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Passive Exposure Attenuates Distraction During Visual Search

Bo-Yeong Won and Joy J. Geng
University of California, Davis

Distractions are ubiquitous in our sensory environments. How do we keep them from capturing attention? Existing research has focused primarily on mechanisms of strategic control or statistical learning, both of which require knowledge (explicit or implicit) of what features *belong to distractors* before suppression occurs. Here, we test the hypothesis that *task-free exposure* to stimuli is sufficient to attenuate their effect as distractors later on. In 3 experiments, subjects were exposed to either colored or achromatic circles on "circle displays" interleaved with "target search displays." Later, new distractors were introduced into the search displays using colors from the circle displays. We consistently found that passively viewed colors produced less interference when introduced as new visual search distractors. We conclude that learning during passive exposure was due to habituation mechanisms that attenuate sensory responsivity to recurring stimuli, allowing attention to operate more efficiently to select task-relevant targets or novel stimuli.

Keywords: attention, distractor suppression, habituation, visual search

The world is filled with distractions, and the ability to ignore them is critical for goal-oriented behaviors to succeed. Two main theories exist within the literature for how attention attenuates distractor processing. The first hypothesizes that distractors are suppressed through "top-down" strategic control (Arita, Carlisle, & Woodman, 2012; Carlisle, Arita, Pardo, & Woodman, 2011). The second hypothesizes that distractor suppression occurs through statistical learning of experienced distractors (Chetverikov, Campana, & Kristjánsson, 2017; Ferrante et al., 2018; Geyer, Müller, & Krummenacher, 2006; Leber, Gwinn, Hong, & O'Toole, 2016; Stilwell & Vecera, 2019b; Vatterott & Vecera, 2012; Wang & Theeuwes, 2018; Won, Kosoyan, & Geng, 2019; Zhang, Allenmark, Liesefeld, Shi, & Müller, 2019). A core supposition of both is that distractor suppression occurs only after the observer has knowledge, explicit or implicit, of what defines a distractor within the current context. These theories imply that one must know what features *belong to distractors before* they can be suppressed. The current studies test a new hypothesis that attention to distractors may be attenuated, but not necessarily eliminated, by habituation, a nonassociative or *task-free* learning mechanism that reduces neural responses to stimuli based on passive exposure (Bonetti & Turatto, 2019; Chelazzi, Marini, Pascucci, & Turatto, 2019; Turatto, Bonetti, Pascucci, & Chelazzi, 2018).

Habituation is characterized by the progressive decrease in an orienting response to sensory stimulation that cannot be explained by sensory adaptation or fatigue (Gover & Abrams, 2009; Rankin et al., 2009; Sokolov, 1963; Thompson, 2009). Habituation is a form of nonassociative learning that is ubiquitous across species. It is hypothesized to serve as a precursor to other types of learning or sensory processing by filtering out stimuli that are irrelevant or unsurprising (Ramaswami, 2014). One potential importance for attention lies in its role as a "firewall" that "triages sensory information into actionable and non-actionable categories" (Poon & Young, 2006). In other words, habituation may reduce the amount of information that attention must adjudicate between by filtering stimuli that are predictably unimportant for behavior, leaving only more relevant or unpredicted stimuli for further processing. In natural environments where much information is stable over time, habituation can operate continuously to dampen responsivity to sensory noise and enhance attentional mechanisms to select targets and suppress specific distractors (Desimone & Duncan, 1995).

Although habituation mechanisms are ubiquitous across animal species, its effect on visual attention has been proposed only recently (Turatto & Pascucci, 2016). Turatto and colleagues reported habituation of oculomotor responses to recurring salient distractors (Bonetti & Turatto, 2019; Chelazzi et al., 2019; Turatto, Bonetti, & Pascucci, 2018; Turatto, Bonetti, Pascucci, et al., 2018). The results of these studies are analogous to the earliest studies of habituation on the motor orienting reflex (Barry, 2009; Harris, 1943; Sokolov, 1963; Thompson & Spencer, 1966) and suggest that habituation mechanisms contribute to learned distractor suppression. However, habituation was measured within the context of an active task in most of these studies, which left open the possibility that other mechanisms (e.g., associative or strategic

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Bo-Yeong Won, Center for Mind and Brain, University of California, Davis; Joy J. Geng, Center for Mind and Brain and Department of Psychology, University of California, Davis.

The data were presented at the 2019 annual meetings for the Vision Science Society and the Cognitive Neuroscience Society. All the data are available at https://osf.io/2qzt5/?view_only=368961f48f83451b83e31a6c0ada29e0.

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Bo-Yeong Won and Joy J. Geng developed the study concept and design, collected data, performed the data analysis and interpretation, and wrote the article. Both authors approved the final version of the article for submission.

Correspondence concerning this article should be addressed to Bo-Yeong Won, Center for Mind and Brain, University of California, Davis, 267 Cousteau Place, Davis, CA 95618. E-mail: bywon@ucdavis.edu

ones) also contributed to the behavioral effects. Only one study has provided direct evidence that habituation occurs with *passive exposure* to salient visual stimuli (Turatto, Bonetti, Pascucci, et al., 2018). In that study, observers were asked to passively view a series of displays, some of which included a salient (i.e., luminance onset) stimulus. When the salient stimulus later became a distractor during a target discrimination task, attentional capture was attenuated compared to when the displays were not first passively viewed. The authors concluded that the passive exposure habituated the visual system to the salient stimulus, which reduced its effective saliency as a distractor during a later active task.

Two questions remained, which are essential to understanding the contribution of habituation on distractor suppression. The first methodological issue is whether the habituation effects depended on the use of identical stimulus displays during passive exposure and the active task. Because the same stimuli were used during both, it is possible that surreptitious suppression of the salient stimulus during passive viewing led to direct benefits in suppression during the active task. The second theoretical issue relates to the presence of residual interference from the salient distractor once the active task started. The authors attributed the cost to changes in task demands when the active task began (e.g., adjusting to new stimulus-response mappings). An alternative possibility, however, is that the residual interference from previously habituated distractors reflects the true degree of stimulus attenuation afforded by habituation mechanisms for visual attention.

In order to address these two open questions, we use a novel two-phase paradigm. During the first "training" phase, observers were passively exposed to one set of colors on "circle displays" while actively learning about the target and another set of distractors on "visual search" displays. Importantly, we used nonsalient colors for all nontargets in order to reduce the possibility of active suppression that is often induced by salient bottom-up signals (Bravo & Nakayama, 1992; Koch & Ullman, 1985; Wolfe & Horowitz, 2017). The circle displays were also visually distinct (and retinotopically nonoverlapping) with the visual search displays, rendering confusion between the two unlikely. During the second "testing" phase, a subset of the "habituated" colors from the circle displays were introduced as new visual search distractors. Critically, the new visual search distractors only resembled the circle displays in terms of the color spectrum used (and not the shapes or stimulus locations), reducing the likelihood that the two stimulus displays would be directly associated (see Figure 1). Performance on *new* distractor visual search trials (with the habituated colors) was contrasted against a control group that only saw achromatic circles on "circle" displays during training. We hypothesized that the new distractors would produce less interference in the group that saw the color circles due to habituation.

Our experiments collectively address the first open question of whether habituation operates independently of active suppression (a) by using nonsalient passive displays that are interleaved with the active search task and have very different visual properties and (b) by directly asking observers to attend to a noncolor property of the circle displays (in Experiment 2). It also addresses the second open question regarding the source of previously observed residual interference of the habituated by holding task demands constant throughout the training and testing phases. This novel task affords measurement of the unique effect of prior exposure to colored stimuli on attentional interference by new distractors.

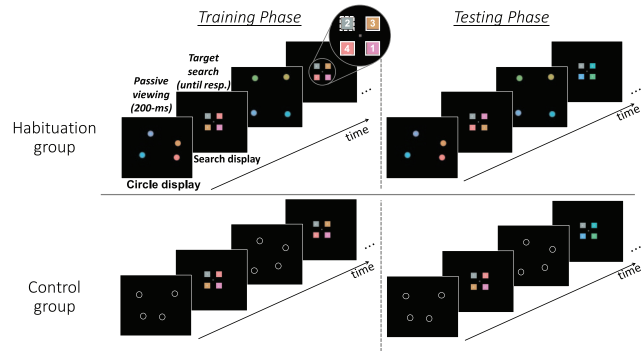

Figure 1. Illustration of trials from Experiment 1. Participants were asked to ignore circle displays but search for a gray square (target, dotted line) among colored squares (distractors, solid line) on visual search displays. In the habituation group, the circle displays had colored circles, and in the control group, the circle displays had unfilled circles. During training, the three colored distractors were always the same (*trained*). During testing, a *new* set of colored distractors was randomly interleaved with *trained* distractors (see text). The dotted line of target and the solid lines of distractors are for illustration purposes. See the online article for the color version of this figure.

General Method

Stimuli and Apparatus

Each participant sat in a sound-attenuated, dimly lit room, around 60 cm from the monitor. Stimuli were displayed on a 27-in. Asus LCD monitor (2,560 × 1,440 pixels, 60 Hz). Stimuli were generated using MathWorks with Psychtoolbox extensions (Brainard, 1997; Pelli, 1997).

Search displays. Search displays contained three colored squares (i.e., distractors) and a gray square (i.e., target). Colors for distractors were chosen from 16 equally spaced colors that only varied in hue (CIELAB space; $L^* = 70$, center: $a = 0$, $b = 0$, radius of 39; Table 1; Bae, Olkkonen, Allred, & Flombaum, 2015). The gray color for the target stimulus was generated by averaging all 16 distractor colors. During training (128 trials), a gray target appeared with three fixed distractors (colors 16, 2, 4 or 8, 10, 12 counterbalanced between subjects; Table 1).

During testing (256 trials), the same gray target appeared with one of three sets of distractors—*trained* (i.e., the same distractors seen during training), *trained-similar* (1, 3, 5 or 7, 9, 11), and *new* (8, 10, 12 or 16, 2, 4). *Trained* distractor displays appeared six times more frequently (192 trials) than the *trained-similar* or *new* distractor trials (32 trials each). The uneven distribution was used to maintain distractor expectations to minimize the immediate effect of active suppression on the *trained-similar* and *new* distractors.[1] The *trained-*

[1] In this study, we had all three sets of distractors to replicate our previous findings that *trained-similar* distractors were similarly suppressed with *trained* distractors ($ps > .3$; Won & Geng, 2018). However, because the main purpose of this experiment was to test if the interference from *new* distractors would be attenuated in the habituation group compared to the control group, we combined *trained-similar* distractors trials and *trained* distractors trials for the analyses. Note that the results were similar whether or not the *trained-similar* trials were combined with the *trained* distractor trials.

Table 1
Distractor Color Coordinates in CIELAB Color Space

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
a	39	36	28	15	0	−15	−28	−36	−39	−36	−28	−15	0	15	28	36
b	0	15	28	36	39	36	28	15	0	−15	−28	−36	−39	−36	−28	−15

similar condition was included to add variability in the distractor sets, but we expected learned suppression from the *trained* distractors to generalize to the *trained-similar* color set because of its similarity (Won & Geng, 2018). Each square subtended 1.1° × 1.1° of horizontal and vertical visual angle and was located in one of four quadrants and centered 1.80° of horizontal and vertical visual angle from the fixation cross. On each trial, each square was randomly assigned one number (1–4) drawn in white. The task was to manually report the number within the target. Auditory feedback was provided (a three-"chirp" sequence lasting 300-ms for correct responses; a single high-pitched 100-ms tone followed by an additional 3-s blank period for incorrect responses).

Circle displays. Circle displays contained four circles (diameter: 1.1°). Each circle was presented in one quadrant and randomly jittered between −.4° and +.4° of horizontal and vertical visual angle. The placement of each circle was randomly chosen among 12 locations. The 12 possible locations were drawn from a 4 × 4 grid (8.9° × 8.9°) that excluded the four most central locations (i.e., close to the fixation). The central locations were avoided because they overlapped with the visual search displays. The habituation group saw the four circles filled with four different colors chosen from 180 equally spaced colors that only varied in hue (the same parameters with those for distractor colors). In each display, each of four colors was at least 10 consecutive colors (20°) apart from each other in a color wheel that consisted of 180 colors to prevent color uniformity. For the control group, circles were not filled with any colors but just drawn with a white outline.

Analysis

Overall accuracy was high in all experiments (Experiment 1: habituation group: 97.8%, control group: 96.8%; Experiment 2: habituation group: 97.5%, control group: 96.9%; Experiment 3: habituation group: 96.7%, control group: 97.2%). We therefore only use reaction time (RT) data from testing trials in subsequent analyses to test our hypotheses regarding the attenuation of attention to *new* distractors in the habituation versus control groups. RTs were trimmed per person to exclude values within a condition greater than 3 standard deviations from the mean. We also provided the Bayes factors (BFs) that quantify the relative likelihood of obtaining the observed data under the null hypothesis compared to the alternative hypothesis (Rouder, Speckman, Sun, Morey, & Iverson, 2009). Evidence in favor of the null hypothesis is denoted as BF_{01}, and in favor of the alternative hypothesis as BF_{10}.

Experiment 1

Method

Participants. Forty undergraduates from the University of California, Davis (UC Davis) participated for course credit (habituation group: N = 20, mean age = 21.3 years, SD = 2.5, range = 18–27, 16 females, 0 left-handed; control group: N = 20, mean age = 20.5 years, SD = 1.9, range = 18–26, 20 females, 2 left-handed). The sample size of 20 was determined based on the previous study from which we adopted the experimental design (Won & Geng, 2018). All participants had normal or corrected-to-normal vision and provided informed consent in accordance with National Institutes of Health guidelines provided through the UC Davis Institutional Review Board.

Design and procedure. Each trial began with a 200-ms blank followed by 200-ms circle display, a 200-ms blank screen, a 200-ms fixation display, and then the target search display. Participants were instructed that there was no task associated with the circle displays and they could be ignored, but the central display of squares in the search displays was always task relevant. Participants were also told they should search for the gray square in the search display and report the number inside using the keyboard as rapidly as possible without sacrificing accuracy. The search display was removed immediately after response. Offset of the search display was followed by 200 ms of a white fixation and auditory feedback (see Figure 1).

Results

First, to test the hypothesis that the habituation group should experience less interference when *new* distractors are introduced, we directly compared search RT interference in the habituation and control groups using a one-tailed t test. The results were consistent with our hypothesis, showing the habituation group experienced significantly less interference than the control group from *new* distractors during testing, $t(38) = 2.214$, $p = .016$, Cohen's $d = .700$, $BF_{10} = 3.962$. Second, we tested the hypothesis that despite attenuation, the habituation group would continue to experience some interference. To test this, we compared the mean RT in each group against zero. We found a significant effect in both groups (habituation group: $t(19) = 2.443$, $p = .012$, Cohen's $d = .546$, $BF_{10} = 4.828$; control group: $t(19) = 3.764$, $p < .001$, Cohen's $d = .842$, $BF_{10} = 57.657$). These results are consistent with our hypotheses and demonstrate that interference from *new* distractors was attenuated following passive exposure but not eliminated (see Figure 2).

We next examined how interference from the *new* distractors changed as a function of direct experience. We hypothesized that interference would decrease over time in both groups, consistent with previous findings that statistical learning of distractor features can eliminate interference entirely (Vatterott, Mozer, & Vecera, 2018; Won et al., 2019). To test the effect of direct experience with *new* distractors on search interference in each group, the data from the testing phase were divided into four blocks and compared against zero. This resulted in statistically significant (nonzero) interference in Blocks 1 and 2 but not in Blocks 3 and 4 in the

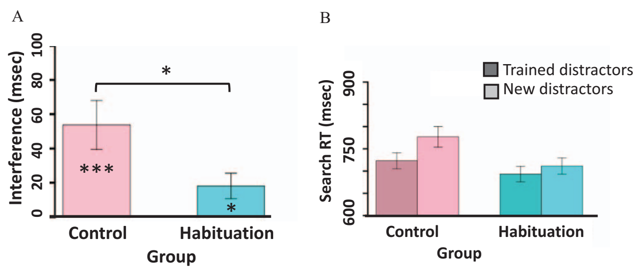

Figure 2. Results from Experiment 1. (A) Search interference (i.e., search reaction time [RT] to *new* distractors minus search RT to *trained* distractors) in the habituation and control groups. Greater distractor interference was found by *new* distractors in the control than habituation group, but both groups experienced significant interference. (B) Search RT to *trained* and *new* distractor visual search trials in the control and habituation groups. Error bars show ± between-subjects standard error of the mean. * $p < .05$. *** $p < .001$. See the online article for the color version of this figure.

habituation group (first block: $t(19) = 2.059$, $p = .027$, Cohen's $d = .460$, $BF_{10} = 2.549$; second block: $t(19) = 2.248$, $p = .018$, Cohen's $d = .503$, $BF_{10} = 3.466$; third block: $t(19) = .043$, $p = .483$, $BF_{01} = 4.165$; fourth block: $t(19) = .779$, $p = .223$, $BF_{01} = 2.145$). There was more than four times the evidence for the null than the alternative hypothesis in Block 3 and two times in Block 4. In contrast, all four blocks in the control group were significant, although the BFs indicate that evidence for a difference decreased over time (first block: $t(19) = 3.475$, $p = .001$, Cohen's $d = .777$, $BF_{10} = 32.646$; second block: $t(19) = 2.852$, $p = .005$, Cohen's $d = .638$, $BF_{10} = 10.002$; third block: $t(19) = 3.098$, $p = .003$, Cohen's $d = .693$, $BF_{10} = 15.841$; fourth block: $t(19) = 1.905$, $p = .036$, Cohen's $d = .426$, $BF_{10} = 2.005$).

These results suggest that direct experience with the *new* distractors led to continued attenuation of interference from those distractors in both groups. However, because the habituation group began the testing phase with less interference by the *new* distractors, interference was completely eliminated after two blocks of active experience. The interference was never eliminated in the control group, but there was a steady decline in the degree of interference. This continued attenuation can be seen in the reduction of evidence in favor of the alternative hypothesis over each block, ranging from very strong evidence in Block 1 to weak evidence in Block 4 (see Figure 3).

Experiment 2

Experiment 1 showed that passive exposure to colors in circle displays attenuated interference from *new* distractors in subsequent active visual search. However, it is possible that our instruction to ignore the circle displays might have encouraged participants to surreptitiously and actively suppress the circle displays, including the colors—a behavior we wished to avoid. To rule out the possibility of surreptitious suppression of the circle colors, we asked participants to count the number of circles in the circle displays. The counting task forced observers to attend to the circles but not to their colors. To preview the results, we replicated the results from Experiment 1, suggesting that the attenuation of interference in the habituation group is not due to a surreptitious "active suppression" of stimuli but rather due to the passive processing of colors.

Method

Participants. Forty undergraduates (20 each group) from UC Davis (habituation group: $N = 20$, mean age = 19.8 years, $SD = 1.5$, range = 18–24; 17 females, 1 left-handed; control group: $N = 20$, mean age = 21.0 years, $SD = 3.5$, range = 18–33; 14 females, 2 left-handed) participated for course credit.

Design and procedure. Everything was identical to Experiment 1 except that the circle display was occasionally (12.3% of trials, 54 trials) followed by a number question that asked how many circles (three, four, or five) were present in the preceding display in the training and testing phases. The search display was identical to Experiment 1 in the remaining trials (87.7%, 384 trials; Figure 4).

Results

Counting accuracy. The accuracy of the counting task did not differ between groups (habituation group: 92.1%; control group: 89.7%), $t(38) = .825$, $p = .414$, $BF_{01} = 2.471$, suggesting a similar degree of attention paid to the colored and achromatic circles.

Mean RT. Similar to Experiment 1, we first tested RT interference between groups and found a significant difference, $t(38) = 2.011$, $p = .026$, Cohen's $d = .636$, $BF_{10} = 2.838$ (see Figure 5). In replication of Experiment 1, the attenuation of interference in the habituation group was stronger than in the control group. To quantify this expected null difference, we compared the magnitude of interference between experiments using Bayesian analysis of variance (ANOVA; JASP Version 0.11.1). We specified the alternative model with RT interference as the dependent variable, with group (control and habituation) and experiment (exp1 and exp2) and their interaction as fixed factors. The null model only included the factor of group (control, habituation), which was significant in both experiments (see above). The default prior for fixed effects (.5) was used. The results found no evidence for a between-

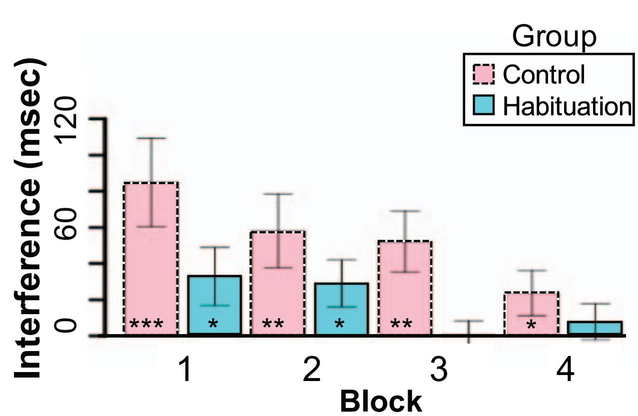

Figure 3. Experiment 1 search reaction time (RT) interference (RT *new* minus RT *trained*) across four blocks in the two groups. Error bars show ± between-subjects standard error of the mean. * $p < .05$. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

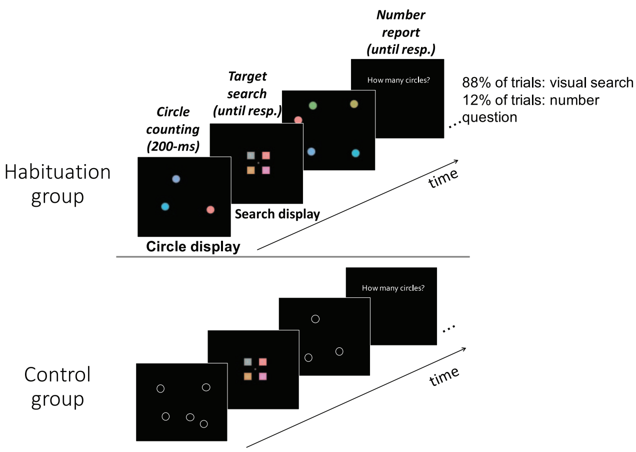

Figure 4. An example of a two-trial sequence from Experiment 2. The first trial was composed of a circle display followed by a search display (identical to Experiment 1). On the second trial, the circle display was followed by a question regarding the number of circles on the previous display. This task ensured attention to the circle display as a whole without attention specifically to the color of the stimuli. Because the number questions occurred randomly, participants had to count circles on every circle display to perform well. Top: example trials from the habituation group; bottom: example trials from the control group. See the online article for the color version of this figure.

experiments interaction ($F < 1$, $p = .574$, $BF_{01} = 12.167$). Moreover, the BF indicates there is more than 12 times the evidence for the null model than the alternative, suggesting that the effect of group on the magnitude of *new* distractor interference did not differ across experiments. This result demonstrates that the attenuation of interference was equivalent between experiments, rendering the possibility that the results from Experiment 1 were due to surreptitious active suppression of colored circles in the circle displays unlikely.

Next, we compared RT interference in each group against zero to test the hypothesis that there would be residual interference in the habituation condition. Consistent with this, we again found strong evidence for significant interference by *new* distractors in both groups (habituation group: $t(19) = 3.180$, $p = .002$, Cohen's $d = .711$, $BF_{10} = 18.494$; control group: $t(19) = 4.829$ $p < .001$, Cohen's $d = 1.080$, $BF_{10} = 484.879$).

RT across blocks. We next examined RT interference in each group across blocks in order to test if distractor attenuation increases with experience of the *new* distractors. The habituation group experienced significant interference in Blocks 1 and 2, but examination of the BFs suggests caution in interpretation since evidence for either the alternative or null hypothesis in each block was weak (first block: $t(19) = 1.709$, $p = .052$, Cohen's $d = .382$, $BF_{10} = 1.496$; second block: $t(19) = 2.646$, $p = .008$, Cohen's $d = .592$, $BF_{10} = 6.894$; third block: $t(19) = 1.650$, $p = .058$, Cohen's $d = .369$, $BF_{10} = 1.374$; fourth block: $t(19) = 1.612$, $p = .062$, Cohen's $d = .360$, $BF_{10} = 1.301$). Altogether, the results suggest that there was little to no interference across all four blocks. The control group showed significant interference in Blocks 1–3 (first block: $t(19) = 3.745$, $p < .001$, Cohen's $d = .837$, $BF_{10} = 55.495$; second block: $t(19) = 2.662$, $p = .008$, Cohen's $d = .595$, $BF_{10} = 7.095$; third block: $t(19) = 3.626$, $p < .001$, Cohen's $d = .811$, $BF_{10} = 43.953$; fourth block: $t(19) = 1.223$, $p = .118$, Cohen's $d = .274$, $BF_{01} = 1.288$). The pattern of results again suggests that RT interference decreased over time, consistent with the notion that learned distractor suppression operates over and above that of habituation alone (see Figure 6).

Experiment 3

In the previous two experiments, we found that passive exposure to colors in the circle displays attenuated, but did not eliminate, interference from *new* distractors in later visual search displays. However, because the colors of circle displays were randomly chosen from the entire range of the color wheel, only a subset of circle displays contained colors that matched the *new* distractors; this might have resulted in relatively weak habituation (therefore leaving residual interference). If more frequent and specific exposure to colors that match new distractors during training leads to stronger habituation, then using a narrower set of circle colors should lead to greater suppression of *new* distractors later on during the testing phase. Additionally, to confirm that habituation only occurs for the seen colors and does not generalize from very different colors (i.e., preserves stimulus specificity; Rankin et al.,

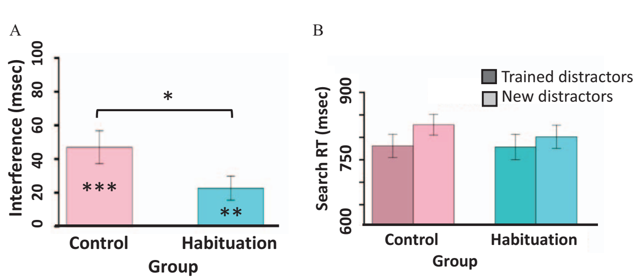

Figure 5. Results from Experiment 2. (A) Search interference (reaction time [RT] difference between *trained* and *new* distractors) in Experiment 2. (B) Search RT to *trained* and *new* distractor visual search trials in the control and habituation groups. Error bars show ± between-subjects standard error of the mean. * $p < .05$. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

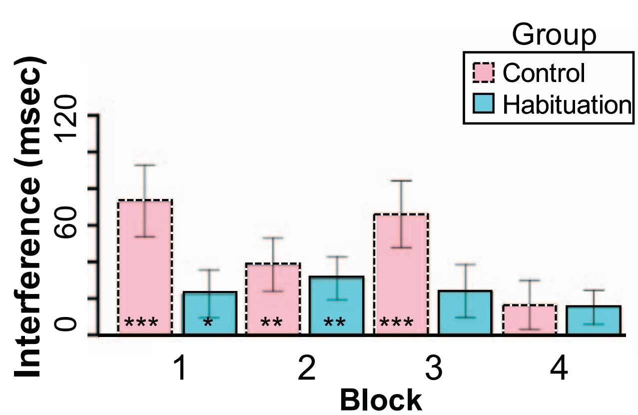

Figure 6. Experiment 2 search interference across four blocks. Error bars show ± between-subjects standard error of the mean. * $p < .05$. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

2009), we added colors to the control group circle displays that matched the *trained* distractors (see Figure 7). We hypothesized that the habituation group would experience less interference from *new* distractors than the control group, in replication of Experiments 1 and 2.

Method

Participants. Forty undergraduates (20 each group) from UC Davis (habituation group: N = 20, mean age = 21.7 years, SD = 2.2, range = 19–26; 14 females, 0 left-handed; control group: N = 20, mean age = 21.5 years, SD = 2.9, range = 18–29; 9 females, 1 left-handed) participated for course credit.

Design and procedure. Everything was identical to Experiment 1 except that the colors of circles in the circle displays were chosen from a limited range (see Figure 7). Each of four colors in the circle display was at least 8 consecutive colors (16°) apart from each other in a color wheel that consists of 180 colors. During the training phase, the habituation group only saw circle displays with colors from a restricted range opposite to *trained* visual search distractors. The colors seen by the habituation group overlapped with future *new* distractors. The control group saw circle displays with colors from a restricted range that overlapped with the *trained* and *trained-similar* distractor sets. As in the previous experiments, there was no difference in performance between the *trained* and *trained-similar* distractors, and therefore the data were collapsed. The distractors in visual search displays were identical to those in previous experiments.

Results

Mean RT. Similar to previous experiments, we first compared RT interference directly between groups and again found less interference from *new* distractors in the habituation group compared to the control group, $t(38) = 3.007$, $p = .002$, Cohen's d = .951, $BF_{10} = 17.909$ (see Figure 8). Importantly, we again replicate the finding that there was residual interference in the habituation group: Both groups showed significant interference from *new* distractors compared to zero (habituation group: $t(19) = 3.154$, $p = .003$, Cohen's d = .705, $BF_{10} = 17.615$; control group: $t(19) = 6.176$, $p < .001$, Cohen's d = 1.381, BF_{10} = 6,795.112).

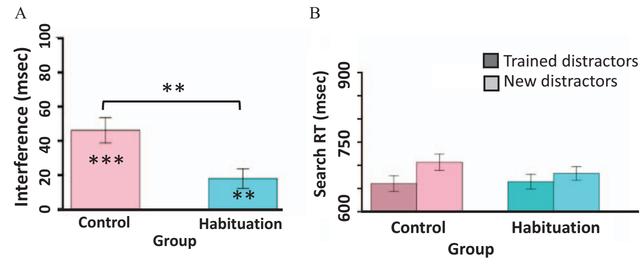

Figure 8. Results from Experiment 3. (A) Search interference (reaction time [RT] difference between *new* distractors and *trained* distractors) in the two groups. (B) Search RT to *trained* and *new* distractor visual search trials in the control and habituation groups. Error bars show ± between-subjects standard error of the mean. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

In order to quantify the similarity of the results with Experiments 1, we compared the magnitude of attenuation to *new* distractors between experiments by using a Bayesian ANOVA with factors experiment (exp1, exp3) and group (control, habituation). The interaction was not significant, suggesting a comparable magnitude of attenuation in the habituation group compared to the control group between experiments, $F < 1$, $p = .693$, BF_{01} = 11.701. The BF, which compared the full model against a null model that included only the factor of group, indicates more than 11 times the evidence for the null model. This suggests that the effect of group on the magnitude of *new* distractor interference did not differ across experiments. A similar result was found when comparing interference between Experiments 2 and 3 ($F < 1$, p = .796, BF_{01} = 12.970).

The fact that there is residual interference following habituation even when habituation training was increased, and that the size of interference did not differ between experiments, suggests that habituation mechanisms in this task may afford some attenuation but not complete elimination of interference from *new* distractors.

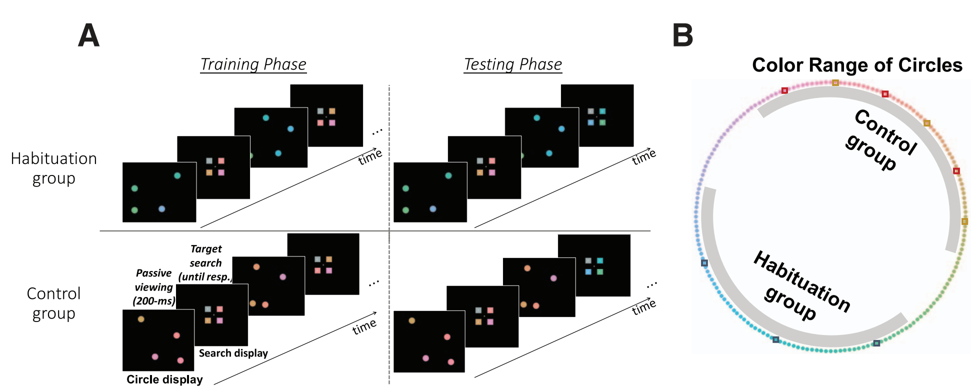

Figure 7. Experiment 3 trial procedure. (A) An example of a two-trial sequence illustrating the circle displays for both groups. (B) The color wheel used in three experiments. The gray band indicates the range of colors used for the circle displays in the habituation and control groups; dark gray squares indicate new distractor colors; red squares (darker gray) indicate *trained* distractor colors; orange squares (light gray) indicates *trained-similar* distractor colors. See the online article for the color version of this figure.

RT across blocks. As in the previous experiments, we next examined whether the residual interference in the habituation group to *new* distractors decreased with active experience. Comparison of RT interference in each group against zero resulted in significant effects only in the first two blocks in the habituation group (first block: $t(19) = 2.034$, $p = .028$, Cohen's $d = .455$, $BF_{10} = 2.451$; second block: $t(19) = 2.699$, $p = .007$, Cohen's $d = .604$, $BF_{10} = 7.577$; third block: $t(19) = 1.436$, $p = .084$, Cohen's $d = .321$, $BF_{10} = 1.022$; fourth block: $t(19) = .940$, $p = .179$, Cohen's $d = .210$, $BF_{01} = 1.800$). This is consistent with the notion that direct experience with the *new* colored stimuli as active distractors led to additional suppression. In contrast, interference was significant in all blocks in the control group, although the strength of evidence for a difference also decreased over blocks (first block: $t(19) = 4.542$, $p < .001$, Cohen's $d = 1.016$, $BF_{10} = 272.886$; second block: $t(19) = 2.985$, $p = .004$, Cohen's $d = .667$, $BF_{10} = 12.792$; third block: $t(19) = 4.193$, $p < .001$, Cohen's $d = .938$, $BF_{10} = 135.570$; fourth block: $t(19) = 2.925$, $p = .004$, Cohen's $d = .654$, $BF_{10} = 11.452$). This pattern converges with Experiments 1 and 2, suggesting that passive exposure to the circle displays resulted in attenuated distractor interference but that the elimination of interference only occurred with continued exposure to the colors as active distractors within the visual search task (see Figure 9).

Discussion

The primary question of interest addressed in these studies was whether passive exposure to circle displays containing nonsalient colored stimuli would attenuate interference by those colors when they later appeared as distractors in visual search. The circle displays were constructed to be dissimilar from visual search displays by using objects of different shapes and presented in different configurations and at different visual eccentricities. The colors were also heterogenous and nonsalient. The purpose of using these displays was to minimize the likelihood that observers would actively suppress the stimuli (e.g., by confusing them with distractors or in response to automatic bottom-up capture) and prevent retinotopic sensory adaptation. In all three experiments, we found positive evidence that passive exposure to colored stimuli reduced, but did not fully eliminate, behavioral interference when they later appeared as distractors. This suggests that habituation mechanisms during passive exposure reduced sensory responsivity and thus attentional priority to those colors when they became task-relevant distractors. Our results are novel and go beyond previous studies in several ways.

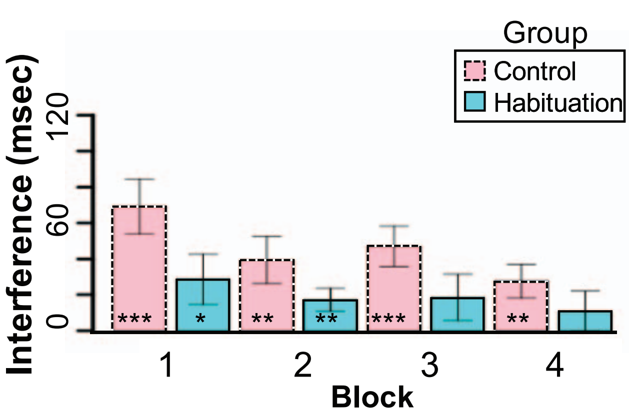

Figure 9. Search interference across four blocks in Experiment 3. Error bars show ± between-subjects standard error of the mean. * $p < .05$. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

First, we introduce a novel paradigm and find consistent evidence that attention is attenuated to nonsalient colored distractors that were previously seen in a task-free context. Previous studies of habituation on visual attention used salient nontargets defined by luminance, and the current data extend those findings to a new feature domain. Thus, habituation appears to operate on nonsalient stimuli seen in task-irrelevant contexts, suggesting that it might play an important ongoing role in natural vision where most stimuli tend to be nonsalient, are stable over space and time, and maintain their status as behaviorally irrelevant (e.g., imagine in an auditorium, the seating, carpet, and walls). Habituation might operate rapidly on those stimuli and, by doing so, "triage" the vast majority of visual information from continued processing, allowing selective attention to operate on a smaller subset of plausibly important information.

Second, our results shed new light on interpretation of persistent distractor costs following habituation. All three studies found (approximately 20 ms) residual interference following habituation, which suggests that habituation following passive exposure attenuates but does not completely eliminate attentive processing of perceptual stimuli. Similar findings have been reported in the visual (Turatto, Bonetti, Pascucci, et al., 2018) as well as auditory domains (Bell, Röer, Dentale, & Buchner, 2012). For example, Turatto, Bonetti, Pascucci, et al. (2018) observed an initial RT cost that lasted for up to 10 trials following passive exposure to salient distractors. However, because their task required a change in performance demands between the period of passive exposure (no response required) and active discrimination (task response required), they attributed the remaining cost to changes in stimulus-response requirements. In our study, it was unnecessary to implement new stimulus-response mappings since the only thing that changed was the appearance of distractor colors. The fact that a performance cost remained argues that habituation following passive exposure in our training task did not completely wipe out distraction by new distractor stimuli but did attenuate priority compared to the same stimuli without prior exposure. Interference was only resolved completely after the testing phase began, which included active experience with the *new* distractors as well as continued exposure to the circle displays. This indicates that while habituation can occur during both passive and active tasks, the effect of habituation following passive exposure may be either weaker than under active tasks or that maximum suppression relies on the contribution of other mechanisms engaged during active tasks (Geng, Won, & Carlisle, 2019).

Third, we introduced an active dual-task during the circle displays in Experiment 2 to test if habituation to color would occur even when subjects attend to the number of circles in the display. The circle counting task ensured that subjects attended actively to the display as a whole, which precludes the ability to suppress the circle stimuli but also left the color feature dimension of each circle irrelevant. The fact that we continued to see a similar magnitude of distractor attenuation for the habituated colors between Experiment 1 and Experiment 2 suggests that it is the task irrelevance of the colors that led to habituation, not that they were viewed during a passive exposure in Experiment 1. The results also suggest that irrelevant features in one context might continue to be tagged as irrelevant in the next unless there is evidence to the contrary.

Finally, our results demonstrate that habituation was specific to the exposed stimulus colors, which is predicted by models of habituation (Thompson, 2009). In Experiment 3, the habituated color stimuli on circle displays during training were limited to a specific range (e.g., bluish) and kept separate from the *trained* distractors (e.g., reddish) in the habituation group. The control group also saw colored habituation displays, but the colors were in the same range as the *trained* distractors. We found that attention to *new* distractors was attenuated only in the habituation group that saw passive circle display colors that overlapped with *new* distractors. However, the fact that we also observed habituation effects in the first two studies with variable colors suggests that habituation might flexibly occur at different levels of sensory processing depending on the statistics of exposure—for example, occurring at the level of a feature dimension (Müller, Heller, & Ziegler, 1995) or a specific stimulus. Such flexibility has been observed in statistical learning paradigms of distractor suppression (Stilwell & Vecera, 2019a; Vatterott et al., 2018; Vatterott & Vecera, 2012; Won et al., 2019). Interestingly, however, the attenuation of *new* distractors was not stronger in Experiment 3 than in the Experiment 1, suggesting that simply seeing more specific habituation displays did not immediately increase suppression. However, it is possible that longer or more specific habituation training could have led to stronger suppression, and this is a question of active investigation.

The current work provides clear evidence of a role for passive exposure, presumed to be supported by habituation mechanisms, in efficient attentional processing (Bonetti & Turatto, 2019; Turatto, Bonetti, & Pascucci, 2018; Turatto, Bonetti, Pascucci, et al., 2018; Turatto & Pascucci, 2016). Habituation may serve as an early filter that attenuates processing of previously encountered sensory information that did not elicit attentive processing or a behavioral response (Gover & Abrams, 2009; Poon & Young, 2006; Rankin et al., 2009; Yamaguchi, Hale, D'Esposito, & Knight, 2004). This characterization relates to recent models of predictive coding (Auksztulewicz, Friston, & Nobre, 2017; Friston, 2012; Parr & Friston, 2018)—both theorize that neurons encode a model of the expected relevance of stimuli. The relationship between habituation and predictive coding has yet to be explored but will be important for understanding how passive exposure improves attentional selection. In sum, our data suggest that habituation aids attentive processing by "triaging" sensory information and providing a less crowded "stage" on which more cognitively intensive attentional mechanisms may operate to adjudicate between remaining competing stimuli.

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