absent. By contrast, following the filtering cost hypothesis and assuming that, when the target coincides with the singleton, the singleton does not need to be filtered out (this was an alternative explanation of the results of Experiments 1 and 2A), we expect no RT differences when the target coincides with the singleton and when the singleton is not present.

Method

Subjects. Thirteen students of the University of Padua (8 males and 5 females), all right-handed and with normal or corrected-to-normal vision, served as naive subjects. They were recruited following the same criteria as those in the previous experiments.

Apparatus and Stimuli. The apparatus and stimuli were the same as those in Experiment 2A.

Design and Procedure. The design and procedure were the same as those in Experiment 2A, with a few exceptions. First, the target appeared with the same probability in each of the four disks. Second, the color singleton was present only on 61.5% (320/520) of the trials. Each block consisted in 80 singleton-present trials and 50 singleton-absent trials. In the singleton-present trials, the target was present on 60% (48/80) of the trials. In the singleton-absent trials, the target was present on 60% (30/50). The subjects performed a single experimental session consisting of four blocks of 130 trials each.

Results and Discussion

In this experiment, fewer than 4% of all the observations were discarded because of the outlier-latency criterion. Mean correct RTs were entered into a two-way repeated measures ANOVA, in which the factors were target position and blocks. The only significant factor was target position [$F(2,24) = 11.940, p < .001$]. Neither the main effect of blocks nor the target position × blocks interaction was significant. Pairwise comparisons of target position data revealed that RTs at p0 (M = 697 msec, SD = 132) were significantly faster than RTs at p2 (M = 733 msec, SD = 154)—that is, at the fastest of the nonsingleton positions (RT difference, 36 msec, $p < .01$; see Figure 4). Likewise, when accuracy was analyzed (see Figure 3), there was a significant main effect of target position [$F(2,24) = 11.652, p < .001$], and pairwise comparisons revealed that the error rate at p0 (M = 16%) was significantly lower than the error rate at p2 (M = 24%)—that is, at the most accurate of the nonsingleton positions ($p < .02$). These findings replicated those of the previous experiments showing that a color singleton affected attention deployment in the visual field by considering either RTs or accuracy as a dependent variable.

We also compared RTs when the target was inside the color singleton with those when the singleton was absent. On average, the subjects found the target more rapidly when it was coincident with the colored disk than when it was inside a green element and the singleton was not in the display (RT difference, 33 msec, $p < .02$, two-tailed). Again, the percentage of errors paralleled the RT data, showing that, when searching for the target, the subjects made fewer errors at p0 than when the color singleton was absent ($p < .03$, two-tailed). As was discussed earlier, this is the pattern of results that one should expect if the advantage for target detection in the color singleton were due to a spatial shift of attention, rather than to a filtering cost.

GENERAL DISCUSSION

Whereas top-down attentional selection for color is well documented (e.g., Bacon & Egeth, 1994; Folk et al., 1992), evidence that color can attract attention in a bottom-up fashion is inconclusive (e.g., Folk & Annett, 1994; Gibson & Jiang, 1998; Jonides & Yantis, 1988; Pashler, 1988; Theeuwes, 1992; Todd & Kramer, 1994). However, as was already noted, almost all the models of visual attention predict that a singleton in any dimension (including color) produces a peak of activation in the bottom-up feature map and, because of this, should elicit an attentional capture (for a similar suggestion, see also, Todd & Kramer, 1994).

Given these premises, our study was aimed at further exploring attentional capture mechanisms specifically for the color attribute. In order to demonstrate a real stimulus-driven capture for color, it was necessary to exclude any relevant attentional set for this feature. We reasoned that the lack of evidence for a bottom-up capture by an irrelevant color singleton might have been related to practice. In previous studies, subjects probably were able to ignore the odd-colored item, and because we suspected that the ability to override the color information could be related to the subjects' experience, we recruited subjects who were naive of visual search tasks. A further characteristic of our experiments was that we employed a method different from set sizes—namely, the *distance* method—to evaluate involuntary shifts of attention. As will be discussed below, we think that, in contrast to previous studies (e.g., Jonides & Yantis, 1988), this might have been another crucial aspect that allowed automatic attentional capture by color to be observed in the present study. In addition, it might be worth noting that we used a T–L task, in which letters with different orientations were presented over colored objects, whereas the most common stimuli employed in previous research were normally upright-oriented colored letters (e.g., Folk & Annett, 1994; Gibson & Jiang, 1998).

The results of our experiments can be summarized as follows. Experiment 1 showed that an irrelevant color singleton affected the deployment of attention in a stimulus-driven manner. Experiments 2A and 2B extended previous results, demonstrating that, unless explicitly counteracted, such a capture occurred even when detrimental. Finally, Experiment 3 addressed the nature of such a capture, confirming that the color singleton produced a spatial shift of attention.

These findings are of relevance for two main reasons. First, they give support to many contemporary models of visual attention (e.g., Cave, 1999; Cave & Wolfe, 1990; Koch & Ullman, 1985; Wolfe, 1994, 1996), showing that a color singleton is able to produce an involuntary shift of attention simply on the basis of its saliency (Theeuwes, 1992). In fact, these models predict that the visual environment is ultimately coded in a *saliency* map (the activation map, in the terminology of Cave & Wolfe, 1990), which emphasizes interesting or conspicuous locations in the visual field. Within this topographical representation of the visual field, the activation at any given location is a function of the discrepancy between that location and the neighboring units: the greater the difference, the higher the peak of activation. Attention would be deployed on the basis of activation levels, with the most salient locations inspected first (see also Nothdurft, 1993).

Second, the present results challenge the notion that attentional capture is *always* contingent on a given control setting (Folk et al., 1992, 1993). In fact, in the contingent involuntary orienting perspective, an involuntary shift of attention to a given stimulus depends on whether the stimulus shares feature(s) that is (are) critical to performing the task. By contrast, the present results showed that, while the subjects were searching for a target letter, an irrelevant color singleton evoked a stimulus-driven capture. Of course, we cannot conclude that the attentional shift in Folk et al. (1992) was not involuntary. We agree with the authors when they conclude that the attentional shift produced by an irrelevant distractor (sharing a feature critical for the task) is an involuntary attentional capture. However, we believe that we have provided evidence that an unintentional shift of attention, relying exclusively on stimulus feature or perceptual salience, is also possible (see also Scholl, 2000; Theeuwes & Burger, 1998; Turatto & Galfano, 2000).

It is conceivable that all kinds of discontinuities (i.e., dynamic and static) present in the visual field are able to summon attention in a real bottom-up fashion when they confer enough salience to an object (Cave & Wolfe, 1990; Nothdurft, 1993). The difference between various stimulus properties, such as onset, color, size, form, and orientation, might lie in the degree of top-down control that a subject can exert to disregard the attentional capture produced by each of these stimulus features. From this point of view, the empirical evidence suggests that abrupt visual onset, even when task irrelevant, has a specific strength in summoning attention in a real stimulus-driven manner (e.g., Jonides, 1981; Jonides & Yantis, 1988; Müller & Rabbitt, 1989; Yantis & Jonides, 1984). However, later studies have shown that attentional capture is not all-or-none. Attentional capture evoked by abrupt onset is very hard to suppress but can be prevented if attention is fully focused on a given spatial position (see, e.g., Warner et al., 1990; Yantis & Jonides, 1990). Even abrupt onset cannot produce mandatory capture.

Top-down modulation of bottom-up attentional capture might be easier to achieve for color, or other static discontinuities, than for onset. These different degrees of top-down control can be thought of as a hierarchy of modulation (Yantis & Johnson, 1990), in which the hardest capture to override is that caused by abrupt onset and the easiest is the one from static discontinuities. The strength of top-down influence that is required to overcome an attentional capture could be related to the different kinds of information conveyed by two distinct physiological visual pathways, the parvocellular and the magnocellular pathways (Ungerleider & Haxby, 1994). As was suggested by Folk and Remington (1998, p. 857), because the magnocellular system "carries particularly important ecological information regarding dynamic changes," it "may be more impervious to top-down influence than the parvocellular system."

Moreover, the display-size method might be less than ideal for exploring attentional capture by color or other static discontinuities. In fact, the sudden simultaneous presentation of all the stimuli in an array also produces a global onset, which potentially could compete with the local signal from the color singleton, preventing attention from being attracted to its location. A demonstration of such an effect comes from *change blindness* studies (e.g., Simons & Levin, 1997). In the case of the *mudsplashes* technique (e.g., O'Regan, Rensink, & Clark, 1999), a set of strong local transients compete with the target change and so tend to draw attention away from the target. Similarly, the display-size method could be inadequate to let attentional capture by color emerge: The local color signal, which by itself might be able to draw attention, would have to compete with the transient signal produced by global onset of the whole display. If we consider the peak of activation coming from the color singleton as the relevant signal and those coming from the distractors as noise, it is clear that the signal/noise ratio decreases as the set size increases. The use of a single set size allowed us to keep the signal/noise ratio constant.

A similar position has been suggested by Martin-Emerson and Kramer (1997), who demonstrated that even onset no longer captured attention when the number of no-onset elements increased from 5 to 13. They reasoned that whenever a new object appears in the visual field, an interrupt signal is generated in order to give attentional priority to processing that object (Yantis & Johnson, 1990). However, this mechanism can be affected by the amount of noise created by other concomitant transient signals, which in their experiment was generated by removing elements of the no-onset letters. The *interrupt threshold hypothesis* suggests that the greater the number of elements, the greater the noise they will produce, which, in turn, would mask the local transient signal coming from the onset and would prevent attention from being attracted by the new object.

A recent study from Gibson and Jiang (1998), in which accuracy was used as an index of attentional selection, was devoted to exploring whether the lack of evidence for attentional capture by color was due to the way in which the phenomenon had been previously investigated. Basically, the new method adopted consisted in submitting subjects, in a first segment of trials, to a visual search task for prespecified target letters (H or U) among other letters. Then, on the surprise-encounter trial, the target appeared unexpectedly as a color singleton. From that moment on, one of the two possible targets was always the singleton element in the array. The authors compared subjects' performance in the surprise trial with that in previous trials and that in subsequent trials. The results showed that accuracy on the surprise trial was lower than accuracy on the subsequent trials in which targets were the colored element in the array. This is not a surprising result, in that subjects might have strategically learned to pay attention to the color. In fact, starting from the surprise trial, color became relevant for the task, being consistently associated with the target. Therefore, in order to evaluate a possible capture by color, it could be at least misleading to compare performance in the surprise trial, in which, presumably, the single bottom-up component was involved, with that in the subsequent trials, in which both bottom-up and top-down components were implicated (see, e.g., Cave & Wolfe, 1990). However, the comparison between accuracy in the surprise trial and accuracy in the previous trials, in which no singleton was presented, revealed no statistical differences between these conditions, leading the authors to conclude that the color element was not selected first and, therefore, did not capture attention (Gibson & Jiang, 1998). This result is clearly at odds with our data, and it is difficult to see how to reconcile this discrepancy.

In conclusion, although the issue of stimulus-driven capture is somewhat controversial in the literature, we planned our experiments while respecting Yantis's (1993) criteria—namely, the investigated stimulus property must be independent of either the defining or the reported attribute of the target. This can be done with a procedure in which the target is at the singleton location on only $1/n$ of the trials (where n is the display size). Such a method, which we used in our experiments, can discriminate whether various features can force attention to an item that has no higher probability of being the target than does any other item in the display (see, e.g., Jonides & Yantis, 1988).

In addition, exogenous orienting need not be completely obligatory to be considered automatic. We do not expect to find an attentional capture for color by this more stringent definition, because even onset, which can certainly produce a stronger bottom-up signal, does not meet this criterion (e.g., Yantis & Jonides, 1990). By contrast, our data are consistent with Spence and Driver (1994) in that the concept of automaticity defined as a completely mandatory reflex could be a naive notion with respect to exogenous orienting. As they noted, even lowlevel reflexes, such as the knee-jerk, are subject to some degree of strategic modification (Matthews, 1991). Our data show that color can elicit automatic orienting in the weaker sense of taking place by default when an observer has no particular intention with regard to the observed stimuli. Note that this is also all that one could claim about orienting to an onset singleton.

Our data are consistent with many theoretical models of visual attention (e.g., Cave, 1999; Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Koch & Ullman, 1985; Treisman & Sato, 1990; Wolfe, 1994, 1996), which are fundamental pieces of the literature on this issue. Indeed, failure to find bottom-up attention induced by color would present serious problems for these models. We have found that color can elicit bottom-up attention in our experimental paradigm, despite the results of earlier experimental designs, aimed at other theoretical issues, that did not find such an effect.

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NOTES

1. Clearly, one cannot definitely assume that the subjects' attentional set relies only on the stimulus properties defined by the experimental conditions. Subtle aspects of the task might lead to an attentional set different from that defined by the experimenter (e.g., Bacon & Egeth, 1994). However, the experimental condition should be such as to limit this risk as much as possible.

2. The photometric and colorimetric measurements were carried out by means of a Minolta chromameter CS-100. The green (CIE x,y chromaticity coordinates of .270/.618; RGB palette value set at 0, 28, 0) and red elements (CIE x,y chromaticity coordinates of .598/.347; RGB palette value set at 41, 0, 0) had a luminance of 2.5 cd/m^2.

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