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The Role of Within-Dimension Singleton Priming in Visual Search

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The authors report a newly identified intertrial priming phenomenon, within-dimension singleton priming, by which search for a target that happens to be a singleton on the current trial is faster when the target on the previous trial had also been a singleton on the same dimension rather than a nonsingleton. This effect was replicated in 6 experiments with different procedures, with singletons on various dimensions, when the featural contrast defining the singleton remained the same or changed within a dimension from one trial to the next, and when the target was a singleton on a target-defining dimension or on an irrelevant dimension. These findings cannot be explained by previously demonstrated intertrial repetition effects such as dimension-specific priming or priming of popout. Theoretical implications of the within-dimension singleton priming phenomenon are discussed relative to the dimension-weighting hypothesis, the role of stimulus-driven salience in feature-guided search, and the roles of intertrial priming and goal-directed factors in visual search.

Keywords: visual search, singleton search, intertrial priming

In the last 30 years or so, a tremendous amount of research has been devoted to the investigation of the mechanisms underlying search for a predefined visual target. Visual search is one of the most basic cognitive activities, as both humans and animals spend a large part of their waking hours searching the environment for target objects. Moreover, because searching for a target entails directing one's attention to it, visual search is one of the central paradigms used in the study of visual attention.

Two ways in which attentional selection may be controlled during visual search have been distinguished. Goal-directed, or top-down, control of attention refers to the ability of the observer's goals or intentions to determine which areas, attributes, or objects are selected for further visual processing. Stimulus-driven, or bottom-up, control refers to the capacity of certain stimulus properties to attract attention.

Early studies of visual search have assumed that both goal-directed and stimulus-driven factors contribute to search performance (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Treisman & Gormican, 1988; Wolfe, 1994; see Lamy & Tsal, 1999, for a discussion). More recent research has focused on the relative contributions of these two sources of guidance and investigated the extent to which the set adopted by the observer can control which objects in the visual field receive attentional priority. At one end of the continuum, Theeuwes (e.g., 2004) proposed that attentional priority is entirely under the control of exogenous, stimulus-driven factors, which entails that attention is directed to the most salient object in the visual field regardless of the observers' goals. At the other end, Folk, Remington, and Johnston (1992) have claimed that what objects receive attentional priority is contingent on attentional goal settings, such that a salient object outside the observer's set does not capture attention (for similar viewpoints, see Bacon & Egeth, 1994; Lamy & Egeth, 2003; Lamy, Leber, & Egeth, 2004; Lamy & Tsal, 1999; Yantis & Egeth, 1999). Despite the numerous published studies on the roles of stimulus-driven and goal-directed factors in the allocation of attention during visual search, this issue remains controversial (see Ruz & Lupianez, 2002, for an extensive review).

Recent research has demonstrated a striking role for a third class of factors in visual search: Several mechanisms have been discovered by which intertrial memory traces bias the allocation of attention in the visual field. Müller, Heller, and Ziegler (1995; see also Found & Müller, 1996) observed that attending to a target defined along a particular feature dimension, such as orientation (for instance, a unique vertical bar among horizontal bars), facilitated detection of a target defined along that same dimension on subsequent trials (see also Egeth, 1977; Treisman, 1988). Using superimposed shapes similar to those used by Rock and Gutman (1981), DeSchepper and Treisman (1996) reported that ignoring a distractor on one trial made it easier to ignore the same item on subsequent trials and more difficult to attend to it. Maljkovic and Nakayama (1994) discovered that in search for a singleton target, when the unique feature 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 is different, a phenomenon that they called priming of popout. Performance was also enhanced when the target occupied the same spatial position on consecutive trials (Maljkovic & Nakayama, 1996).

Maljkovic and Nakayama (2000) suggested that such intertrial effects reflect short-term implicit memory processes that "could bias intentional shifts and eye movements without need for a

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supervisory control and would ensure that objects of recent interest would be repeatedly sampled. Furthermore, the short-term nature of the memory would make sure that the appropriate biasing would be up to date, tuned to the current objects of interest" (p.593).

In the present article we report a newly identified type of intertrial repetition priming. We investigated whether repetition of the status of the target as a singleton, rather than repetition of the dimension defining it or of its particular value on that dimension, also produces performance benefits. That is, we examined whether visual search is speeded when the target is a singleton on consecutive trials. To do so, we compared search performance on singleton-target trials when the previous target had also been a singleton relative to when it had not been a singleton. To ensure that an attentional set for singleton targets could not account for the sought after intertrial carryover effects, in all the experiments described here, the target was a singleton only on a minority of trials and possessed the same known target feature on each trial. For instance, in Experiment 1, the target was always a circle among diamonds, but there could be one, three, or five identical target circles on each trial. Thus, task demands should induce the subjects to adopt a feature-based search strategy rather than to search for a singleton target. If subjects monitored the displays for a singleton, their search would be highly inefficient on most of the trials.

Experiment 1

The procedure of this experiment was similar to that of Bacon and Egeth's (1994) Experiment 2. Subjects searched for one, three, or five identical target circles among diamond-shaped nontargets and were required to determine the orientation of the line segments within the target items. The displays contained a singleton target, that is, just one circle in the display, on only one third of the trials. We examined the effect of the repetition of the number of targets (henceforth, target-number repetition) when the target was a singleton (one-target trials) relative to when it was not (three- or five-target trials). The effect of a single target-number repetition for a given target-number condition (one, three, or five targets) was defined as the difference in performance on trials from this target-number condition when the previous trial had also been from the same target-number condition relative to when the previous trial had been from a different target-number condition. For instance, in the present experiment, the one-target repetition effect was defined as the difference in performance on one-target trials when the previous trial had also been a one-target trial relative to when it had been a three- or five-target trial. Furthermore, the effect of *n* target-number repetitions was defined as the difference in performance when the *n* previous trials had all been from the same target-number condition relative to when the previous trial had been from a different target-number condition. Importantly, repetition of the target feature (as described by Maljkovic & Nakayama, 1994) could play no role in the present experiment because the target had the same feature on every single trial, such that the target feature repeated from one trial to the next in all conditions.

Method

Subjects

Subjects were 6 Tel Aviv University undergraduate students who were paid the equivalent of $20 for their participation. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus

Displays were generated by an Intel Pentium 4 computer attached to a 15-in. TFT monitor, using 1024 × 768 resolution graphics mode. Responses were collected via the computer keyboard. Viewing distance was set at 50 cm using a chinrest.

Stimuli

An example of the stimulus displays is presented in Figure 1. The fixation display was a gray 0.2° × 0.2° plus sign (+), in the center of a black background. Stimulus displays consisted of the fixation display with the addition of nine colored shapes (circles and diamonds). The shapes were presented equally spaced along the circumference of an imaginary circle, centered at fixation. At a viewing distance of 50 cm, the centers of the shapes were 2.5° away from fixation. Circles subtended 1.8° in diameter, and diamonds were 45°-rotated squares, 1.3° on a side. Centered inside each shape was a horizontal or vertical line segment (0.5° in length). All shapes were red, Commission Internationale de l'Eclairage (CIE) coordinates .630/.340, and drawn with a 2-pixel stroke. The lines inside the shapes were gray (CIE coordinates .348/.374) and drawn with a 1-pixel stroke. The target shape was always the circle. There were one, three, or five circles among diamonds in the one-, three- and five-target conditions, respectively. Each circle contained a line segment in the same orientation. Line orientation in each nontarget shape was randomly chosen with the constraint that the number of lines of each orientation in each display always differed exactly by one.

Procedure

The subjects were instructed to determine the orientation of the line segment(s) inside the target shape(s) and to respond by press-

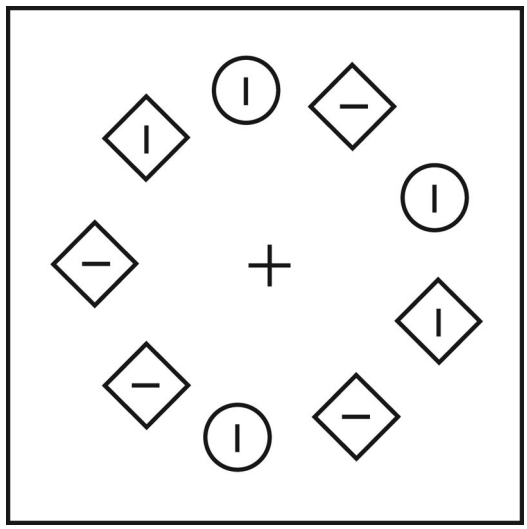

Figure 1. Typical stimulus display in Experiment 1. The example depicts a three-target trial. The surrounding shapes were red and the enclosed lines were gray. The background was black.

ing designated keys on the computer keyboard (the "z" key for horizontal and the "3" keypad key for vertical, with key-to-response mapping being counterbalanced between subjects). They were instructed to respond as quickly as possible while maintaining high accuracy. Error trials were followed by a 500-ms feedback beep. Subjects were informed that the display would contain one, three, or five targets with equal probability and that all the targets would contain line segments sharing the same orientation.

Each trial began with the presentation of the fixation display. After 500 ms, it was replaced by the stimulus display, which remained visible for 2,000 ms or until response. The screen went blank for 500 ms before the next trial began. Eye movements were not monitored, but subjects were explicitly requested to maintain fixation throughout each trial.

Design

There were two within-subject randomly mixed variables: number of targets (one, three, or five) and target-number repetitions (number of consecutive trials with the same number of targets, zero to four). The target shapes were equally likely to appear in any of the nine possible locations. On each trial, line orientation was randomly assigned to each shape in the display, with the constraints that the number of lines of each orientation in each display always differed exactly by one and that all target shapes in the same display shared the same line orientation, which was equally likely to be horizontal or vertical.

Subjects participated in four identical sessions, with a period of 3 to 7 days separating one session from the next. Each session began with one practice block, which was terminated after 50 trials or 20 correct answers. It was followed by nine blocks of 80 experimental trials. Thus, each subject completed 2,880 trials (720 trials in each of the four sessions). Subjects were allowed a rest period after each block.

Results

In all the experiments reported in this study, analyses were performed on the means of the log transformed reaction times (RTs). For each subject, RTs were sorted into the cells formed by the relevant conditions and an RT exceeding the mean of a given cell by more than 3 standard deviations was trimmed. In all experiments, this procedure removed less than 1% of all observations.

In all RT analyses of the data from Experiment 1, error trials (3.3% of all trials) were excluded. Preliminary analyses revealed a main effect of session, $F(3, 15) = 25.12$, $p < .0001$, with RTs decreasing as a function of practice. Because this effect did not interact with any of the factors of interest, it will not be discussed further.

An analysis of variance (ANOVA) was conducted with number of targets (one, three, or five) and target-number repetitions (zero to four) as factors. Mean RT data on correct trials and percent errors are presented in Figure 2.

RTs. The main effect of the number of targets was significant, $F(2, 10) = 18.70$, $p < .0004$, reflecting that the more targets the display contained, the easier it was to find at least one target (redundancy gains). The main effect of target-number repetition was also significant, $F(4, 20) = 3.03$, $p < .05$. The interaction between these factors was significant, $F(8, 40) = 3.65$, $p < .003$.

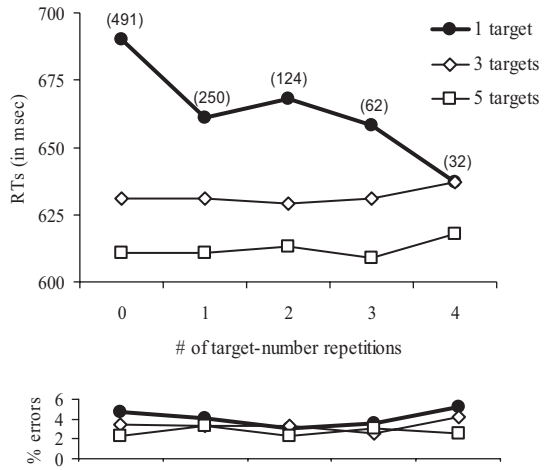

Figure 2. Experiment 1: Mean reaction times (RTs) in ms for one-, three- and five-target trials as a function of the number of successive trials with the same number of targets. The numbers in parentheses represent the average number of trials per subject in each of the relevant conditions. Trial numbers for the three- and five-target conditions were similar to those of the one-target condition (± 5%).

Separate ANOVAs for each condition of number of targets revealed that whereas RTs decreased as the number of consecutive one-target trials increased, $F(4, 20) = 8.31$, $p < .0004$, there was no significant effect of target-number repetition in the three- or five-target conditions (Fs < 1). Further analyses revealed that the performance advantage on successive one-target trials did not significantly increase beyond one repetition, all ps $> .1$, for the additional effects of two, three, and four repetitions.

Accuracy. Only the main effect of the number of targets approached significance, $F(2, 10) = 3.82$, $p < .06$, again reflecting redundancy gains, all other Fs < 1.

Further analyses were conducted in order to determine how far back performance for a singleton target on trial n was influenced by the occurrence of a singleton target on trial $n - i$, where i can have any value that is smaller than n. These analyses were similar to those conducted by Maljkovic and Nakayama (1994) on the priming of popout effect. For singleton targets on the current trial, we compared trials in which the target on trial $n - i$ had also been a singleton versus a nonsingleton (three- and five-target trials). In contrast with Maljkovic and Nakayama, however, we excluded singleton-target trials that were preceded by an uninterrupted series of i singleton-target trials. This allowed us to obtain a true estimate of the influence of a singleton-target i trials back that was not contaminated by the effects of repeated singleton-target trials on successive trials. We conducted the analyses for increasing values of i and stopped at the value of i where no advantage for a singleton target was detected. In addition, we conducted the same analyses for the trials occurring after the current trial (that is, for $n + i$ instead of $n - i$). These trials, which could have no effect on the current trial, provided a baseline of the variability of RTs. The results of these analyses are presented in Figure 3. A singleton-target trial speeded search for a singleton target on trial n when it was as far as two trials back. The effect of a singleton target on the previous trial, that is, on trial $n - 1$, was significant, $F(1, 5) =$

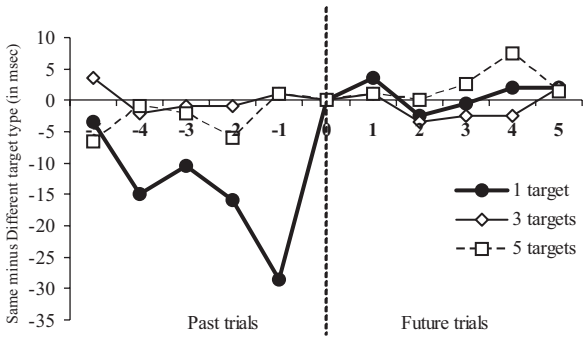

Figure 3. Experiment 1: Influence of the number of targets on a single trial in the past (to the left of the dotted line) on the reaction time (RT) on the current trial. The graph represents the difference in RTs between trials in which the trial ($n - i$) contained the same number of targets as the current trial relative to trials in which the trial ($n - i$) contained a different number of targets. The x-axis represents i. Negative values of i represent past trials and $i = 0$ represents the current trial. Positive values of i represent future trials, which provide a baseline of variability. See text for further details.

16.00, $p < .02$, and so was the effect of a singleton target on trial $n - 2$, $F(1, 5) = 7.81$, $p < .04$. The effect of a singleton target on trial $n - 3$ was nonsignificant, $F < 1$.

Discussion

The results of Experiment 1 show a clear advantage of repeated singleton-target trials. This effect does not simply result from repetition of the number of targets but specifically from singleton repetition because repeated three- or five-target trials had no effect on performance. This null effect cannot be accounted for by floor effects. There was considerable improvement in three- and five-target trials from the first session to the last, 697 ms versus 572 ms, $p < .0001$, and 667 ms versus 561 ms, $p < .0001$, respectively, yet target-number repetition did not yield a performance advantage over five consecutive repetitions even in the first session, in which there was considerable room for further RT reductions, Fs < 1 for both three- and five-target displays. In contrast, the target-number repetition effect was significant in the first session for one-target displays, $F(4, 20) = 4.59$, $p < .001$. In addition, three-target trials were significantly slower than five-target trials across the experiment, $F(1, 5) = 9.12$, $p < .03$, such that there was still room for improvement in the three-target condition.

However, an alternative account for the benefit of singleton-target repetition might be that searching for a singleton target on the previous trial improves performance, regardless of the number of targets on the current trial. To test this possibility, an additional ANOVA was conducted on correct RTs with number of targets on the previous trial (one, three, or five) and number of targets on the current trial (three or five). The main effect of number of targets on the current trial was again significant, $F(1, 5) = 34.78$, $p < .002$, but there was no effect of the number of targets on the previous trial, $F < 1$, and no interaction between the two factors, $F(1, 5) = 1.16$, $p > .3$. Thus, the results of Experiment 1 reflected a benefit of singleton-target repetition rather than a general facilitation when the target on the previous trial had been a singleton. The maximum effect of singleton-target repetition was attained after just one repetition, with additional repetitions producing only nonsignificant reductions in RT (see Figure 2). Moreover, a singleton-target trial benefited from a previous singleton target as far as two trials back (even when the previous trial had not been a singleton-target trial).

Examination of the cumulative effects of several singleton repetitions and of the effects of a singleton-target trial on subsequent singleton-target trials requires a large number of trials, divided into several experimental sessions. In the following experiments, these will not be investigated further, and only effects of one to two singleton-target repetitions will be examined with more subjects participating in only one session.

Experiment 2

The advantage of searching for a singleton when the target on the previous trial had also been a singleton relative to when it had been a nonsingleton is critically dependent on the nonsingleton condition used for comparison, an issue that we will henceforth refer to as the "baseline problem." Indeed, if, for whatever reasons, searching for a singleton target when there had been three or five targets in the previous trial incurs a cost, then the advantage in the repeated singleton-target condition observed in Experiment 1 may be idiosyncratic to the specific nonsingleton conditions used.

The objective of Experiment 2 was to seek converging evidence for the findings of Experiment 1 by using a different nonsingleton baseline condition. On each trial, subjects had to search for a single unique red circle. In the shape-singleton condition (one sixth of the trials), all nontargets were red diamonds. In the color-singleton condition (one sixth of the trials), all nontargets were green circles. In the conjunction condition (two thirds of the trials), half of the nontargets were green circles, and the remaining nontargets were red diamonds. Thus, on the majority of the trials, the target was defined by the conjunction of two features and could not be found by searching for a feature singleton. Note that although the dimensions on which the target differed from the nontargets varied between conditions, this was achieved by varying the identity of the nontargets: The target was identical on each trial throughout the experiment.

Method

Subjects

Subjects were 12 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, Stimuli, Procedure, and Design

The apparatus, stimuli, procedure, and design were the same as in Experiment 1, except for the following changes. Unlike Experiment 1, which had trials with one, three, or five targets, there was always just one target in Experiment 2, and it was the unique red circle in all conditions. There were three display types, corresponding to three target-type conditions. The target was the unique red circle in all of the conditions. In the color-singleton condition, nontarget shapes were eight green (CIE coordinates .280/.593) circles. In the shape-singleton condition, nontarget shapes were

eight red diamonds. In the conjunction-search condition, nontarget shapes were four green circles and four red diamonds.

There were two within-subject, randomly mixed variables: target type (color-singleton, shape-singleton, and conjunction target) and target-type repetitions (number of consecutive trials with the same target type). There were 10 blocks of 75 experimental trials each. Thus, each subject completed 750 trials.

Results

Mean RTs and percent errors are presented in Figure 4. In all RT analyses, error trials (4.7% of all trials) were excluded.

Within-Dimension Singleton Priming

To examine whether repetition of a singleton target produced an advantage, we combined the shape-singleton and color-singleton conditions into one singleton-search condition. In the following analysis, we included only singleton trials that were preceded by either a conjunction trial or a same-singleton trial. Thus, trial sequences in which a shape singleton was followed by a color singleton or a color singleton by a shape singleton were excluded from the present analysis (but are considered in a later analysis). An ANOVA was conducted with search type (singleton vs. conjunction) and target-type repetition (zero, one, or two) as factors.

RTs. Both main effects were significant, with faster RTs on singleton-target than on conjunction-target trials, $F(1, 11) = 298.77$, $p < .0001$, and faster RTs as the number of repetitions of the same target type increased, $F(2, 22) = 8.10$, $p < .03$. The interaction between these factors was also significant $F(2, 22) = 5.76$, $p < .01$. Further analyses revealed that search on a shape-singleton trial or on a color-singleton trial was faster when the target had been a shape singleton or a color singleton, respectively, on previous trials, relative to when it had been a conjunction target, $F(2, 22) = 12.36$, $p < .0003$. Paired comparisons revealed faster RTs with one singleton-target repetition relative to no repetition, $F(1, 11) = 28.87$, $p < .0002$, and no further improvement with two repetitions relative to only one, $F < 1$. In contrast, conjunction-search trials were equally slow whether the target on previous trials had been a singleton or a conjunction target, $F(2, 22) = 1.03$, $p > .3$.

Accuracy. None of the effects approached significance, Fs < 1.

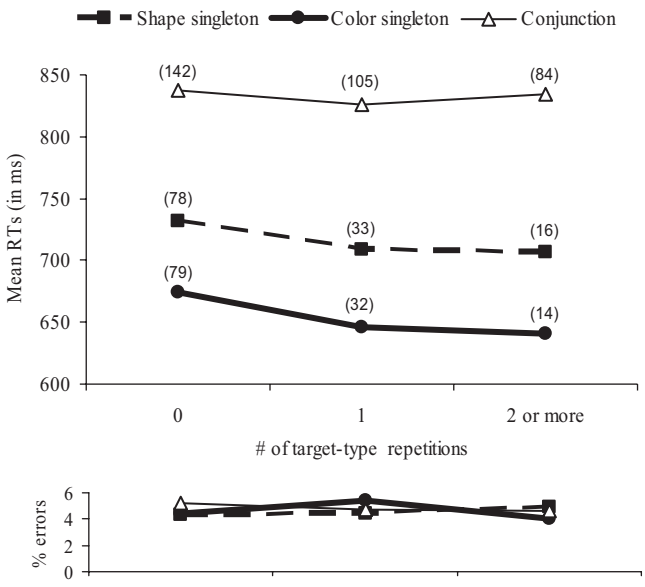

Figure 4. Experiment 2: Mean reaction times (RTs) in ms for shape-singleton, color-singleton, and conjunction-target trials as a function of the number of successive trials with the same target type. (Trials in which different singletons succeeded each other are excluded). For example, the triangle at the upper right represents the mean RT when the current trial was a conjunction trial that was immediately preceded by two other conjunction trials. The numbers in parentheses represent the average number of trials per subject in each of the relevant conditions. The numbers do not add up to the total number of trials because the condition involving two consecutive singleton targets defined in different dimensions is not represented in this figure.

Effect of Salience on Within-Dimension Singleton Priming

The color singleton was more salient than the shape singleton. To examine whether within-dimension singleton priming is affected by the salience of the singleton target, we compared the benefit on repeated singleton-target trials within the color versus shape dimensions. An ANOVA on the same data (that is, also excluding sequences with different singletons immediately following one another) was conducted with singleton type (shape vs. color) and target-type repetition (zero, one, or two) as factors.

RTs. The ANOVA revealed a main effect of singleton condition, confirming that search for the color singleton was indeed faster than search for the shape singleton, $F(1, 11) = 32.10$, $p < .0001$. The effect of target-type repetition was also significant, $F(2, 22) = 15.66$, $p < .0001$. However, the interaction between the two factors was nonsignificant, $F < 1$, suggesting that within-dimension singleton priming was of similar magnitude for the two singleton types, and thus appeared not to be modulated by singleton salience.

Accuracy. None of the effects approached significance, Fs < 1.

Singleton Priming Across Dimensions

We examined whether singleton priming occurred when the two consecutive singleton targets were of different types. In other words, we asked whether there is an advantage when searching for a shape singleton or a color singleton when the target on the preceding trial had been a color singleton or a shape singleton, respectively, relative to when it had been a conjunction target. To answer this question we conducted a planned comparison between singleton trials that were preceded by a trial with the alternative singleton versus by a conjunction trial. There was no difference between the two conditions in either RTs, 698 ms versus 704 ms, respectively, or accuracy, 96.8% versus 95.7%, respectively, ts < 1.

Discussion

The benefit on repeated singleton-target trials was replicated with a different nonsingleton condition, namely, when displays on the majority of the trials contained a conjunction target rather than multiple identical targets, thereby reducing the baseline problem.

Within-dimension singleton priming was not modulated by singleton salience in the present experiment: The color singleton was far more salient than the shape singleton, yet the two types of singleton produced a within-dimension singleton priming effect of the same magnitude.

There was no between-dimension singleton priming: Directing one's attention to a singleton on trial *n* did not facilitate search for a singleton defined on a different dimension on trial *n + 1*. It is important to note that this finding does not imply that feature repetition effects (as described by Maljkovic & Nakayama, 1994) were responsible for the within-dimension singleton-priming effect. Target-feature repetition effects could play no role because the target color and shape were identical throughout the experiment. Neither could nontarget-feature repetition explain the present findings. Had nontarget feature repetition accounted for the advantage on singleton-singleton sequences relative to conjunction-singleton sequences, the same advantage should have been observed for conjunction-conjunction sequences relative to singleton-conjunction sequences. This is because the amount of nontarget feature repetition was exactly the same in the two instances.

The finding that a benefit on repeated singleton-target trials occurred only within the same dimension but not across dimensions raises the question of how within-dimension singleton priming relates to the dimension-specific priming effect reported by Müller and colleagues (e.g., Found & Müller, 1996; Krummenacher et al., 2001; Müller et al., 1995; Müller & O'Grady, 2000; Pollmann, Weidner, Müller, & von Cramon, 2000; Weidner, Pollmann, Müller, & von Cramon, 2002; see also Treisman, 1988). These authors conducted experiments in which observers had to detect the presence of a singleton feature, with the target-defining dimension varying randomly across trials (cross-dimensional search). For instance, nontargets were small gray tilted bars across the experiment, but the target varied from trial to trial and was the unique white bar (singleton on the color dimension), the unique horizontal bar (orientation dimension), or the unique small bar (size dimension). Dimension-specific intertrial effects were observed; that is, detection of a target on a given trial was slowed when the target-defining dimension changed from the preceding to the current trial relative to when it remained the same.

Müller and colleagues suggested a dimension-weighting account (DWA) of these findings, which, in line with leading theories of visual search (Cave & Wolfe, 1990; Koch & Ullman, 1985; Treisman & Gelade, 1980) assumes that attentional priorities of the various objects present in the visual field are coded on a master map of activations. This account suggests that "detection of a feature target requires that attentional weight be allocated to the corresponding dimension-specific module to amplify its saliency signal on the master map of activations. . . . The dimensional weight pattern established in this process persists into the next trial, producing a dimension-specific RT advantage for a target defined within the same dimension as the preceding target" (Weidner et al., 2002, p.318).

The DWA cannot account for the within-dimension singleton priming effects reported in the first two experiments. According to DWA, a change in attentional weighting is triggered when a certain dimension is useful in order to complete the task at hand, for instance to find a target that differs from the distractors on that dimension or to report a response-critical attribute within that dimension (Müller & O'Grady, 2000). Thus, this account predicts that in Experiment 2, the conjunction-conjunction sequence should benefit relative to a singleton-conjunction sequence because the former sequence does not require a change in attentional weighting, whereas the latter sequence does (from "all weights on shape," for instance, to "weights shared between color and shape"). This advantage was not observed, as conjunction-search trials were equally slow whether the target on previous trials had been a singleton or a conjunction target (see results section above).

The DWA also predicts that a conjunction-singleton sequence (e.g., a color singleton following a conjunction target) should benefit relative to a different-singleton sequence (e.g., a color singleton following a shape singleton). Indeed, some weight was allocated to color on the previous trial in the conjunction-singleton sequence. Thus, this condition required less of a change in attentional weighting than the different-singleton sequence, in which no weight was allocated to color on the previous trial. Yet, this advantage was not observed (see the null effect of cross-dimensional singleton priming in the results section above).

In addition, according to DWA, weights are shifted between dimensions. Thus, this account cannot explain the within-dimension singleton priming effects reported in Experiment 1, in which the target was defined within the same dimension on all trials. Therefore, the conclusion from the first two experiments is that singleton priming occurs only with successive singletons within the same dimension but cannot be accounted for by DWA.

Experiment 3

In both Experiments 1 and 2, within-dimension singleton priming was observed only when the repeated singleton sequences involved displays that presented the same feature contrast. The main objective of Experiment 3 was to examine whether the within-dimension singleton-priming effect can also be observed when the successive displays differ, that is, when on successive trials the singleton target is defined by different feature contrasts within the same dimension (e.g., a red singleton circle among green circles followed by the same red circle among blue circles). The second objective of this experiment was to reexamine cross-dimensional singleton priming that we failed to observe in Experiment 2.

In Experiments 1 and 2, the targets were identical throughout each experiment and only nontargets changed from trial to trial. This state of affairs was necessary to allow the study of singleton-target repetition effects, which requires that the target should not be a singleton on each trial. Yet, the target had to be defined in some way, so it was defined by its specific features. Therefore, there was no uncertainty concerning the target features. In contrast, in studies of dimension-specific priming effects (e.g., Müller et al., 2000), the target typically changes from trial to trial, and the nontargets remain constant. Thus, on each trial, subjects are uncertain as to what the next target will be.

The third objective of Experiment 3 was to inspect whether dimension-specific repetition effects, that is, facilitation when targets on two successive trials are defined within the same dimension relative to when they are defined within different dimensions, can occur in the absence of target-feature uncertainty. On each trial, the targets were either one or four red circles. Dimension-specific repetition effects would occur if, for instance, searching

for red circles among red squares (targets defined on the shape dimension) was easier when the display on the previous trial had included red circles among red diamonds (targets also defined on the shape dimension) rather than red circles among green circles (targets defined on the color dimension).

Method

Subjects

Subjects were 12 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, Stimuli, Procedure, and Design

The apparatus, stimuli, procedure, and design were the same as in Experiment 1, except for the following changes. On each trial, the display contained either one target (one third of the trials) or four targets (two thirds of the trials). Again, the targets were red circles (either one or four) on each trial. There were four nontarget conditions. In the shape condition, nontarget shapes were either red diamonds or red squares. In the color condition, nontarget shapes were either green circles or blue circles. Each of the resulting four nontarget conditions was equiprobable for each of the two target-number conditions.

There were four within-subject randomly mixed variables: target type (singleton vs. nonsingleton), target-type repetition (repetition vs. no repetition), dimension (shape or color), and dimension repetition (repetition vs. no repetition). On repeated-dimension trials, nontargets could either remain the same or change from one trial to the next (feature repetition, zero or one). Again, there were 10 blocks of 75 experimental trials each. Thus, each subject completed 750 trials.

Results

Mean RT data on correct trials and percent errors are presented in Figure 5. In all RT analyses, error trials (2.6% of all trials) were excluded. Preliminary analyses showed that the effect of dimension was highly significant, $t(11) = 10.48$, $p < .0001$, with faster RTs on color- than on shape-singleton trials; but, because this variable interacted with none of the factors of interest, it is not considered further.

Within-Dimension Singleton Priming With Sequences Involving Different Feature Contrasts

In order to determine whether within-dimension singleton priming can be observed when successive singletons are defined with different nontarget features within the same dimension, a first ANOVA with feature repetition (repetition vs. no repetition) and target-number repetition (repetition vs. no repetition) as factors was conducted on trials in which the target was a singleton and was preceded by a trial containing either one or four targets defined within the same dimension. That is, we excluded trials including four targets and trials in which the target differed from nontargets on different dimensions from one trial to the next. Only the main effect of target-number repetition (i.e., within-dimension singleton priming) was significant, $F(1, 11) = 27.44$, $p < .0003$. There was no effect of feature repetition, $F < 1$, and no interaction between the two factors, $F(1, 11) = 1.91$, $p > .1$, indicating that within-dimension singleton priming was equally large whether the singleton target was defined by the same or by different featural contrasts, 28 ms, $F(1, 11) = 6.64$, $p < .03$, and 37 ms, $F(1, 11) = 8.73$, $p < .02$, respectively.

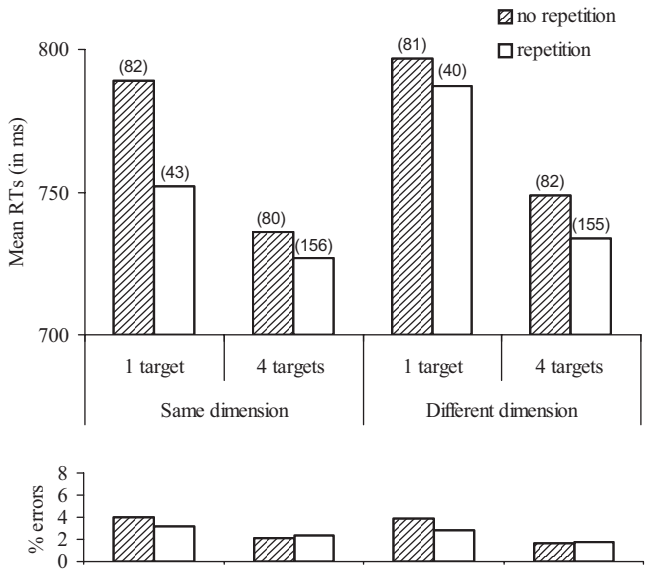

Figure 5. Experiment 3: Mean reaction times (RTs) in ms for singleton-target (one-target) trials and nonsingleton-target (four-target) trials as a function of whether target type repeated or did not repeat on successive trials and a function of whether the feature contrast that characterized the target occurred within the same dimension or between different dimensions. The numbers in parentheses represent the average number of trials per subject in each of the relevant conditions.

Accuracy. The interaction between feature repetition and within-dimension singleton priming approached significance, $F(1, 11) = 3.54$, $p < .09$. Further analyses revealed that within-dimension singleton priming was significant on same-feature trials, $F(1, 11) = 8.86$, $p < .02$, but not on different-feature trials, $F < 1$.

Singleton Priming Across Dimensions

In order to examine whether the absence of cross-dimension singleton priming reported in Experiment 2 would be replicated in the present experiment, a second ANOVA with dimension repetition (repetition vs. no repetition), number of targets (one vs. four) and target-number repetitions (repetition vs. no repetition) as factors was conducted.

RTs. All main effects were significant, $F(1, 22) = 13.04$, $p < .005$, $F(1, 11) = 28.20$, $p < .0002$, $F(1, 11) = 20.91$, $p < .0008$, for dimension repetition, number of targets, and target-number repetition, respectively. The three-way interaction between these factors was significant, $F(1, 11) = 8.71$, $p < .02$. No other interaction approached significance. Paired comparisons revealed that the effect of target-number repetition was significant only for singleton targets on the same dimension, $F(1, 11) = 35.37$, $p <$

.0001. There was no singleton priming with successive singleton targets defined on different dimensions, $F(1, 11) = 1.36$, $p > .2$, and no effect of target-number repetition when the nonsingleton targets differed from the nontargets on either the same dimension, $F(1, 11) = 2.12$, $p > .1$, or different dimensions, $F(1, 11) = 2.64$, $p > .1$.

Accuracy. The only significant effect was the main effect of number of targets, $F(1, 11) = 11.32$, $p < .007$.

Dimension-Specific Repetition Priming

Finally, in order to examine dimension-specific repetition effects when the target features are known, a third ANOVA with dimension repetition (repetition vs. no repetition), number of targets on the current trial (one vs. four) and number of targets on the previous trial (one vs. four), was conducted. In order to measure pure dimension priming, we eliminated the potential effects of feature repetition by excluding trials in which successive displays contained the same feature contrast. Planned contrasts were conducted for each of the four possible sequences of target number on successive trials. For instance, in order to measure dimension-specific effects for sequences including four targets preceded by one target, we compared performance on trials containing four red circles among green circles when the previous trial had contained one red circle, for instance, among blue circles (different feature, same dimension) versus one red circle among red squares (different dimension). The effect of dimension repetition was significant only for repeated-singleton sequences, 38 ms, $F(1, 11) = 5.45$, $p < .04$, all other Fs < 1 (1 ms, 3 ms, and 6 ms, for sequences including four targets preceded by four targets, four preceded by one, and one preceded by four, respectively). No effect involving dimension priming was observed on accuracy data.

Discussion

The results showed that within-dimension singleton priming is not contingent on the target being defined by the same feature contrast on successive trials and is not even modulated by a change in feature contrast (e.g., a red target among green nontargets followed by a red target among blue nontargets), although such modulation was observed for accuracy data. Again, feature repetition could not account for the within-dimension singleton priming effect because, in this experiment, as in the previous two, the target was the same on every trial.

Consistent with the findings of Experiment 2, singleton priming was not observed when the singletons on successive trials were defined in different dimensions, indicating that there is no cross-dimensional singleton priming. Finally, dimension-specific repetition effects were observed even when the target features were fixed and, thus, known throughout the experiment. However, this effect occurred only for repeated-singleton sequences. The implications of this finding for the DWA proposed by Müller and colleagues (e.g., Müller, et al., 1995) are addressed in the General Discussion.

Experiment 4

In the first three experiments, within-dimension singleton priming was demonstrated when the repeated singleton was unique on a defining dimension of the target. In Experiment 1, the targets were defined by their shape; and; on one-target trials, the target was a singleton on the shape dimension. In Experiments 2 and 3, the targets were defined by both their shape and color, and on singleton trials, the target was a singleton on either the shape or the color dimension. The objective of Experiment 4 was to investigate whether within-dimension singleton priming can be observed when the target is a singleton on a task-irrelevant dimension.

The paradigm we used to address this issue was similar to one designed by Jonides and Yantis (1988). Subjects searched for a target that was defined by its specific shape and appeared among heterogeneously shaped nontargets. One shape in each display differed from the rest on the irrelevant dimension of color; that is, it was a color singleton. The position of the singleton was uncorrelated with the position of the target, so there was no incentive for observers to attend deliberately to the color singleton. If within-dimension singleton priming occurs for singletons on an irrelevant dimension, then on singleton-target trials (i.e., trials when the target happens to be a singleton), search should be faster when the target on the preceding trial also happened to have been a singleton relative to when it had been a nonsingleton.

Method

Subjects

Subjects were 11 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, Stimuli, Procedure, and Design

The apparatus, stimuli, procedure, and design were the same as in Experiment 1, except for the following changes. Stimulus displays consisted of five colored shapes: a diamond, a square, a circle, a seven-point star, and a four-petal flower. The sizes of the circle, diamond, and square were the same as in Experiment 1. The star and the flower could each be enclosed in an imaginary circle with a diameter of 1.8°. On each trial, four shapes shared the same color, and one had a unique color. The colors were green and blue and were matched for luminance.

Each subject was randomly assigned one of three possible target shapes (the square, the diamond, or the circle). The probability of the target shape being the color singleton was at chance; that is, the target shape and unique color coincided on one fifth of the trials.

There were two between-subject variables, singleton color (green or blue) and target shape (circle, square, or diamond) and two within-subject randomly mixed variables: target type (singleton vs. nonsingleton) and target-type repetition (number of consecutive trials with the same target type, zero or one). On each trial, the shapes, colors, and locations were randomly assigned. There were 10 blocks of 76 experimental trials each. Thus, each subject completed 760 trials.

Results

Mean RT data on correct trials and percent errors are presented in Figure 6. In all RT analyses, error trials (6.1% of all trials) were excluded. An ANOVA with target-type (singleton vs. nonsingle-

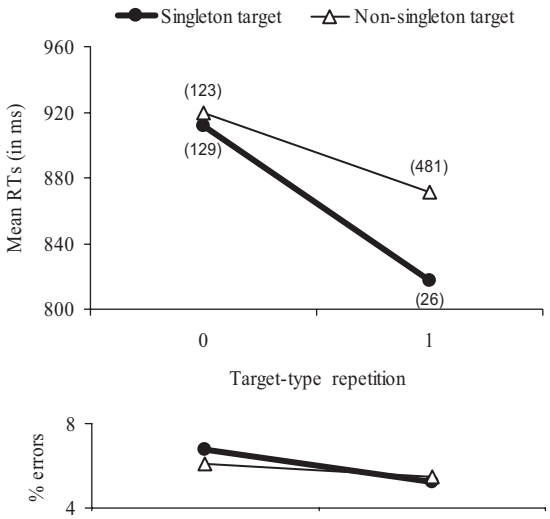

Figure 6. Experiment 4: Mean reaction times (RTs) in ms for singleton-target and nonsingleton-target trials as a function of whether target type repeated or did not repeat on successive trials. The numbers in parentheses represent the average number of trials per subject in each of the relevant conditions.

ton) and target-type repetitions (repetition vs. no repetition) as factors was conducted.

RTs. There was no significant main effect of target type, $F(1, 10) = 2.36$, $p > .15$. The main effect of target-type repetition was significant, $F(1, 10) = 21.18$, $p < .001$, and interacted with target type, $F(1, 10) = 5.37$, $p < .05$. Further analyses revealed that singleton-target trials were faster when the previous target had also been a singleton rather than a nonsingleton, $F(1, 10) = 27.07$, $p < .0004$. However, nonsingleton-target trials also were faster when the target on the previous trial had been a nonsingleton than when it had been a singleton $F(1, 10) = 7.62$, $p < .03$. Thus, we observed a repetition priming effect for both singleton and nonsingleton targets. The significant interaction revealed that within-dimension singleton priming was larger than nonsingleton priming.

Accuracy. None of the effects approached significance.

Discussion

Subjects were faster to respond to a target that happened to be a singleton when the target on the previous trial also happened to have been a singleton than when it had been a nonsingleton. This finding suggests that within-dimension singleton priming occurs even when the target is a singleton on a task-irrelevant dimension. It remains possible, however, that a necessary condition for within-dimension singleton priming to occur is that the target's unique feature should remain the same on successive trials. Indeed, in Experiments 1–4, in which within-dimension singleton priming was observed, the two successive singleton targets always had the same unique feature. Thus, it is not clear whether within-dimension singleton priming is observed when the unique features of the two successive singleton targets differ.

The results also showed an advantage of the repetition of a nonsingleton target, albeit significantly smaller. Subjects were faster to respond to a nonsingleton target when the target on the previous trial had also been a nonsingleton than when it had been a singleton. This effect stands in contrast with the null effects that were observed for repetition of a nonsingleton target in Experiments 1–3.

The following aspect of the present experiment may account for the emergence of a nonsingleton-priming effect: For each type of target (singleton and nonsingleton), repetition and no-repetition trials differed not only in the type of target in the preceding trial but also in whether the attended item had the same color or a different color on successive trials. This situation arose because for any given subject, the singleton and nonsingleton colors were fixed throughout the experiment such that a change in target type also entailed a change in target color, that is, target-type repetition and color repetition were confounded. This confound was not present in Experiments 1–3 because target color remained constant throughout the experiment.

Huang, Holcombe, and Pashler (2004) recently reported that priming of popout can occur on an irrelevant dimension.[1] In their study, half of the items were of one color and the other half of a different color. Subjects searched for an odd-sized target. When target size was repeated from the previous trial, repetition of target color speeded the response. In the present experiment, the target feature on the target-defining dimension (shape) remained the same throughout the experiment. On the basis of Huang et al.'s results, one would therefore expect same-target-color trials to have been faster than different-target-color trials in Experiment 4. Repetition priming of an irrelevant feature of the target (here, color) may thus account for part or all of the nonsingleton-priming effect observed.

In contrast, such feature-repetition priming is unlikely to account for the entire within-dimension singleton priming effect observed in Experiment 4. First, the magnitude of feature repetition should be the same when comparing singleton–singleton sequences to nonsingleton–singleton sequences (i.e., the comparison that measures within-dimension singleton priming) and when comparing nonsingleton–nonsingleton sequences to singleton–nonsingleton sequences (i.e., the comparison that measures nonsingleton priming), because the same feature variation occurred in the two comparisons. The finding that within-dimension singleton priming was significantly larger than nonsingleton priming indi-

[1] These findings appear to be at odds with Maljkovic and Nakayama's (1994) claim that repetition of a target feature on a dimension that is not a target-defining dimension has no effect on performance. In their study, subjects searched for the odd-colored diamond in the display and reported whether the right or left side of the target diamond was truncated. Maljkovic and Nakayama (1994, Exp. 6) found that subjects were equally fast whether the target shape had been truncated on the same or a different side on consecutive trials. Note however, that, contrary to Huang et al.'s (2004) study, the reporting feature and motor response were confounded in Maljkovic and Nakayama's experiment: Subjects pressed the left or right mouse button if the left or right side was truncated, respectively. We found strong response-repetition priming effects in all the experiments of the present study. These effects are reported in the Appendix. However, response repetition effects became apparent only after two response repetitions (i.e., three consecutive same-response trials, see Figure A1). Thus, the fact that Maljkovic and Nakayama (1994) examined only the effect of one response repetition may account for the discrepancy between our results and theirs.

cates that there was more to the within-dimension singleton priming effect than just feature priming. Second, within-dimension singleton priming was also obtained in Experiments 1–4, in which target-feature repetition could not be a factor because singleton and nonsingleton targets were identical.

Experiment 5

The objective of Experiment 5 was to investigate whether within-dimension singleton priming is contingent on the repetition of the target's unique feature. We also examined whether target-color repetition might account for the nonsingleton priming effect observed in Experiment 4.

This experiment was similar to Experiment 4 except that the color singleton could have one of two colors on each trial, as could the other items (nonsingletons). The two possible colors for the singleton item always differed from the two possible colors for the nonsingleton items. Examples of the stimulus displays are presented in Figure 7.

We had three predictions with the present design. First, we expected to replicate the singleton and nonsingleton priming effects when the display colors remained the same on successive trials ("Same-color displays" panel in Figure 7): In such trials, a change in target type also entailed a change in target color, as was the case in Experiment 4, such that nonsingleton repetition and target-color repetition were again confounded. Second, if within-dimension singleton priming is not contingent on the repetition of the singleton target's unique feature, namely, its color, then this effect should still be observed when the target color changes on consecutive singleton-target trials (upper row of the "Different-color displays" panel in Figure 7). Third, if target-color repetition priming accounts for all the nonsingleton repetition effect, then the nonsingleton repetition effect should be abolished when the target color changes on consecutive nonsingleton-target trials (lower row of the "Different-color displays" panel in Figure 7).

Method

Subjects

Subjects were 12 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, Stimuli, Procedure, and Design

The apparatus, stimuli, procedure, and design were the same as in Experiment 4, except for the following changes. Each display consisted of four shapes (a circle, a square, a diamond, and a star) instead of five. For half of the subjects, on a given trial the three nonsingleton shapes were either all pink or all yellow (CIE coordinates .310/.350 or 310/.350, respectively) and the unique color was either green or blue (CIE coordinates .310/.350 or 310/.350, respectively). The remaining subjects were run with the opposite color assignment.

There were two between-subject variables, target shape (circle, square, or diamond) and color assignment. There were four within-

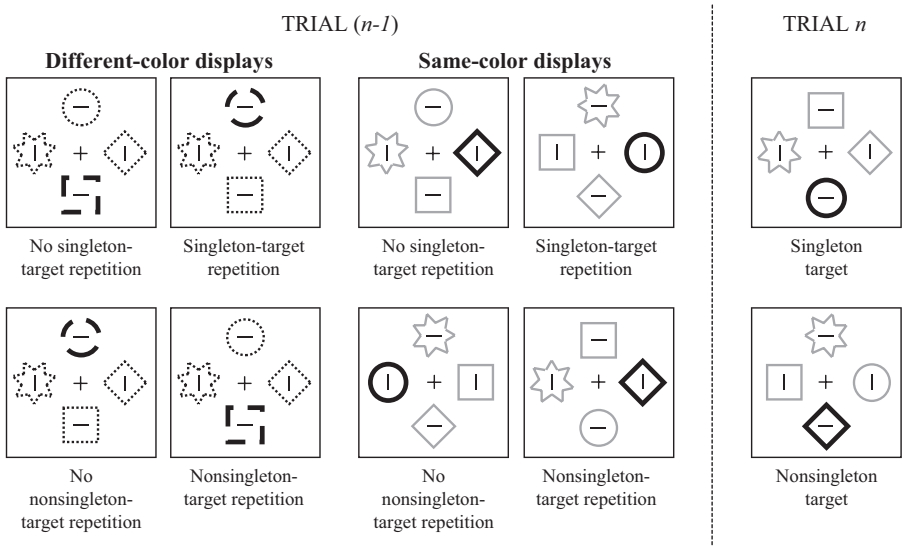

Figure 7. Examples of stimulus display sequences in Experiment 5 for a circle target when the target on the current trial was a singleton (upper row) or a nonsingleton (lower row). Displays on the current trial appear to the right of the dotted line. Displays on the previous trial appear to the left of the dotted line. On same-color displays both the singleton and nonsingleton colors remained the same on the current trial relative to the previous trial. On different-color displays both the singleton and nonsingleton colors changed on the current trial relative to the previous trial. Trial sequences in which either only the singleton color or only the nonsingleton color changed are not shown. The thick black lines were blue (or green). The thick dashed lines were green (or blue, respectively). The thin gray lines were pink (or yellow). The thin black dotted lines were yellow (or pink, respectively). The thin black lines were gray. The background was black.

subject randomly mixed variables: singleton color, nonsingleton color, target type (singleton vs. nonsingleton), and target-type repetition (repetition vs. no repetition). On each trial, the shapes, colors, and locations were randomly assigned. There were 10 blocks of 87 experimental trials each. Thus, each subject completed 870 trials.

Results

Mean RT data on correct trials and percent errors are presented in Figure 8. In all RT analyses, error trials (4.2% of all trials) were excluded.

Replication of Experiment 4 Findings

In order to examine whether the basic findings of Experiment 4 were replicated in the present experiment, we excluded the trial sequences that entailed a color change and conducted an ANOVA with target-type (singleton vs. nonsingleton) and target-type repetition (repetition vs. no repetition) as factors on trial sequences in which the display colors, that is, both the singleton and nonsingleton colors, remained unchanged. Thus, in this analysis, a change in target type was confounded with a change in target color.

RTs. The main effect of target type was nonsignificant, $F < 1$. The main effect of target-type repetition was significant, $F(1, 11) = 31.42$, $p < .0002$, and interacted with target type, $F(1, 11) = 5.42$, $p < .04$. Paired comparisons showed that both within-dimension singleton priming and nonsingleton priming were again significant, $F(1, 11) = 18.91$, $p < .002$ and $F(1, 11) = 17.50$, $p < .002$, respectively, with the significant interaction reflecting the fact that within-dimension singleton priming was larger than nonsingleton priming.

Accuracy. Main effects were nonsignificant, but the interaction between target type and target-type repetition was significant, $F(1, 11) = 6.34$, $p < .03$. Paired contrasts revealed no significant effect.

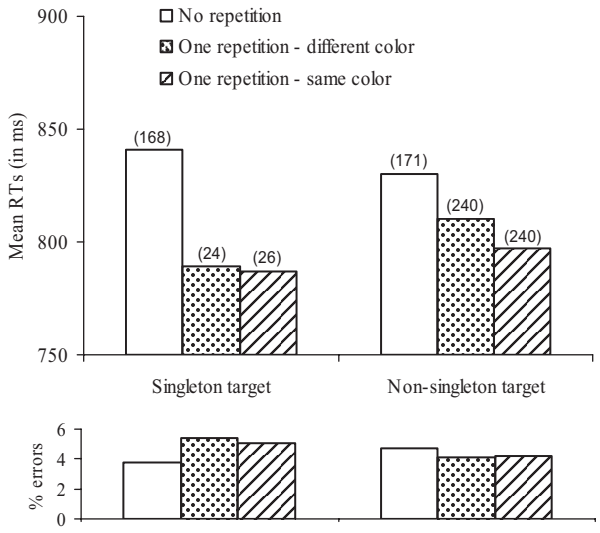

Figure 8. Experiment 5: Mean reaction times (RTs) in ms for singleton-target and nonsingleton-target trials for same-color displays and for different-color displays as a function of whether target type on successive trials repeated or did not repeat. The numbers in parentheses represent the average number of trials per subject in each of the relevant conditions.

Within-Dimension Singleton- and Nonsingleton-Priming With Change in Target Color

Next, we examined whether within-dimension singleton priming and nonsingleton priming were observed when the colors of the successive same-type targets changed. We conducted an ANOVA with target type and target-type repetition as factors on trials in which the display colors changed from one trial to the next.

RTs. The main effect of target-type repetition was significant, $F(1, 11) = 25.73$, $p < .0004$, and interacted with target type, $F(1, 11) = 9.94$, $p < .01$. Paired contrasts showed that both within-dimension singleton priming and nonsingleton priming effects were significant, $F(1, 11) = 21.95$, $p < .0007$ and $F(1, 11) = 13.42$, $p < .004$, respectively, with the former being significantly larger than the latter. The main effect of target type was nonsignificant, $F < 1$.

Accuracy. None of the effects approached significance.

Discussion

The results of Experiment 5 show that within-dimension singleton priming is not contingent on repetition of the target's unique feature, as this effect was observed for trial sequences in which the target color did not repeat.

We had hypothesized that the nonsingleton repetition effect observed in Experiment 4 had resulted from the fact that the target had the same color on consecutive nonsingleton-target trials, whereas on trials that served as a baseline for the measurement of nonsingleton repetition (i.e., nonsingleton trials that were preceded by a singleton trial), the target color changed. In other words, we had conjectured that color priming rather than nonsingleton priming had occurred. However, in the present experiment, nonsingleton priming was observed for trial sequences in which the target color did not repeat. Therefore, the nonsingleton priming effect observed in the present experiment could not be attributed to target-color repetition.

What then might be the nature of the nonsingleton priming effect observed in Experiments 4 and 5? A potentially consequential difference between Experiments 4 and 5 and Experiments 1–3 (in which no nonsingleton priming was observed) is that when the target was a nonsingleton on successive trials, subjects had to ignore an irrelevant singleton on both trials, whereas when the target was a nonsingleton that came after a singleton-target trial, subjects had to ignore a just-attended singleton.

This situation was specific to Experiments 4 and 5, because in Experiments 1–3 the displays contained a singleton only when this singleton was the target and a singleton was never ignored. Accordingly, one may suggest that the nonsingleton priming effect observed in Experiments 4 and 5 reflects the cost of ignoring a just-attended singleton. This possibility was examined (and confirmed) in Experiment 6.

Experiment 6

The objective of this experiment was to examine nonsingleton priming using a measure that is not contaminated with a potential

cost of ignoring a just-attended singleton. In this experiment, subjects again searched for a specific shape. The critical change introduced was the addition of displays that contained items of two different colors but no color singleton (singleton-absent trials). Each display contained four elements. On singleton-present trials, the display contained one oddly colored item and three same-colored items. On singleton-absent trials, the display contained two items of one color with the two remaining items of a different color.

In this experiment, we used a different method for the calculation of within-dimension singleton priming. This effect was defined as the advantage of searching for a singleton target when the target had been a singleton on the same dimension in the previous trial relative to when it had been an item of the same color in a singleton-absent display. Similarly, nonsingleton priming was defined as the advantage of searching for a nonsingleton target when the target had been a nonsingleton in the previous trial relative to when it had been an item of the same color in a singleton-absent display. This new definition provided a better measure of nonsingleton priming because it eliminated the potential effect of ignoring a singleton that had been attended in the previous trial. Moreover, it allowed for the comparison of singleton and nonsingleton priming using the same baseline, namely, the singleton-absent condition. As we explained earlier, the baseline condition used to calculate target-type repetition effects is critical and in all the previous experiments (Experiments 1–5) this baseline differed for singleton and for nonsingleton priming. Thus, the present design eliminated the baseline problem entirely.

In the present experiment, we expected to replicate the findings of Experiments 4 and 5, specifically, a nonsingleton priming effect when the singleton-absent displays were excluded from analysis and the repetition effects were calculated using the same method as in Experiments 4 and 5. However, we expected nonsingleton priming to be eliminated when repetition effects are calculated using the singleton-absent condition as a baseline. This finding would suggest that nonsingleton priming results from the effect of ignoring a singleton that had been attended in the previous trial. In contrast, we expected a within-dimension singleton priming effect using both calculation methods because the benefit of singleton-target repetition observed in Experiment 5 is unlikely to have resulted only from a cost in the baseline condition (that is, a cost of attending to a singleton on the current trial when this singleton had been ignored on the previous trial), rather than also from a benefit of attending to a singleton defined within the same dimension on consecutive trials. Indeed, within-dimension singleton priming was observed also in Experiments 1–3, in which the baseline condition did not entail ignoring a singleton on the previous trial.

Method

Subjects

Subjects were 15 Tel Aviv University undergraduate students who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, Stimuli, Procedure, and Design

The apparatus, stimuli, procedure, and design were the same as in Experiment 4, except for the following changes. Each display contained four items instead of five. There were two display types. Singleton-present displays contained one oddly colored item (singleton) and three same-colored items (nonsingletons). Both the singleton and nonsingleton colors remained constant throughout the experiment. The odd item was either the target (singleton-target condition) or a nontarget (nonsingleton-target condition). Singleton-absent displays contained two items of one color with the two remaining items of a different color, and targets in this condition will henceforth be referred to as singleton-absent targets. Thus, there were three target-type conditions: singleton (one eighth of the trials), nonsingleton (three eighths of the trials), and singleton-absent (one half of the trials). The colors were the same as those used in Experiment 3.

There was one between-subject variable, target shape (circle, square, or diamond), and two within-subject randomly mixed variables, target type (singleton, nonsingleton, and target-absent) and target-type repetition. On each trial, the shapes, colors, and locations were randomly assigned. There were eight blocks of 100 experimental trials each. Thus, each subject completed 800 trials.

Results and Discussion

Mean RT data on correct trials and percent errors are presented in Figure 9. In all RT analyses, error trials (3.8% of all trials) were excluded. The data from one subject were excluded because this subject made more than 15% errors.

Replication of Experiments 4 and 5 Findings

In order to examine whether the basic findings of Experiment 4 and 5 were replicated in the present experiment, we excluded trials in which the target was a singleton-absent target on the current trial and/or had been a singleton-absent target on the previous trial, and conducted an ANOVA with target-type (singleton vs. nonsingleton) and target-type repetition (repetition vs. no repetition) as factors on the remaining data.

RTs. The main effect of target-type was nonsignificant, $F < 1$. The main effect of target-type repetition was significant, $F(1, 14) = 22.64$, $p < .0003$, and interacted with target type, $F(1, 14) = 23.45$, $p < .0003$. Further analyses revealed significant singleton and nonsingleton-priming effects: Singleton-target trials were faster when the target on the previous trial had also been a singleton relative to a nonsingleton target, $F(1, 14) = 28.34$, $p < .0001$, and nonsingleton target trials were faster when the target on the previous trial had been a nonsingleton relative to a singleton, $F(1, 14) = 6.62$, $p < .03$. The significant interaction revealed that within-dimension singleton priming was larger than nonsingleton priming. These results replicate the results found in Experiments 4 and 5.

Accuracy. No effect approached significance.

Singleton-Priming Cost

Next, we examined whether a singleton-priming cost, or the cost of ignoring a singleton on the current trial when this singleton had been the target on the previous trial, occurred in the present

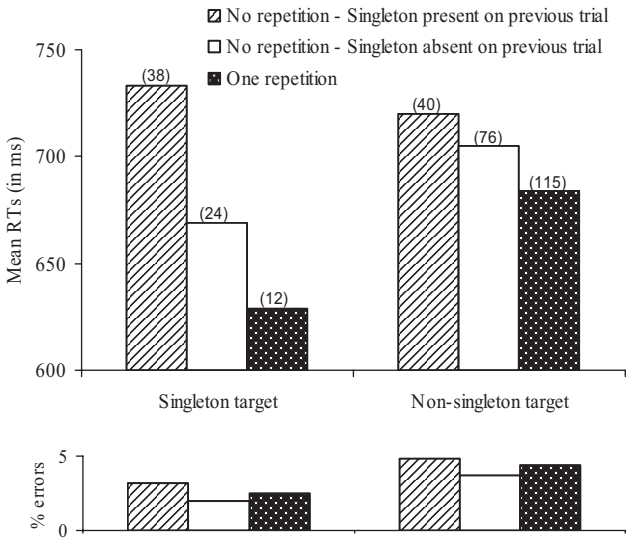

Figure 9. Experiment 6: Mean reaction times (RTs) in ms for singleton-target and nonsingleton-target trials as a function of whether target type on successive trials repeated or did not repeat. On trials in which target type did not repeat (no-repetition trials), data from trial sequences in which the previous trial did not include a color singleton (singleton absent on previous trial) are shown separately from sequences in which the previous trial contained a color singleton (singleton present on previous trial). On one-repetition trials, the fact that the target on the previous trial was either a singleton or a nonsingleton entails that a singleton was always present on the previous trial. The numbers in parentheses represent the average number of trials per subject in each of the relevant conditions. The numbers do not add up to the total number of trials because singleton-absent trials as well as singleton-present trials preceded by a different-color target are not represented in this figure.

experiment. This cost was measured as the difference in performance on a nonsingleton trial when the previous trial had been a singleton-target trial versus a singleton-absent trial. This effect was significant, 28 ms, $F(1, 14) = 2.23$, $p < .05$.

Finally, in order to test the hypothesis that nonsingleton priming resulted from this cost, that is, from the cost of ignoring a singleton that had been attended in the previous trial, we examined whether this effect was eliminated when the singleton-absent condition was used as a baseline. A planned comparison between searches for a nonsingleton target when the target had been a nonsingleton in the previous trial relative to when it had been an item of the same color in a singleton-absent display revealed no significant difference in either RT, $t(14) = 1.07$, $p > .3$, or accuracy data, $t(14) = 1.06$, $p > .3$, that is, there was no nonsingleton priming. In contrast, search for a singleton target was significantly faster when the target had been a singleton in the previous trial relative to when it had been an item of the same color in a singleton-absent display, $t(14) = 4.19$, $p < .0009$, thus revealing a within-dimension singleton priming effect. Note again that feature repetition could not account for this effect because the target had the same color on successive trials in the two compared sequences. Accuracy data showed no significant effect, $t < 1$.

The within-dimension singleton priming effect was again replicated, both when the baseline condition contained a singleton and when it did not. In contrast, the nonsingleton priming effect was eliminated when the baseline condition did not contain a singleton. These findings suggest that nonsingleton priming is not a real phenomenon.

General Discussion

Summary of the Findings

The findings of the present study suggest that attending to a featural target that happens to be a singleton leaves a memory trace that facilitates response to a featural singleton on the same dimension in the next trial. This new, previously unreported phenomenon, which we call within-dimension singleton priming, ranged in magnitude from 30 to 70 ms and was highly significant across the six experiments reported here. It was a short-lived effect (it lasted for two trials) with no cumulative effects beyond one repetition. In all experiments, the target was defined by its shape (Experiments 1, 4–6) or by a specific conjunction of color and shape (Experiments 2 and 3), and was a singleton on only a minority of the trials. It was therefore far more advantageous for the subjects to search for the feature(s) that defined the target than to monitor the displays for the most salient object.

Within-dimension singleton priming proved to be a robust phenomenon. This effect was observed for different characterizations of the nonsingleton targets (and, thus, for different baseline conditions). Namely, it was observed when there could be several identical targets within each display (Experiments 1 and 3), when the target was most often a conjunction target and appeared among nontargets that shared either its shape or its color (Experiment 2), and when the target was defined by its specific shape among heterogeneously shaped nontargets and was as likely to be a color singleton among homogenously colored shapes as any of the nontargets surrounding it (Experiments 4–6).

Moreover, within-dimension singleton priming occurred whether the target happened to be a singleton on a target-defining dimension (Experiments 1–3) or on a task-irrelevant dimension (Experiments 4–6). Within-dimension singleton priming occurred on different dimensions: It was observed when the target happened to be a singleton on the shape dimension (Experiments 1–3) or on the color dimension (Experiments 3–6).

Finally, within-dimension singleton priming was observed when the featural contrast defining the singleton was different on successive trials, as a result of a change in either the nontarget feature (Experiment 3) or the target feature (Experiment 5) within the same dimension. Cross-dimensional singleton priming, which is a benefit of singleton-target repetition when the singletons on successive trials are defined on different dimensions, did not occur.

Relation to DWA

A benefit of singleton-target repetition occurred within dimensions but not across dimensions. Moreover, this within-dimension singleton priming effect was of the same magnitude whether the singleton targets on successive trials were featurally identical or different within the same dimension (Experiments 2 and 3). These findings are consistent with the main thrust of the DWA described by Müller and colleagues (e.g., Müller, Krummenacher, & Heller, 2004), namely, that the visual system is organized in categories or

domains of attributes and that this organization affects the allocation of attentional weights.

However, several aspects of the present results show that within-dimension singleton priming cannot be explained by the DWA in its current form. First, in Experiment 1, within-dimension singleton priming was the advantage of searching for a singleton when the target had been a singleton in the same dimension on the previous trial, relative to when the target had not been a singleton on the previous trial but had also been defined within the same dimension. Thus, within-dimension singleton priming could not reflect a dimension-specific priming effect because the targets were defined within the same dimension throughout the experiment.

Second, in terms of the underlying mechanisms, dimension weighting is thought to operate under conditions in which there is uncertainty concerning the target identity, which was not the case in the present study. In Müller and colleagues' studies (e.g., Müller et al., 2004), the target changed from trial to trial, against background nontargets that remained the same on each trial. In contrast, in all the experiments from the present study, there was no target uncertainty. In Experiments 1–3, the targets were identical throughout each experiment and only nontargets changed from trial to trial. Therefore, it is unlikely that within-dimension singleton priming results from a mechanism by which weights are shifted between dimensions until the defining dimension of the target on the current trial is checked, as hypothesized by the dimension weighting account (e.g., Weidner et al., 2002), because, when the target is known, there is no need for shifting weights between different dimensions in order to find it. In Experiments 4–6, the target-defining feature (a specific shape) was always known and uncertainty occurred only on the irrelevant dimension of color, on which the target was occasionally a singleton. Dimension weighting would seem to be an implausible account for within-dimension singleton priming on a task-irrelevant dimension because it would assume a search process that checks dimensions known to be irrelevant despite the target-defining feature being known.

Third, in Experiments 2 and 3, repetition of the dimensions that were useful to finding the target did not produce an advantage unless the target was a singleton on successive trials. For instance, in Experiment 2, conjunction–conjunction sequences that required no change in attentional weighting were no faster than singleton–conjunction sequences in which a change in weights was required. In the same vein, there was no advantage of responding to four red target circles among green circles, for instance, when the target(s) on the previous trial had been defined within the same dimension (color) relative to a different dimension (shape, e.g., a red circle or red circles among red squares).

To conclude, in order to accommodate the present findings into the DWA, one would have to modify this account to stipulate (a) that, at least when there is no target uncertainty, changes in dimension attentional weighting occurs only when successive targets are singletons; (b) that, rather than serving the search process, such changes in attentional weighting occur automatically even when the target defining features are known; and (c) that attentional weighting occurs also for dimensions known by the observer not to be useful in finding the target: for instance, for a dimension in which the target happens to be unique on a given trial, but in which the target on the next trial is as likely to be unique as any distractor. In addition, one would have to suggest that a different mechanism, within-dimension singleton priming, accounts for the advantage of successive singleton targets within a given dimension (Experiments 1 and 3), which involves no dimension change and can therefore be explained by no version of DWA.

We suggest two more parsimonious alternative accounts that share several basic tenets with the DWA but differ from it in important ways. According to the first account, a singleton-priming mechanism that involves a loop of activation between a specific dimension salience map and the master map may underlie both within-dimension singleton priming effects reported here and the dimension-specific priming effects reported by Müller and colleagues (e.g., Müller et al., 2004). When an object that happens to be a singleton on a certain dimension (say, color) is attended, a corollary and automatic outcome of such selection is that the output of the map that represents salience on the color dimension is amplified. As a result, this output receives higher weighting in the master map, such that, on the next trial, stimulus-driven salience on the color dimension contributes to a larger extent to attentional priority setting than when the previously attended object was not a singleton (as revealed by within-dimension singleton priming) or was a singleton on a different dimension (as is revealed by dimension-specific priming).

A second possibility might be that a within-dimension singleton priming mechanism operates when the target features are known, as was the case in all the experiments reported here, whereas the dimension-weighting mechanism advocated by Müller and colleagues (e.g., Müller et al., 2004) prevails under conditions of target uncertainty, which require searching within different dimension maps. Further research is clearly needed to test the proposed mechanisms.

Relation to Previously Demonstrated Intertrial Repetition Effects

Olivers and Humphreys (2003) examined intertrial effects in a search for a singleton target—always a larger bar among smaller distractor bars. On most of the trials the display contained an irrelevant singleton on either the color or the orientation dimension, that is, on a dimension different from the target-defining dimension (size). As in the present Experiments 4–6, the irrelevant singleton distractor was as likely to coincide with the target as with any of the nontargets. Olivers and Humphreys found that when the target was a singleton on another dimension in addition to the size dimension, RTs were faster when the target on the previous trial had also been a singleton on an additional dimension but only if this dimension had been the same as on the previous trial. This effect is similar to the within-dimension singleton priming effect we reported in Experiments 4–6, except for one crucial difference. In the present experiments, subjects could not adopt an attentional set for singletons, because the target was a singleton on only a minority of the trials. In contrast, in Olivers and Humphreys' (2003) study, a defining characteristic of the target was that it was a size singleton on each trial, such that subjects were induced to adopt an attentional set for singletons. As a result, the dimension-specific singleton priming effects observed in that experiment might be contingent on "singleton-ness" being task relevant. The conclusion that can be drawn from that study, namely, that when searching for a singleton target, dimension-specific singleton priming occurs, is different from our conclusion that

when subjects happen to attend to a singleton in search for a nonsalient target defined by its features, they respond faster to a target that happens to be a singleton on the same dimension on the next trial. The implications with regard to the role of within-dimension singleton priming in attentional capture by irrelevant singletons are discussed in the next section.

Within-dimension singleton priming also differs from the priming of popout effect described by Maljkovic and Nakayama (1994). Priming of popout (e.g., Goolsby & Suzuki, 2001; Hillstrom, 2000) refers to a benefit of focusing attention on targets that have the same feature on successive trials relative to different features. Because within-dimension singleton priming occurred for comparisons in which the target feature was the same on successive trials for all conditions, that is, for both the singleton-target condition and the nonsingleton target condition that served as a baseline (Experiments 1–3, 6), or changed on successive trials for all conditions (Experiment 5), the effect cannot be attributed to priming of popout.

Finally, within-dimension singleton priming is also different from the dimension-specific intertrial effects described by Müller and colleagues (e.g., Müller et al., 1995). Although repeated-singleton sequences were similar to the repeated-dimension sequences in Müller and colleagues' studies, the baselines differed in a consequential way. For the dimension-specific intertrial effect, the baseline was a condition in which the target was also a singleton on the previous trial, but in a different dimension. In contrast, within-dimension singleton priming occurred with a baseline condition in which the target was not a singleton on the previous trial and was defined within the same dimension (Experiments 1, 3, and 6).

Implications of Within-Dimension Singleton Priming for Attentional Capture

The present findings are also relevant to the study of attentional capture by irrelevant featural singletons. Current theorizing on this topic shows a sharp dichotomy. Certain authors (e.g., Kim & Cave, 1999) claim that attention is automatically captured by the most salient object in the display with goal-directed factors (e.g., guidance by knowledge of the target feature) operating on the speed at which attention can be disengaged from the most salient object. In contrast, other authors (e.g., Folk et al., 1992; Yantis & Egeth, 1999) have suggested that goal-directed factors determine attentional priority and that a salient object captures attention only if subjects adopt a set for searching for discrepant objects.

In Yantis and Egeth's (1999) study, subjects searched for a nonsalient target (vertical among tilted bars). In each display, one bar was highly salient on an irrelevant dimension (e.g., color). The position of the singleton was uncorrelated with the position of the target, so there was no incentive for observers to attend to the color singleton. Whether or not the target happened to coincide with the color singleton affected neither mean search RTs nor search slopes. The authors concluded that a salient distractor does not capture attention.

Yantis and Egeth's (1999) findings reach further than this, however. Specifically, they entail that there is no role for stimulus-driven factors in feature-guided search. Indeed, they not only suggest that an irrelevant singleton does not capture attention but also that a given target receives an equal amount of attention whether it is salient or nonsalient. Such a conclusion is clearly at odds with recent findings from our lab (Lamy Camel, et al., 2006; Lamy et al., 2004). Both studies involved search for a target that was not a singleton and was defined by its specific feature. Lamy et al. (2004, Experiment 3) reported that an irrelevant item that shared the target feature produced more distraction when it appeared against a homogenous background (high salience) than against a heterogeneous background (low salience). In the same vein, Lamy Camel, et al. (2006) showed that interference by an irrelevant singleton was larger in densely packed displays (high salience) than in sparse displays (low salience). As is explained below, within-dimension singleton priming might account for this apparent inconsistency.

In Experiments 4–6 of the present study, we replicated Yantis and Egeth's finding. There was no significant effect of the type of target, that is, search was not faster when the target happened to be the color singleton than when it was a nonsingleton. However, after one target-type repetition, singleton-target trials were faster than nonsingleton-target trials. This observation raises an alternative account for the absence of salience-based effects in Yantis and Egeth's (1999) experiments, as well as in Experiments 4–6 of the present study, that challenges these authors' conclusion that stimulus-driven salience plays no role in search for a nonsalient target. Because the target was a singleton on a minority of the trials, a singleton-target trial was usually preceded by a trial in which the color singleton had to be ignored. Moreover, as the color of the singleton remained constant, on most singleton-target trials, subjects had to attend to a color that had been ignored on the previous trials. In contrast, a nonsingleton trial was preceded on most trials by trials in which a same-color nonsingleton had to be attended. In other words, if color priming and the cost of attending to an object that had just been ignored on the previous trial could have been eliminated in Yantis and Egeth's (1999) experiment, then search might have proved to be faster when the target was a singleton than when it was a nonsingleton.

A similar idea was suggested by Olivers and Humphreys (2003), but their experiment could not test it. They showed that capture by an irrelevant singleton was modulated by intertrial priming effects; but they showed this in search for a singleton target, that is, when singletons were task relevant. As such, their findings did not address the issue of attentional capture in feature-based search that was the focus of Yantis and Egeth's (1999) study, and the crux of which was that an irrelevant singleton does not affect search when subjects do not adopt a set for singletons. Because the present study involved only tasks that did not entail a set for singletons, it could test the alternative account for Yantis and Egeth's results.

The clearest opportunity to test this alternative account for Yantis and Egeth's results in terms of intertrial priming effects was provided by Experiment 6. We further analyzed the data and compared performance on singleton- versus nonsingleton-target trials when the preceding trial had been a singleton-absent trial in which the target color was the same as on the current trial, that is, when subjects had not ignored a singleton on the previous trial. We found that singleton-target trials were significantly faster than nonsingleton-target trials, 700 ms versus 735 ms, respectively, $t(14) = 2.19$, $p < .05$.

Yantis and Egeth's (1999) findings are the only findings to date that suggest no role for salience in feature-based search (in contrast with Folk & Remington, 1998, or Bacon & Egeth, 1994, for

instance, who only claim that salient singletons do not necessarily capture attention). The present results suggest that failure to observe effects of stimulus-driven salience in feature-based search in Yantis and Egeth's (1999) study resulted from the intertrial contingencies inherent to their procedure. However, because this issue was not the focus of the present study, we are currently conducting additional experiments in order to further establish this conclusion.

Effects of Goal-Directed Guidance Versus Intertrial Repetition Priming

Guidance of attention by the various forms of intertrial repetition priming (namely, priming of popout, e.g., Maljkovic & Nakayama, 1994; negative priming, e.g., DeSchepper & Treisman, 1996; dimension priming, e.g., Müller et al., 1995) results from the experience the observer has gained from prior trials rather than from the characteristics of the stimulus displays. As such, these do not belong to the category of stimulus-driven factors and fall instead into the category of top-down processes, but in the anatomical sense of the term, that is, a category of processes that originate in nonsensory areas and are typically implemented by feedback connections. Intertrial priming effects, however, should be distinguished from top-down processes in the psychological sense (for which "goal-directed processes" is a less ambiguous appellation) because they lack the voluntary–conscious component that is traditionally attributed to goal-directed factors. Indeed, they do not appear to be under conscious or strategic control and the observer does not typically have access to the contents of the underlying memory traces (Chun & Nakayama, 2000; see also, Müller et al., 2004). The term "implicit top-down factors" (Wolfe, Butcher, Lee, & Hyle, 2003) has therefore been used to convey the distinction between intertrial priming and goal-directed effects.

In fact, several authors have proposed intertrial repetition priming as an alternative account for effects that have traditionally been attributed to goal-directed guidance of attention. Accordingly, they have claimed that the role of goal-directed factors in visual search, which in much of the current literature is thought to be central (e.g., Bacon & Egeth, 1994; Folk et al, 1992; Lamy et al., 2004; Yantis & Egeth, 1999), may be largely overrated. For instance, it was suggested that priming of popout accounts for effects attributed to feature-based guidance: Knowledge of the target feature over an entire session was found to produce a similar performance advantage as several consecutive same-feature targets in the absence of such knowledge (e.g., Kristjansson, Wang, & Nakayama, 2002; Maljkovic & Nakayama, 1994, Exp. 7; but see Lamy, Carmel, Egeth, & Leber, 2006, for a different account). In the same vein, Lamy, Bar-Anan, Egeth, and Carmel (2006) recently suggested a feature-based search mechanism that benefits from implicit memory of the target's salience on previous trials (within-dimension singleton priming) as an alternative to the singleton-detection mode that is traditionally thought to underlie search for a known singleton (e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003; Yantis & Egeth, 1999).

Thus, intertrial priming effects appear to play a crucial role in visual search and the present article concerning within-dimension singleton priming as a newly identified phenomenon within this category further extends this role. Theories of visual search (e.g., Duncan & Humphreys, 1989; Grossberg, Mingolla, & Ross, 1994; Palmer, 1995; Treisman & Gormican, 1988; Wolfe, 1994) that typically include only stimulus-driven and goal-directed components should therefore be updated to account for the large body of findings that has accumulated on these phenomena in recent years (e.g., Bichot & Schall, 2002; Goolsby & Suzuki, 2001; Kristjansson et al., 2002; Krummenacher, Müller, & Heller, 2001; Kumada, 2001; Wolfe et al., 2003).

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Appendix

We examined the effect of the reporting (or response) feature in the present article in additional analyses with up to five consecutive same-response sequences. Mean RTs on correct trials are presented in Figure 10. The effect of response repetition was highly significant in all the experiments: $F(4, 20) = 22.23$, $p < 0.0001$, $F(4, 44) = 20.68$, $p < 0.0001$, $F(4, 44) = 24.16$, $p < 0.0001$, $F(4, 44) = 3.74$, $p < 0.02$, $F(4, 44) = 17.79$, $p < 0.0001$, and $F(4, 32) = 9.01$, $p < 0.0001$ for Experiments 1–6, respectively. However, it is noteworthy that this effect typically became apparent only after two repetitions. Indeed, in all the experiments except for Experiment 4, the effect of one repetition was nonsignificant but the effect of one additional repetition (three consecutive same-response trials relative to two) was highly significant $F(1, 5) = 5.91$, $p < 0.06$ and $F(1, 5) = 17.52$, $p < 0.009$ for Experiment 1, $F < 1$ and $F(1, 11) = 2.75$, $p < 0.0006$ for Experiment 2, $F < 1$ and $F(1, 11) = 6.73$, $p < 0.03$ for Experiment 3, $F < 1$ and $F(1, 11) = 19.54$, $p < 0.002$ for Experiment 4, and $F(1, 8) = 1.95$, $p = 0.2$, and $F(1, 8) = 19.75$, $p < 0.003$ in Experiment 6. Both effects were significant in Experiment 5, $F(1, 11) = 17.45$, $p < 0.002$ and $F(1, 11) = 24.06$, $p < 0.0005$. The smallest number of trials considered in the above analyses, that is, the minimum number of trials for four consecutive response repetitions for an individual subject was 12.

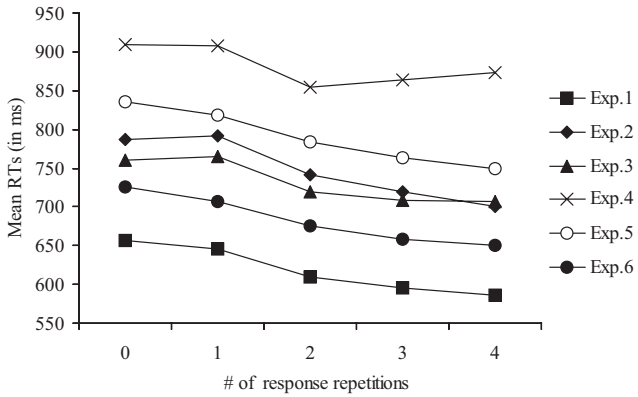

Figure A1. Mean reaction times (RTs) in ms in Experiments 1–6 as a function of the number of successive trials requiring the same motor response.

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