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Global enhancement of target color - not proactive suppression - explains attentional deployment during visual search

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Global enhancement of target color - not proactive suppression - explains attentional deployment during visual search

Running Head: Feature Enhancement in Visual Search

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Abstract

The current study touches on a central debate in the area of attention: how the human brain handles distraction by salient stimuli. The idea of proactive suppression proposes a new fundamental perceptual mechanism to resolve this question, whereby attentional capture by a task-irrelevant salient distractor can be preempted through top-down inhibitory mechanisms (Gaspelin et al., 2015). In this study, we replicate empirical effects underlying this claim, but show that they are better explained by an alternative mechanism, global target feature enhancement. Identical to original studies using a capture-probe dual task design, observers recalled fewer letters superimposed upon color singleton distractors, relative to other irrelevant search items (fillers). However, given that fillers (but not singleton distractors) always matched the color of the target, this effect could have been due to global featural attention to the target color rather than suppression of the singleton distractor. After manipulating the color of fillers such that they no longer matched the target color, probe recall associated with these was reduced, causing the relative "suppression" of singleton distractors to be abolished. We then manipulated the color similarity of targets and fillers, and found that filler probe recall was graded as a function of this color similarity, even within a single search context. This strongly suggests that increased attention to fillers due to global target color enhancement underlies the difference in attention among distractor items, not proactive distractor suppression. In contrast with feature enhancement and reactive suppression, the proposed proactive suppression mechanism still lacks convincing behavioral evidence.

Keywords: visual search, global feature enhancement, attentional suppression, distractor suppression, proactive suppression

Word Count: 12,200

1. Introduction

For several decades, the field of attention has been dominated by the attentional capture debate. This centers around a core perceptual function: how does the human brain effectively deal with particularly strong, but irrelevant, perceptual signals? Early views of goal-driven attentional selection posited that due to top-down modulation, only target features benefit from preferential processing, while stimuli with irrelevant features would not capture attention (e.g., Folk & Remington, 1998; Lamy et al., 2004). Researchers have increasingly focused on situations where salient percepts sometimes fail to automatically capture attention when expected to do so, leading to the development of theories proposing that observers can effectively suppress unwanted attentional capture.

Theories of *distractor suppression* presuppose that attentional capture can be counteracted, though they differ in when and how distractor handling occurs during the perceptual process (Geng, 2014). Most views suggest that following covert attentional capture, the brain quickly disengages and moves on from irrelevant stimuli; i.e., they are *reactive* (e.g., Theeuwes, 2010; Moher & Egeth, 2012; Won et al., 2019). But a "strong" form of this theory - *proactive* distractor suppression - hypothesizes a new fundamental mechanism of perception, whereby salient signals are inhibited before they can capture attention[1].

A recent theory of proactive suppression, the *signal suppression hypothesis* (SSH), holds that following sufficient exposure to a salient distractor, the visual system can learn to preemptively

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[1] The proposed proactive suppression of *features* should not be confused with preattentive or proactive suppression of visual field *locations*. The latter involves retinal locations that are associated with distractors through statistical learning, and suppressed in a manner independent of visual feature processing (Leber et al., 2016; B. Wang & Theeuwes, 2018; Stilwell et al., 2019).

inhibit it through top-down mechanisms (Gaspelin et al., 2015; Sawaki & Luck, 2010). The primary behavioral evidence motivating SSH comes from the capture-probe visual search task, in which on probe task trials, probes (e.g., letters) are superimposed upon the search items and observers report any remembered letters. Gaspelin and colleagues (Gaspelin et al., 2015; Gaspelin & Luck, 2018b, 2019) found reduced recall for letters in the singleton distractor relative to other irrelevant nonsingleton items (which we call *fillers*). This empirical pattern of a probe recall difference between singleton and fillers is now firmly established in the literature, although there is active debate regarding its causes (for a collection of views on this issue, see Luck et al., 2021; see also Lamy, 2021; B. Wang & Theeuwes, 2020). Based on this data pattern, SSH proponents argue that singleton distractors are attentionally suppressed, describing the results as *below baseline suppression*, *probe suppression,* or *distractor suppression*. Because these terms are explanatory labels that presuppose a suppressive mechanism, we refer to the empirical phenomenon as the *putative distractor suppression effect* (PDSE) hereafter. While the PDSE is the core behavioral effect underlying SSH, other results showing reduced singleton processing relative to fillers have been found in initial saccades (Gaspelin et al., 2017; Gaspelin & Luck, 2018a; Gaspelin et al., 2019) and brain imaging (Adam & Serences, 2021; Cosman et al., 2018). Proponents of SSH also argue that the P_D electrophysiological component indexes proactive featural suppression (Gaspelin & Luck, 2018b; Stilwell et al., 2022), although the functional significance of the P_D is strongly debated (e.g., Feldmann-Wüstefeld & Schubö, 2016; Kerzel & Burra, 2020; Liesefeld et al., 2021; Sawaki & Luck, 2013; van Moorselaar & Slagter, 2019), and a recent investigation of steady-state signals found no evidence of suppression in early visual areas (Forschack et al., 2022).

A key claim of the signal suppression hypothesis is that proactive suppression is based upon the *first-order features* of a singleton distractor (e.g., its particular color value), and that observers learn to suppress these (viewpoint of Gaspelin & Luck, in Luck et al., 2021; Stilwell & Gaspelin, 2021). For example, Gaspelin and colleagues show in several experiments that PDSE only occurs

when item colors are consistent across the session (Gaspelin et al., 2017; 2018a), or within blocks (Gaspelin et al., 2019; for findings of reduced capture by consistent singletons, see also Graves & Egeth, 2015; Kerzel & Barras, 2015; Vatterott & Vecera, 2012). Those experiments demonstrated that it was not sufficient that a distractor was merely salient within each stimulus array; in fact, oculomotor and attentional *capture* was observed when the particular color of the singleton distractor changed trial-to-trial. This was taken as evidence against second-order and global salience suppression models, which propose that feature-independent salience itself could be suppressed (e.g., Found & Müller, 1996; Liesefeld et al., 2021). More recent evidence has called into question the importance of relative singleton salience (as a function of search array size) in the capture-probe task (Lien et al., 2021; Stilwell & Gaspelin, 2021; B. Wang & Theeuwes, 2020). Nevertheless, SSH explicitly requires that that a singleton distractor's features must be consistent and repeating for PDSE to be observed (Gaspelin & Luck, 2018a); in this way, top-down feature knowledge can override bottom-up distractor salience.

We present and test an alternative explanation for PDSE, that is based on neural mechanisms of feature-based attention (Treue & Trujillo, 1999) and guided search (Wolfe, 1994). In the capture-probe design, the search target and fillers generally differ only in shape, but share a color (e.g., green). The well-known global facilitation effect of the target's constituent features (GTFE) will cause all green items in the visual field to be enhanced and boosted in the attentional priority map (Andersen et al., 2011; Forschack et al., 2017; Saenz et al., 2002; Treue & Trujillo, 1999). The green target and green target-like fillers will benefit from more post-attentional resources, meaning they are more likely to be encoded into working memory and are more likely to be attended first in serial search (Wolfe, 1994). Meanwhile, any singleton distractor that shares no features with the target will not be attentionally facilitated. Due to the relative differences in enhancement for target, target-like fillers, and singleton distractor, probe recall differences among these item types emerge: singleton distractors will not be enhanced or prioritized, but will nevertheless appear to be "below baseline" relative to enhanced fillers. In the

search task, differential enhancement also explains how the presence of a singleton improves performance: because fewer items match the target template (i.e., three vs four green items), they benefit more from limited attention, improving search task performance and target identification.

In previous capture-probe studies, nonsingleton fillers have been treated as a neutral baseline because they were assumed to be task-irrelevant and to lack attentional facilitation or suppression. A series of recent studies using a similar dual-task design developed by Chang and Egeth (2019, 2021; Hamblin-Frohman et al., 2022; Kawashima & Amano, 2022) has challenged this assumption. In these studies, separable effects of target enhancement and distractor suppression on probe performance were investigated by explicitly comparing probe item processing against nonsingleton probes appearing in "neutral" colors. The studies all showed large effects of facilitation by target features, and of suppression associated with singleton distractors, except for an online replication which did not find the suppression effect (Kawashima & Amano, 2022). A notable difference between these four studies and the classic capture-probe task is that the former used cued report of a single probe, rather than the free recall task of the original. Recently, Kerzel and Renaud (2022) compared the effects of these probe task types, finding that they likely tap different mechanisms of perceptual vs decisional suppression; thus, it is unclear how comparable the Chang and Egeth version of the capture-probe task is with the original, in terms of attentional suppression. Nevertheless, a consistent implication of these four studies is that feature enhancement affects processing of nontarget, nonsingleton items in visual search tasks.

When considered in combination with evidence that negative cues are much weaker than positive cues (Arita et al., 2012; Beck & Hollingworth, 2015; Becker et al., 2015), it is clear that the effects of target feature enhancement on other nontarget items should not be ignored. Although this concern has been acknowledged (Chang & Egeth, 2019; Gaspelin et al., 2015; Gaspelin & Luck,

2018a), the assumption that nonsingleton distractor performance reflects an appropriate baseline has not been adequately tested (but see Gaspelin & Luck, 2018a). We hypothesize that the probe recall difference between singleton and nonsingleton distractors – the putative distractor suppression effect - is not a consequence of reduced singleton distractor recall, but of the "baseline shift" of enhanced attention to fillers.

In the five experiments presented here, we used the capture-probe task to test this alternative explanation by manipulating the color of the nonsingleton distractors. Meanwhile, we kept the colors and shapes for target and singleton distractor constant throughout each experiment to enable exposure to and learning of the constituent features, a necessary requirement for PDSE (Gaspelin & Luck, 2018a). Although first-order features of the singleton distractor do not change, we found significant changes in probe recall as a function of filler color, eliminating and even reversing PDSE. The results strongly suggest that global target feature enhancement, not proactive suppression, explains differences among distractor types in the capture-probe task.
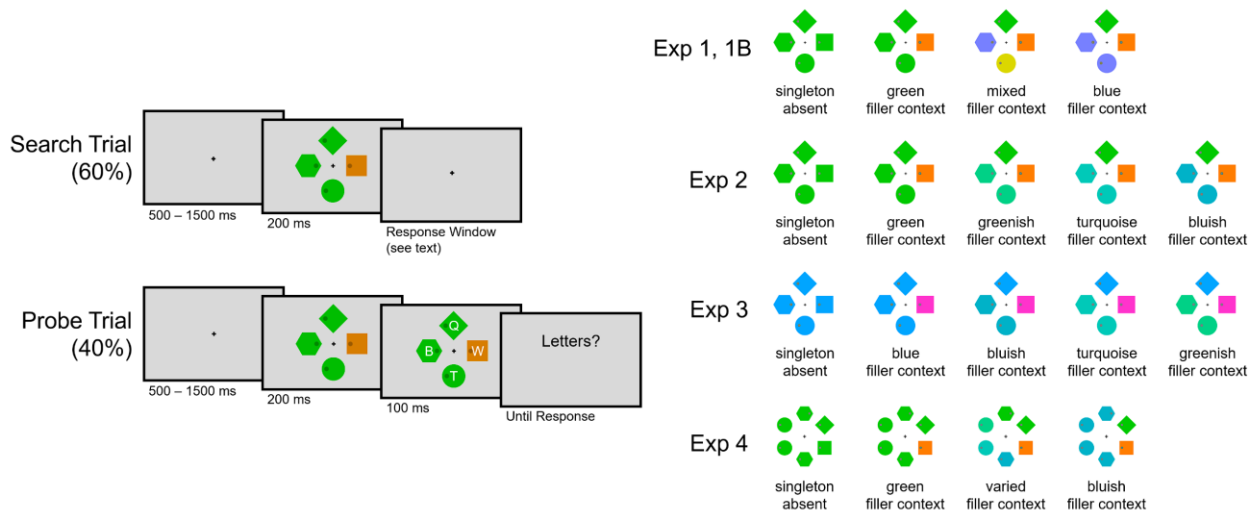
Fig. 1. Left: Trial procedure for Search and Probe tasks used in all experiments. On Search trials, participants indicated the location of the search dot within the target shape (the green diamond). On Probe trials, participants reported any letters they could recall from the array, regardless of which shape they appeared in. Probe trials for Experiment 1B differed, with the inclusion of a backward mask (see text). Right: Examples of possible array conditions for each experiment. Stimuli sizes and colors shown are illustrative only, and vary from actual experimental stimulation. For the color version of this figure, see the online article.

2. Experiments 1 & 1B

Experiment 1 was designed firstly to replicate the basic effect of the capture-probe paradigm, in which singleton distractors show reduced performance relative to fillers. Secondly, if the target color is globally enhanced and facilitates filler probe recall, then changing the color of fillers should reduce performance for those items. We added a condition in which fillers could appear in a third irrelevant color, and another condition in which each filler appeared in a different color, to eliminate the possibility that a salient item could capture attention.

Some parameters of the procedure of Experiment 1 differed from previous studies using the capture-probe task. Experiment 1B replicated Experiment 1 while rolling back some aspects of

the procedure to more closely match previous studies and to confirm that the effects were robust to methodological changes.

2.1. Method

2.1.1. Participants

We tested twenty-four participants in Experiment 1 (7 female, 17 male; mean age: 21.5 years; age range: 20 to 28), and 24 participants in Experiment 1B (18 female, 6 male; mean age: 25.8 years; age range: 20 to 37).

This sample size matches studies by Gaspelin and colleagues (Gaspelin et al., 2015; Gaspelin & Luck, 2018a) and provides a statistical power of 0.89 (at $\alpha < .001$) to detect an effect of the approximate size of probe recall differences in those studies (estimated effect size, $d_z \approx 1.0$). All participants had normal or corrected-to-normal vision. Before the study, participants were informed about the nature of the experiment and provided written informed consent. Participation was compensated by either class credit or financial reimbursement (10€ per hour). The study protocol was in accordance with the Declaration of Helsinki and approved by the local ethics committee.

2.1.2. Apparatus

Stimuli were presented on a 24-inch VIEWPixx /EEG LCD monitor (VPixx Technologies Inc., Canada), set to a resolution of 1920x1080 at 120 Hz. An X-Rite i1Display Pro Colorimeter (X-Rite GmbH, Germany) was used to calibrate monitor colors and measure veridical colors after data collection. Participants were seated comfortably in a dimly lit recording chamber at a viewing distance of 120 cm (maximum luminance: 100.1 cd/m²). Stimuli were created with custom scripts using PsychToolbox 3.0.17 (Brainard, 1997; Kleiner et al., 2007) implemented in Matlab R2020b (The MathWorks, Natick, MA) running in a Linux Ubuntu environment (Version 16.04, xenial). Responses were given on a standard QWERTZ computer keyboard.

Schematic representations of the trial procedure and stimuli are given in Figure 1. All trials began with the appearance of a central fixation cross measuring 0.2 by 0.2 degrees of visual angle with a bar width of 0.04°. After a random delay of 500-1500 ms, a search array appeared for 200 ms. Each array contained four items, located 2° above, below, left of, and right of central fixation. Each item was randomly assigned to one of the four positions on a trial-by-trial basis. Item shapes were identical to the study by Gaspelin and colleagues (2018a) and included a circle (1.35° diameter), a square (1.2° width and height), a diamond (1.2° by 1.2°) and a hexagon (0.74° edge length, 1.3° tall, 1.45° wide). Arrays appeared on a black background (0.6 cd/m^2). Participants were asked to fixate in the center of the screen on all trials, but fixation and eye movements were not otherwise controlled.

Before the main task, each participant perceptually matched four colors used in the experiment to a gray patch (23.1 cd/m^2), using a procedure based on heterochromatic flicker photometry (Wagner & Boynton, 1972). The mean and standard deviation of these colors across participants is given below (and in the following experiments) in CIELab 1976 $L*C*h°$ cylindrical space. The diamond was always green ($L*C*h°$: 56.6±1.5, 83.4±1.8, 141.6±0.1) and served as the "target" for all participants in the search task. The colors of other items were determined by the four array "contexts". In *singleton absent* trials, all items were the same green as the target. In the three remaining array contexts, the square item was orange ($L*C*h°$: 54.1±2.5, 73.5±3.0, 55.4±0.3), and hence, a color singleton[2]. The circle and hexagon nonsingleton fillers were colored either the

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[2] Throughout the manuscript, we refer to a particular distractor as the "singleton distractor", even in contexts where this item is not strictly a color singleton. Specifically, this special distractor is a fixed shape (square in Experiments 1-3, counterbalanced across participants in Experiments 1B and 4), and is potentially suppressible in contexts where it appears in a distinct color (orange in Experiments 1, 2, and

identical green as the target (*green filler context*), one blue and the other yellow (*mixed filler context*; yellow, *L*C*h°*: 54.3±1.2, 54.7±1.0, 104.2±0.1; blue, *L*C*h°*: 52.7±2.3, 57.8±1.5, 269.7±0.6), or both blue (*blue filler context*). In the mixed filler context, the color and filler shape association was random across trials. Note that the green filler context corresponds to "singleton present" trials in previous studies using the capture-probe paradigm (e.g., Gaspelin et al., 2015; Gaspelin & Luck, 2018a, 2018b).

4; red in Experiment 1B; magenta in Experiment 3). We use the term in a general sense to enable comparison across conditions and studies, while accounting for possible effects of distractor shape. We return to the question of whether this distractor is a salient singleton in the General Discussion.

Behavioral Measures by Experiment and Array Context

Array Context	n	Search Performance		Probe Performance					
		Accuracy (%)	RT (ms)	Letters Correct	Letters Incorrect	Target Recall (%)	Filler Recall (%)	Singleton Recall (%)	Distractor Recall Diff. (%)
Experiment 1	24								
singleton absent		90.5 (1.3)	702 (17)	2.8 (0.09)	0.3 (0.04)	84.4 (2.1)	64.0 (2.7)		
green fillers		91.5 (1.4)	661 (17)	2.7 (0.10)	0.3 (0.04)	90.1 (1.5)	66.2 (2.5)	46.8 (4.6)	19.4 (3.0)
mixed fillers		94.4 (0.9)	571 (10)	2.5 (0.12)	0.3 (0.04)	97.2 (0.8)	51.2 (3.8)	54.5 (4.2)	-3.3 (1.6)
blue fillers		94.5 (1.1)	565 (12)	2.5 (0.11)	0.3 (0.05)	96.8 (0.8)	50.9 (3.9)	55.8 (3.7)	-5.0 (2.0)
Experiment 1B	24								
singleton absent		94.6 (0.8)	683 (12)	1.4 (0.10)	0.8 (0.10)	40.9 (2.7)	33.7 (2.7)		
green fillers		96.0 (0.5)	651 (10)	1.4 (0.10)	0.8 (0.11)	42.6 (3.0)	37.6 (2.5)	18.2 (2.6)	19.4 (2.2)
mixed fillers		98.1 (0.4)	569 (9)	1.3 (0.09)	0.8 (0.12)	54.4 (2.9)	25.9 (2.7)	22.6 (2.3)	3.3 (1.8)
blue fillers		98.5 (0.4)	566 (10)	1.3 (0.10)	0.8 (0.11)	56.8 (2.9)	23.9 (2.7)	22.1 (2.9)	1.8 (1.9)
Experiment 2	24								
singleton absent		80.1 (1.5)	682 (16)	2.9 (0.11)	0.3 (0.06)	83.9 (2.2)	70.0 (3.0)		
green fillers		82.5 (1.6)	639 (14)	2.9 (0.10)	0.3 (0.06)	89.1 (1.3)	70.7 (3.0)	57.8 (4.3)	12.9 (3.2)
greenish fillers		86.2 (1.2)	595 (13)	2.9 (0.11)	0.3 (0.06)	93.2 (1.0)	65.6 (3.3)	61.2 (4.1)	4.4 (2.1)
turquoise fillers		86.1 (1.8)	563 (11)	2.8 (0.11)	0.3 (0.06)	94.5 (0.7)	62.4 (3.8)	60.8 (3.9)	1.6 (1.6)
bluish fillers		86.0 (1.5)	563 (10)	2.8 (0.11)	0.3 (0.06)	96.4 (0.5)	61.8 (3.9)	62.4 (3.9)	-0.6 (1.7)
Experiment 3	24								
singleton absent		79.6 (1.3)	676 (10)	3.0 (0.11)	0.3 (0.05)	84.9 (1.8)	72.4 (3.1)		
blue fillers		80.5 (1.5)	648 (11)	3.0 (0.11)	0.3 (0.05)	87.2 (1.7)	75.5 (2.6)	58.3 (5.4)	17.2 (3.9)
bluish fillers		83.7 (1.7)	603 (9)	2.9 (0.11)	0.3 (0.04)	92.0 (1.4)	70.7 (3.1)	59.4 (5.1)	11.4 (2.9)
turquoise fillers		83.5 (1.8)	573 (8)	2.9 (0.12)	0.3 (0.05)	97.2 (0.5)	65.3 (3.9)	64.2 (4.4)	1.1 (1.6)
greenish fillers		84.2 (1.8)	575 (8)	2.9 (0.11)	0.3 (0.05)	95.8 (0.7)	64.9 (3.8)	64.5 (3.7)	0.4 (1.3)
Experiment 4	22								
singleton absent		83.0 (1.4)	691 (13)	3.2 (0.14)	0.6 (0.10)	68.5 (2.9)	51.1 (2.5)		
green fillers		84.8 (1.6)	691 (13)	3.2 (0.14)	0.6 (0.09)	71.0 (3.2)	51.7 (2.4)	46.2 (3.1)	5.5 (2.4)
varied fillers		87.3 (1.3)	661 (9)	3.2 (0.14)	0.6 (0.09)	76.7 (2.6)	48.5 (2.6)*	47.9 (3.1)	0.6 (1.7)*
blue fillers		89.7 (1.4)	621 (7)	3.2 (0.14)	0.5 (0.09)	88.4 (2.2)	45.5 (3.0)	47.8 (2.8)	-2.3 (2.0)

Table 1: Behavioral Measures by Experiment and Array Context. Measures show the mean and standard error of the mean (in parentheses) across participants for each condition. Hits and false alarms indicate mean number of correct and incorrect responded letters. *Means for fillers in Experiment 4 are calculated across all filler colors; see text for details. RT: reaction time.

In search task trials (60% of all trials), subjects were instructed to detect and respond to the location of a dot within the target item by pressing the left or right arrow key within 1.4 seconds. Each item contained a dot 0.2° in diameter at 0.4° right or left from center. Each dot was the same color as the item it appeared on, but at a reduced luminance (Weber contrast) plus a random jitter.

To avoid possible ceiling effects and to reduce effects of individual differences on search performance, we set search dot contrast at a moderate difficulty, such that participants would be 80-90% correct. The base contrast of the dots was determined for each participant using a

threshold setting procedure prior to the main experiment, which also served to familiarize participants with the search and probe tasks. On each trial, the dot contrast was randomly sampled from the range -4% to -20%. A Weibull function was fit to search performance on these trials to find the 85% performance threshold estimate. At least two blocks of 24 search trials (and 16 probe trials) were performed until a stable estimate was reached (Weber contrast mean: -10.6%, SD: 3.0%). A further random contrast jitter of -0.5%, 0%, or +0.5% was applied to search dots on each trial.

On letter probe trials (40% of all trials), the search array appeared as usual but was immediately followed by the presentation of four different white uppercase letters (100.1 cd/m^2; height: 0.5°) in the center of the respective items. Letters were selected without replacement from all letters of the English alphabet. Letters appeared for 100 ms, 200 ms after the onset of the search display. After the letters disappeared, participants were asked to report which letters they recalled by typing letters on the keyboard. Participants were encouraged to report any recalled letters regardless of which items they appeared in, and told that there was no time limit and no penalty for wrong answers.

Each session included 432 search trials and 288 probe trials; these were equally divided into the four array contexts (108 search trials and 72 probe trials per context). The order of trials was randomized, with the constraint that no more than four consecutive search trials and two consecutive probe trials could occur. The experiment was not preregistered; the data and scripts are available upon request.

2.1.4. Procedure and stimuli: Experiment 1B

The procedure of Experiment 1B was identical to Experiment 1, but with the following changes.

The shapes of target, singleton distractor, and nonsingleton distractor items were fully counterbalanced across participants (twelve combinations). Each of the four shapes (diamond,

13

square, hexagon, circle) served as the target shape for six participants. For each group of six participants with a given target shape, the remaining three shapes served as the singleton distractor shape for two participants each. The task association of shapes was fixed for each participant during the experiment. Thus, two participants were presented with diamond targets and square singletons, two saw square targets and circle singletons, two saw hexagon targets and circle singletons, *etc*. This ensured that no similarity between certain item shapes (like diamond and square) could be responsible for the effects.

The colors used were modified from those in Experiment 1 to match chroma values and ensure that the singleton color was red and clearly distinguishable from yellow. The final measured colors were green (*L*C*h°*: 57.8±1.4; 54.7±0.9; 163.5±0.2), yellow (*L*C*h°*: 56.2±1.5; 49.2±1.1; 82.3±0.3), blue (*L*C*h°*: 55.9±2.1; 48.2±1.6; 260.5±0.4), and red (*L*C*h°*: 56.1±2.0; 50.6±1.5; 4.6±0.3).

The response window for the search task was reduced to 1.2 seconds, and participants used the left and right Shift keys to provide their response. We used suprathreshold stimulus dots for the search task, ensuring that these were clearly visible to participants; dot contrast was fixed to 80% Weber contrast, and no threshold setting procedure was performed. The search task dot on search items was reduced in diameter to 0.16°, and was spatially dithered with the base item color: 50% of dot pixels were the original item color, 50% were in a lower luminance color, doubling the effective contrast resolution (i.e. digital halftoning; Ulichney, 1987). Participants practiced on at least 80 search trials before proceeding to the main experiment.

On probe trials, probe task letters appeared simultaneously with search dots (no stimulus onset asynchrony) for 100 ms, before being backward-masked by white masks ('#' symbols) which remained for 500 ms. This follows the procedure used in some previous studies (Gaspelin et al., 2015, Exp. 4; Gaspelin & Luck, 2018a, 2018b; Stilwell & Gaspelin, 2021) to limit the time for encoding into working memory.
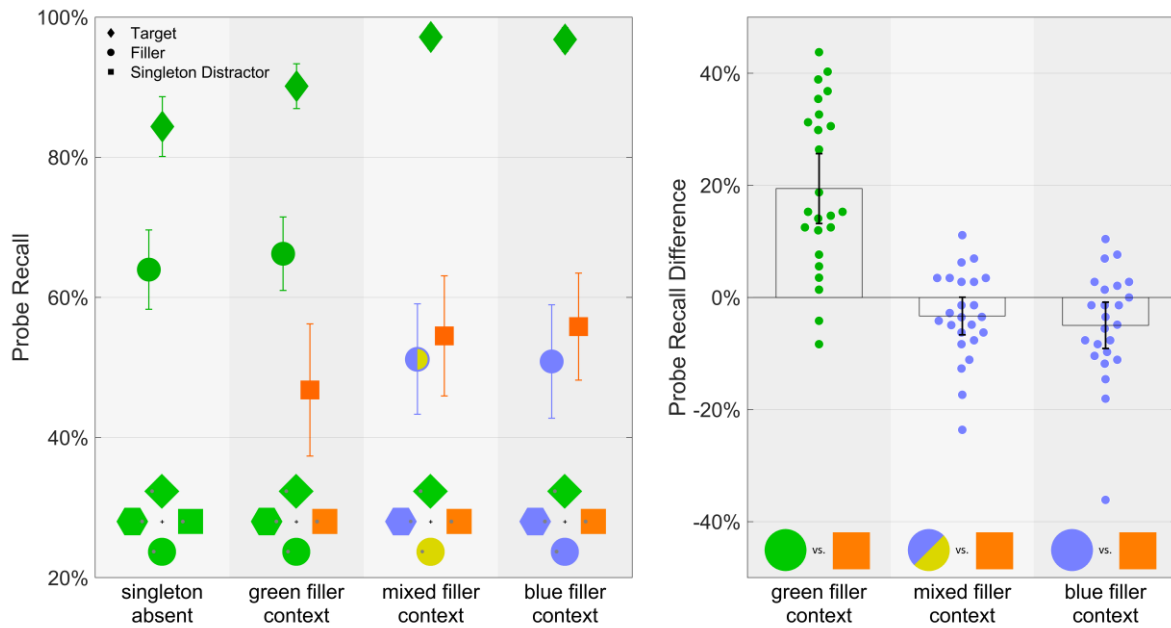
14

Fig. 2. Left: Mean probe recall for probes appearing on targets (diamonds), fillers (circles), and singleton distractors (squares), within each of four array contexts (in columns) in Experiment 1. Marker colors represent the colors of items in each array context. Right: Probe recall difference among distractors, showing fillers minus singleton distractors (participant data shown as circles). Error bars represent 95% confidence interval of the mean. For the color version of this figure, see the online article.

Each session included 540 search trials and 360 probe trials (135 search and 90 probe trials per array type).

2.2. Results: Experiment 1

2.2.1. Search Performance

Behavioral measures for each condition are provided in Table 1. Following Gaspelin & Luck (2015; 2018a), search trials with reaction times faster than 200 ms or with missing or incorrect responses were excluded from further analysis. Search accuracy and mean correct reaction time were submitted to separate one-way repeated measures ANOVAs with four levels of factor *array context* (singleton absent, green fillers, mixed fillers, and blue fillers). For these and all following

15

ANOVAs, degrees of freedom were adjusted using the Greenhouse-Geisser correction as necessary. Array context significantly affected both search accuracy, $F(2.07, 47.69) = 7.64$, $p < .001$, $\eta^2_p = .25$, and reaction time, $F(1.35, 31.11) = 115.81$, $p < .001$, $\eta^2_p = .83$. Following previous studies, we compared measures for singleton absent trials to singleton present trials with green fillers via paired t-tests to investigate the effect of the presence of a singleton distractor on search performance. Search performance was faster (702 ms vs 661 ms, $t(23) = -6.55$, $p < .001$, $d_z = -1.34$) but not significantly more accurate (90.5% vs 91.5%, $t(23) = 1.04$, $p = .31$) when a singleton distractor was present in the array.

2.2.2. Probe Recall

Overall, participants recalled 2.64 letters correctly and reported 0.27 incorrect letters which were not present in the arrays. One-way repeated measures ANOVAs across all array contexts showed that this factor significantly affected overall probe recall, $F(2.15, 49.41) = 24.52$, $p < .001$, $\eta^2_p = .52$, but not the number of incorrect reports, $F(3, 69) = 0.42$, $p = .742$. The recall rate was higher than in other studies using the letter probe recall method (e.g., Gaspelin et al., 2015; Gaspelin & Luck, 2018a), likely because participants used a keyboard rather than a mouse to report letters, and letters were not backward masked.

Probe recall performance was averaged for targets, fillers, and singleton distractors in each of the four array contexts. We first investigated probe recall for targets across all contexts, which can indicate whether attention to targets was affected by other array items. Then, to index the degree of suppression or facilitation for the singleton distractor, we calculated the distractor probe recall difference by subtracting the recall performance for the color singleton distractor from the average of recall performance for circle and hexagon fillers (cf. "probe suppression effect", (Gaspelin & Luck, 2018a)). This measure indicates *relative* differences in attention between fillers and distractors; therefore we followed up with analyses of raw or absolute recall for each nontarget distractor type, across array contexts containing a singleton distractor.

16

A one-way repeated measures ANOVA for target probe recall was significant, $F(1.41,32.51) =$ 31.47, $p < .001$, $\eta^2_{p} = .58$. This shows that changes to other array items affected the attention that was deployed to targets. Because our focus was on distractor processing and because target item processing in the probe task is not commonly investigated, we did not further analyze target probe recall in different conditions.

One-sample t-tests were performed on these distractor probe recall differences for each context of green fillers, mixed fillers, and blue fillers. For the green filler context, a singleton distractor among target-colored fillers showed reduced probe recall, consistent with previous findings, M: 19.4%, SE: 3.0%, $t(23) = 6.44$, $p < .001$, $d_z = 1.31$. The size of this effect is comparable to PDSE reported in previous studies ((Gaspelin et al., 2015), Exp. 2: $d_z = .95$; Exp. 3: $d_z = 1.1$). In contrast, a square distractor among mixed filler colors – which was no longer a singleton – was marginally *enhanced* in probe recall, M: -3.3%, SE: 1.6%, $t(23) = -2.04$, $p = .052$, $d_z = -0.42$. In the blue filler context, probe recall for the singleton distractor was again improved relative to fillers, suggesting attentional capture by the non-target singleton, M: -5.0%, SE: 2.0%, $t(23) = -2.49$, $p = .021$, $d_z = -0.51$.

This analysis suggests that changes to filler context affect relative filler-singleton probe recall. Arguably, distractor probe recall differences could be caused by performance changes to either fillers or to singleton distractors alone. To address this, we submitted filler probe recall to a one-way repeated measures ANOVA with three levels of factor *array context* (green fillers, mixed fillers, and blue fillers); a separate ANOVA was performed on singleton distractor probe recall. The effect of array context was significant for both filler probe recall, $F(1.48,34.13) = 49.34$, $p <$ .001, and for singleton distractors, $F(2,46) = 11.83$, $p < .001$. To investigate whether these effects were driven by certain filler contexts, paired comparisons between levels were performed (three tests), using Holm–Bonferroni corrections with an alpha of .05. For filler probe recall, green fillers showed better recall than mixed fillers or blue fillers (adjusted ps < .001), but there was no

difference between mixed and blue fillers (adjusted p = .79). This was mirrored by the effect of array context on singleton distractor probe recall: the green filler context was associated with worse singleton distractor probe recall relative to mixed or blue filler contexts (adjusted ps < .01), but there was no difference between these latter contexts (adjusted p = .48). Overall, the results showed a PDSE only when nonsingleton fillers matched the color of the target; when these differed greatly in color from the target and the singleton, the effect was abolished or even reversed.
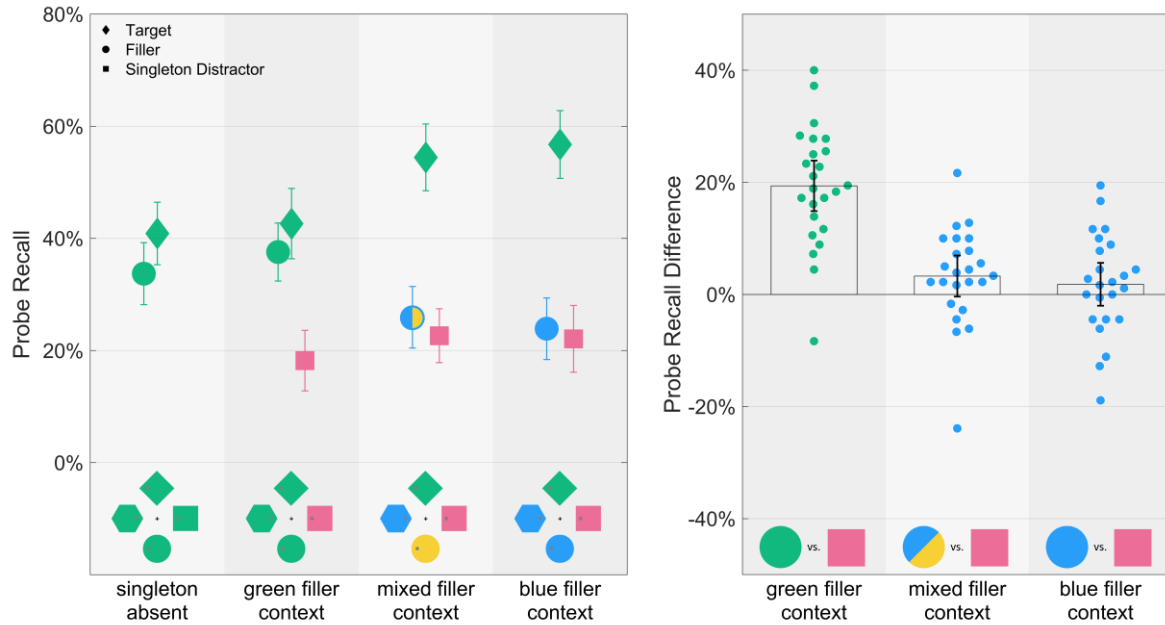
Fig. 3. Left: Mean probe recall for probes appearing on targets (diamonds), fillers (circles), and singleton distractors (squares), within each of four array contexts (in columns) in Experiment 1B. Marker colors represent the colors of items in each array context. Right: Probe recall difference among distractors, showing fillers minus singleton distractors (participant data shown as circles). Error bars represent 95% confidence interval of the mean. For the color version of this figure, see the online article.

2.3. Results: Experiment 1B

2.3.1. Search Performance

Behavioral measures for each condition are provided in Table 1. Search trials were preprocessed in the same way as in Experiment 1. Separate ANOVAs of search performance showed that array context significantly affected both search accuracy, $F(2.14, 49.15) = 25.77$, $p < .001$, $\eta^2_p = .53$, and reaction time, $F(1.34, 30.89) = 136.11$, $p < .001$, $\eta^2_p = .86$. Search performance was both faster (683 ms vs 651 ms, t(23) = -5.90, $p < .001$, $d_z = -1.20$) and more accurate (94.6% vs 96.0%, t(23) = 2.62, $p = .015$, $d_z = 0.53$) when a red singleton distractor was present.

19

2.3.2. Probe Recall

Probe recall was investigated as in Experiment 1. Fewer correct probe letters (1.33) were recalled than in Experiment 1, while more incorrect letters were reported (0.77), suggesting that the use of backward masks interfered with the encoding of probe letters into working memory (Stilwell & Gaspelin, 2021). One-way repeated measures ANOVAs across all array contexts showed that array context significantly affected overall probe recall accuracy, $F(2.02,46.35) = 17.98$, $p < .001$, $\eta^2_{p} = .44$, but not the incorrect report rate, $F(3,69) = 0.31$, $p = .815$. For targets, probe recall was affected by array context, $F(3,69) = 42.02$, $p < .001$, $\eta^2_{p} = .65$.

One-sample t-tests were performed on distractor probe recall differences, separately for each context containing singleton distractors. A PDSE was seen for red singletons among green nonsingletons, M: 19.4%, SE: 2.2%, t(23) = 8.88, $p < .001$, $d_z = 1.81$. There was a marginal trend in the mixed filler context, M: 3.3%, SE: 1.8%, t(23) = 1.85, $p = .077$, $d_z = 0.38$, but not for blue fillers, M: 1.8%, SE: 1.9%, t(23) = 0.97, $p = .340$.

Separate one-way repeated measures ANOVAs and follow-up paired comparisons were performed to investigate the effect of array contexts on absolute filler and singleton distractor probe recall in isolation. Array context significantly affected recall for both fillers, $F(1.56,35.96) = 53.35$, $p < .001$, $\eta^2_{p} = .70$, and singleton distractors, $F(2,46) = 8.08$, $p < .001$, $\eta^2_{p} = .26$. Paired comparisons showed that for filler probe recall, probes on green fillers were better recalled than those on mixed fillers or blue fillers (adjusted ps < .001), but there was no significant difference between mixed and blue fillers after corrections (adjusted $p = .059$). A similar pattern emerged for singleton distractor probe recall: singleton distractor probe recall was worse when among green fillers relative to mixed or blue filler contexts (adjusted ps < .01), but there was no difference between mixed and blue filler contexts (adjusted $p = .69$). The pattern of results was remarkably similar to that in Experiment 1: the difference between singleton and nonsingleton

20

distractors was clear when fillers matched the target, but was largely eliminated when no distractors were green.

2.4. Interim Discussion

In Experiments 1 and 1B, we replicated the PDSE seen in the classic capture-probe paradigm: probe recall for singleton distractors was reduced in comparison to nonsingleton target-colored fillers. When fillers were blue (a third color unrelated to target or singleton distractor) or blue and yellow (i.e., all array items were a different color), probe recall associated with those fillers was no better than for singleton distractors in the same array. The results in the probe recall task show that PDSE is abolished when filler items differ in color from the target. This occurred despite the fact that the features associated with the singleton distractor remained constant in all of the three contexts, and so suppression of the singleton distractor was possible and advantageous. This conflicts with the predictions of SSH, which firmly posits that suppression occurs for a consistent, first-order feature (Gaspelin & Luck, 2018a).

Furthermore, the findings were robust to significant procedural changes between the Experiments 1 and 1B. Letter masks used in Experiment 1B reduced the overall recall of letters, but differences among item types remained, showing that working memory encoding was affected by early attentional enhancement. Item shape associations were counterbalanced, reducing the influence of shape similarity. Finally, search target dots were clearly visible and performance was at ceiling, confirming that probe recall effects are not dependent on the difficulty of the search task.

The results call into question why PDSE should depend on the filler context. In Experiments 2 and 3, we explicitly tested whether global enhancement of target color could explain variation in attention to fillers, and the difference in probe recall between distractor types.

21

3. Experiments 2 & 3

These experiments directly tested whether global feature enhancement of target color could explain variation in attention to fillers, by manipulating the color similarity of target and fillers. If attention is tuned to the target color, one would expect that fillers more similar to the target would be facilitated more (Martinovic et al., 2018), and so we hypothesized that such fillers would show improved probe recall.

In Experiment 2, four filler colors were used which varied in hue distance to the target green: green (identical), "greenish", "turquoise", and "bluish". The latter colors were determined individually for participants using a color categorization task before the visual search experiment. If attentional enhancement of fillers is modulated by their similarity to the target color, then green fillers should show the best recall performance, with performance declining as filler colors become less green and more blue. These filler colors were perceptually matched but their physical luminance could not be explicitly equated. We therefore used a similar color set in Experiment 3, but mirrored the task associations for greens and blues: the target diamond became blue, and fillers were blue, bluish, turquoise, and greenish. Thus, filler colors would span a similar arc of hue space between blue and green, but attentional effects would be modulated in the opposite direction. Here, target-matching blue fillers should be attended more than greener fillers.

3.1. Method

3.1.1. Participants

Participants for Experiment 2 and 3 were recruited, compensated, and provided consent as described in Experiment 1. Twenty-four participants took part in Experiment 2 and are included in the analysis (14 female, 10 male; mean age: 23.0 years; age range: 19 to 35). One further participant withdrew following task training; one other participant was excluded based on poor

performance on the probe task (detailed below). Another twenty-four participants took part in Experiment 3 and are included in the analysis (13 female, 11 male; mean age: 23.1 years; age range: 19 to 35).

3.1.2. Apparatus

Stimuli were presented on a 28-inch ProPixx DLP projector (VPixx Technologies Inc., Canada), set to a resolution of 1920x1080 at 120 Hz (maximum luminance: 630.8 cd/m²). Note that, as this luminance range was much larger than in Experiment 1, the lightness (L^*) values given below for stimuli are smaller despite higher physical luminance. Other apparatus details were identical to those in Experiment 1.

3.1.3. Procedure

The procedure of Experiments 2 and 3 was similar to that of previous experiments, but with the following changes.

As in Experiment 1B, the response window for the search task was reduced to 1.2 seconds, and participants used the left and right Shift keys to provide their response. In the threshold setting procedure before the main task, at least three blocks of 35 search trials each were performed to find the 84% accuracy Weber contrast. Contrast was varied during this procedure following a 1-up/4-down staircase, and a Weibull psychometric function was fit to search performance; some participants performed additional blocks until a stable estimate of threshold was found.

The background was black throughout the tasks (0.5 cd/m²). Probe letters were white (630.8 cd/m²). Each session included 540 search trials and 360 probe trials (108 search and 72 probe trials per array type).

Stimuli: Experiment 2

Three colors were perceptually matched for each participant to approximately 48 cd/m² via heterochromatic flicker photometry (Wagner & Boynton, 1972). These colors were green for

targets ($L^*C^*h^\circ$: 35.2±1.1, 96.1±2.2, 151.9±0.0), orange for the singleton distractor ($L^*C^*h^\circ$: 33.7±1.6, 53.3±2.0, 70.5±0.9), and blue for an anchor color used in determining filler colors ($L^*C^*h^\circ$: 33.4±1.5, 35.8±1.1, 240.7±1.2; explained below).

All participants searched for a green diamond. Five array contexts were used, including a *singleton absent* and *green filler context* that were identical to Experiment 1. The color of the remaining filler items was manipulated in three other filler contexts (*greenish filler context*, *turquoise filler context*, and *bluish filler context*); in these, the orange square again served as a singleton distractor.

The specific colors used as "greenish", "turquoise", and "bluish" were determined on a per-participant basis. First, a range of 200 blue/green test colors was generated spanning the color space between the participant's target green and anchor blue (i.e., by interpolating between their luminance, chroma, and hue values). Each participant then completed a yes/no color categorization task, in which they endorsed whether each test color belonged to a particular color category (blue/"blau" or green/"grün", in separate blocks). Samples were selected using the automated psi-marginal adaptive method (Prins, 2013) so as to fit independent Cumulative Normal psychometric functions of "is blue" and "is green" to the color range. One category boundary color was determined from each function (that is, one color which would be endorsed as blue on 50% of tests, and one for green). The hue angle halfway between these category boundary colors served as each participant's turquoise. Two colors with hues ~20° below and above this value were used as greenish and bluish, respectively. Because of the limits imposed by green and blue phosphors, some colors were outside of the screen's displayable range; when this occurred, the maximum phosphor output was used without adjusting other phosphors. As this introduced some variation in the displayed hue and chroma values, we measured and report the veridical color values as they appeared to participants. Across participants, these colors were

24

greenish ($L^*C^*h^\circ$: 34.7±1.2, 76.3±4.8, 162.0±3.2), turquoise ($L^*C^*h^\circ$: 36.0±1.2, 54.8±4.9, 180.8±4.6), and bluish ($L^*C^*h^\circ$: 37.6±1.2, 40.0±1.8, 215.0±6.6).

450 Stimuli: Experiment 3

The singleton distractor color was reflected to the opposite side of color space to become magenta, approximating the color distance of green vs. orange in Experiments 1 and 2. Heterochromatic flicker photometry was performed for blue (targets; $L^*C^*h^\circ$: 34.1±1.0, 36.9±0.8, 214.7±0.8), magenta (singleton distractor; $L^*C^*h^\circ$: 32.0±1.0, 51.5±1.8, 341.3±0.3), and green (filler anchor; $L^*C^*h^\circ$: 35.4±1.2, 96.5±2.3, 151.9±0.0).

The target was a blue diamond for all participants. This blue color was chosen such that its color distance from turquoise would approximately match the distance between green and turquoise in Experiment 2. In *singleton absent* trials, all items were the same blue color. In the four other singleton present trials, the singleton distractor was magenta. The filler colors in these contexts
460 matched either the target blue (*blue filler context*) or were *bluish*, *turquoise*, or *greenish*. Specific filler colors were determined for each participant using an identical procedure to Experiment 2 (bluish, $L^*C^*h^\circ$: 37.3±1.2, 41.3±2.1, 207.0±5.7; turquoise, $L^*C^*h^\circ$: 35.8±1.1, 57.6±4.7, 177.4±4.3; greenish, $L^*C^*h^\circ$: 34.8±1.1, 72.1±3.8, 159.2±3.6).
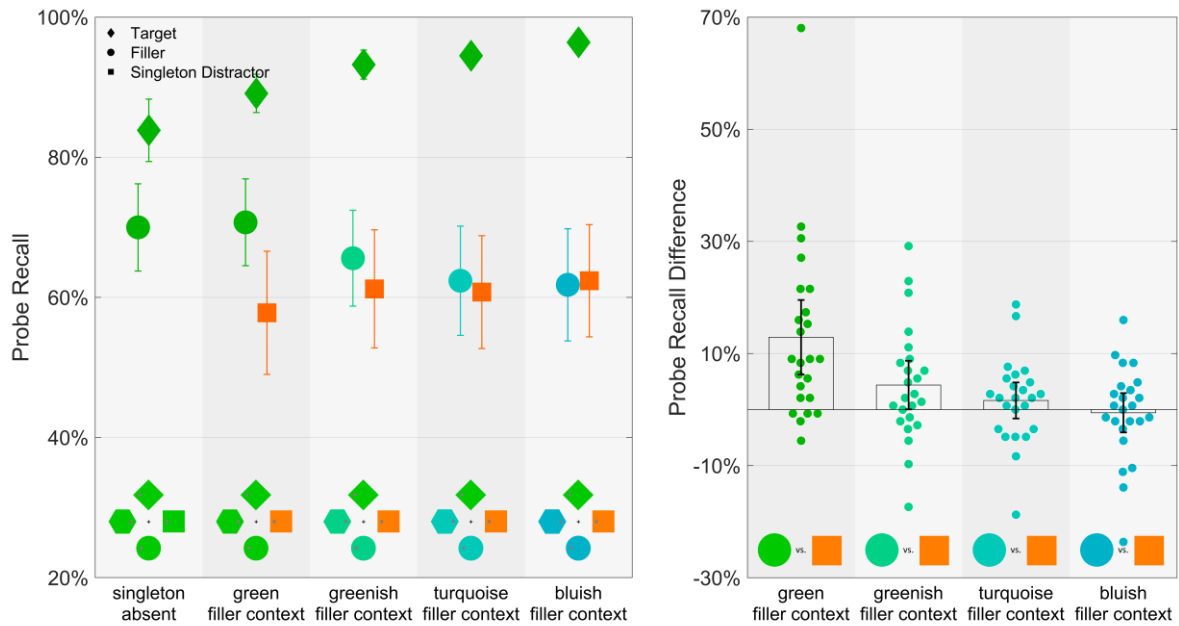
Fig. 4. Left: Mean probe recall for probes appearing on targets (diamonds), fillers (circles), and singleton distractors (squares), within each of five array contexts (in columns) in Experiment 2. Marker colors represent the colors of items in each array context. Right: Probe recall difference among distractors, showing fillers minus singleton distractors (participant data shown as circles). Error bars represent 95% confidence interval of the mean. For the color version of this figure, see the online article.

3.2. Results: Experiment 2

3.2.1. Search Performance

Behavioral measures for each condition are provided in Table 1. Overall search accuracy was closer to the desired value (84%) than in Experiment 1, likely as a result of additional threshold estimation and practice trials. Search trial performance was analyzed as in Experiment 1. Array context significantly affected both reaction time, $F(1.71, 39.42) = 106.26$, $p < .001$, $\eta^2_p = .82$, and search accuracy, $F(4, 92) = 9.38$, $p < .001$, $\eta^2_p = .29$. We again compared performance on singleton absent trials to singleton present trials with green fillers. Search performance was faster (682

26

ms vs 639 ms), $t(23) = -8.99$, $p < .001$, $d_z = -1.83$, and marginally more accurate (80.1% vs 82.6%), $t(23) = 1.72$, $p = .099$, $d_z = 0.35$, when a singleton distractor was present in the array.

3.2.2. Probe Recall

One participant exclusively reported letters appearing on the target probe, leading to an average recall rate of 25%; as this was more than 3.5 SD lower than the group average, this participant was excluded from analysis and replaced with a new participant.

We analyzed the probe recall measures as in Experiment 1. Overall, participants recalled 2.86 letters correctly and reported 0.32 incorrect letters which were not present in the arrays. Correctly reported letters, $F(2.84,65.41) = 10.33$, $p < .001$, $\eta^2_p = .31$, but not incorrect reports, $F(4,92) = 0.47$, $p = .755$, differed with array context. Probe recall for targets was also significantly affected by array context, $F(1.68,38.59) = 22.42$, $p < .001$, $\eta^2_p = .49$.

One-sample t-tests revealed that a singleton distractor among target-colored fillers again showed reduced probe recall, M: 12.9%, SE: 3.2%, $t(23) = 4.01$, $p < .001$, $d_z = .82$, replicating the effect seen in Experiments 1 and 1B and previous studies. When among greenish fillers, singleton distractor probe performance was still reduced, but to a lesser extent, M: 4.4%, SE: 2.1%, $t(23) = 2.08$, $p = .049$, $d_z = 0.42$. Singleton distractor probe performance did not differ from filler performance when the latter were turquoise, M: 1.6%, SE: 1.6%, $t(23) = 1.04$, $p = .31$, or bluish, M: -0.6%, SE: 1.7%, $t(23) = -0.34$, $p = .74$.

As in Experiment 1, we performed separate one-way repeated measures ANOVAs with four levels of factor *array context* (green fillers, greenish fillers, turquoise fillers, blueish fillers) for filler probe recall and singleton distractor probe recall. For fillers, the effect of array context was significant, $F(1.97,45.48) = 20.43$, $p < .001$, $\eta^2_p = .47$, and was therefore followed up with paired comparisons between levels (six tests), corrected for using the Holm–Bonferroni method with an alpha of .05. All paired comparisons were significant (adjusted ps < .014), save for the difference

in probe recall for turquoise and bluish fillers (adjusted p = .46). In contrast, the one-way repeated measures ANOVA for singleton distractors showed a non-significant effect of array context, $F(3,69)$ = 2.13, p = .11. We nevertheless followed up with paired comparisons among levels; no comparison was significant following Holm-Bonferroni corrections (all adjusted ps > .25). Thus, filler probe recall appears to be modulated by the degree of similarity between target and filler colors, while singleton distractor probe recall is not significantly affected by changes to filler colors in array context.
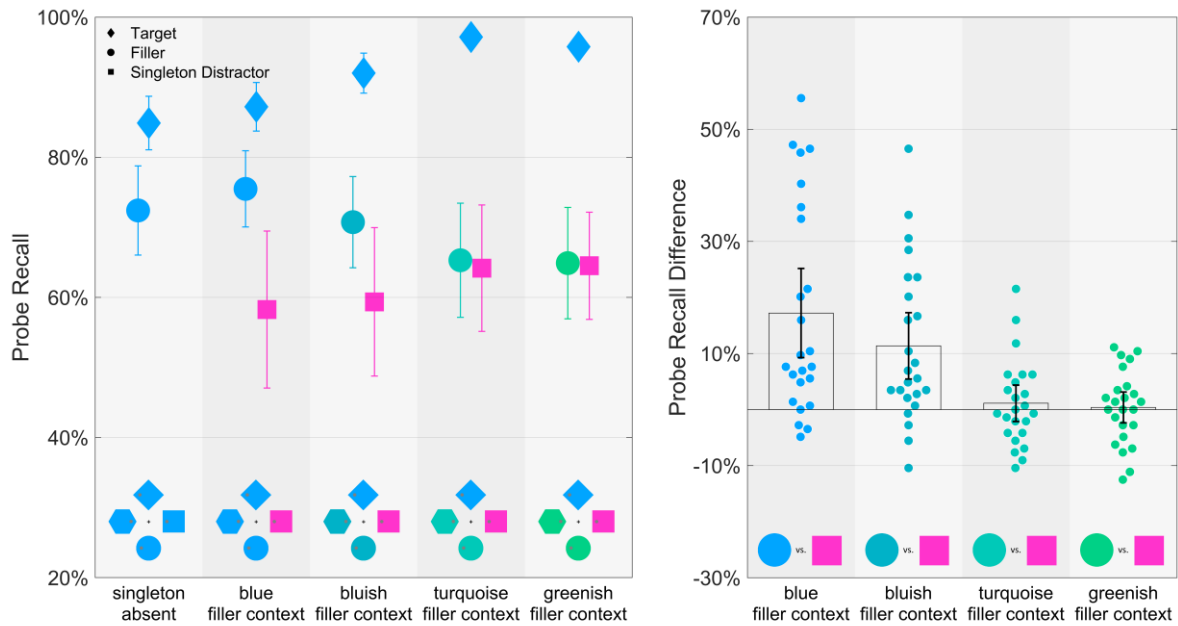
Fig. 5. Left: Mean probe recall for probes appearing on targets (diamonds), fillers (circles), and singleton distractors (squares), within each of five array contexts (in columns) in Experiment 3. Marker colors represent the colors of items in each array context. Right: Probe recall difference among distractors, showing fillers minus singleton distractors (participant data shown as circles). Error bars represent 95% confidence interval of the mean. For the color version of this figure, see the online article.

3.3. Results: Experiment 3

3.3.1. Search Performance

Behavioral measures for each condition are provided in Table 1. Search trial performance was calculated following the criteria in previous experiments. Array context again significantly affected both reaction time, $F(2.52,58.06) = 151.85$, $p < .001$, $\eta^2_p = .87$, and search accuracy, $F(2.27,52.14) = 4.81$, $p = .009$, $\eta^2_p = .17$. Search performance was faster (676 ms vs 648 ms), t(23) = -6.53, $p < .001$, $d_z = $ -1.33, but not significantly more accurate (79.6% vs 80.5%), $t(23) = 0.71$, $p = .49$, on blue filler, singleton present trials relative to singleton absent trials.

29

3.3.2. Probe Recall

Participants recalled 2.95 correct letters and reported 0.32 incorrect letters. Array context affected correct recall, $F(2.75, 63.29) = 6.61$, $p < .001$, $\eta^2_p = .22$, but not incorrect reports, $F(4, 92) = 0.21$, $p = .935$. Target probe recall also significantly differed based on array context, $F(2.30, 52.79) = 25.88$, $p < .001$, $\eta^2_p = .53$.

One-sample t-tests were performed on the distractor probe recall difference for blue, bluish, turquoise, and greenish filler array contexts. A singleton distractor again showed reduced probe recall when it was presented among target-colored fillers, M: 17.2%, SE: 3.9%, $t(23) = 4.47$, $p < .001$, $d_z = .91$, and when among bluish fillers, M: 11.4%, SE: 2.9%, $t(23) = 3.96$, $p < .001$, $d_z = 0.81$. In contrast, there was no significant drop in singleton distractor probe performance relative to either turquoise fillers, M: 1.1%, SE: 1.6%, $t(23) = 0.72$, $p = .48$, or greenish fillers, M: 0.4%, SE: 1.3%, $t(23) = 0.28$, $p = .78$.

Filler and singleton distractor probe recall were submitted to separate one-way repeated measures ANOVAs with four levels of factor *array context* (blue fillers, bluish fillers, turquoise fillers, greenish fillers). The effect of array context was significant for probes appearing on filler items, $F(1.84, 42.26) = 25.2$, $p < .001$, $\eta^2_p = .52$. This was followed up with six paired comparisons between levels; similar to Experiment 2, these paired comparisons were all significant (adjusted ps < .0017) except for between turquoise and greenish fillers (adjusted $p = .62$). Unlike Experiment 2, singleton distractor probe recall significantly differed as a function of filler color, $F(3, 69) = 4.22$, $p = .008$, but no follow-up paired comparisons among levels were significant after Holm-Bonferroni corrections (all adjusted ps > .091). It is clear that filler probe recall differed depending on filler color, and while there is some evidence that distractor probe recall was also marginally affected by filler context, no systematic effect between levels was detected.

3.4. Interim Discussion

In Experiments 2 and 3, we again replicated PDSE in the search and probe tasks, when nonsingleton distractors matched the color of the target. But as fillers became more different in color from the green target, probe recall for those decreased while performance for singleton distractors stayed about the same. When these fillers were sufficiently different from the target (i.e. turquoise or bluish), there was no longer any difference in probe recall for singleton distractors and fillers.

It could be argued that some effect of color salience, chroma, or luminance could have driven probe recall effects among fillers, rather than their target similarity. For example, in Experiment 2, white probe letters could have been more difficult to identify on bluer relative to greener backgrounds. In Experiment 3, blue-green colors were again used as filler colors, but the task association with the target was mirrored - "blueness" was associated with the target, rather than "greenness". The resulting effects on filler probe recall were also mirrored, declining as filler colors became more dissimilar from the target color. Thus, the graded attentional effect of Experiment 2 was not due to specific properties of the color set used.

The results of Experiments 2 and 3 demonstrate that attention to the nonsingleton distractors is modulated by their similarity to the target, strongly suggesting the influence of GTFE. This poses a challenge to SSH and its explanation of the putative distractor suppression effect: it cannot be assumed that nonsingleton distractors are unaffected by attention. Nevertheless, there was limited evidence that recall on singleton distractors was also affected by the array context; it could therefore be argued that proactive distractor suppression was hindered by changes to the fillers (although such an effect would seem to be disallowed by the signal suppression hypothesis; (Gaspelin et al., 2015)). Experiment 4 therefore tested whether filler probe recall would be affected by target-filler similarity within a single condition, when singleton probe recall would be fixed.

31

4. Experiment 4

Experiment 4 extended Experiment 2 to address three possible concerns. Chiefly, we manipulated the color of nonsingleton distractors within a single condition, rather than across conditions, as in Experiments 2 and 3. Within this single array context, we expected filler probe recall to be graded with respect to how similar they were to the target color. Second, it has been argued that increasing the number of search items can abolish (B. Wang & Theeuwes, 2020) or reduce (Stilwell & Gaspelin, 2021) the effect size of PDSE. To confirm that our results would extend to other array sizes, we increased the number of search items from four to six. Finally, we counterbalanced the target and distractor shape associations across participants as in Experiment 1B, to ensure that "shape affinity" between diamond and square items could not drive the observed effects.

4.1. Method

4.1.1. Participants

Participants were recruited as previously described. Twenty-two participants were included in the analysis (18 female, 4 male; mean age: 21.9 years; age range: 19 to 26). One further participant was replaced due to failure to perform the color categorization task; two other participants were excluded from the analysis, without replacement, based on poor search task performance.

4.1.2. Apparatus

The apparatus was identical to that used in Experiment 1.

4.1.3. Stimuli and procedure

The procedure, stimuli, and design were similar to those in Experiment 2, with stimulus parameters modified for different display apparatus.

First, a "turquoise" hue was selected for each participant using a color categorization procedure similar to Experiments 2 and 3, except that the lightness and chroma of the color space was fixed, and only hue was varied (*L*C*h°:* 52, 32, 140-220). The hue halfway between the participant's turquoise and target green (152°) was used as "greenish"; a "bluish" hue was used which was this same distance from turquoise. As a result, green, greenish, turquoise, and bluish were equally spaced in hue space; the mean hue angle between neighboring hues was 9.5° (*SD:* 5.0).

Each participant perceptually matched these colors, plus target green and singleton orange, to 28.1 cd/m^2 using heterochromatic flicker photometry. The final five colors used were green (*L*C*h°:* 54.2±0.5; 35.4±0.4; 155.4±0.2), greenish (*L*C*h°:* 54.0+-1.0; 36.5+-0.7; 164.4+-4.8), turquoise (*L*C*h°:* 54.2±0.8; 37.6±1.0; 173.2±9.1), bluish (*L*C*h°:* 54.2±1.0; 37.8±1.1; 181.8±13.5), and orange (*L*C*h°:* 53.7±0.8; 33.9±0.5; 67.8±0.4).

Search arrays were comprised of 6 items, rather than 4. These items included diamond, square, hexagon, and circle shapes. Shape and task association was counterbalanced across participants as in Experiment 1B; for each participant, one shape was fixed as the target shape and always appeared in green, while another shape was fixed as the color singleton distractor, which appeared in orange on singleton present trials. The two remaining shapes were used twice each for the four filler items (see figure). As in Experiment 1B, each of the twelve crossed combinations of target and singleton shape associations was presented to two participants. Colors for items in the search arrays were determined by the search *array context. Singleton absent, green filler context*, and *bluish filler context* trials appeared 20% each, and were analogous to conditions in Experiment 2. A new context, *varied filler context*, was presented on 40% of trials. In this context, in addition to a green target and orange singleton distractor, one each of the four fillers appeared in green, greenish, turquoise, and bluish. On these trials, there was no fixed association between filler color and filler shape.
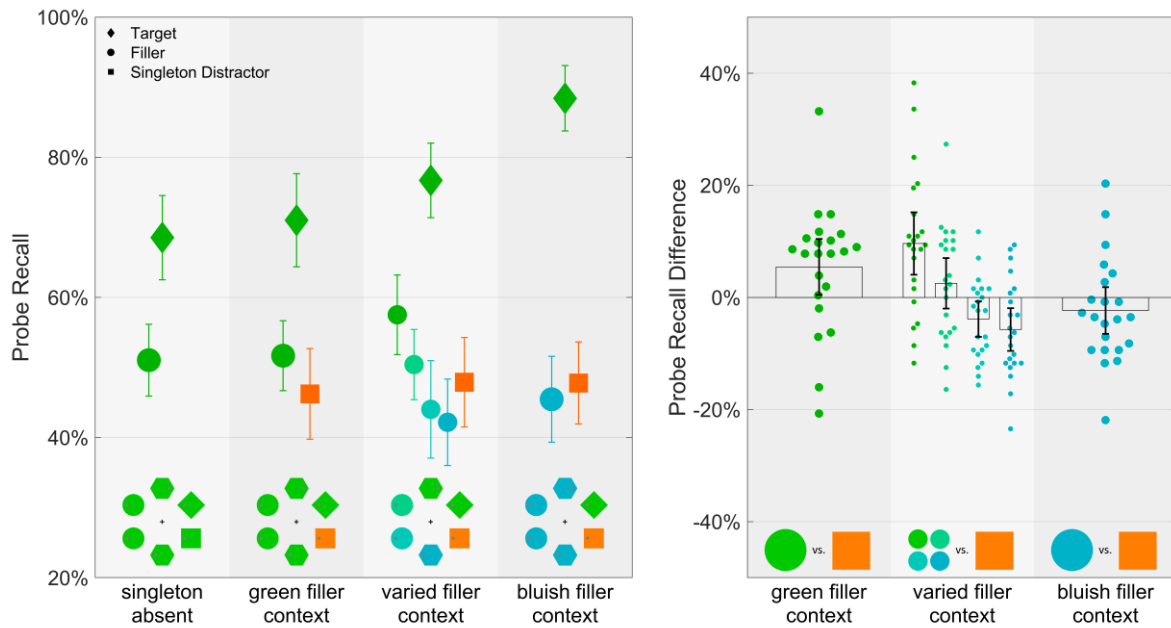
Fig. 6. Left: Mean probe recall for probes appearing on targets (diamonds), fillers (circles), and singleton distractors (squares), within each of five array contexts (in columns) in Experiment 4. Marker colors represent the colors of items in each array context. Right: Probe recall difference among distractors, showing fillers minus singleton distractors (participant data shown as circles). Error bars represent 95% confidence interval of the mean. For the color version of this figure, see the online article.

Each session included 540 search trials and 360 probe trials. On probe trials, letters appeared on all six items, and participants were able to enter up to six recalled letters.

4.2 Results

4.2.1. Search Performance

Two participants showed very low accuracy on the search task (70.6%, 69.3%). As these participants were about 3 SD worse than the remainder of the participants, they were excluded from analysis without replacement.

Behavioral measures for each condition are provided in Table 1. Search task analysis followed the previous experiments. Search reaction time, $F(1.27,26.57) = 28.85$, $p < .001$, $\eta^2_p = .58$, and accuracy, $F(2.10,44.04) = 8.50$, $p < .001$, $\eta^2_p = .29$, differed based on array context. Unlike previous experiments, search responses were not significantly worse in reaction time (691 ms vs 691 ms), $t(21) = -0.031$, $p = .97$, or accuracy (83.0% vs 84.8%), $t(21) = 1.36$, $p = .19$, when comparing the search task performance in singleton absent trials to the green filler context trials. This absence of a "suppression" effect is not surprising and has been seen in other capture-probe experiments with array sizes of six or more items (Gaspelin et al., 2015, Exp. 1; B. Wang & Theeuwes, 2020; Stilwell & Gaspelin, 2021). It is a matter of current debate whether this results from weakened suppression, capture by a more salient singleton, or the increased number of search items.

4.2.2. Probe Recall

In the probe task, participants recalled and average of 3.20 probe letters accurately, with 0.55 incorrect reports. Notably, this performance is well above probe accuracy for larger array sizes reported previously (B. Wang & Theeuwes, 2020; Stilwell & Gaspelin, 2021); this difference is likely due attributable to the visual masking and cursor-based responding used in those studies. Neither correct probe recall, $F(3,63) = 1.77$, $p = .163$, nor incorrect reports, $F(3,63) = 0.24$, $p = .865$, were significantly affected by array context, but probe recall for targets showed a significant difference across levels, $F(1.48,31.11) = 25.75$, $p < .001$, $\eta^2_p = .55$.

We first analyzed the probe recall difference between green fillers and the singleton distractor appearing in the green filler context. Like in previous experiments, a one-sample t-test showed that the singleton distractor showed significantly reduced recall, $M: 5.4\%$, $SE: 2.4\%$, $t(21) = 2.27$, $p = .034$, $d_z = .48$. This effect is notably weaker than in 4-item experiments, replicating studies showing that PDSE is greatly reduced or even reversed as the search array increases in size (Gaspelin et al., 2015; Stilwell & Gaspelin, 2021; B. Wang & Theeuwes, 2020).

We then considered relative distractor recall in bluish filler context; here, multiple fillers appeared in a third, irrelevant color that would not be expected to undergo attentional facilitation or suppression, along with an orange color singleton. There was no significant difference in a one-sample t-test between the color singleton distractor and bluish fillers in probe recall, M: -2.3%, SE: 2.0%, $t(21) = -1.16$, $p = .26$, suggesting again that the color singleton was not suppressed.

In the varied filler context, fillers appeared in different colors within a single search array, allowing us to explore attentional facilitation changes among fillers, while controlling for possible contextual effects on the color singleton. First, the average probe recall for these fillers did not significantly differ from that of the singleton distractor in the same array, M: 0.6%, SE: 1.7%, $t(21) = .37$, $p = .71$. Similarly to the analysis of filler probe recall across contexts in Experiments 2 and 3, we performed a one-way repeated measures ANOVA on filler probe recall *within* the varied filler context, with four levels of factor *filler color* (green, greenish, turquoise, bluish). As this effect was significant, $F(1.87,39.3) = 24.48$, $p < .001$, $\eta^2_p = .54$, we followed up with Holm–Bonferroni-corrected paired comparisons between filler colors. Mirroring the paired comparisons in Experiments 2 and 3, there were significant differences between all filler color pairs (adjusted ps < .006), except between turquoise and bluish (adjusted $p = .18$).

Separate one-way repeated measures ANOVAs revealed that array context significantly affected absolute probe recall of fillers, $F(1.54,32.39) = 14.16$, $p < .001$, $\eta^2_p = .40$, but not singleton distractors, $F(2,42) = 0.56$, $p = .574$.

Finally, we quantified the effects that could be due to global target-feature enhancement in this task, by comparing probe recall for green and bluish fillers in two ways. We calculated an across-context GTFE effect, by subtracting the probe recall difference in the green filler context from the difference in the bluish filler context. This measure provides an estimate of our hypothesized effect of target template-driven filler enhancement while controlling for effects of the color singleton in each context. We also calculated a within-context GTFE effect, from the difference

in probe recall between green and bluish fillers in the varied filler context. Because these fillers appeared in the same context, there is no need to control for any effects caused by the accompanying color singleton. Significantly better probe recall on green fillers than on bluish fillers occurred in both the across-context GTFE effect, $t(21) = 3.00$, $p = .007$, $d_z = .64$, and the within-context GTFE effect, $t(21) = 5.93$, $p < .001$, $d_z = 1.26$. Furthermore, these measures correlated well across participants, $r(21) = .65$, $p = .011$.

4.3. Interim Discussion

In Experiment 4, we replicated the effects seen in previous experiments. Putative distractor suppression was observed only when accompanying nonsingleton distractors matched the color of the target. This effect was abolished when fillers appeared in a third irrelevant color. We also increased the array size and counterbalanced item shapes, showing that the effects were not incidental to either of those factors.

Critically, within a single condition involving fillers of varied colors, the modulation of filler probe recall was again seen. Green fillers which matched the target showed improved recall relative to less green fillers in the same context. This shows that the changes to filler performance in Experiments 2 and 3 did not result from contextual changes, but results from differential attentional enhancement, driven by the target-filler color similarity.

We calculated two separate measures of the hypothesized effect of global target-feature enhancement. These effects were large and strongly correlated. At minimum, it is clear that attentional modulation among fillers, independently of any effects on the color singleton, is not negligible and must be considered in attentional suppression studies.

5. General Discussion

The purpose of this study was to shed light on basic attentional mechanisms in the human brain, involved in how we deal with perceptual distraction. Research in this area has recently undergone a theoretical shift, with the proposal of new fundamental mechanisms that promise to significantly change our understanding of the visual system (viewpoint of Gaspelin & Luck, in Luck et al., 2021). These proposed mechanisms involve top-down control of sensory information, prior to these being acted upon by attention (as commonly understood). We designed the current series of experiments to achieve two goals with consideration to these theoretical developments, and the findings used in support of them. First, we replicated the classic "distractor suppression" effect observed in the capture-probe paradigm, and showed that the effect fails to appear in conditions where it is predicted. In five experiments, probe recall for singleton distractors was reduced relative to fillers, when those fillers matched the target color. But when the colors of accompanying fillers were changed, this distractor difference was reduced or abolished. Arrays with one or two irrelevant filler colors showed no PDSE; in fact, singleton distractors appeared to capture attention in some contexts. Experiments 2 and 3 demonstrated that the difference between fillers and singleton distractors was abolished when filler colors were sufficiently different from target color. The disappearance of PDSE occurred despite that the features of color singleton distractors were consistent in all experiments, in order to allow participants to establish templates for rejecting (and suppressing) the singleton distractor.

Second, we tested an alternative account based on global feature-based enhancement. In Experiments 2, 3, and 4, the color similarity of targets and nonsingleton distractors was manipulated, which we hypothesized would affect attention to the latter. Filler probe recall was indeed graded: greater similarity between the target and filler color led to greater probe recall for fillers, with mixed evidence for change in singleton distractor probe recall. Experiment 3 confirmed that this graded attention facilitation was due to the similarity to the target template,

38

not some incidental color effect, while Experiment 4 demonstrated this target feature enhancement among fillers appearing in the same search array. Because the probe recall difference among distractor types has been used to infer distractor suppression, changes in attention to nonsingleton distractors can explain the appearance and disappearance of that effect in the current and previous studies.

Proactive suppression fails to explain the current findings

A central tenet of the signal suppression hypothesis states that proactive feature suppression "critically depend[s] on first-order feature values" of the singleton distractor (Gaspelin & Luck, 2018a). Such suppressive templates are thought to be formed by exposure to features over time, necessitating that they be constant and predictable (Gaspelin & Luck, 2018a; Gaspelin et al., 2019). Within the presented experiments, there were no changes to color singleton feature values or task demands across contexts, and color singletons were present in at least 75% of trials, so it certainly would have been possible and advantageous for participants to suppress the color singleton. Nevertheless, PDSE was clearly modulated by the array context – it occurred in target-colored filler contexts in every experiment, but was reduced or abolished in other singleton present contexts. Analysis of absolute recall performance for distractor types strongly suggests that the relative "suppression" is actually driven by changes to filler performance.

Regardless, it could be argued that PDSE was affected when the color singleton's salience changed along with the filler context; that is, due to reduced singleton salience, the ability to suppress the singleton's first-order features is reduced in turn. There are several reasons why this is unlikely to explain the current findings. From a theory standpoint, SSH explicitly states that proactive suppression is not driven by salience and that it occurs before salience analysis: "Whereas the original version of the signal suppression hypothesis proposed that suppression could operate directly on the priority signal […] the current version assumes that suppression operates by modulating the gain for specific feature values prior to the saliency computations"

39

(viewpoint of Gaspelin & Luck, in Luck et al., 2021, p. 8; see also Gaspelin & Luck, 2018a, Table 1: First-order vs Second-order feature suppression). This sets SSH apart from other theories of distractor suppression that operate on feature salience, such as the Dimensional Weighting Account (Found & Müller, 1996; Liesefeld et al., 2021).

Empirically, Gaspelin and others have shown that PDSE is tied to the particular feature value ("suppress red items"), not salience itself ("suppress color singletons") (e.g., Gaspelin & Luck, 2018a; Gaspelin et al., 2019). The most recent findings consistently demonstrate that increased salience in fact *reduces* PDSE, perhaps by triggering attentional capture. In competing studies, search array sizes of between six and thirty items were presented to participants, affecting the salience of singleton distractors (B. Wang & Theeuwes, 2020; Stilwell & Gaspelin, 2021). In both studies, the degree of singleton suppression was reduced as singleton salience increased, and was reversed in the study of Wang & Theeuwes (2020). The two groups nevertheless reached different conclusions about whether suppression still occurred for highly salient singletons. Lien et al. (2021) provide another line of evidence that "the mechanism underlying the observed suppression might have nothing to do with singleton salience." They compared PDSE for six-item search arrays with a single color singleton with the effect for arrays with three distractor "tripletons". They showed that although these "tripletons" were no longer salient or singletons, they were associated with an even greater probe recall reduction. It is clear that PDSE is not dependent on the salience of the singleton distractor.

This leaves the question of why color singletons would not capture attention in the capture-probe task, if not suppressed or prevented in some way. The straightforward explanation is that although these unique distractors are singletons, they are not salient enough to "pop-out" and capture attention in the first place. Theeuwes and colleagues have argued that in a feature search task such as this one, where participants focus on finding a particular shape among a limited number of heterogeneous distractors, capture does not occur (viewpoint of Theeuwes, in Luck et

40

al., 2021; Theeuwes, 2010; B. Wang & Theeuwes, 2020). Capture instead *can* occur when a sufficient number of array elements promotes pop-out of the salient distractor (B. Wang & Theeuwes, 2020); or when a singleton distractor appears among homogenous shapes (Gaspelin et al., 2015, Exp. 1, 2017, Exp. 1); or when a singleton is novel (Ernst et al., 2020) as in experiments appearing to show "learned suppression" of new colors (Gaspelin et al., 2019; Gaspelin & Luck, 2018a, Exp. 4; Vatterott & Vecera, 2012). Otherwise, there is no strong capture to be overcome in the classic capture-probe task and the current experiments, meaning that some other mechanism (namely, target feature enhancement) could explain the difference in attention among singleton and target-matching distractors.

The current results could be accommodated in a proactive suppression framework if it is allowed that all non-target features - not only singleton features - be suppressed. If "multiple-feature suppression templates" for red, blue, and yellow suppressed these items equally, then there would be no difference between nonsingleton and singleton distractors in some conditions. There is mixed evidence for this possibility (Vatterott et al., 2018; Won & Geng, 2018; but see Gaspelin et al., 2019, Exp. 4), and it is unclear whether previous findings are better seen as support for second-order suppression accounts (Gaspelin & Luck, 2018a; Won et al., 2019). Allowing multiple-feature suppression in SSH also begs the question of what the determinants of suppression template formation would be. In the above experiments, there were notable differences in the frequency and salience of color distractor features, which presumably would affect whether and how suppression acts upon these. For example, orange/red singletons were three times more common than yellow fillers in Experiment 1 and 1B, yet we found no differences in probe recall between them when they appeared together. As formulated, it is unclear how SSH could account for the apparently equivalent suppression of qualitatively different distractor features.

In the current research, we created experimental situations which included all the ingredients for proactive distractor suppression. This suppression failed to appear in key conditions, despite being predicted by the signal suppression hypothesis. A proactive suppression mechanism based on basic feature values (Gaspelin & Luck, 2018a) does not seem adequate to explain why distractor probe recall was dependent on the features of contextual elements.

GTFE parsimoniously explains difference in attention among distractors

The novel mechanism of proactive feature suppression would greatly complicate our understanding of the brain, in order to explain a very limited set of results in attentional studies, like those cited above. Those results, and the results of the current experiments, are counterintuitive when viewed as effects of proactive distractor suppression – but are easily explained under an account appealing to global target-feature enhancement (Saenz et al., 2002; Andersen et al., 2011; Forschack et al., 2017) and guided search (Wolfe, 1994).

Under our enhancement-based view of the capture-probe task, observers first form attentional templates for the target's features (e.g., green and diamond shape features). Locations with these or similar (e.g. greenish) features are enhanced in global feature maps and combined in an attentional priority map. Post-attentional functions and resources, such as serial search order (Wolfe, 1994) and working memory span (Stilwell & Gaspelin, 2021), are deployed using this prioritization. Targets are processed first, followed by non-targets that share some target features; non-matching items (like color singletons) receive only minimal resources.

From this, we infer that the number of target-matching items – *not* the mere presence of a singleton distractor – is the main determinant of differences in behavioral measures of attention. Although not a focus of our analyses, the patterns for search reaction time, search accuracy, and target probe recall in the five experiments were consistent with this view: target processing was enhanced when fewer items possessed target features. In the presence of a singleton distractor, only three target-like items need be enhanced, so the target is more quickly identified and

42

processed then when there are four target-like items. Target-related measures appeared to be best in each experiment when the target was the only enhanced item (i.e., the only target-colored item).

810   Meanwhile, the differences between singleton and nonsingleton distractors (PDSE) can be attributed to their differential *enhancement*, rather than singleton suppression. If neither distractor type matches target features, neither is enhanced, and so the difference in probe recall disappears. This explains why PDSE is abolished in the current experiments when fillers appeared in non-target-matching colors. In search arrays with six or more items, limited post-attentional resources are spread more thinly among target-like items. This reduces the measurable enhancement for fillers and reduces PDSE in turn, as seen in the current Experiment 4 and in previous studies with large search arrays (Gaspelin et al., 2015; B. Wang & Theeuwes, 2020; Stilwell & Gaspelin, 2021).

Evidence from Experiments 2, 3 and 4 demonstrated that attentional enhancement was graded 820   as a function of filler-target similarity. Invariably, fillers matching the target color showed the best performance among distractors, with probe recall falling off with color distance. Graded attentional facilitation for a visual feature is a tenet of the feature similarity gain model (Martinez-Trujillo & Treue, 2004; Treue & Trujillo, 1999), and color similarity between cue and target affects the strength of capture (Anderson & Folk, 2010; Kerzel, 2019). The attention to target color seen here fits also with findings of color attentional filters that are narrowly tuned in hue space (Sun et al., 2016). For example, when attending to a cued color, color coherence detection drops off as a function of cue and target hue distance (Y. Wang et al., 2015). The fall in recall performance appeared to reach a baseline when fillers were dissimilar enough from targets: in Experiment 2 for example, probe recall for turquoise, bluish, and orange distractors did not 830   differ when targets were green. "Turquoise" was selected for each participant as the hue that was equally categorized as green and blue, and so presented a color category boundary. This suggests

that a categorical effect could be at play: attention is facilitated within color categories, but is limited by category boundaries (Fang et al., 2019).

Our conclusions are seemingly at odds with recent studies investigating both distractor suppression and target enhancement in a similar search and probe task (Chang & Egeth, 2019, 2021; Hamblin-Frohman et al., 2022). There, attentional enhancement for target features has consistently been found, along with evidence for suppression of singleton distractor features (but see Kawashima & Amano, 2022). Two methodological variations in the Chang and Egeth design could account for the differences, and suggest caution in comparing their findings with those using the classic capture-probe paradigm. For one, the probe task uses new shapes and additional colors for nontarget "neutral" stimuli employed as a baseline which do not appear in the search task, unlike in the current experiments and original capture-probe task. While this eliminates the effect of attentional associations from the search task, it also unbalances the frequency of the presentation of different colors, which could have unexpected effects on attention. Secondly, the Chang and Egeth probe task uses cued report of a single item in place of the classic paradigm's free report task, meaning that it may index distinct mechanisms of attention or post-attentional biases (Kerzel & Renaud, 2022). Ultimately, our findings and those of studies using the Chang and Egeth design are consistent in showing that featural enhancement of nontarget items is a significant factor in visual search tasks, which can be confounded with distractor suppression if not accounted for.

Alternative accounts for distractor modulation

Besides global target facilitation, the current results could potentially be accounted for by dimension-based suppression, like that proposed by the dimensional weighting account (DWA; Found & Müller, 1996; Liesefeld & Müller, 2019). Under DWA, attention is driven by salience maps for each feature dimension, which can be up- or downweighted to meet task demands. On the one hand, weighting of entire color dimensions does not seem sufficient to explain current

44

and previous capture-probe task effects, because weightings would affect both target and distractor color features. But, the same authors also allow that specific subdimensions of color could be associated with their own dedicated salience maps (e.g., for "redness" rather than for more general color dimensions like hue) (Found & Müller, 1996; Liesefeld et al., 2019; cf. Witzel & Gegenfurtner, 2018). If so, separate weighting of color subdimensions might explain the findings in the current work. For example, salience maps for "redness" could be downweighted to prevent automatic capture by the singleton distractor, while targets and fillers benefit from boosts to the "greenness" subdimension. As fillers become turquoise or bluish, they lose the upweighting spillover from the target, and potentially become downweighted as they are now salient in a "blueness" subdimension.

A second possibility is that segmentation of the stimulus array – i.e., grouping of the items by color - explains the experimental results (Martinovic et al., 2009; Wuerger et al., 2011). Similar colors in the stimulus array could be grouped preattentively (and perhaps prioritized based on their features), with search proceeding sequentially among such segmented color-groups. When distractor items are sufficiently different, they are segmented into their own color segments and essentially ignored. But when filler colors are similar enough to the target (e.g., greenish and green), they may be grouped together, with fillers benefiting from the same task-driven enhancement as the target. Filler colors that are more distinct from the target are less likely to be grouped with it, explaining improved target probe recall and search task performance as well as filler performance. Arguably, the action of such a segmentation mechanism could mean that proactive distractor suppression would not be necessary, as the target (especially if unique in the search array) would be easy to locate based on color. This view is nevertheless still incompatible with the SSH formulation of proactive suppression, because that suppression is theorized to occur automatically, prior to, and without regard for salience and other computations of the stimulus array. Functionally, segmentation seems indistinguishable from a differential enhancement explanation – in both cases, target features underlie a latent mechanism that drives increased

attention. While such color grouping could determine how visual representations might be operated upon cognitively and behaviorally (e.g., serial search), it fails to explain how or why such preattentively grouping occurs in the first instance.

Critically, as with our own explanation of GTFE, these alternative accounts allow that fillers will be somehow affected by attention in the capture-probe task, and remove the need to hypothesize a proactive mechanism of suppression.

Conclusion

To explain distractor suppression in attention, the signal suppression hypothesis proposes a novel mechanism whereby particular sensory feature values are themselves inhibited prior to saliency computations (viewpoint of Gaspelin & Luck, in Luck et al., 2021; Gaspelin & Luck, 2018a). The proposal that bottom-up processing of stimulus features can be suppressed proactively by top-down influences would amount to a paradigm shift in how we understand not only visual attention, but also the interaction of high-level and low-level neural processing. This would significantly change our understanding of the brain, in order to explain a very limited set of results in attentional studies.

The present results provide a more parsimonious explanation for the behavioral correlate underlying this claim, which builds upon the existing understanding of attention: the global enhancement of target features. Attention simply tunes to the task-relevant perceptual features of the search target, and this facilitation affects the entire search array, increasing performance for target-matching nonsingleton distractors. Such enhancement can explain the behavioral effects characterized as distractor suppression, removing the need to hypothesize a new proactive suppression mechanism of attention.

Author contributions

910 MO, JM, NF, CG, and MMM conceived the study. MO, RL, NF programmed the experimental paradigm. MO, RL, NF analyzed the data. MMM received funding. MO, JM, and MMM wrote the manuscript.

Competing interests declaration

The authors declare no conflict of interest.

Context

The natural world contains a number of warning signals in bold colors, such as in red, which stand out in our vision. Stimulus-driven theories of attention claim that such salient features capture our attention automatically by producing an "attend-to-me" signal. But recent evidence suggests that foreknowledge of a feature (i.e., color) can be used to preempt this attentional 920 capture before it occurs. Behaviorally, this *signal suppression* has been shown when attentional measures for a predictable salient distractor were significantly reduced compared to other distracting stimuli in a search display. We show that this effect is better explained as an enhancement of other target-matching distractors, due to global feature-based facilitation. The results undermine central predictions of the signal suppression hypothesis, and constrain current theory regarding how observers deal with distraction in the visual environment.

47

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