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

Nicholas Gaspelin[1], Carly J. Leonard[1], and Steven J. Luck[1,2]
[1]Center for Mind and Brain and [2]Department of Psychology, University of California, Davis

Abstract
Researchers have long debated whether attentional capture is purely stimulus driven or purely goal driven. In the current study, we tested 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 an irrelevant color singleton. 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 the irrelevant singleton, accuracy was greater for the letter inside the singleton distractor than for letters inside nonsingleton distractors. 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 letters inside nonsingleton distractors, an indication of active suppression of processing at the singleton location.

Objects that differ from an otherwise-homogeneous background (*feature singletons*, such as the red circle in the search arrays in Fig. 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 on whether singletons automatically "capture" visual attention.

According to *stimulus-driven* theories, singletons automatically capture visual attention, regardless of the observer's 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 study (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, and this led to slowed response times (RTs). This *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). These theories explain singleton-presence costs in the additional-singleton paradigm by noting that the target is a shape singleton, which might lead participants to intentionally search for any singleton (*singleton-detection mode*). Bacon and Egeth (1994) forced participants to search for a specific shape (*feature-search mode*) by intermixing trials on which the target was no longer a shape singleton (e.g., a circle among diamond, square, and triangle distractors) with trials on which the target was a shape singleton (e.g., a circle among diamond distractors). Singleton-presence costs were eliminated, even when the target was a singleton. These results suggest that top-down goals can override bottom-up salience. However, proponents of stimulus-driven capture have

Corresponding Author:
Nicholas Gaspelin, University of California, Davis, Center for Mind and Brain, 267 Cousteau Place, Davis, CA 95618
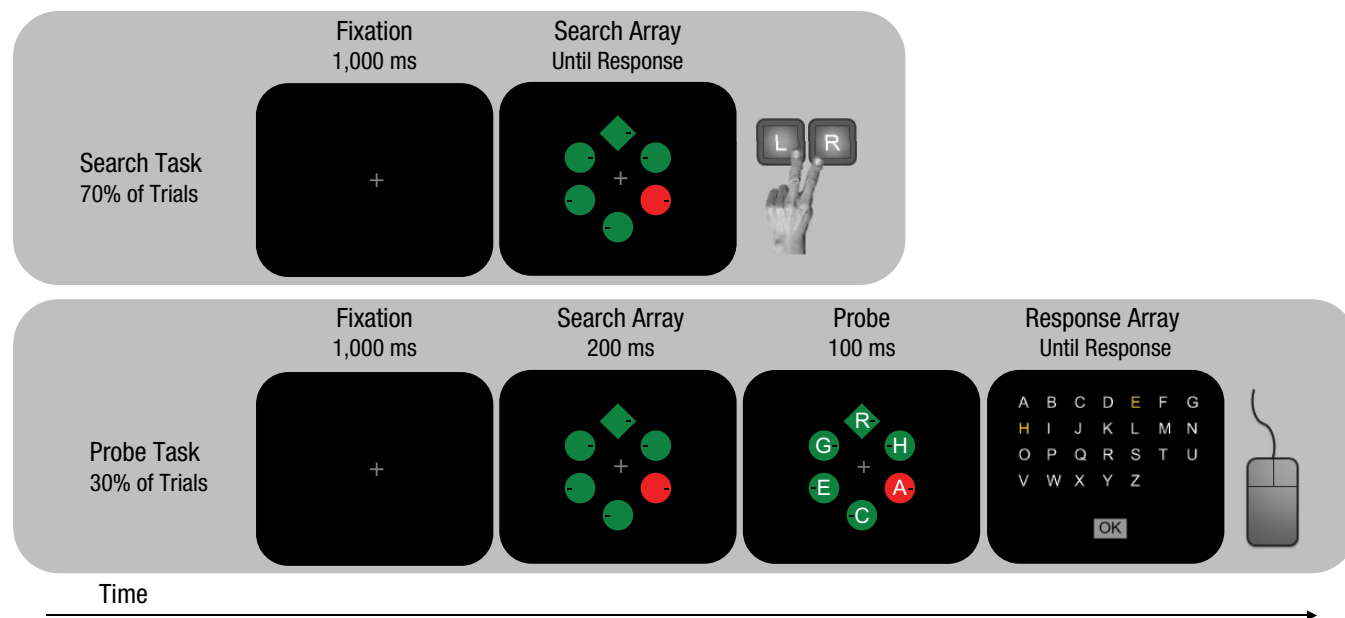E-mail: ngaspelin@ucdavis.edu

Fig. 1. The capture-probe paradigm. On search trials, participants search for a target shape in a display of colored shapes and respond (via button press) by indicating whether a small black dot is on the left or right side of the target. On infrequent probe trials, an array of probe letters is superimposed on the search array for a brief period. Participants then report (via mouse click) as many letters as they can recall. Note that the illustration of the probe task describes the sequence used in Experiments 1 through 3. Experiment 4 used an alternative timing that eliminated the delay between the search array and probe letters.

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).

Researchers have also obtained conflicting results in several other paradigms, with the two sides of the theoretical debate 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, 2015), or understand the development of attentional control (Gaspelin, Margett-Jordan, & Ruthruff, 2015).

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, which is consistent with stimulus-driven theories. However, this salience signal can subsequently be suppressed, resulting in no attentional capture, which is 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, Gee, Gottlieb, Bisley, and Goldberg (2006) found that highly trained monkeys made fewer first saccades to singleton distractors than to nonsingleton distractors. This oculomotor suppression was accompanied by decreased activity in areas of lateral intraparietal cortex representing the singleton location. Also, Gaspar and McDonald (2014) found that P_D effects were larger on trials with fast target-detection times than on trials with slow target-detection times, a result suggesting that suppression of singletons helped participants locate targets. Finally, salient distractors impair search performance when they appear near the target, which indicates that inhibition of a 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 processing 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 (inspired by Kim & Cave, 1995) involves randomly intermixing frequent search trials with infrequent probe trials (see Fig. 1). On search trials, participants search for a target shape while ignoring an irrelevant color singleton. Their task is to report whether a small black dot is on the left or right side of the target shape. On probe trials, the search array is initially displayed just as on search trials, but then a letter is superimposed on each search item. After a short delay, the entire array disappears, and participants attempt to recall as many letters as possible. This paradigm 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 the nonsingleton-distractor locations. Alternatively, if the color singleton is suppressed, participants should be less likely to recall probes at the singleton-distractor location than probes at the 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 targets were shape singletons, which encourage participants to search using singleton-detection mode and are known to produce large singleton-presence costs. If the capture-probe paradigm is a valid measure of resource allocation, probe recall under these conditions should be enhanced at the singleton-distractor location compared with the nonsingleton-distractor locations.

Method

Participants. Twenty-four undergraduate students participated for course credit (16 females, 8 males; 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 studies (Bacon & Egeth, 1994; Theeuwes, 1992) and probe studies (Kim & Cave, 1995) suggested that this sample size would yield ample power.

Stimuli. Stimuli were presented, using PsychToolbox (Brainard, 1997), on an LCD with a black background (2.2 cd/m²), at a distance of 70 cm (see Fig. 2a). Search displays contained six shapes, five diamonds (1.6° × 1.6°)

and one circle (1.4° in diameter) or one diamond and five circles, drawn in green (30.5 cd/m², x = .30, y = .61) or red (30.4 cd/m², 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 the right edge of the shape. On probe trials, an uppercase letter (0.8° tall) was presented in white (132.0 cd/m²) Arial typeface at the center of each shape. A subsequent response screen displayed all letters from the English alphabet in white. A gray fixation cross (30.3 cd/m², 0.4° × 0.4°) was continuously visible except during the response screen of probe trials and during intertrial intervals.

Design and procedure. The search target was defined as the unique shape, which was unpredictably a circle among diamonds or a diamond among circles (see Fig. 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 the key labeled "L" or "R" on the keyboard, using the left hand). The location of the target and the side of the target on which the dot appeared varied randomly. All items were the same color on 50% of the trials (red for half of the participants and green for the others); on the remaining trials, the target and four distractors were the same color, and the remaining distractor was the other color. The location of this color-singleton distractor was random except that it was never at the target location. For this reason, participants were encouraged to ignore the color singleton. Search trials began with the presentation of a blank screen for 500 ms, followed by a fixation screen for 1,000 ms. Next, the search array appeared, remaining on-screen until the participant responded. If the participant took too long to respond (more than 2,000 ms), a time-out display ("Too Slow") appeared for 500 ms. If the response was incorrect, a 200-Hz tone sounded for 500 ms.

On probe trials (30% of trials), the search array appeared for 200 ms. Next, a letter-probe array, consisting of a letter superimposed on each shape, appeared for 100 ms. The letters on a given trial were selected at random, without replacement, from the 26 letters of the English alphabet. Next, the response screen appeared. Instead of making a dot-location response, participants used the computer mouse to click on all letters on the response screen that they remembered seeing in the probe display (with no time pressure). Participants clicked on zero to six letters; each letter turned yellow when selected. When participants were finished, they clicked on a gray "OK" box (4.5° × 2.5°). Note that the response screen appeared immediately after the probe display, serving as a mask.

Pilot testing indicated that, to achieve good performance, participants needed substantial practice with the search task alone before the probe trials were
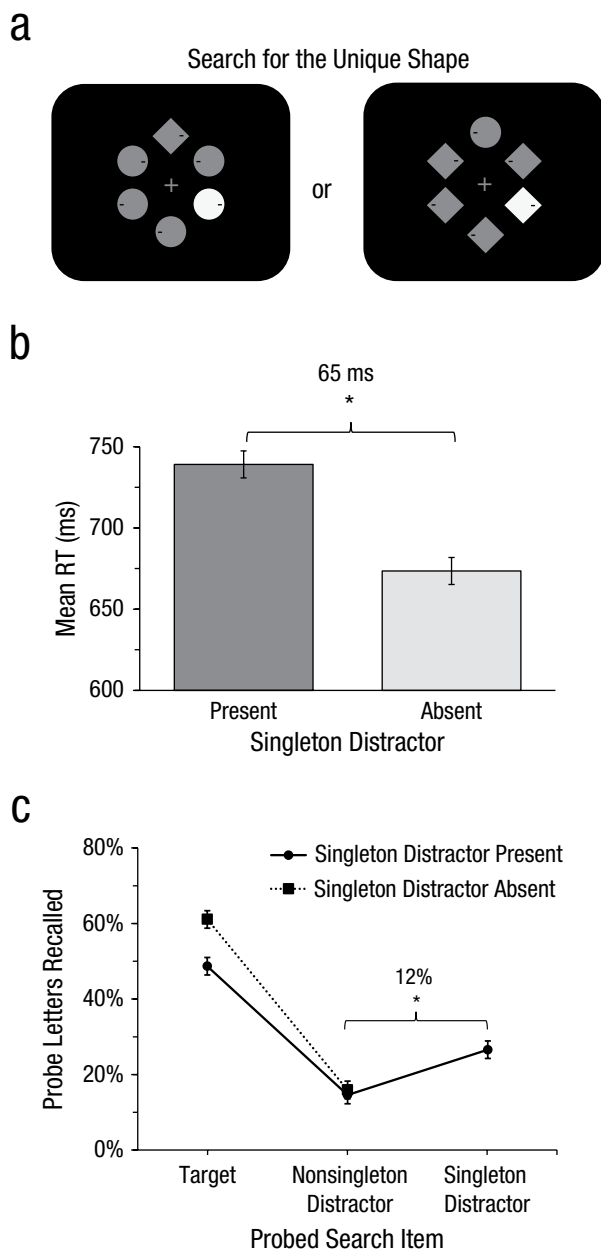
a

Search for the Unique Shape

or

b

c

Fig. 2. Stimuli and results for Experiment 1. Each search array (a) consisted of a diamond target among circle distractors or a circle target among diamond distractors. Circle-target and diamond-target trials were randomly intermixed to require singleton-detection mode. Note that in the experiment, the shapes were green and red, distinguished here by gray versus white. The graphs show (b) mean response time (RT) in the search task and (c) the percentage of probe letters reported as a function of search-item type. In both graphs, results are presented separately for trials on which the color-singleton distractor was present and trials on which it was absent. Error bars represent within-subjects 95% confidence intervals (Loftus & Masson, 1994). Asterisks indicate significant differences (*$p < .001$).

added. Consequently, participants in the main experiment first practiced only the search task for two blocks of 48 trials. Then, they practiced the combined capture-probe paradigm for two blocks of 48 trials. The main

experiment consisted of 10 blocks of 48 trials, for a total of 144 probe trials, 72 with and 72 without an irrelevant singleton. Participants received block-by-block feedback on their mean 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 1,500 ms (1.1% of trials) were excluded from all search-task analyses. Additionally, trials with an incorrect response (4.5%) were excluded from search-task RT analyses. In what follows, *singleton-present* and *singleton-absent* refer to the presence or absence of the irrelevant color singleton. 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); the 65-ms singleton-presence cost was significant, $t(23) = 11.49$, $p < .001$. 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 with the 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, and 82.2% of these letters 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 these means are far lower than the capacity of working memory, and these low numbers presumably reflect the fact that the response screen was presented immediately after the probe letters and served as a potent mask (see Fig. 1).

As shown in Figure 2c and Table 1, probe letters at the singleton-distractor location were nearly twice as likely to be recalled as probe letters at the nonsingleton-distractor locations. A planned *t* test confirmed that probe recall accuracy was higher at the singleton-distractor location (26.6%) than at the 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 color singleton affected the report of probe letters at the target and nonsingleton-distractor locations. If

Table 1. Percentage of Probes Recalled in Experiments 1 Through 4

Experiment and trial type	Probe location		
	Target	Nonsingleton distractor	Singleton distractor
Experiment 1			
Singleton present	48.7%	14.7%	26.6%
Singleton absent	60.9%	15.8%	—
Experiment 2			
Singleton present	56.7%	15.4%	9.6%
Singleton absent	54.5%	14.4%	—
Experiment 3			
Singleton present	65.0%	27.9%	15.5%
Singleton absent	64.9%	24.2%	—
Experiment 4			
Singleton present	39.0%	32.6%	24.2%
Singleton absent	35.2%	31.8%	—

resources are attracted by the color singleton, then fewer resources should be available for the other locations, and performance at these locations should therefore be reduced on singleton-present trials compared with 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. This result provides 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 singleton distractor, 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 the color singleton's presence on performance at the target and nonsingleton-distractor locations were analyzed in a two-way analysis of variance (ANOVA) with factors of singleton presence (present vs. absent) and probe type (target vs. nonsingleton distractor); to obtain a balanced factorial design, we excluded data from the singleton-distractor location. This analysis indicated that recall accuracy was significantly higher for probes at the target location (54.8%) than for probes at the nonsingleton-distractor locations (15.3%), $F(1, 23) = 85.440$, $p < .001$, $\eta_p^2 = .788$. This 39.5% difference reflects enhanced attentional allocation to the target. The analysis 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, a significant Singleton Presence × Probe Type interaction, $F(1, 23) = 24.325$, $p < .001$, $\eta_p^2 = .514$, confirmed that the presence of the color singleton affected performance more at the target location than at the nonsingleton-distractor locations. Follow-up t tests indicated that the difference

between singleton-present and singleton-absent trials was significant for probes at the target location (12.2%), $t(23) = 5.75$, $p < .001$, but did not quite reach significance for probes 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.

The results of Experiment 1 demonstrate the validity of the capture-probe paradigm. In a task that should produce singleton capture according to all theories, we observed enhanced processing at the singleton-distractor location compared with the nonsingleton-distractor locations. We also observed that the presence of the irrelevant singleton led to impaired processing of probes at the target location, which is consistent with an allocation of resources to the color singleton. 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 altered the search arrays to encourage 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 tested three competing theoretical positions. Stimulus-driven theories propose that a singleton always captures attention, which means that performance should be enhanced for probes presented at the singleton-distractor location (as in Experiment 1). Goal-driven theories assume no special processing of a singleton, which means that recall for probes at the singleton-distractor and nonsingleton-distractor locations should be equivalent. The signal-suppression hypothesis proposes that irrelevant singletons are actively suppressed, so that recall for probes at the singleton-distractor location should be impaired relative to recall for probes at the nonsingleton-distractor locations.

Method

The methods were identical to those of Experiment 1 with the following changes. First, a new set of 24 students participated (18 females, 6 males; mean age = 20.0 years). Second, the search arrays were modified to encourage participants to look for a specific shape, rather than singletons (see Fig. 3a). Specifically, each search array 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
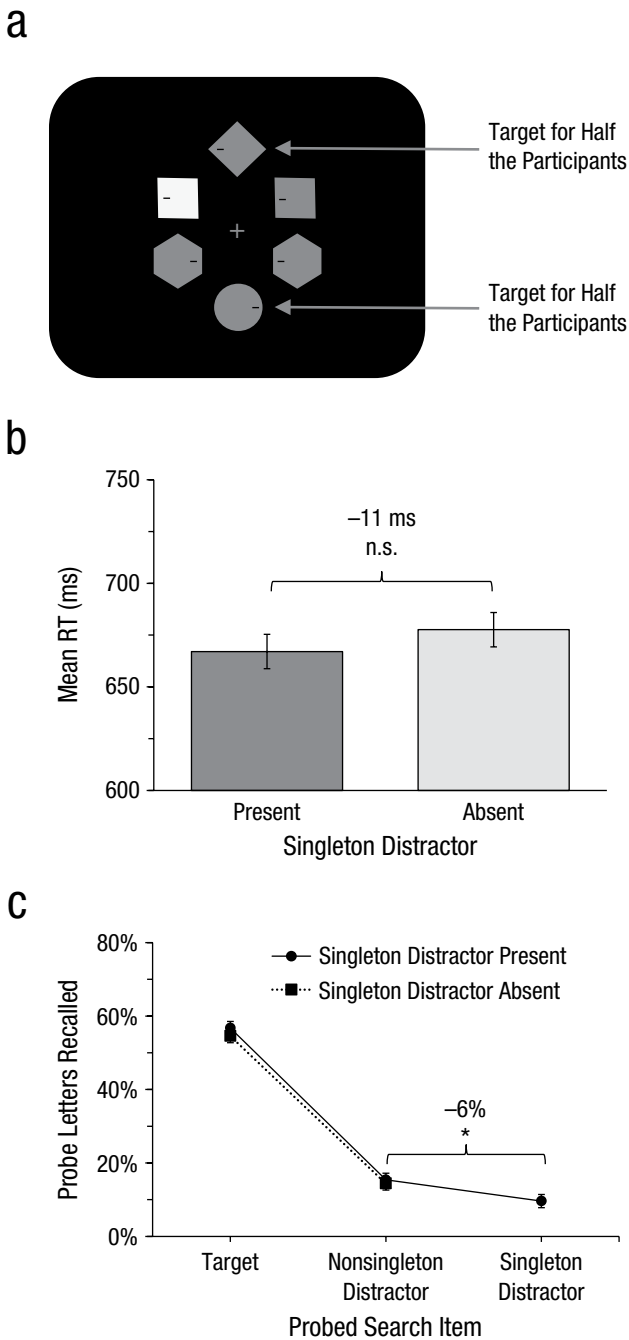
a

b

c

Fig. 3. Stimuli and results for Experiment 2. Each search array (a) consisted of a diamond, a circle, two squares, and two hexagons; the target was always the diamond for half of the participants and always the circle for the other half. Because the target was the same shape on every trial and the distractors were heterogeneous, this task discouraged participants from searching for singletons. Note that in the experiment, the shapes were green and red, distinguished here by gray versus white. The graphs show (b) mean response time (RT) in the search task and (c) the percentage of probe letters reported as a function of search-item type. In both graphs, results are presented separately for trials on which the singleton distractor was present and trials on which it was absent. Error bars represent within-subjects 95% confidence intervals (Loftus & Masson, 1994). Asterisks indicate a significant difference (*$p < .001$).

distractor shapes, this experiment promoted shape-based search and eliminated any incentives to intentionally search for singletons (Bacon & Egeth, 1994).

Results

Search-task analysis. Trials with an RT less than 200 ms or greater than 1,500 ms (0.1% of trials) were excluded from all search-task analyses. Additionally, trials with an incorrect response (2.8%) were excluded from search-task RT analyses. Whereas the presence of a color singleton slowed 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 (Fig. 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, $t(23) = 1.95$, $p = .063$. These results are the opposite of what one would expect if the singleton distractor captured attention. In addition, error rates were consistent with the RT trend; participants committed marginally more errors on singleton-absent trials (3.0%) than on singleton-present trials (2.4%), $t(23) = 1.81$, $p = .08$.

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

As predicted by the signal-suppression hypothesis, probe letters at the singleton-distractor location were significantly less likely to be reported (9.6%) than were probe letters at 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-distractor location compared with the nonsingleton-distractor locations (see Fig. 3c and Table 1).

We also analyzed the effect of the color singleton's presence on probe detection at the target and nonsingleton-distractor locations (see Fig. 3c) in a two-way ANOVA (excluding the singleton-distractor location, as in Experiment 1). Whereas probe detection was impaired on singleton-present trials compared with 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 (difference of 1.6%), $F(1, 23) = 6.498$, $p < .05$, $\eta_p^2 = .220$. This is exactly what would be expected if processing at the singleton-distractor 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 (difference of 40.7%), $F(1, 23) = 90.739$, $p < .001$, $\eta_p^2 = .798$. This enhancement of performance at the target location presumably reflects the allocation of attention to the target shape. The interaction of singleton presence and probe 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 location of a singleton distractor relative to the locations of nonsingleton-distractors. 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-distractor locations. Our goal in Experiment 3 was to investigate whether the singleton-suppression effect can be increased by bringing overall accuracy away from floor, which we achieved by decreasing the set size from 6 to 4.

Method

The methods were identical to those of Experiment 2 except for the following changes. First, a new set of 24 students participated (20 females, 4 males; mean age = 19.3 years). Second, the search arrays were reduced to a set size of 4 (see Fig. 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. Trials with an RT less than 200 ms or greater than 1,500 ms (0.8% of trials) were excluded from all search-task analyses. Additionally, trials with an incorrect response (3.1%) were excluded from search-task RT analyses. Search RTs were significantly faster on singleton-present trials (630 ms) than on singleton-absent trials (652 ms; see Fig. 4b), $t(23) = 5.01$, $p < .001$. This 22-ms benefit of singleton presence is in the direction opposite what one would expect if the singleton captured attention. However, it is what would be expected if processing at the singleton-distractor location was suppressed, freeing resources for the other objects. Participants did not commit significantly more errors on singleton-present trials (3.1%) than on singleton-absent trials (2.7%), $t(23) < 1$, $p > .10$.
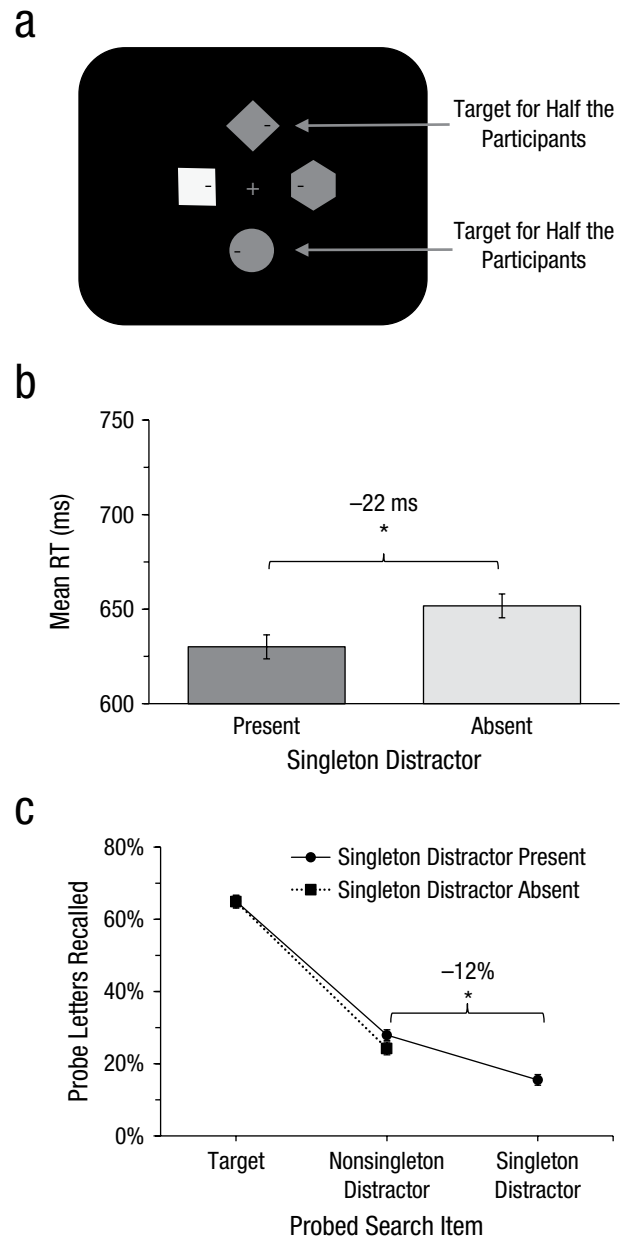

Fig. 4. Stimuli and results for Experiment 3. Each search array (a) consisted of a diamond, a circle, a square, and a hexagon; the target was always the diamond for half of the participants and always the circle for the other half. Note that in the experiment, the shapes were green and red, distinguished here by gray versus white. The graphs show (b) mean response time (RT) in the search task and (c) the percentage of probe letters reported as a function of search-item type. In both graphs, results are presented separately for trials on which the singleton distractor was present and trials on which it was absent. Error bars represent within-subjects 95% confidence intervals (Loftus & Masson, 1994). Asterisks indicate a significant difference (*$p < .001$).

Probe-task analysis. Participants reported an average of 1.7 letters per probe trials, and 93.5% of these letters 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 predicted lower accuracy for probes at the singleton-distractor location than for probes at the nonsingleton-distractor locations. Indeed, this is what we found (singleton-distractor location: 15.5%; nonsingleton-distractor locations: 27.9%; see Fig. 4c and Table 1), $t(23) = 5.61$, $p < .001$. 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-distractor 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, Experiment 3 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.

We again analyzed the color singleton's effect on probe accuracy at the target and nonsingleton-distractor locations (excluding the singleton-distractor location itself; see Fig. 4c). 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, $F(1, 23) = 4.52$, $p < .05$, $\eta_p^2 = .164$. This benefit was observed mainly at the nonsingleton-distractor locations, and there was a significant interaction between singleton presence and probe type, $F(1, 23) = 6.17$, $p < .05$, $\eta_p^2 = .212$. These results are also consistent with a suppression of processing at the singleton-distractor location.

Experiment 4

Experiment 4 tested an alternative 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, according to this account, 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. In Experiment 4, we tested this alternative

explanation by eliminating the probe delay. Thus, if attention initially moved to the singleton distractor, there was no time for rapid disengagement from the singleton. Under these conditions, the rapid-disengagement account predicts enhanced, rather than suppressed, processing at the singleton-distractor location. The signal-suppression hypothesis, however, again predicts that the singleton distractor is never attended, and therefore a singleton-suppression effect should be observed.

Method

The methods were identical to those of Experiment 3, with the following exceptions. A new set of 24 students participated (21 females, 3 males; 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 and 100 ms, this duration should have been too quick for participants to disengage attention from the singleton distractor (e.g., Horowitz, Wolfe, Alvarez, Cohen, & Kuzmova, 2009). Furthermore, we minimized any movement of spatial attention within iconic memory by immediately replacing the probe letters with masks ("#") embedded inside the shapes for 500 ms (Loftus, Johnson, & Shimamura, 1985) before the response display was presented.

Results

Search-task analysis. Trials with an RT less than 200 ms or greater than 1,500 ms (0.2% of trials) were removed from all search-task analyses. Additionally, trials with an incorrect response (2.1%) were excluded from the search-task RT analyses. The results for RT in the search task are summarized in Figure 5a. As in Experiment 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 benefit* is consistent with active suppression of the singleton distractor. Error rates were similar for 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 per trial, and 77.5% of these 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 5b (and Table 1), probe recall accuracy was significantly lower at the singleton-distractor location (24.2%) than at the nonsingleton-distractor locations (32.6%), $t(23) = 4.6$, $p < .001$. This approximately 8% suppression effect replicates the findings of Experiments 2
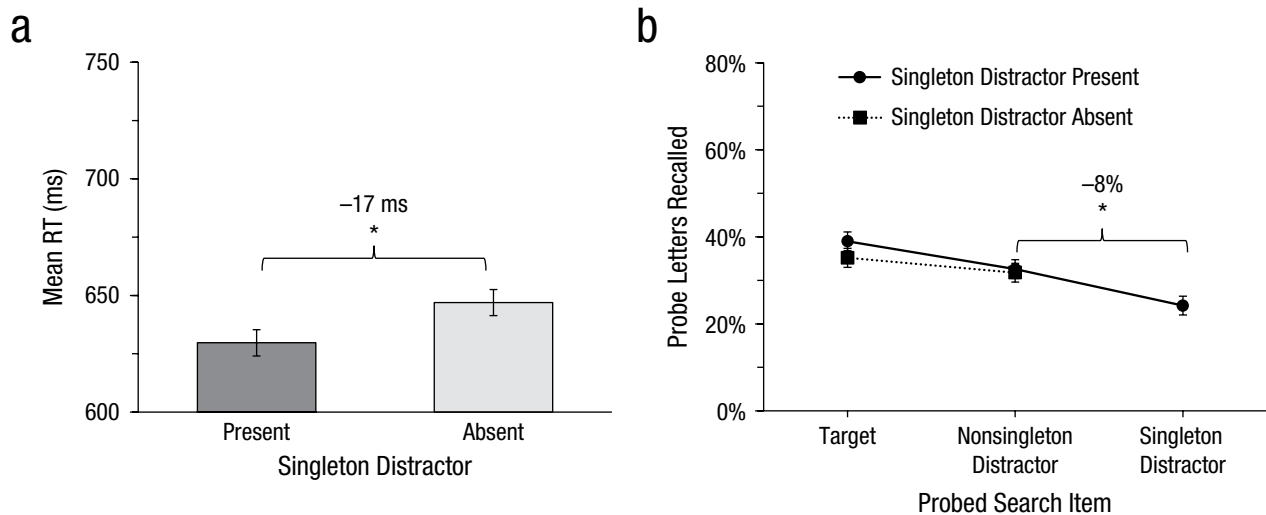
Fig. 5. Results for Experiment 4. The graphs show (a) mean response time (RT) in the search task and (b) the percentage of probe letters reported as a function of search-item type. In both graphs, results are presented separately for trials on which the singleton distractor was present and trials on which it was absent. Error bars represent within-subjects 95% confidence intervals (Loftus & Masson, 1994). Asterisks indicate a significant difference (*$p < .001$).

and 3 and is inconsistent with the rapid-disengagement account, but is consistent with the signal-suppression hypothesis.

We also analyzed the color singleton's effect on accuracy for probes at the target and nonsingleton-distractor locations (see Fig. 5b). Once again, recall accuracy was significantly higher for probes at the target location compared with those at the nonsingleton-distractor locations, $F(1, 23) = 12.605$, $p < .01$, $\eta_p^2 = .354$. Recall accuracy was also higher on singleton-present trials than on singleton-absent trials, $F(1, 23) = 13.685$, $p < .01$, $\eta_p^2 = .373$, which is consistent with a freeing of resources from the singleton-distractor location. The interaction between singleton presence and probe type was nonsignificant, $F(1, 23) = 2.037$, $p > .10$. These results provide additional evidence that processing at the singleton-distractor 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 presenting a powerful mask after the letters) 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 have been reduced. Indeed, probe accuracy at the target location was 27.9 percentage points lower in Experiment 4 (short search-array duration) than in Experiment 3 (long search-array duration), $t(46) = 7.40$, $p < .001$. Probe accuracy at the singleton-distractor location, however, was increased by 8.7 percentage points in Experiment 4 relative to Experiment 3, $t(46) = 2.337$,

$p < .05$, and there was a marginally significant increase of 6.2 percentage points in accuracy at the nonsingleton-distractor locations, $t(46) = 2.91$, $p = .06$. The target-enhancement effect (probe accuracy for targets minus probe accuracy for nonsingleton distractors) was approximately one sixth as large in Experiment 4 ($M = 4.9\%$, 95% confidence interval = [2.2, 7.7]) as in Experiment 3 ($M = 38.9\%$, 95% confidence interval = [33.3, 44.5]). In contrast, the singleton-suppression effect 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 color singleton was rapidly suppressed, whereas the allocation of attention to the target increased 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 attentional capture (Folk & Remington, 2010; Folk et al., 1992; Theeuwes, 1992, 2010). These behavioral findings also complement ERP studies showing a P_D component elicited by 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 the singleton-distractor location than at the nonsingleton-distractor locations, which is consistent with attentional capture by the irrelevant singleton.

Experiment 2 demonstrated that processing at the singleton-distractor 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 bias toward the target, with no special processing of irrelevant singletons. However, the signal-suppression hypothesis predicts that the irrelevant 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 the singleton-distractor location than at the nonsingleton-distractor locations.

In Experiment 3, we reduced the set size to bring overall probe accuracy away from the floor, which caused even larger suppression effects. Experiment 4 demonstrated that the suppression of processing at the singleton-distractor location 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 location, the nonsingleton-distractor locations, or both was increased on singleton-present trials compared with singleton-absent trials, which suggests that attentional resources were freed from the singleton and devoted to the other items.

A dot-probe paradigm has produced RT results complementary to the suppression effects observed in the present study (e.g., Kim & Cave, 1999; Lamy, Tsal, & Egeth, 2003). For example, Lamy et al. (Experiment 2) had participants search displays of shapes for a specific target (e.g., a green circle). After the shapes disappeared, a small black dot appeared at a random search location, and participants made a speeded detection response. RTs were slower for probes at singleton-distractor locations than for probes at nonsingleton-distractor locations, which suggests that color singletons were suppressed. However, participants were required to make the probe response before the search response on every trial, which may have altered the strategy they used to perform the search task. Moreover, the search task was unspeeded, so it was impossible to measure singleton-presence costs. In the present study, participants made a speeded search response on the majority of trials, which obviates these problems.

An alternative explanation of the suppression effects observed in the present 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 processing at the nonsingleton-distractor locations rather than suppression of processing at the singleton-distractor locations. 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 singleton-suppression effects (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 our data by agreeing that singletons automatically generate a priority signal. Similarly, stimulus-driven accounts could accommodate our results by agreeing that the priority signal generated by a singleton can be suppressed before an attentional shift occurs. In other words, these traditionally opposed theoretical accounts can be merged in the form of the signal-suppression hypothesis.

Author Contributions

N. Gaspelin and S. J. Luck developed the study concept and design. Stimulus-presentation programs and data-analysis programs were developed by N. Gaspelin and C. J. Leonard. All authors drafted the manuscript and approved the final version for submission.

Declaration of Conflicting Interests

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