Task-irrelevant stimulus salience affects visual search ☆

Dominique Lamy *, Loren Zoaris

Department of Psychology, Tel Aviv University, Ramat Aviv, POB 39040, Tel Aviv 69978, Israel

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ABSTRACT

The relative contributions of stimulus salience and task-related goals in guiding attention remain an issue of debate. Several studies have demonstrated that top-down factors play an important role, as they often override capture by salient irrelevant objects. However, Yantis and Egeth [Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 661–676.] have made the more radical claim that salience plays no role in visual search unless the observer adopts an attentional set for singletons or "singleton-detection mode". We reexamine their claim while disentangling effects of stimulus salience from effects of attentional set and inter-trial repetition. The results show that stimulus salience guides attention even when salience is task irrelevant.

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Most current models of attention assume that selection is the result of the joint influence of goal-directed (or top-down) and stimulus-driven (or bottom-up) factors (e.g., Bundesen, 1990, 1998; Desimone & Duncan, 1995; Itti & Koch, 2000; Koch & Ullman, 1985; Treisman & Sato, 1990; Wolfe, 2007). Bottom-up signals depend on how different an object is from its neighbors, that is, on local contrast. Top-down signals depend on the degree of match between an object and the set of target properties specified by task demands. For instance, the Guided Search model (e.g., Cave & Wolfe, 1990; Wolfe, 1994, 2007) posits that an item's overall level of attentional priority is the sum of its bottom-up activation level and its top-down activation level. Likewise, according to the biased competition model (Desimone & Duncan, 1995; Kastner & Ungerleider, 2000), both goal-directed and stimulus-driven factors play a role in biasing neural activity across the visual hierarchy and thereby determine which object in the visual field wins the competition for representation in the brain.

Despite this apparent consensus, the relative contributions of bottom-up and top-down factors in the allocation of attentional priority have been hotly debated (see Pashler, Johnston, & Ruthruff, 2001; Rauschenberger, 2003; Ruz & Lupianez, 2002 for reviews). Common sense suggests that salient objects in a visual scene should draw attention involuntarily, and indeed "one would like to know the fortunate (or unfortunate) man who could receive a box on the ear and not attend to it" (Sully, *The Human Mind*, quoted in Wolfe, 1998). Yet, following seminal studies by Folk, Remington, and Johnston (1992), Bacon and Egeth (1994) and Yantis and Egeth

(1999), many findings have been reported that favor the idea that perceptual salience does not affect attentional priority in a purely automatic and uncontrolled fashion, and that its effects are mostly contingent on top-down settings (e.g., Folk, Leber, & Egeth, 2002; Folk & Remington, 1998; Gibson & Jiang, 1998; Lamy & Egeth, 2003; Lamy & Tsal, 1999; Leber & Egeth, 2006; Pashler, 1988; Pashler et al., 2001).

According to this view, whether a salient distractor captures attention depends on the relation between distractor properties and the properties used to find targets. Folk et al. (1992) showed that a color singleton distractor elicits a shift of attention to its location when subjects search for a color target but not when they search for an onset target, whereas an onset distractor produces the opposite pattern. They concluded that attentional capture is contingent on attentional control settings. In the same vein, using a distinction initially suggested by Pashler (1988), Bacon and Egeth (1994) proposed that in search for a shape-defined target, an irrelevant color singleton captures attention only when task demands allow subjects to engage in a salience-based search mode (using the so-called "singleton-detection mode") but not when task demands induce them to search for a specific shape (using the so-called "feature-search mode").

Such findings are typically held to demonstrate that stimulus salience per se plays no role in visual search: not the stimulus salience of a distractor determines whether this distractor will capture attention, but rather the extent to which this distractor's salient property matches the target-defining property. However, this conclusion is not warranted. In fact, results such as Folk et al.'s (1992) and Bacon and Egeth's (1994) do not necessarily contradict models of visual search positing that bottom-up and top-down factors jointly contribute to the allocation of attentional priority (e.g., Wolfe, 2007), because in these studies, bottom-up

and top-down factors were typically pit against each other. According to the aforementioned visual search models, attentional shifts are made to the location with the highest overall priority. Thus, the finding that salient irrelevant distractors did not capture attention could simply reflect the fact that the influence of the observers' task-related goals was strong enough to override effects of the irrelevant distractors' salience.

The study by Yantis and Egeth (1999), however, does not lend itself to this interpretation and may therefore impose far-reaching constraints on current models of attention and prove our intuitions wrong. Subjects searched for a non-salient target (a vertical bar among tilted bars in various orientations). Each display also contained a color singleton, the unique red bar among blue ones. When the unique red bar coincided with the vertical target on each trial (Experiment 2), search was highly efficient, as reflected by flat search slopes, which suggests that top attentional priority was allocated to the red singleton. By contrast, when the locations of the vertical target and red singleton were uncorrelated (Experiment 3), search slopes for a target that happened to be the red singleton (singleton-target trials) were steep. They were significantly shallower than when the target was not the red singleton (non-singleton-target trials), 39.7 ms vs. 53.3 ms per item, respectively, but still much larger than would be expected if the red singleton had captured attention.

Yantis and Egeth's (1999) findings suggest that unless subjects adopt an attentional set for singletons, stimulus-driven salience plays little or no role in the guidance of attention. Thus, unlike previous findings (e.g., Bacon & Egeth, 1994; Folk et al., 1992), they unambiguously challenge visual search theories according to which "the bottom-up calculation of feature differences in each dimension takes place regardless of the current search instruction and is simply added to the attentional weight associated with top-down template matching" (p. 675). Indeed, such a mechanism would inevitably entail that the vertical target should receive the highest attentional priority weight in the visual array because it should benefit from both the highest top-down activation and the highest bottom-up activation. And if this were the case, the condition in which the target happens to be the red singleton should elicit flat search slopes, yet this clearly did not happen in Yantis and Egeth's study.

In contradiction with this finding, effects of salience on visual search have been reported with irrelevant singletons that did not match current attentional control settings (Lamy, 2005; Lamy, Bar-Anan, Egeth, & Carmel, 2006; Lamy, Leber, & Egeth, 2004; Theeuwes, 2004; Yeh & Liao, 2008). For instance, Lamy, Bar-Anan, et al. (2006) found that while interference by an irrelevant color singleton in search for a shape target was not observed in sparse displays (low salience of the color singleton), such interference emerged with more densely packed displays (high salience of the color singleton). Likewise, in an experiment similar to Folk et al.'s color target condition, an onset singleton was found not to capture spatial attention when it was dim, but to do so when it was bright (Lamy, 2005, Exp. 3). If increasing the salience of a distractor on an irrelevant dimension can override top-down attentional settings, then increasing the salience of a task-relevant target on an irrelevant dimension (as was done in Yantis and Egeth's study (1999)) should boost the attentional priority of this target.

It may be noteworthy that in the cited studies showing increased attentional capture with increased distractor salience, set size was typically not manipulated. Theeuwes (2004; see also Belopolsky, Zwaan, Theeuwes, & Kramer, 2007) suggested that when search is not strictly parallel, subjects narrow their attentional window and search serially through the display. As a result, an irrelevant singleton outside the attentional window does not capture attention. Thus, as search was highly serial in Yantis and Egeth's study, Theeuwes' argument may resolve the conflict in the literature if one assumes that search in previous studies showing effects of salience was parallel (e.g., Lamy, 2005; Lamy et al., 2004, Lamy, Bar-Anan, et al., 2006).

However, several findings weaken the notion that strictly parallel search slopes are the critical factor for attentional capture by a salient distractor to occur. Indeed, both Leber and Egeth (2006) and Lamy, Carmel, Egeth, and Leber (2006) reported instances of strictly parallel search in which salient distractors failed to capture attention. We will return to Theeuwes' (2004) account in the general discussion.

In the present study, we suggest that several aspects inherent to the structure of the task used by Yantis and Egeth (1999) may have masked the effects of stimulus salience. First, the irrelevant singleton was always red and the remaining items were always blue. That is, the colors of the color singleton and that of the other items in the display were not counterbalanced. This has two important consequences. The first is that subjects could adopt an inhibitory set against the feature red (e.g., Lamy & Egeth, 2003; Lamy et al., 2004; Theeuwes & Burger, 1998), which could have offset the effects of the irrelevant singleton salience. The second consequence of this aspect of the design concerns inter-trial priming effects. Maljkovic and Nakayama (1994) showed that in search for a singleton target, the unique feature of which varies randomly from trial to trial, the deployment of focal visual attention is faster when the target feature is the same as in past trials than when it changes, a phenomenon known as priming-of-popout (PoP). While Maljkovic and Nakayama suggested that such repetition effects occur only when the target-*defining* feature repeats, more recent studies have shown that they occur also when an *irrelevant* feature of the target repeats (e.g., Fecteau, 2007; Huang, Holcombe, & Pashler, 2004; Lamy, Kosover, Aviani, Harari, & Levekovitz, 2008). In the non-singleton-target condition of Yantis and Egeth's experiment, the target was most often of the same color (blue) as in the previous trial because the target coincided with the red singleton only on a minority of trials. By contrast, when the target was the red singleton, the target color is most likely to have been blue in the previous trial. Thus, inter-trial color repetition effects played against the singleton target.

Finally, we have recently reported that attending to a singleton is easier when the target on the previous trial had also been a singleton than when it had not been a singleton (Lamy, Bar-Anan, et al., 2006; Lamy, Bar-Anan, & Egeth, 2008). It is therefore possible that attending to a singleton when a singleton has been ignored on the previous trial might incur a cost. To the extent that there is such a cost, it is likely have occurred in Yantis and Egeth's experiment because the color singleton was the target on only a minority of trials and had therefore been ignored on most of the trials preceding a singleton-target trial.

To preview, we show that when the influence of these factors is eliminated, capture by the salient color singleton emerges, thus resolving the apparent contradiction between Yantis and Egeth's results and findings supporting the notion that stimulus-driven salience per se affects the allocation of attentional priority in visual search.

1. Experiment 1

This experiment was a replication of Yantis and Egeth's (1999) third experiment using a two-choice forced discrimination task instead of a detection task. This change in the procedure was introduced in order to maximize the number of trials in which color repetition effects could be examined. Indeed, the effect of repeating the target color can be measured only for target-present trials preceded by a target-present trial, that is, on only 25% of the trials in a detection task and on 100% of the trials in a discrimination

task. The target was a vertical bar among 3 or 5 bars in different orientations. A small filled circle was appended at one end of each bar. Subjects had to report whether the filled circle appeared at the upper or lower end of the target bar. As in Yantis and Egeth's (1999), each display contained a color singleton, the position of which was uncorrelated with the target position, and the color of which remained fixed throughout the experiment. Relative to a detection task, a discrimination task involves the additional requirement of focusing attention on the target in order to identify the response feature (but see Theeuwes, van der Burg, & Belopolsky, 2008). As attentional priority allocation is thought to occur at the preattentive stage, the use of a different task should be inconsequential for the present purposes. Thus, we expected to replicate Yantis and Egeth's critical finding, namely, steep search slopes when the target happened to be the color singleton.

1.1. Method

1.1.1. Participants

Subjects were twelve Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

1.1.2. Apparatus

Displays were generated by an Intel Pentium 4 computer attached to a 15″ CRT monitor, using 640 × 480 resolution graphics mode. Responses were collected via the computer keyboard. A chin-rest was used to set viewing distance at 50 cm from the monitor.

1.1.3. Stimuli

The fixation display was a white 0.2° × 0.2° plus sign (+), in the center of a black background. The stimulus displays consisted of either four or six oriented bars, each of which subtended 0.6° of visual angle in length and was 1-pixel thick. At one end of each bar, either the upper end or the lower end, a filled circle subtending 0.2° in diameter was affixed. The bars appeared within an imaginary 8 × 8 matrix centered at fixation, each cell of which subtended 1.2° in side. Each bar was centered inside its cell with a random jitter between −0.2° and 0.2°. Bar locations within the matrix were randomly selected with the constraints that two bars never appeared at adjacent locations.

Each display contained one vertical bar (the target), while the remaining bars were tilted by either by 30° or −30° from the vertical. On each trial, one bar (the color singleton) was red and the remaining bars (the non-singletons) were all blue for half of the subjects, with the reverse color assignment for the remaining half of the subjects (see Fig. 1).
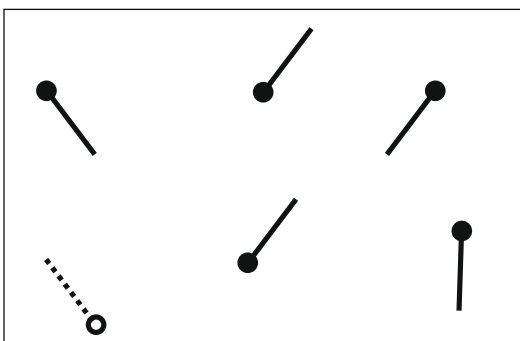
Fig. 1. Sample display from Experiment 1. The dashed line represents the color of the singleton, red for half of the subjects and blue for the other half. In this example, the singleton is not the target (which is the vertical line).

1.1.4. Design

The location of the color singleton was uncorrelated with the location of the target, that is, the color singleton was the target on $1/d$ on the trials, where d is the display size (either 4 or 6). For each bar in the display (including the target), the filled circle was as likely to be affixed at the upper or at the lower end and each display contained an equal number of lower-end and upper-end filled circles. Singleton and non-singleton colors were counterbalanced between subjects, with each display containing a red singleton among blue non-singletons for half the subjects and a blue singleton among red non-singletons for the remaining half.

1.1.5. Procedure

The subjects had to determine whether the filled circle affixed to the target (the vertical bar) was at the lower or at the upper end, by pressing either 2 or 8, respectively, on the numerical keypad. Thus, key locations were congruent with the filled circle position, which minimized variability resulting from response-to-key mapping. The subjects were instructed to respond as quickly as possible, while maintaining high accuracy. Error trials were followed by a 500-msec feedback beep. Eye movements were not monitored, but subjects were explicitly requested to maintain fixation throughout each trial.

Each trial began with the fixation display. After 500 msec, the stimulus display followed, and remained visible for 2000 msec or until response. The screen went blank for 500 msec before the next trial began. The experiment began with a block of 20 practice trials, followed by 480 experimental trials divided into five blocks of 96 trials each.

1.2. Results

Mean reaction time (RT) and accuracy data are presented in Fig. 2. In all RT analyses, error trials (3.2%) were excluded. In this and the next two experiments, outliers (i.e., trials in which RT exceeded the mean of the relevant cell by more than 2.5 standard deviations) were excluded removing less than 1% of all trials. An Analysis of Variance (ANOVA) was conducted with set size and target type as within-subject factors.
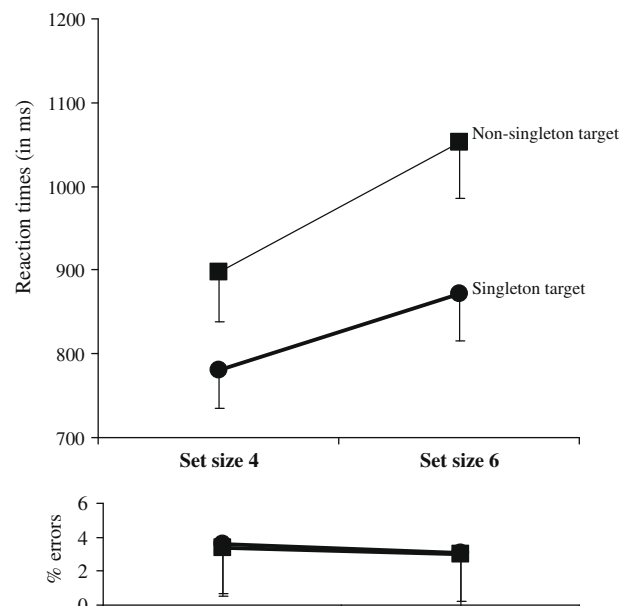
Fig. 2. Experiment 1. Mean response times (RTs) in milliseconds (upper panel) and error rates (bottom panel) by set size and by target type.

Reaction times. The main effects of set size, $F(1,11) = 77.59$, $p < 0.0001$ and of target type, $F(1,11) = 18.11$, $p < 0.0007$, were significant, and so was the interaction between the two factors, $F(1,11) = 6.88$, $p < 0.03$. The mean search slope was flatter in the singleton-target than in the non-singleton-target condition, but it was significantly larger than zero in both conditions, 46 ms, $F(1,11) = 17.57$, $p < 0.002$ and 77 ms, $F(1,11) = 105.15$, $p < 0.0001$, respectively.

Accuracy. No effect approached significance, all Fs < 1.

1.3. Discussion

The objective of the present experiment was to replicate Yantis and Egeth's (1999), (Experiment 3) findings with a discrimination task instead of a detection task. The replication was successful. Indeed, while the singleton enjoyed a priority advantage relative to the non-singleton, search slopes on singleton-target trials remained steep, with a mean search rate similar to that reported in Yantis and Egeth's study (46 ms. vs. 40 ms per item, respectively). This finding suggests that the singleton did not capture attention. By contrast with Yantis and Egeth's results, however, we found faster RTs when the target was a singleton relative to when it was not, across set sizes. As search rates rather than overall RTs reflect attentional priority, this difference between the two findings does not affect the main conclusion from the present experiment. One may speculate that the use of a compound task (in which the defining and response features are distinct) instead of a detection task, may account for the RT advantage on singleton-target trials: once the target was detected, maintaining attention on the target to report the response feature may have been easier when the target was more highly discriminable.

2. Experiment 2

In Yantis and Egeth's (1999) experiment (as well as in Experiment 1 of the present study), the singleton and non-singleton colors were fixed. Thus, knowing the singleton color in advance may have allowed subjects to deliberately adopt a strategy against attending to the singleton color. Such an inhibitory tag may have offset the advantage that salience conferred to the singleton, which would account for the null effect reported by these authors. Yantis and Egeth rejected this argument by showing that capture by a color singleton did not occur even when the salient feature was unpredictable (Experiment 8). On each trial, the singleton could be a bright item among dim ones, a moving item among static ones, a large item among small ones, or a color singleton. However, the conclusions from this finding rely on the unwarranted assumption that no more that one property at a time can guide attention. The inhibitory set account for the failure of the color singleton to capture attention in Yantis and Egeth's study would still be valid if, for instance, one assumes that subjects are able to suppress one feature per dimension.

To more effectively prevent subjects from adopting a set against the known color of the singleton, in Experiment 2, singleton and non-singleton colors switched unpredictably from one trial to the next. With this design, we could eliminate both the hypothesized color set and the imbalance in inter-trial color repetition between singleton and non-singleton-target trials. Indeed here, by contrast with the situation that prevailed in the previous experiment, the target on a given trial, whether a singleton or a non-singleton, was equally likely to be of the same color or of a different color relative to the target on the previous trial. If these factors indeed masked attentional capture by the color singleton in Yantis and Egeth's (1999) study as well as in Experiment 1, then the search slopes observed when the target happens to be the color singleton should be reduced in the present experiment.

2.1. Method

2.1.1. Participants

Subjects were ten Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

2.1.2. Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were the same as in Experiment 1 except that the singleton and non-singleton colors were counterbalanced and randomly mixed within subjects rather than counterbalanced between-subjects.

2.2. Results

Mean RTs and accuracy data are presented in Fig. 3. In all RT analyses, error trials (1.5%) were excluded.

Reaction times. An ANOVA with target type, repetition of target color and set size as within-subject factors revealed significant main effects of target type, $F(1,9) = 95.79$, $p < 0.0001$, target color repetition, $F(1,9) = 13.41$, $p < 0.006$ and set size, $F(1,9) = 196.15$, $p < 0.0001$. The interaction between target type and set size was significant, $F(1,9) = 11.48$, $p < 0.008$. The mean search slope was flatter in the singleton-target than in the non-singleton-target condition, but it was significantly larger than zero in both conditions, 26 ms, $F(1,9) = 7.00$, $p < 0.03$ and 74 ms, $F(1,9) = 146.09$, $p < 0.0001$, respectively. The interaction between repetition of target color and set size was significant, $F(1,9) = 7.47$, $p < 0.03$. Repetition of target color reduced search slopes from 83 ms per item, $F(1,9) = 426.35$, $p < 0.0001$, to 58 ms, $F(1,9) = 55.68$, $p < 0.0001$. This reduction did not differ significantly whether the target was a singleton or a non-singleton, $F < 1$.

Accuracy. No effect approached significance, all ps > 0.2.

2.3. Discussion

In this experiment, search for a singleton target yielded numerically flatter slopes than in Experiment 1 (26 ms vs. 45 ms per item, respectively), yet an analysis of RTs on singleton-target trials with experiment as a between-subjects factor and set size as a within-subject factor showed that this difference was not significant,
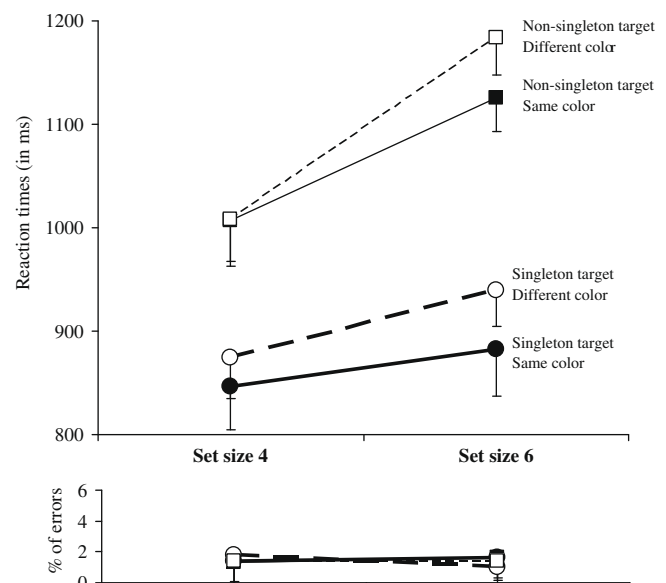
Fig. 3. Experiment 2. Mean response times (RTs) in milliseconds (upper panel) and error rates (bottom panel) by set size, target type and repetition of target color from the previous trial (same vs. different).

$F < 1$. However, this null finding does not imply that counterbalancing the singleton and non-singleton colors had no effect on search slopes because, as expected, we observed significant effects of target-color repetition on search efficiency. Specifically, search slopes were steeper when the color of the current target was different from that of the target in the previous trial relative to when it was the same. Because the target was only rarely a singleton in Experiment 1 and in Yantis and Egeth's (1999) study and because the color of the singleton was fixed, the color of the target had most often not been repeated (and had therefore been ignored) on the previous trial when the target happened to be a singleton on the current trial. Thus, we may conclude that inter-trial color repetition costs indeed must have reduced the color singleton-target's attentional priority in these studies. The fact that eliminating this cost (as well as the potential inhibitory set against the fixed color of the singleton) in Experiment 2 did not translate into a significant between-experiment difference may therefore be attributed to large between-subjects variability.

In Experiment 2, the color singleton still failed to capture attention, as search slopes still significantly differed from zero. We have recently reported that attending to a singleton is easier when the target on the previous trial had also been a singleton than when it had not been a singleton (Lamy, Bar-Anan, et al., 2006, 2008) and surmised that attending to a singleton when a singleton has been ignored on the previous trial might incur a cost. Since in Experiments 1 and 2 as in Yantis and Egeth's study, a singleton was most likely to have been ignored on the previous trial when the target was a singleton on a given trial, such a cost may have masked capture by the color singleton.

Consistent with this possibility, planned comparisons showed that in this experiment, while search slopes for a color singleton target were significant when the color singleton had been ignored in the previous trial, $F(1,9) = 8.18$, $p < 0.02$, they were non-significant when the color singleton had been the target in the previous trial, $F(1,9) = 3.20$, $p = 0.1$. However, this finding may be limited for two reasons. The first reason is that the comparison underlying the reported inter-trial effect included a very small number of trials (eight trials for set size six in the condition in which the target happened to be a singleton on two successive trials), so it is not clear how stable our conclusion would turn out to be with more trials. The second reason is that this comparison does not allow us to determine whether a cost of attending to a distracting singleton that had been ignored on the previous trial or a benefit of attending to a color singleton on consecutive trials affected search slopes. Obviously, only the latter effect is relevant to our claim that the structure of Yantis and Egeth's task burdened performance on singleton-target trials.

3. Experiment 3

The objective of this experiment was to eliminate the cost of attending to a singleton when a singleton has been ignored on the previous trial. To this end, trials in which the displays contained no color singleton were added. In these trials, the display was made up of an equal number of red and blue bars and the target was as likely to be red or blue (see Lamy, Bar-Anan, et al., 2008, Experiment 6, for a similar design). Thus, the experiment included three display conditions: the singleton-target and non-singleton-target conditions as in the previous two experiments, and the singleton-absent condition. The singleton and non-singleton colors were again counterbalanced. Of main interest were the slopes for a singleton target when the preceding trial had contained no singleton. In this case, the singleton target should no longer suffer from the cost of attending to a singleton when a singleton had been ignored in the preceding trial.

In this experiment, the color singleton was still as irrelevant to the task as it had been in the previous experiments, but it no longer suffered from any of the costs that we have identified in the specific procedure used by Yantis and Egeth (1999). Namely, (1) subjects could not adopt an inhibitory set against the color of the color singleton because this color changed from trial to trial, (2) for the same reason, the color singleton was as likely to suffer as it was to benefit from color repetition effects and (3) the cost of ignoring a singleton on the previous trial was eliminated because the previous trial did not contain a singleton. Thus, if stimulus-based salience plays a role in visual search even when the subjects cannot use a salience-based strategy, search should be efficient in this experiment when the target happens to be the color singleton.

3.1. Method

3.1.1. Participants

Subjects were eleven Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected visual acuity and normal color vision.

3.1.2. Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were the same as in Experiment 2, except that trials in which the display contained an equal number of red and blue bars (singleton-absent trials) were randomly mixed with the singleton-present trials (i.e., singleton-target trials in which a singleton was present and was the target and non-singleton-target trials in which a singleton was present but was not the target). The experiment included an equal number of singleton-present and singleton-absent trials. On all trials (i.e., on singleton-absent trials and on singleton-present trials), the target was equally likely to be red or blue. There were 1000 experimental trials, divided into 10 blocks (see Fig. 4).

3.2. Results

Mean RT and accuracy data are presented in Fig. 5. In all RT analyses, error trials (3.9%) were excluded.

An ANOVA with set size, target type and target color repetition as within-subject factors was conducted only on the singleton- and non-singleton-target trials that were preceded by a trial in which
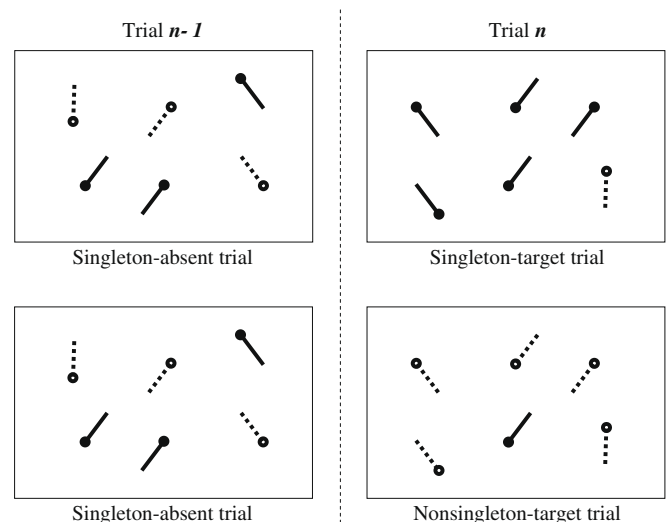
Fig. 4. Sample displays from Experiment 3, representing the two critical conditions: singleton-target trial (upper row) and non-singleton-target trial (lower row) preceded by a singleton-absent trial.
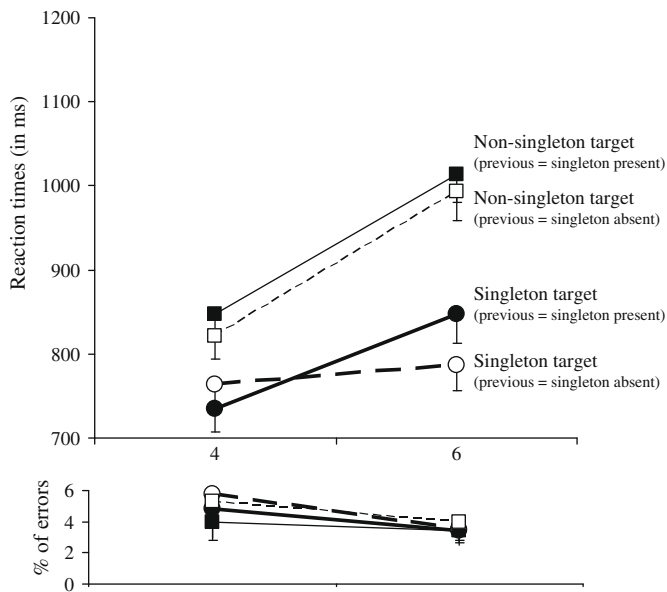
Fig. 5. Experiment 3. Mean response times (RTs) in milliseconds (upper panel) and error rates (bottom panel) by set size, target type on the current trial (singleton-target vs. non-singleton-target) and display type in the previous trial (singleton-present vs. singleton-absent).

the singleton was absent. Thus, in this analysis, the cost of searching for a singleton target that had been ignored on the previous trial was eliminated.

Reaction times. The main effects of target type (singleton vs. non-singleton), $F(1,10) = 40.64$, $p < 0.0001$, set size, $F(1,10) = 74.36$, $p < 0.0001$ and target color repetition, $F(1,10) = 9.91$, $p < 0.02$, were significant. The interaction between target type and set size was also significant, $F(1,10) = 20.49$, $p < 0.001$, reflecting that search slopes were flatter in the singleton-target than in the non-singleton-target condition. Whereas search slopes were significantly larger than zero when the target was a non-singleton, 86 ms per item, $F(1,10) = 63.01$, $p < 0.0001$, they were not significantly larger than zero when the target was a singleton, 12 ms per item, $F(1,10) = 1.52$, $p > 0.2$. This interaction was not modulated by target color repetition, $F < 1$.

Accuracy. No effect approached significance, all $Fs < 1$.

Next, we sought to verify that eliminating the cost of attending to a singleton that had been ignored on the previous trial was indeed a critical factor in increasing search efficiency when the target was the color singleton. To do so, we conducted an ANOVA on singleton-target trials with set size, display condition on the previous trial (non-singleton-target condition, in which the color singleton had been ignored on the previous trial vs. singleton-absent condition, in which there was no singleton on the previous trial) and target color repetition as within-subject factors. The main effect of set size was significant, $F(1,10) = 15.15$, $p < 0.003$ and the main effect of display condition on the previous trial was non-significant, $F(1,10) = 1.20$, $p > 0.3$. Crucially, the interaction between set size and display condition on the previous trial was significant, $F(1,10) = 5.30$, $p < 0.05$. Relative to the 12-ms slopes observed when the color singleton had been absent on the previous trial, search slopes were as steep as 50 ms per item, $F(1,10) = 13.68$, $p < 0.005$, when the color singleton had been ignored on the previous trial. This interaction was not modulated by target color repetition.

The same ANOVA was conducted on non-singleton-target trials. Only the main effect of set size was significant, $F(1,10) = 146.55$, $p < 0.0001$. Both the effect of previous target type (non-singleton-

target vs. singleton-absent) and the interaction between this factor and set size were non-significant, $Fs < 1$.

Accuracy. No effect approached significance.

Finally, in order to determine whether repetition of target color reduced search slopes in this experiment as it did in Experiment 2, we conducted an ANOVA with display condition (singleton-target, non-singleton-target and singleton-absent), target color repetition and set size as within-subject factors. The interaction between target color repetition and set size was significant, $F(1,11) = 5.38$, $p < 0.05$. Repetition of target color reduced search slopes from 87 ms to 72 ms per item. This effect was similar in the three display conditions, $F < 1$.

Accuracy. The interaction between repetition of color and set size was significant, $F(1,10) = 5.07$, $p < 0.05$, with a smaller cost of increasing set size when the target repeated from one trial to the next than when it switched. No other effect approached significance, all $ps > 0.2$.

3.3. Discussion

In this experiment, we found that search for a singleton target is inefficient when a singleton has been ignored on the previous trial but becomes efficient when the display in the previous trial contained an equal number of items in the two possible colors, that is, did not contain a color singleton. Thus, the cost of attending to a singleton that had been ignored on the previous trial also contributed to mask the effects of stimulus-driven salience on visual search in Yantis and Egeth's (1999) study, on top of inter-trial color repetition effects and of potential effects of a set against the singleton color. We may therefore conclude that stimulus-driven salience affects the allocation of attentional priority in visual search, even when task demands do not induce the observers to search for the items with maximum local contrast.

It is surprising, however, that search slopes on singleton-target trials were much steeper in the analysis of Experiment 3 that replicated the trial sequence that prevailed in Experiment 2, namely, singleton-target trials preceded by a singleton-present trial, than in Experiment 2 itself (50 ms vs. 26 ms per item, respectively). Again, a between-experiment ANOVA on singleton-target trials preceded by a singleton-present trial was conducted with experiment as a between-subjects factor and set size as a within-subject factor and revealed that the interaction between the two factors was non-significant, $F < 1$. In other words, despite the numerical difference in slopes, these did not differ significantly for the same condition in Experiment 2 and in Experiment 3. Again, this finding suggests that between-experiment comparisons are of little use in this study because of large between-subjects variability. Within-subject comparisons, however, did confirm that inter-trial color repetition effects and the cost associated with ignoring the color singleton on the previous trial made search inefficient on singleton-target trials. By eliminating these costs, we unveiled the ability of the salient color singleton to capture attention in a task in which singletons were irrelevant.

On non-singleton-target trials, search slopes were not affected by whether or not a singleton had been ignored on the previous trial. This result was expected because if the color singleton captures attention, this should not affect the rate at which each item in the display is scanned, but only which item is scanned first. However, one would expect slower overall RTs on non-singleton trials and faster RTs on singleton-target trials when the previous trial had contained no singleton than when a singleton had been ignored on the previous trial. Yet, for both comparisons, there was no significant main effect of the display type on the previous trial on overall RTs. We have no reasonable explanation for this null effect. However, as the critical index of attentional efficiency

is search slope rather than overall RTs, this null effect does not undermine the main conclusions from this experiment.

Bacon and Egeth (1994) have suggested that when the target is reliably a singleton, subjects engage in singleton-detection mode, even when doing so appears to be detrimental to the task at hand. One could argue that in Experiment 3, when there is no irrelevant singleton to avoid on the previous trial, subjects may "slip" into singleton-detection mode on the next trial. This would explain why the salient singleton captured attention in Experiment 3 when the previous trial contained no singleton.[1]

This argument, however, raises the question of what might be the conditions that promote a singleton-detection mode. The original formulation of the notion of singleton-detection mode implied that this strategy is resorted to only when "singleton-ness" is a defining characteristic of the target. Indeed, Bacon and Egeth (1994) showed that an irrelevant singleton captured attention when the target was a less salient singleton with a known shape on 100% of the trials, but that the same irrelevant singleton failed to capture attention when the target was a singleton on only one third of the trials (which is still more than chance, considering that the displays contained more than three items). The authors concluded that in the latter case, subjects relied on the known shape of the target, that is, used feature-search mode. In the present case, the target and singleton were uncorrelated: thus, not only was singleton-ness not a defining feature of the target but it was utterly non-predictive. In our view, to argue that even when there is no usefulness whatsoever in adopting singleton-detection mode people nonetheless do so, is tantamount to claiming the influence of bottom-up processes: it means an effect of bottom-up salience in the absence of a set for singletons.

4. General discussion

4.1. Summary of the findings

The objective of the present study was to reexamine the claim put forward by Yantis and Egeth (1999), that the role of stimulus-driven salience in guiding search is contingent on task-related attentional settings. We suggested that the particular task used to support this claim included several aspects that burdened performance on singleton-target trials. In order to test this hypothesis, we started out replicating Yantis and Egeth's (1999) findings using a discrimination task (Experiment 1) and showed that an orientation target that happened to be a color singleton indeed appeared to receive relatively low attentional priority (with significant 46-ms per item search slopes). We then successively peeled off the effects that we thought were likely to have masked the ability of the color singleton to draw attention. We first prevented subjects from adopting a top-down set against the color of the irrelevant color singleton, and eliminated inter-trial color repetition costs (Experiment 2). We then abolished the cost of attending to a singleton when a singleton had been ignored on the previous trial (Experiment 3). We ended up with a singleton that was still just as irrelevant to the task as it was initially, but yielded reasonably efficient search (with non-significant 12-ms per item search slopes).

4.2. The role of stimulus salience in visual search

From a theoretical standpoint, the results from the present study invalidate the radical claim that stimulus-driven salience plays no role in visual search when salience is irrelevant to the task at hand (Yantis & Egeth, 1999). Consistent with recent findings from our lab (Lamy, Bar-Anan, et al., 2006; Lamy, Carmel, et al.,

2006), the present results further challenge the distinction between a default singleton-detection mode, in which subjects are thought to engage whenever the target is reliably a singleton, and a feature-search mode in which subjects are thought engage when salience-based search does not allow finding the target (Bacon & Egeth, 1994). On the one hand, we have shown that subjects use their knowledge of the target-defining feature when the target is a singleton on every trial, which contradicts the notion of a default singleton-detection mode (Lamy, Carmel, et al., 2006). On the other hand, the findings from the present study show that in feature-guided search, the more salient an irrelevant object is, the more attentional priority it receives, which contradicts the notion of a feature-search mode that is impervious to the effects of bottom-up salience. Taken together, these findings argue against the idea that stimulus-driven and goal-directed effects on attentional priority are strictly encapsulated within the singleton-detection and feature-search modes, respectively. Instead, they support the idea promoted by leading theories of visual search, that attentional priorities are determined by the joint influence of top-down and bottom-up factors, whatever the attentional set promoted by the task. Of course, a purely salience-based search may occur, but only when no property other than the target's salience can be used to guide search (i.e., when the target is reliably a singleton, the salient feature of which changes unpredictably from trial to trial; e.g., Bravo & Nakayama, 1992).

These conclusions converge with Theeuwes' (2004) view against the distinction between singleton-detection and feature-search modes. However, our findings provide clear evidence countering Theeuwes' (2004) account, according to which attentional capture by a salient distractor does not occur when search is serial. In his study, he showed that when an irrelevant singleton is made less salient by reducing display size, search slopes increase (albeit only to the level of 13 ms per item) and a distractor that captured attention when display size and density were high no longer interferes with search. The findings from the present Experiment 3, together with previous findings, refute the two predictions that follow from Theeuwes' (2004) hypothesis. On the one hand, there are instances in which salient distractors fail to capture attention in strictly parallel search (e.g., Lamy, Carmel, et al., 2006; Leber & Egeth, 2006). On the other hand, here we show an instance of attentional capture by a salient item with steep search slopes (Experiment 3).

In fact, although early studies have shown that focusing attention on a known location prevents attentional capture from highly salient distractors (Theeuwes, 1991; Yantis & Jonides, 1990), later studies have demonstrated that the spatial focusing of attention cannot be the critical factor (Folk et al., 2002; Lamy et al., 2004). Indeed, they showed that when attention is highly focused in the center of the display for identification of a target in a rapid serial visual presentation (RSVP) stream, a distractor in the periphery can capture attention. Taken together, these findings suggest that neither serial search nor spatially focused attention suffice to prevent attentional capture.

4.3. Relation to previous inter-trial singleton-repetition effects

We recently showed that attending to a singleton on a given trial is faster if a singleton within the same dimension had also been attended in a previous trial (Lamy, Bar-Anan, et al., 2008) . For instance, subjects had to report the orientation of a line appearing in one, three or five circles among squares in a 9-item display. The line orientation was identical in each target when the display contained multiple targets. We showed that for one-target trials (i.e., singleton-target trials), RTs were faster when the display on the previous trial had also contained only one-target relative to three or five targets. Such a repetition effect of the number of tar-

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[1] We thank an anonymous reviewer for this suggestion.

gets on successive trials did not occur when the display had contained three targets on successive trials or five targets on successive trials. This singleton-priming effect was replicated in five additional experiments. Several previous studies have shown that the facilitating effect of attending to the same target on consecutive trials is paralleled by a cost of attending to a target that has just been ignored (e.g., positive and negative priming, Tipper & Cranston, 1985; target activation and distractor inhibition effects in PoP, Lamy, Antebi, Aviani, & Carmel, 2008). In the same vein, the cost reported here when attending to a singleton that has just been ignored parallels the singleton-priming effect reported by Lamy, Bar-Anan, et al. (2008).

Geyer, Müller, and Krummenachen (2008) also reported effects of the presence of an irrelevant color singleton on the previous trial on the attention received by this irrelevant singleton on the current trial. They found interference to be larger when the irrelevant color singleton had been absent on the previous trial relative to when it had been present. That is, the color singleton captured attention to a lesser extent when the same color singleton had been ignored on the previous trial relative to when it had been absent. This effect is entirely consistent with the cost of attending to a recently ignored singleton we found in Experiment 3. Although there are important differences between the two studies, namely, while Geyer et al. (2008) measured attentional capture as interference by an irrelevant color singleton by comparing performance on singleton-present relative to singleton-absent trials, we measured capture as null search slopes when the target happens to be the color singleton, we believe that the two effects reflect the same mechanism and that this effect contributed to mask the influence of bottom-up salience in Yantis and Egeth's (1999) study.

4.4. Implications for mechanisms of priming-of-popout

The findings from the present study may further our understanding of target-feature repetition effects. First, repetition of the target color from one trial to the next speeded overall search times, that is, inter-trial repetition priming effects similar to the PoP effects reported by Maljkovic and Nakayama (1994) were observed, despite the fact color was irrelevant to the task. On the one hand, this finding invalidates Maljkovic and Nakayama's claim that only repetition of the attention-focusing property of the target speeds search. On the other hand, however, it should be noted that in the task we used, the target-defining feature (vertical orientation) repeated from trial to trial, whereas in Maljkovic and Nakayama's study, it varied randomly from trial to trial. Huang and Pashler (2005) showed that repetition of an irrelevant feature of the target on two consecutive trials facilitates search when the target-defining feature also repeats, whereas it slows search when the target-defining feature changes. Thus, consistent with this report, our finding suggests that repetition of an irrelevant feature of the target affects search performance, but we showed this only with a defining property of the target that repeats on every trial (see also Lamy, Kosover, et al., 2008).

Second, repetition of the target color on successive trials significantly reduced search slopes. We may thus conclude that the attentional priority allocated to a target increases when an irrelevant feature of this target repeats vs. changes from the previous trial. There is no consensus to date as to whether inter-trial repetition of target features affects attentional selection (e.g., Goolsby & Suzuki, 2001; Maljkovic & Nakayama, 1994) or post-selective processes (e.g., Huang & Pashler, 2005; Huang et al., 2004). Our finding strongly supports the former view, but only to the extent that the various feature repetition effects involved (repetition of target-defining feature, repetition of an irrelevant feature of the target with/without target-defining feature uncertainty) reflect

the same mechanism. Further research is needed to clarify this issue.

4.5. Methodological implications

From a methodological viewpoint, the present study illustrates the fact the different empirical strategies typically used to study the relative contributions of bottom-up and top-down factors in visual search, are not equivalent in the type of inferences that they permit. The empirical strategy of pitting bottom-up and top-down factors against each other (e.g., Theeuwes',1991,1992 additional singleton paradigm; Folk et al.'s 1992, 1998 spatial cueing paradigm,) can only be used to show that bottom-up salience plays a role in guiding attention (as its effects may sometimes override the effects of task-related goals, e.g., Theeuwes, 1992) or that task-related goals play a role (as their effects may sometimes override the effects of stimulus salience, e.g., Folk et al., 1992). However, this strategy is not suited to the investigation of whether only one of the two classes of factors can guide attention at the preattentive stage, because attentional capture by an irrelevant singleton or the absence thereof only reflects which of these factors has the strongest influence in a given task. By contrast, this question can be adequately addressed by probing whether added top-down knowledge (e.g., Bravo & Nakayama, 1992) or added physical salience (Yantis & Egeth, 1999) enhances attentional priority.

The second point, first put forward by Maljkovic and Nakayama (1994); see also Lamy, Carmel, et al., 2006; Olivers & Humphreys, 2003), is that unintended inter-trial repetition effects may substantially influence visual search performance, such that failure to take these into account may lead to erroneous conclusions. For example, in the present study we have shown that imbalance in the probability of target-color repetition in the different target conditions masked the effects of stimulus salience. In other studies, repetition effects are confounded with the adoption of a top-down set. Consider for instance, Yantis and Egeth's (1999) Experiment 6, in which "informativeness value" of the color singleton was manipulated by varying the probability of the coincidence between the target and color singleton. These authors showed that the more often the target happened to coincide with the color singleton, the more efficient search was on singleton-target trials. However, their manipulation also changed various inter-trial contingencies, the role of which has been demonstrated in the present study. Namely, the "high-informativeness" condition also involved more frequent target-color repetitions, more opportunities to attend to a singleton when a singleton had been attended on the previous trial and fewer opportunities to attend to a singleton when a singleton had been ignored in the previous trial. Such inter-trial effects offer an alternative to these authors' conclusion that the informational value of the singleton induced the subjects to adopt a default singleton-detection mode.

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