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Direct Evidence for Active Suppression of Salient-but-Irrelevant Sensory Inputs

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Abstract

Researchers have long debated whether attentional capture is purely stimulus-driven or purely goal-driven. In the current study, we test a hybrid account called the *signal suppression hypothesis*, which posits that stimuli automatically produce a bottom-up salience signal, but that this signal can be suppressed via top-down control processes. To test this account, we used a new capture-probe paradigm in which participants searched for a target shape while ignoring irrelevant color singletons. On occasional probe trials, letters were briefly presented inside the search shapes, and participants attempted to report these letters. Under conditions that promoted capture by singletons, accuracy was greater for the letter inside this singleton than for letters inside nonsingleton objects. However, when the conditions were changed to avoid capture by the singleton, accuracy for the letter inside the irrelevant singleton was reduced below the level observed for nonsingleton objects, indicating active suppression of the singleton.

Keywords

attentional capture; visual search; spatial attention; suppression; inhibition

Objects that differ from an otherwise-homogenous background (*feature singletons*, such as the red circle in Figure 1) are phenomenologically salient and seem to automatically attract visual attention. Indeed, singletons are used in daily life to alert people to important information, (e.g., red indicator lights on relatively homogeneous dashboards). However, researchers still disagree whether singletons automatically "capture" visual attention.

According to *stimulus-driven* theories, singletons automatically capture visual attention, regardless of current goals (Franconeri & Simons, 2003; Jonides & Yantis, 1988; Theeuwes, 1992). These theories are commonly supported by studies using the additional singleton paradigm. In a classic version (Theeuwes, 1992), participants searched displays of diamonds for a circle target and reported the orientation of a line inside the circle. On some trials, a uniquely colored distractor appeared, leading to slowed response times (RTs). This

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Author Contributions
N.G. and S.J.L. developed the study concept and design. Stimulus presentation programs and data analysis programs were developed by N.G. and C.J.L. All authors drafted the manuscript and approved of the final version for submission.

singleton-presence cost was taken as evidence that the color singleton temporarily captured attention, slowing attentional allocation to the target.

In contrast, *goal-driven* theories propose that an individual's intentions determine whether salient stimuli capture attention (Folk, Remington, & Johnston, 1992). Goal-driven theories explain singleton-presence costs by noting that the target is a shape singleton in the additional singleton paradigm, which might lead participants to intentionally search for any singleton (*singleton detection mode*). Bacon and Egeth (1994) forced participants to search for a specific feature such as shape (*feature search mode*) by intermixing trials where the target was no longer a shape singleton (e.g., a circle amongst diamond, square, and triangle distractors). Singleton-presence costs were eliminated, even on trials where the target was a singleton, suggesting that top-down goals can override bottom-up salience. However, proponents of stimulus-driven capture have argued that the lack of singleton-presence costs in this study could be explained by a serial processing strategy (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; but see Gaspelin, Ruthruff, Lien, & Jung, 2012).

The stimulus-driven and goal-driven theorists have also found conflicting results in several other paradigms, with each side providing different interpretations of the results (e.g., Folk & Remington, 1998; Theeuwes, 2010). This fundamental disagreement about the nature of attentional capture needs resolution. Without a coherent theory of attentional capture, it is difficult to create computational models of search (Wolfe, 2007), design effective warning signals (Johnston, Ruthruff, & Lien, 2014), or understand the development of attentional control (Gaspelin, Margett-Jordan, & Ruthruff, 2014)

In an attempt to resolve this controversy, Sawaki and Luck (2010) proposed a hybrid model of attentional capture, called the *signal suppression hypothesis*, which incorporates components of both stimulus-driven and goal-driven theories. According to the signal suppression hypothesis, singletons automatically generate a salience signal, consistent with stimulus-driven theories. However, this salience signal can subsequently be suppressed, resulting in no attentional capture, consistent with goal-driven theories.

Signal suppression can explain why attentional capture occurs under some situations but not others (see Sawaki & Luck, 2014). At present, most evidence for active suppression comes from event-related potential (ERP) studies focusing on an inhibition-related component called the *distractor positivity* (P_D; Hickey, Di Lollo, & McDonald, 2009). Specifically, several studies have shown that a P_D component is elicited by singleton distractors under conditions that minimize behavioral singleton-presence costs (Burra & Kerzel, 2014; Eimer & Kiss, 2008; Gaspar & McDonald, 2014; Jannati, Gaspar, & McDonald, 2013; Sawaki & Luck, 2010, 2011).

Behavioral evidence for attentional suppression, however, is limited. For example, Ipata, and colleagues (2006) found that highly trained monkeys made fewer first saccades to singleton distractors than nonsingleton distractors, which was accompanied by decreased activity at the singleton location in the lateral intraparietal area. Also, Gaspar and McDonald (2014) found that P_D effects were larger on trials with fast target-detection times than slow target-detection times, suggesting that singletons suppression helped participants locate the target.

Finally, salient distractors impair search performance when they appear near the target, indicating that inhibition of the salient distractor may spread to nearby items (Gaspar & McDonald, 2014; Jannati et al., 2013).

In summary, previous research suggests that suppression allows participants to avoid attentional capture. However, little research has directly shown that covert processing of the singleton item is suppressed below the level of a nonsingleton item. The goal of the present study was to examine this possibility by means of a novel *capture-probe paradigm* that assesses processing at each location in the stimulus array.

Our capture-probe paradigm (see Figure 1; based on Kim & Cave, 1995) involves randomly intermixing frequent search trials with infrequent probe trials. On search trials, participants search for a target shape while ignoring an irrelevant color singleton. On probe trials, letters briefly appear superimposed on each search item, and participants attempt to recall as many letters as possible. This provides information about the allocation of processing resources at every location in the array. If the color singleton captures attention, participants should be more likely to report probes at the singleton-distractor location than probes at nonsingleton-distractor locations. Alternatively, if the color singleton is suppressed, participants should be less likely to recall probes at singleton-distractor locations than at nonsingleton-distractor locations (a *singleton-suppression effect*)

Experiment 1

Experiment 1 was designed to validate the capture-probe paradigm by creating conditions in which irrelevant singletons are known to capture attention. Specifically, the target itself was a shape singleton, which encourages participants to use a singleton detection mode strategy and is known to produce large singleton-presence costs. If the capture-probe paradigm is a valid measure of resource allocation, we should observe enhanced probe recall at the singleton-distractor location compared to nonsingleton-distractor locations.

Methods

Participants—Twenty-four undergraduate students participated for course credit (16 females; mean age: 19.9 years). All participants had normal color vision, had normal or corrected-to-normal visual acuity, and provided informed consent. Previous additional singleton paradigm studies (Bacon & Egeth, 1994; Theeuwes, 1992) and probe studies (Kim & Cave, 1995) suggested this sample size would yield ample power.

Stimuli—Stimuli were presented using PsychToolbox (Brainard, 1997) on an LCD with a black background at a distance of 70 cm (see Figure 2A). Search displays contained diamonds (1.6° by 1.6°) and circles (1.4° diameter) drawn in green (30.5 cd/m^2, $x = .30$, $y = .61$) or red (30.4 cd/m^2, $x = .64$, $y = .34$). Each shape was centered 2.0° from fixation and contained a 0.2° black dot located 0.2° from either the left or right side of the shape. On probe trials, upper-case letters (0.8° tall) were presented in white (132.0 cd/m^2) at the center of each shape using an Arial font. A subsequent response screen contained all letters from the English alphabet in white. A gray fixation cross (30.3 cd/m^2, 0.4° × 0.4°) was continuously visible except during the response screen and intertrial interval.

Design & Procedure

The search target was defined as the unique shape, which was unpredictably a circle amongst identical diamonds or a diamond amongst identical circles (see Figure 2A). On search trials (70% of trials), the task was to report whether the black dot was on the left or right side of the target shape (by pressing keys labeled “L” or “R” on the keyboard with their left hand). Target location and dot side varied randomly. All items were a single color on 50% of trials (red for half of the participants and green for the others), and one item was drawn in the other color on the remaining trials. The location of this color singleton distractor was random except that it was never the target location. Participants were told this and were encouraged to ignore the color singleton. Search trials began with a presentation of a blank screen for 500 ms followed by a fixation screen for 1000 ms. Next, the search array appeared until response. If participants took too long to respond (more than 2000 ms), a timeout display appeared with the text “Too Slow” for 500 ms. If the response was incorrect, a 200 Hz tone sounded for 500 ms.

On probe trials (30% of trials), a letter was presented inside each shape. The letters on a given trial were selected at random, without replacement, from the 26 letters of the English alphabet. On these trials, participants did not make a dot-location response but instead used the mouse to click on all letters on a response screen that they remembered seeing in the probe display (with no time pressure). The search array appeared for 200 ms on these trials and was immediately followed by the letter-probe array for 100 ms. Next, the response screen appeared, and participants selected between zero and six letters via mouse-click. Note that this response screen appeared immediately after the probe display, serving as a mask. Each letter in the response screen turned yellow when clicked, and the participant clicked a gray OK box (4.5° × 2.5°) when finished.

Pilot testing indicated that, to achieve good performance, participants needed substantial practice with the search task alone before the probe trials were added. Consequently, participants first practiced only the search task for two blocks of 48 trials. Then, participants practiced the combined capture-probe paradigm for two blocks of 48 trials. The main experiment consisted of 10 blocks of 48 trials, yielding 144 probe trials, 72 with and 72 without an irrelevant singleton. Participants received block-by-block feedback on mean response time (RT) and accuracy. We would like to emphasize that single-task practice and a limited number of probe trials are essential to obtain reliable results in this paradigm.

Results

Search-task analysis—Trials with an RT less than 200 ms or greater than 1500 ms (1.1% of trials) or with an incorrect response were excluded from search-trial analyses. As shown in Figure 2B, responses in the search task were slower when the color singleton was present (739 ms) than when it was absent (674 ms) – a 65 ms singleton-presence cost, $t(23) = 11.49$, $p < .001$. Participants also committed fewer errors on singleton-absent trials (3.4%) than on singleton-present trials (5.1%), $t(23) = 3.42$, $p < .01$. These results confirm that this task effectively yielded strong attentional capture by the irrelevant color singleton on the search trials, even though they were interspersed with occasional probe trials. Given these search task results, all theories of attentional capture would predict enhanced processing at the singleton-distractor location compared to nonsingleton-distractor locations on probe trials. Such a finding would validate the probe-capture paradigm as a means of measuring processing at each individual location.

Probe-task analysis—Participants reported an average of 1.8 letters per trial, 82.2% of which were actually present in the probe array. Participants reported roughly equal numbers of letters on singleton-absent trials (1.9) and singleton-present trials (1.8), $t(23) = 1.65$, $p > .10$. Note that this is far lower than the capacity of working memory, and this low number presumably reflects the fact that the response screen was presented immediately after the probe letters and served as a potent mask (see Figure 1).

As shown in Figure 2C, probe letters at the singleton location were nearly twice as likely to be recalled as probe letters at nonsingleton-distractor locations. A planned *t* test confirmed that probe recall accuracy was higher at the singleton location (26.6%) than at nonsingleton-distractor locations (14.7%), $t(23) = 3.86$, $p < .001$. This demonstrates that the probe task is a sensitive measure of attentional allocation to individual items.

We also examined how the presence or absence of the singleton impacted the report of probe letters at the target and nonsingleton-distractor locations. If resources are attracted by the singleton distractor, then fewer resources should be available for the other locations, and performance at these locations should therefore be reduced on singleton-present trials compared to singleton-absent trials. As shown in Figure 2C, probe recall at the target location was 12% lower when the color singleton was present than when it was absent, providing additional evidence that the color singleton drew attention away from the target. Probe recall at the nonsingleton-distractor locations was not influenced by the presence or absence of the color singleton, although this may reflect a lack of sensitivity given that performance was already quite low for probes at the nonsingleton-distractor locations.

These effects of singleton presence on performance at the target and nonsingleton-distractor locations were analyzed in a two-way ANOVA with factors of singleton presence and probe-item type (target vs. nonsingleton distractor); this ANOVA excluded data from the singleton location itself (which was necessary to obtain a balanced factorial design). This ANOVA indicated that recall accuracy was significantly higher for probes at the target location (54.8%) than for probes at nonsingleton distractor (15.3%) locations, $F(1, 23) = 85.440$, $p < .001$, $\eta_p^2 = .788$. This 39.5% target enhancement effect reflects attentional allocation to the target. The ANOVA also indicated that probe recall accuracy was significantly higher overall on singleton-absent trials than on singleton-present trials, $F(1, 23) = 39.119$, $p < .001$, $\eta_p^2 = .630$. Finally, this ANOVA confirmed that singleton presence impacted performance more at the target location than at the nonsingleton-distractor locations, leading to a significant singleton presence X probe type interaction, $F(1, 23) = 24.325$, $p < .001$, $\eta_p^2 = .514$. Follow-up *t* tests indicated that the difference between singleton-present and singleton-absent conditions was significant for probes at the target location (12.2%), $t(23) = 5.75$, $p < .001$, but did not quite reach significance at the nonsingleton-distractor locations (1.1%), $t(23) = 2.012$, $p = .06$. These results provide additional evidence that attentional resources were attracted by the irrelevant singleton.

These results demonstrate the validity of the capture-probe paradigm. In a task that all theories would expect to produce singleton capture, we observed enhanced processing at the singleton distractor compared to the nonsingleton distractors. We also observed that the presence of the singleton led to impaired processing of probes at the target location, consistent with an allocation of resources to the singleton location. These results indicate that the capture-probe paradigm provides a valid means of assessing processing at each location under more controversial conditions.

Experiment 2

In Experiment 2, we encouraged participants to search for a specific feature value. This should discourage singleton detection mode, eliminating singleton-presence costs in the search task. The data from the probe trials tests three competing theoretical positions. Stimulus-driven theories propose that the singleton always captures attention, leading to *enhanced* performance for probes presented at the singleton location (as in Experiment 1). Goal-driven theories assume no special processing of the singleton, leading to *equivalent* recall for probes at the singleton distractors and nonsingleton distractors. The signal suppression hypothesis proposes that singletons will be actively suppressed, leading to *impaired* recall for probes at the singleton-distractor location relative to nonsingleton-distractor locations.

Methods

The methods were identical to those of Experiment 1 with the following changes. First, a new set of twenty-four students participated (18 females; mean age: 20.0 years). Second, search displays were modified to encourage participants to look for a specific shape, rather than singletons (see Figure 3A). Specifically, each search display contained six shapes: a diamond, a circle, two squares (1.2° in width and height), and two hexagons (1.5° in width and height). The target was always the diamond for half of the participants and always the circle for the other half. By keeping the target shape constant for a given participant, and by presenting it among a heterogeneous set of distractor shapes, this experiment promoted shape-based search and eliminated any incentives to intentionally search for singletons (Bacon & Egeth, 1994).

Results

Search-task analysis—Whereas the presence of a singleton led to slower search-task RTs in Experiment 1, RTs were no slower on singleton-present trials (667 ms) than on singleton-absent trials (678 ms) in Experiment 2 (Figure 3B). In fact, RTs were 11 ms faster on singleton-present trials than on singleton-absent trials in Experiment 2, although this effect was only marginally significant, $t(23) = 1.95$, $p = .063$. This goes in the opposite direction of what one would expect if the singleton captured attention. In addition, consistent with the RT trend, participants committed marginally more errors on singleton-absent trials (3.0%) than singleton-present trials (2.4%), $t(23) = 1.81$, $p = .08$.

Probe-task analysis—Participants reported an average of 1.7 letters, 82.0% of which were actually present in the probe array. The number of letters on singleton-absent trials (1.7) and singleton-present trials (1.7) did not significantly differ, $t(23) < 1$, $p > .10$.

As predicted by the signal suppression hypothesis, probe letters were significantly less likely to be reported from the singleton location (9.6%) relative to the nonsingleton-distractor locations (15.4%), $t(23) = 4.634$, $p < .001$. In other words, probe recall was impaired by approximately 6% at the singleton location compared to the nonsingleton locations (see Figure 3C).

We also analyzed the effect of singleton presence on probe detection at the target and nonsingleton-distractor locations in a 2-way ANOVA (excluding the singleton location, as in Experiment 1). Whereas probe detection was impaired on singleton-present trials compared to singleton-absent trials in Experiment 1, probe detection at the target and nonsingleton-distractor locations was slightly but significantly higher on singleton-present trials than on singleton-absent trials in the present experiment. This 1.6% effect led to a significant main effect of singleton presence, $F(1, 23) = 6.498$, $p < .05$, $\eta_p^2 = .220$. This is exactly what would be expected if the singleton location was suppressed, freeing resources for the other search items. As in Experiment 1, probe recall accuracy was significantly higher for probes at the target location than for probes at the nonsingleton-distractor locations, $F(1, 23) = 90.739$, $p < .001$, $\eta_p^2 = .798$. This 40.7% target enhancement effect presumably reflects the allocation of attention to the target shape. The interaction of singleton-presence and probe item type did not approach significance, $F(1, 23) < 1$, $p > .10$.

These results provide the first direct evidence that, when a task is designed in a manner that eliminates singleton-presence costs, processing is actively suppressed at the singleton location relative to nonsingleton-distractor locations. This suppression effect, which is inconsistent with both traditional goal-driven and stimulus-driven theories of attentional capture, was directly predicted by the signal suppression hypothesis.

Experiment 3

Although we observed singleton suppression in Experiment 2, the magnitude of this effect was limited by the already-low accuracy for probes at nonsingleton distractors. The goal of Experiment 3 was to show that the suppression effect can be increased by bringing overall accuracy away from floor, which we achieved by decreasing the set size from 6 items to 4 items.

Methods

The methods were identical to those of Experiment 2 except for the following changes. First, a new set of twenty-four students participated (20 females; mean age: 19.3 years). Second, search displays were reduced to a set size of 4 (See Figure 4A). Each display contained one diamond, one circle, one square, and one hexagon. The display was arranged to form a diamond pattern (3.3° in width and height).

Results

Search-task analysis—Search RTs were significantly faster on singleton-present trials (630 ms) than on singleton-absent trials (652 ms; see Figure 4B), $t(23) = 5.01$, $p < .001$. This 22 ms singleton presence *benefit* is in the opposite direction of what one would expect if the singleton captured attention. However, it is what would be expected if the singleton location was suppressed, freeing resources for the other locations. Participants did not commit significantly more errors on singleton-present trials (3.1%) than on singleton-absent trials (2.7%), $t(23) < 1$, $p > .10$.

Probe-task analysis—Participants reported an average of 1.7 letters on probe trials, 93.5% of which were present in the probe array. Participants reported approximately equal numbers of letters on singleton-absent trials (1.7) and singleton-present trials (1.7), $t(23) < 1$, $p > .10$.

To test the assumption that the lower set size in this experiment would lead to an overall increase in probe performance relative to Experiment 2, we collapsed the data across all locations and compared overall performance in Experiments 2 and 3. Overall probe recall accuracy was indeed significantly higher in Experiment 3 (39.5%) than in Experiment 2 (30.1%), $t(46) = 3.18$, $p < .01$.

As in Experiment 2, the signal suppression hypothesis predicts lower accuracy for probes at the singleton distractor than at nonsingleton distractors. Indeed, probe recall accuracy was significantly lower at the singleton distractor (15.5%) than at the nonsingleton distractors (27.9%; see Figure 4C), $t(23) = 5.61$, $p < .001$. This effect was numerically larger than the suppression observed in Experiment 2. To test the significance of this difference, we computed a suppression score for each participant (difference in probe accuracy between the singleton and nonsingleton-distractor locations) and compared the scores across experiments. The approximately 12% suppression effect at set-size 4 in the present experiment was significantly larger than the approximately 6% suppression effect at set-size 6 in Experiment 2, $t(46) = 2.60$, $p = .01$. Thus, the present experiment shows that the singleton-suppression effect observed in the previous experiment is replicable and can be made fairly large by bringing accuracy away from the floor.

As in Experiment 2, we analyzed the singleton’s effect on probe accuracy at the target and nonsingleton-distractor locations (excluding the singleton location itself). Recall accuracy was again higher for probes at target locations than for probes at nonsingleton-distractor locations, $F(1, 23) = 186.02$, $p < .001$, $\eta_p^2 = .890$. Recall accuracy was also slightly but significantly higher on singleton-present trials than on singleton-absent trials, leading to a main effect of singleton presence, $F(1, 23) = 4.52$, $p < .05$, $\eta_p^2 = .164$. This benefit was mainly observed at the nonsingleton-distractor location, leading to a significant interaction between singleton presence and probed item type, $F(1, 23) = 6.17$, $p < .05$, $\eta_p^2 = .212$. These results are also consistent with a suppression of processing at the location of the singleton distractor.

Experiment 4

Experiment 4 tested an alternative stimulus-driven explanation of the suppression effects observed in Experiments 2 and 3. The *rapid disengagement* account proposes that spatial attention is initially captured by the color singleton but rapidly disengages before the probe array appears (Theeuwes, 2010). In other words, top-down suppression occurs *after* an initial attentional shift to the color singleton. This account is plausible given that the probe array did not appear until 200 ms after the onset of the search array in Experiments 2 and 3. Experiment 4 tested this hypothesis by eliminating the probe delay, thereby preventing attention from rapidly disengaging from the singleton before the appearance of the probe letters. Under these conditions, the rapid disengagement account predicts enhancement rather than suppression at the color singleton location. The signal suppression hypothesis, however, again predicts a suppression effect.

Methods

The methods were identical to Experiment 3, with the following exceptions. A new set of 24 students participated (21 females; mean age: 19.9 years). On probe trials, the probe letters appeared simultaneously with the search array for 100 ms. Given that involuntary shifts of spatial attention take between 35–100 ms, this should be too quick for participants to disengage from the singleton item (e.g., Horowitz, Wolfe, Alvarez, Cohen, & Kuzmova, 2009). Furthermore, to minimize any movement of spatial attention within iconic memory, the probe letters were immediately replaced with masks (“#”) embedded inside the shapes for 500 ms (Loftus, Johnson, & Shimamura, 1985) before the response display was presented.

Results

Search-task analysis—The results are summarized in Figure 5. As in Experiments 2 and 3, RTs were significantly faster on singleton-present trials (630 ms) than on singleton-absent trials (647 ms), t(23) = 4.5, p < .001. This −17 ms singleton-presence cost is consistent with active suppression of the singleton. Error rates were similar between singleton-present trials (2.1%) and singleton-absent trials (2.2%), $t(23) < 1$, $p > .10$.

Probe-task analysis—Participants reported an average of 1.9 letters, 77.5% of which had been present in the probe array. Participants reported approximately the same number of letters on singleton-present trials (1.9) and singleton-absent trials (1.9), $t(23) = 1.84$, $p = .08$.

As shown in Figure 5, probe recall accuracy was significantly lower at the color singleton location (24.2%) than at nonsingleton-distractor locations (32.6%), $t(23) = 4.6$, $p < .001$. This approximately 8% suppression effect replicates the findings of Experiments 2 and 3 and is inconsistent with the rapid disengagement account.

We also analyzed the singleton’s effect on accuracy for probes at the target and nonsingleton-distractor locations. Once again, recall accuracy was significantly higher for probes at the target location compared to the nonsingleton-distractor location, $F(1, 23) = 12.605$, $p < .01$, $\eta_p^2 = .354$. Recall accuracy was also higher on singleton-present trials than on singleton-absent trials, $F(1, 23) = 13.685$, $p < .01$, $\eta_p^2 = .373$, consistent with a freeing of resources from the singleton location. The interaction between singleton presence and item type was nonsignificant, $F(1, 23) = 2.037$, $p > .10$. These results provide additional evidence that the singleton location was suppressed, even though the probe letters were presented simultaneously with the search array.

We have assumed that eliminating the delay between the search array and the probe letters (and following the letters with a powerful mask) would reduce the time available for attention to shift first toward and then away from the irrelevant singleton. If this is true, then the time available to shift attention toward the target location should also be reduced. Consistent with this, a comparison of Experiments 3 and 4 showed that probe accuracy at the target location was 27.9% lower in Experiment 4 than in Experiment 3, $t(46) = 7.40$, $p < .001$. Probe accuracy at the singleton location, however, was increased by 8.7% in Experiment 4 relative to Experiment 3, $t(46) = 2.337$, $p < .05$, and there was a marginally significant 6.2% increase in accuracy at the nonsingleton locations, $t(46) = 2.91$, $p = .06$. An implication of this is that the target enhancement effect (probe accuracy for targets minus probe accuracy for nonsingleton distractors) was approximately 1/6th as large in Experiment 4 ($M = 4.9\%$; *95%CI* [2.2, 7.7]) as in Experiment 3 ($M = 38.9\%$; *95%CI* [33.3, 44.5]). In contrast, suppression at the singleton location did not differ significantly between Experiment 3 (approximately 12%) and Experiment 4 (approximately 8%), $t(46) = 1.406$, $p > .10$. These results indicate that the salient singleton is rapidly suppressed, whereas the allocation of attention to the target increases over time.

Discussion

The capture-probe paradigm used in the present study provides direct evidence that salient-but-irrelevant singletons can be actively suppressed when top-down guidance is deployed. These findings are consistent with the signal suppression hypothesis (Sawaki & Luck, 2010), providing a potential resolution to the conflict between stimulus-driven and goal-driven theories of capture (Folk et al., 1992; Folk & Remington, 2010; Theeuwes, 1992, 2010). These behavioral findings also complement ERP studies observing a P_D component for irrelevant singletons in the absence of behavioral capture (Burra & Kerzel, 2014; Eimer & Kiss, 2008; Gaspar & McDonald, 2014; Jannati et al., 2013; Sawaki & Luck, 2010, 2011).

Experiment 1 established the validity and sensitivity of the capture-probe paradigm by using conditions that all theories agree should lead to attentional capture by an irrelevant singleton. As in prior studies, we found large singleton-presence costs on search trials. On probe trials, participants were twice as likely to recall probes at singleton distractors than at nonsingleton distractors, consistent with attentional capture by the irrelevant singleton.

Experiment 2 demonstrated that the singleton location is suppressed under conditions that discourage attentional capture. As in previous studies, no singleton-presence cost was observed on the search trials, which is typically interpreted as the result of attentional biasing toward the target, with no special processing of irrelevant singletons. However, the signal suppression hypothesis predicts that the singleton is actively suppressed to avoid capture. The probe trials allowed us to directly demonstrate this suppression: Participants were less likely to report probes at singleton distractors than at nonsingleton distractors.

In Experiment 3, we reduced the set size to bring overall probe accuracy away from the floor, which caused even larger probe suppression effects. Experiment 4 demonstrated that this suppression effect cannot be explained by an initial capture and subsequent reorienting of attention (i.e., rapid disengagement).

Two additional results are also consistent with suppression of the irrelevant singleton. First, in Experiments 3 and 4, RTs for the search task were actually faster on singleton-present trials than on singleton-absent trials. Analogous “reversed” cue validity effects have been found in precuing studies in which participants were strongly motivated to ignore a particular feature value (Anderson & Folk, 2012; Belopolsky, Schreij, & Theeuwes, 2010). Additional research is needed to isolate the conditions under which this *singleton-presence benefit* is found. Second, accuracy for probes at the target and/or nonsingleton-distractor locations was increased on singleton-present trials compared to singleton-absent trials, suggesting that attentional resources were freed from the singleton and devoted to the other items.

A dot-probe paradigm using reaction times has produced complementary results to the current suppression effects (e.g., Kim & Cave, 1999; Lamy, Tsal, & Egeth, 2003). For example, Lamy and colleagues (Experiment 2) had participants search displays of shapes for a specific target (e.g., green circle). After the shapes disappeared, a small black dot appeared at a random search location, and participants made a speeded detection response. Reaction times were slower for probes at singleton distractors than at nonsingleton distractors, suggesting the singleton was suppressed. However, participants were required to make the probe response *before* the search response on every trial, which may have altered the strategy used to perform the search task. Moreover, the search task was unspeeded, making it impossible to measure singleton-presence costs. In the present study, participants made a speeded search response on the majority of trials, obviating these problems.

An alternative explanation of suppression effects in the current study is a *featural upweighting* account, which proposes that features matching the target-defining property are boosted preattentively (Bichot, Rossi, & Desimone, 2005). This would lead to enhancement of nonsingleton distractors rather than suppression of singleton distractors. Note that the signal suppression hypothesis and the featural upweighting account are not mutually exclusive. Future studies should investigate the role of featural upweighting in producing a relative suppression of processing at singleton compared to nonsingleton-distractor locations (see, e.g., Gaspar & McDonald, 2014).

The present results—and the signal suppression hypothesis in general—provide a rapprochement between stimulus-driven and goal-driven theories of attentional capture. Goal-driven accounts could accommodate the present data by agreeing that singletons automatically generate a priority signal. Similarly, stimulus-driven accounts could accommodate the present results by agreeing that the priority signal generated by a singleton can be suppressed before attentional shifts. In other words, these traditionally opposed theoretical accounts can be merged in the form of the signal suppression hypothesis.

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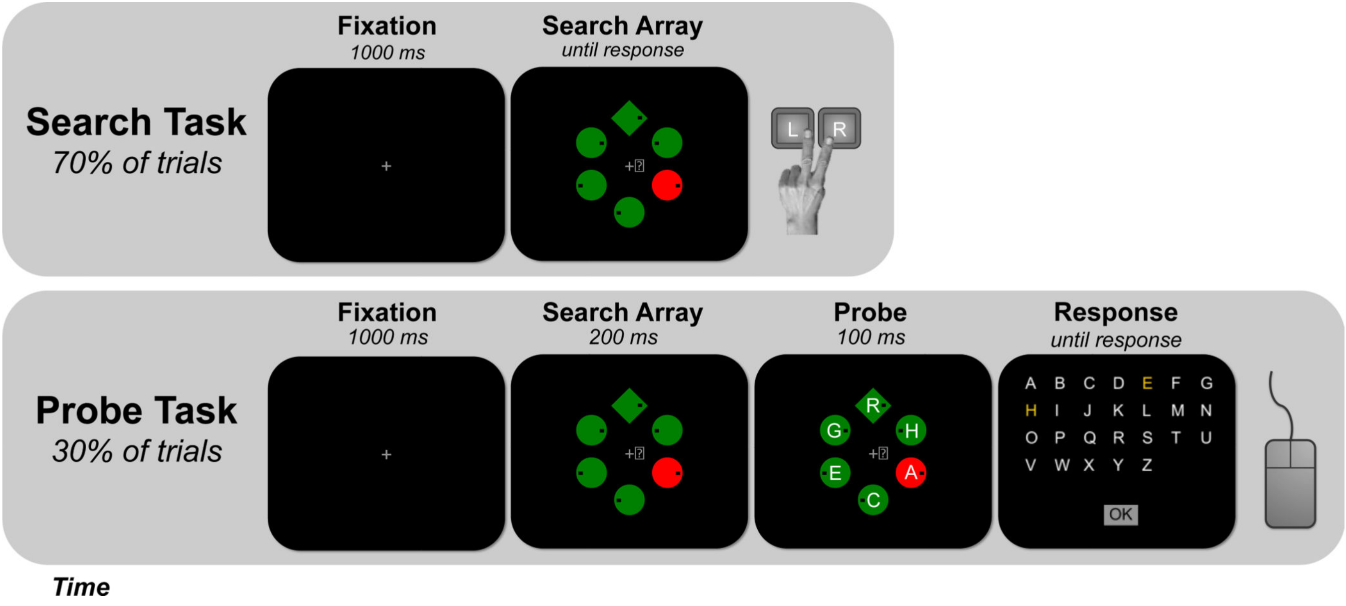

Figure 1.

The capture-probe paradigm. Participants search for the target shape and respond whether a small black dot is on the left or right side (via button press). On infrequent probe trials, the search array appears briefly and is quickly followed by a display with a letter at each search location. Participants report as many letters as they can recall via mouse click.

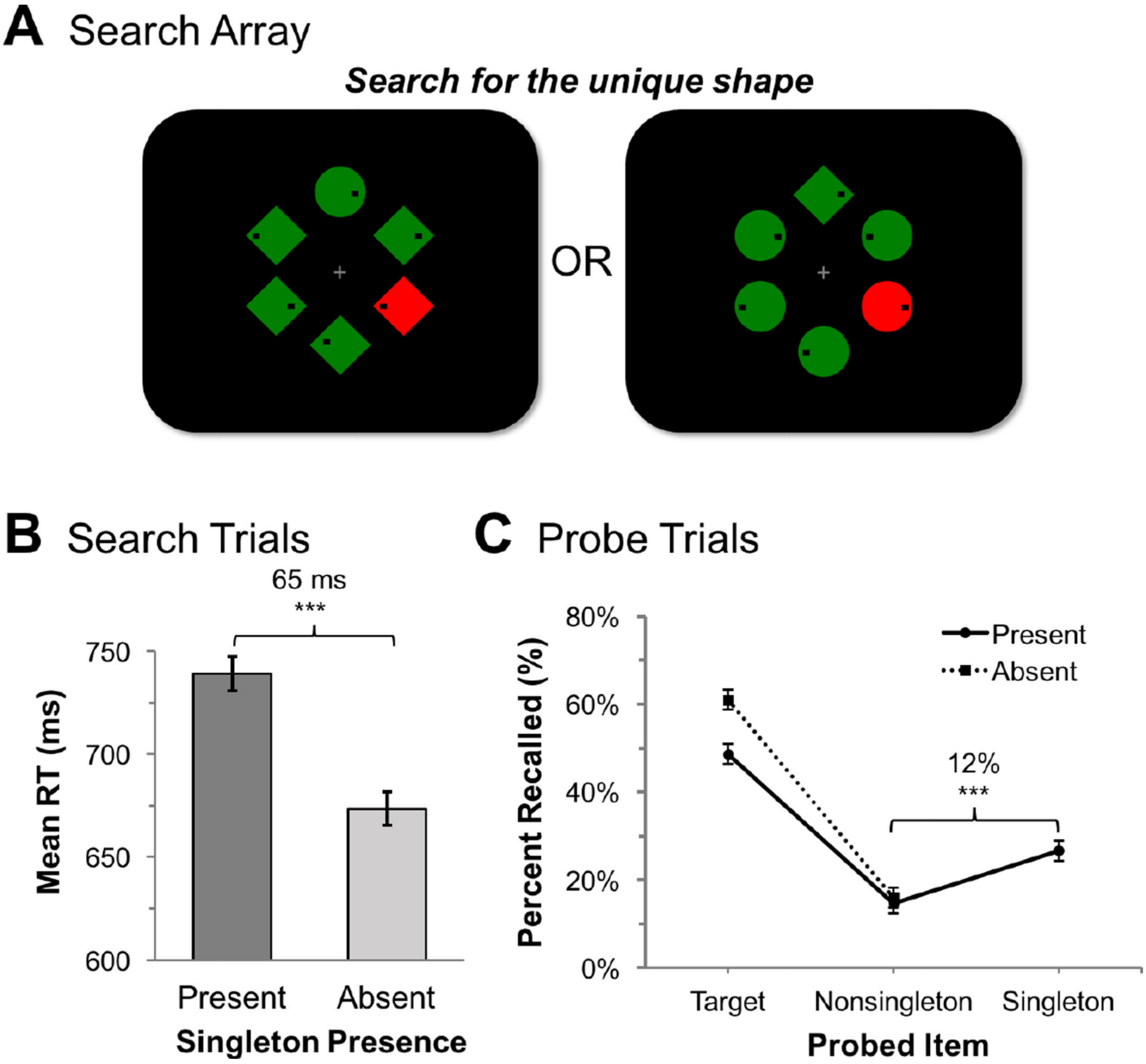

Figure 2.

Stimuli and results for Experiment 1. (A) Circle-target and diamond-target trials were randomly intermixed to require singleton detection mode. (B) Mean RT for the search task. (C) Percentage of probe trials on which the probe letter at a given location was reported. Here and in all subsequent figures, error bars represent the within-subjects 95% confidence interval (Loftus & Masson, 1994).

*** $p < .001$.

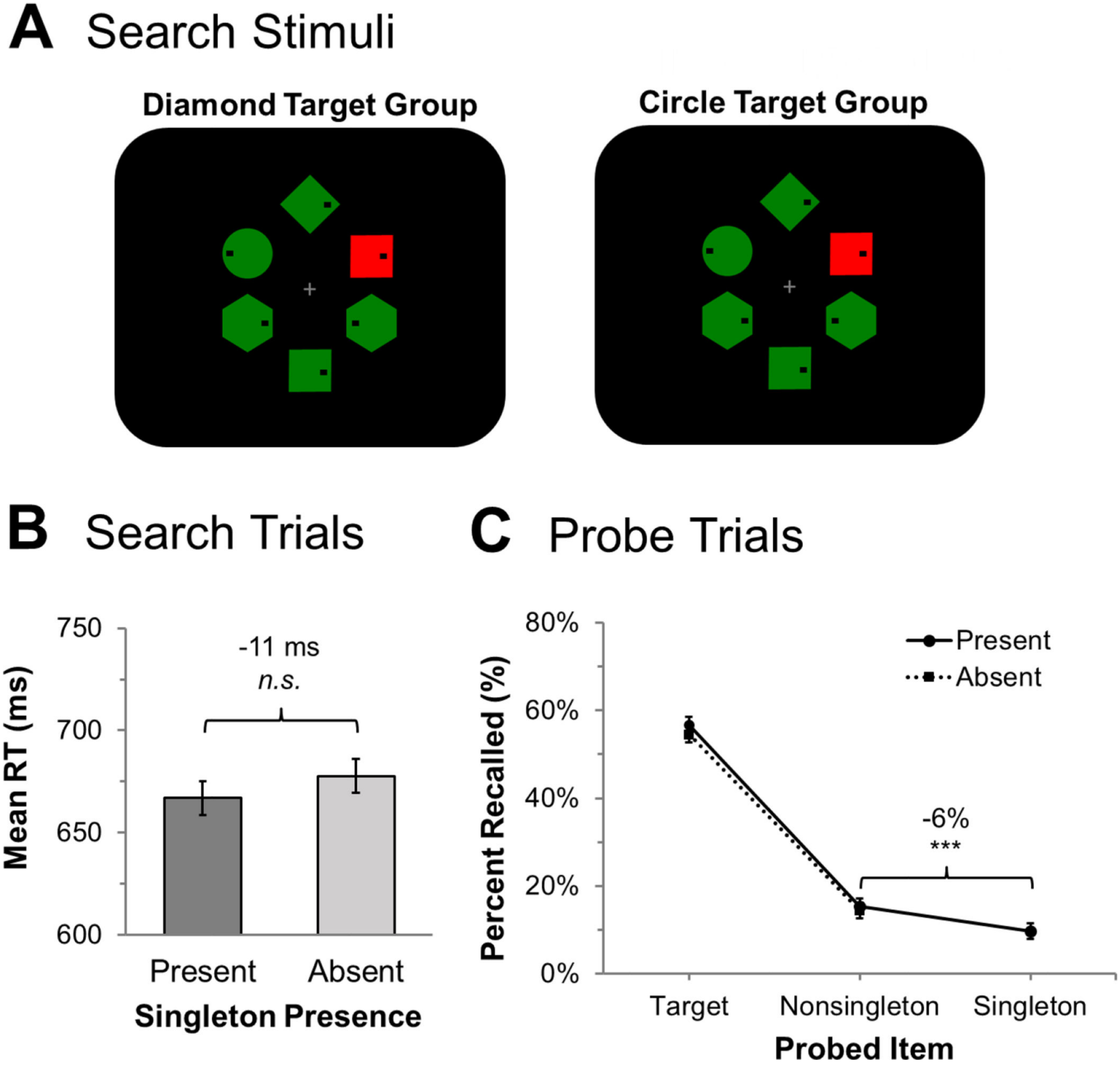

Figure 3.

Stimuli and results for Experiment 2. (A) Because the target was the same shape on every trial and the distractors were heterogeneous, this task discourages participants from searching for singletons. (B) Mean RT on singleton-present and singleton-absent trials in the search task. (C) Recall accuracy at each type of location on probe trials.

*** $p < .001$.

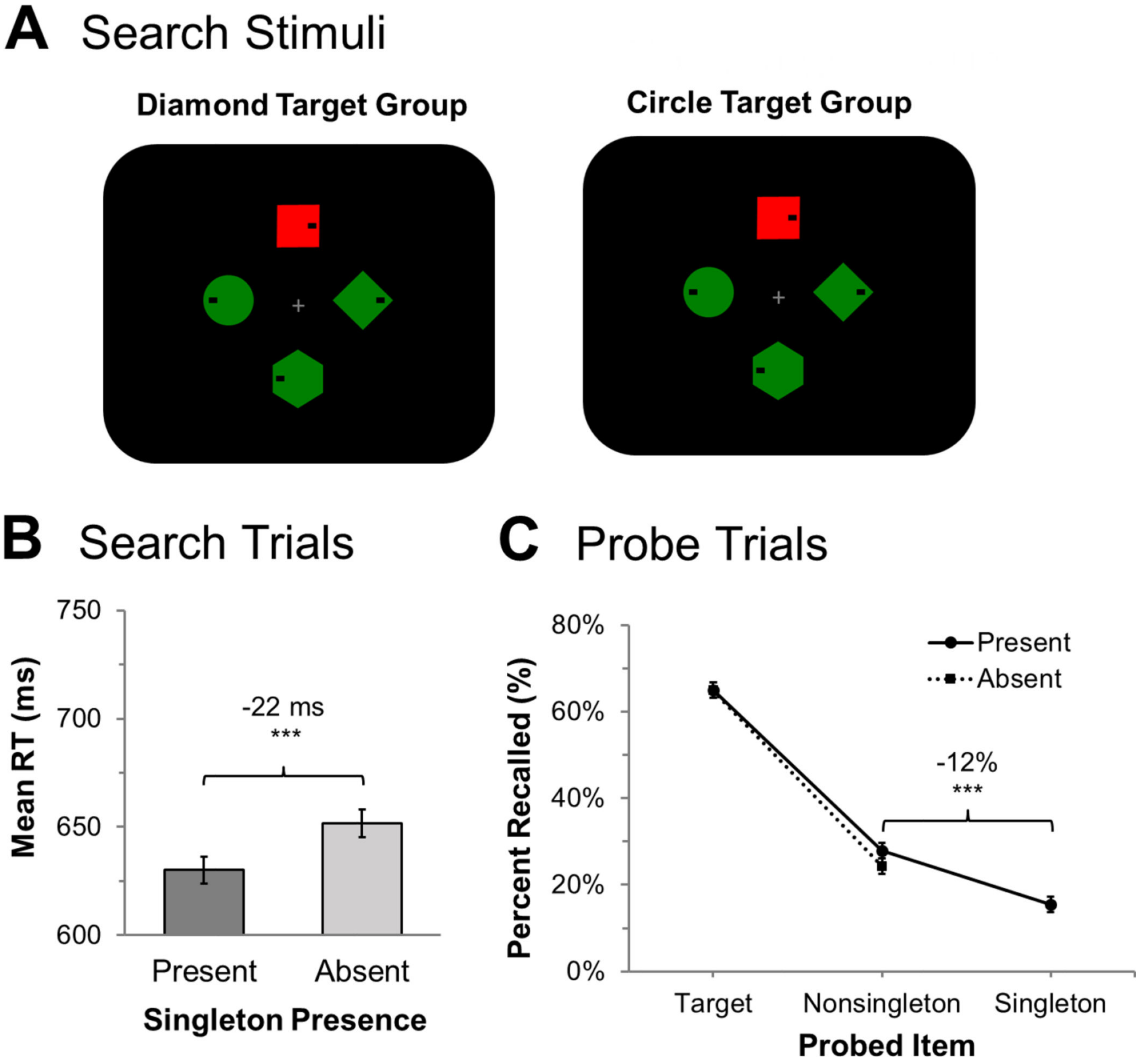

Figure 4.

Stimuli and results for Experiment 3. (A) Because the set size was low, overall performance should be increased, allowing an even larger singleton-suppression effect. (B) Mean RTs by singleton presence. (C) Probe recall accuracy by probed item and singleton presence.

*** $p < .001$

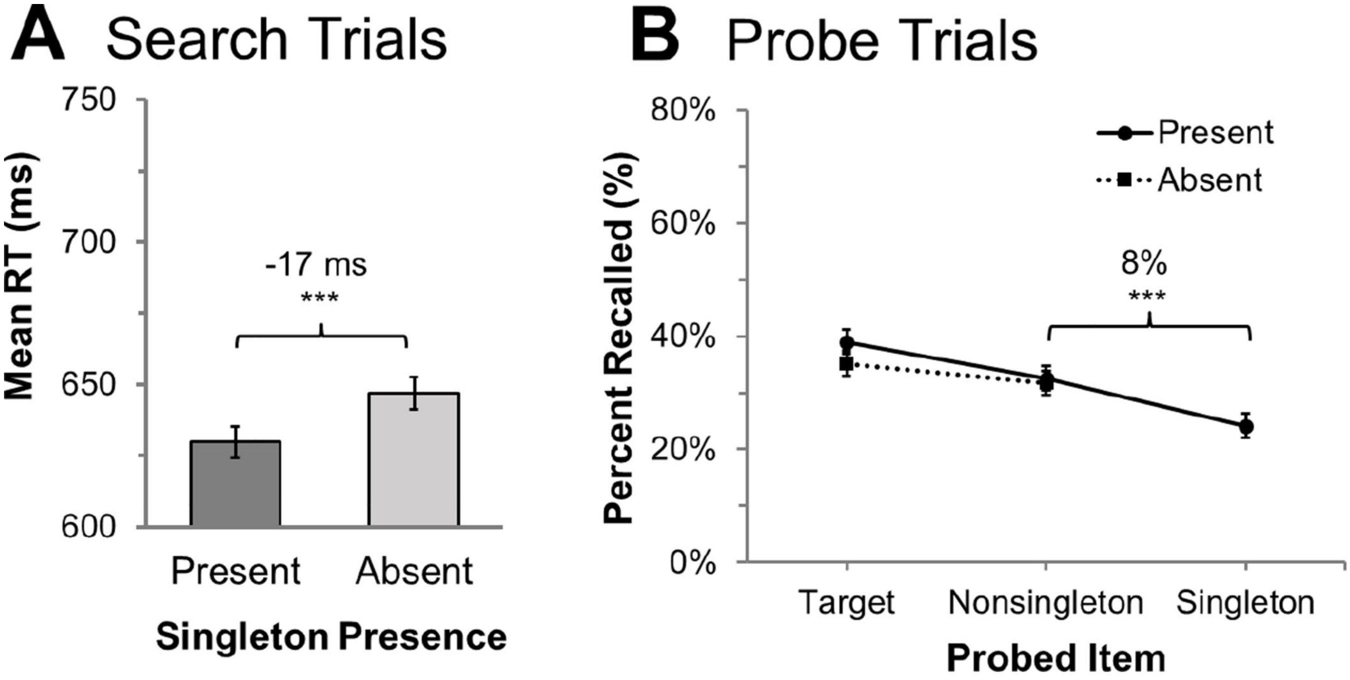

Figure 5.

Results for Experiment 4. (A) Mean RTs by singleton presence. (B) Probe recall accuracy by probed item and singleton presence.

*** p < .001.