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Distractor ignoring is as effective as target enhancement when incidentally learned but not when explicitly cued

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Abstract

Explicit knowledge about upcoming target or distractor features can increase performance in tasks like visual search. However, explicit distractor cues generally result in smaller performance benefits than target cues, suggesting that suppressing irrelevant information is less effective than enhancing relevant information. Is this asymmetry a general principle of feature-based attention? Across four experiments (N = 75 each) we compared the efficiency of target selection and distractor ignoring through either incidental experience or explicit instructions. Participants searched for an orientation-defined target amidst seven distractors—three in the target color and four in another color. In Experiment 1, either targets (Exp. 1a) or distractors (Exp. 1b) were presented more often in a specific color than other possible search colors. Response times showed comparable benefits of learned attention towards (Exp. 1a) and away from (Exp. 1b) the frequent color, suggesting that learned target selection and distractor ignoring can be equally effective. In Experiment 2, participants completed a nearly identical task, only with explicit cues to the target (Exp. 2a) or distractor color (Exp. 2b), inducing voluntary attention. Both target and distractor cues were beneficial for search performance, but distractor cues much less so than target cues, consistent with previous results. Cross-experiment analyses verified that the relative inefficiency of distractor ignoring versus target selection is a unique characteristic of voluntary attention that is not shared by incidentally learned attention, pointing to dissociable mechanisms of voluntary and learned attention to support distractor ignoring.

Keywords Enhancement · Suppression · Voluntary attention · Selection history · Visual search

Introduction

Selective attention involves both selecting relevant information and ignoring irrelevant information. Historically, attention research has predominantly focused on understanding the mechanisms underlying attentional enhancement, but more recently, many studies have focused on investigating how task-irrelevant and distracting information is voluntarily suppressed. One common paradigm used to study distractor ignoring is a modified visual search task in which participants are explicitly told the feature of an upcoming nontarget item. This cueing of distractor features can lead to search benefits compared with not presenting a cue (Arita et al., 2012; Cunningham & Egeth, 2016; Reeder et al., 2017).[1] However, the benefits tend to be smaller relative to when targets are explicitly cued (Addleman & Störmer, 2022; Arita et al., 2012; Beck & Hollingworth, 2015, Exp. 1: Carlisle & Nitka, 2019). These and other results have led to the proposal that ignoring irrelevant information is not just the inverse of attending towards relevant information (Chelazzi et al., 2019) and may rely on distinct mechanisms (van Moorselaar & Slagter, 2020) with distinct behavioral effects (Geng et al., 2019).

Attentional biases do not only arise from explicit cueing; people can also incidentally learn to guide attention based on experience, without instructions to do so. For example, people bias their attention towards frequent target features (Sha et al.,

Significance Searching for a task-relevant item, whether a lost wallet or a tumor on a CT scan, involves both looking for what we care about and ignoring potential distractions. Past work shows that voluntarily attempting to suppress potential distractors is difficult to do well, often yielding no benefits in a task compared with knowing nothing about upcoming distractors. Here, we show that this difficulty can be avoided when someone learns to ignore distraction via incidental experience rather than explicit goals. These results can inform how we train people to avoid distraction in tasks including driving safety and medical image perception.

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[1] The same pattern has been reported for cueing distractor locations (e.g., Chao & Yeh, 2005; Munneke et al., 2008) rather than nonspatial features, but in the present paper we focus on the effects of feature-based attention.

2017) and away from frequent distractor features (Stilwell et al., 2019; Stilwell & Vecera, 2019a, 2019b; Vatterott & Vecera, 2012), even in the absence of explicit information about these statistical regularities in the display. Studies of feature-based ignoring have often used the additional singleton paradigm developed by Theeuwes (1992). In this paradigm, participants typically search for a shape singleton (e.g., a diamond among circles) and report the orientation of a line within the shape. On some trials all items could be in one color (distractor absent trials), and on other trials one distractor could be in a unique color (salient distractor present trials). The typical additional singleton finding is that this distractor slows search considerably, but recent studies have demonstrated that this distraction effect can be reduced with experience (Stilwell and Vecera, 2019b; see Wang & Theeuwes, 2018, for similar effects of learned spatial ignoring). These findings show that incidental experience, in addition to explicit cueing, shapes both target and distractor processing.

Despite known effects of experience on selection and ignoring, it is unclear how the effectiveness of learned feature-based ignoring compares to learned feature-based selection. Some evidence suggests that ignoring distractors based on statistical regularities (learned ignoring) may be more effective than when participants are explicitly cued to ignore a distractor (voluntary ignoring). In one example, after people incidentally learned to effectively suppress a specific color during search without instructions to do so, cueing the to-be-ignored color explicitly actually reduced the behavioral benefits of ignoring (Stilwell & Vecera, 2019a). A similar study combined explicit cues to one consistent distractor color with incidental experience rejecting a different distractor color and showed that learned ignoring may be more efficient than cued ignoring, at least when both are present in a single task (Stilwell & Vecera, 2019b). These results suggest that learning may be a more effective route to ignoring than explicit cueing. However, it is difficult to know if these differences are intrinsic to feature-based ignoring in general, because these studies combined an initial learning phase with explicit cueing later in the same task. Thus, learning in the first phase could influence the use or effectiveness of the cue in the second phase; furthermore, people had different amounts of overall visual search experience in each phase, which could at least partially explain differences in effectiveness between learning and explicit cueing.

Ultimately, understanding the relationships between mechanisms of selection and ignoring is difficult without direct comparisons across experiments using the same experimental paradigm. Thus, in the present study we systematically compare the effectiveness of learned and voluntary target selection and distractor ignoring using large samples that lend themselves to cross-experiment analyses (N = 75 in each of four experiments). All experiments used the same visual search task, differing only in what and how information about the upcoming search colors were provided. In Experiment 1, either targets (Exp. 1a) or distractors (Exp. 1b) were more likely to appear in one particular color, probing learned selection and ignoring, respectively. In Experiment 2, explicit cues provided information about the likely color of targets (Exp. 2a) or distractors (Exp. 2b). To maximize the similarity across experiments, frequent colors were kept constant throughout each experiment, meaning the same color was cued on every trial for participants in Experiment 2 (this color varied across participants).[2] Thus, Experiment 2 differs from Experiment 1 only in that participants are explicitly told the frequent color. To preview our results: Voluntary ignoring of distractors had smaller response time benefits than voluntary target selection, whereas learned selection and ignoring led to comparable response time benefits, with effect sizes smaller than voluntary target selection but larger than voluntary ignoring.

Experiment 1: Learned target selection and learned distractor ignoring

Experiment 1 investigated whether visual search would benefit from selecting (Exp. 1a) or ignoring (Exp. 1b) specific colors more often than others. Participants searched for an orientation-defined colored target and throughout the experiment, unbeknownst to the participants, either the target would appear more often in one color (Exp. 1a) or distractors would appear more often in one color (Exp. 1b). The main question was whether, and to what degree, search performance would be affected by these probabilities despite the lack of explicit instructions about them.

Method

The design, sample size, and analyses plan of Experiment 1 were preregistered (https://aspredicted.org/9ty9y.pdf).

Participants

We collected data from a large, preregistered number of participants in each version of Experiment 1 (N = 75 in each of Exps. 1a and 1b). We collected data until we had 75 participants in each experiment that passed our preregistered inclusion criteria: participants must complete the experiment in

[2] This decision means Experiment 2 combines effects of voluntary attention with potential learning of the consistent cue color. In our view, this decision allows us to measure the strongest version of voluntarily guided feature-based attention, as past work has shown that constant cues yield larger effects than ones varying from trial to trial (Cunningham & Egeth, 2016). We have data from a similar experiment using cues varying from trial to trial in a previously published paper (Addleman & Störmer, 2022), which we compare to the present data in the Cross-Experiment Analyses section.

under 90 minutes, have at least 80% accuracy in each experimental block, and have no more than 10% of trials with outlier response times faster than 200 ms or slower than 4 s. We excluded data from 10 participants in Experiment 1a (two for taking longer than 90 minutes and eight for accuracy below 80% in any experimental block) and data from 16 participants in Experiment 1b (four for taking longer than 90 minutes and 12 for accuracy below 80% in any experimental block). Experiment 1a included 53 women, 21 men, and one nonbinary person with a mean age of 20.2 years (range: 18–29 years). Experiment 1b included 60 women, 12 men, and three people who declined to report their gender, with a mean age of 20.5 years (range: 18–32 years).

All experiments recruited participants who volunteered for extra course credit via online subject pools at the University of California, San Diego, and Dartmouth College. Participants provided informed consent before participating, and experiments were approved by the UCSD and Dartmouth Institutional Review Boards. Participants completed the experiment in a web browser on their own computers (capable of displaying the full 600 × 600-pixel experimental display window).

Stimuli

A black fixation cross was present at the center of the 600 × 600 display window throughout the task. Search items were rings 90 pixels in diameter (~1 degree visual angle viewed at 60 cm from a 13-inch MacBook Pro), with 15 pixel line thickness and a 5 pixel gap at their top, bottom, left, or right (see Fig. 1, left). Each display had seven distractors (defined as items with top or bottom gaps) and one target (right or left gap). Search items were presented along an invisible ring 300 pixels in diameter, with an item at the top of the ring and additional items at 45-degree intervals. For each participant, a random color was chosen from a color circle in CIE L*a*b space (radius 49, centered at L = 45, a = 21.5, b = 11.5; Suchow et al., 2013), and this color plus three additional colors at 90 degree intervals along the color wheel were chosen as search item colors for that participant (for an example, see Fig. 1, right). Each search display contained two of these colors, with four items in each of the two colors. We call the color that the target and three distractors were presented in the "target color," and the color of the four other distractors the "distractor color." These colors were randomized across the item locations on each trial.

Procedure

Each trial began when participants pressed the "down" arrow key, 500 ms after which the stimulus array appeared until a response was made. Participants searched for the item with a rightward or leftward gap and reported its gap location using the "left" and "right" arrow keys. We instructed participants to emphasize both speed ("Please do your best to keep your responses under 1.5 seconds") and accuracy. Speed and accuracy feedback followed each trial.

After five fully random practice trials, participants completed 648 trials presented in six 108-trial blocks. The first four of these blocks ("training blocks") presented either targets (Exp. 1a) or distractors (Exp. 1b) in one of the four colors on 75% of trials, randomly determined for each participant but kept constant throughout the task. This resulted in 75% "valid" trials in which the target (Exp. 1a; distractor in Exp. 1b) appeared in the frequent color, 17% "neutral" trials in which the frequent color was absent from the display, and 8% "invalid" trials in which the cue was inaccurate (the frequent target color appearing as the distractor color in Exp. 1a, or the frequent distractor color appearing as the target color in Exp. 1b). These proportions were fully counterbalanced within each training block and are consistent with requiring 75% valid trials (and randomly assigning another color to appear alongside the frequent color), and on the remaining 25% of trials randomly assigning target (Exp. 1a; or distractor in Exp. 1b) colors from among the other three colors (with another random color also shown).

The last two experimental blocks ('testing blocks') removed the statistical manipulation, so targets and distractors appeared equally often in all four colors. The intention of these blocks was to evaluate evidence for the persistence of learning (as in Jiang et al., 2013). However, the question of persistence is not central here, as we are mostly interested in comparing learned versus voluntary attention, and so for clarity's sake we report only data from the training phase in the main text. Testing phase data is reported in the Supplementary Material and generally shows the same pattern as training phase data, only with smaller effects. This is consistent with partial, but not complete, extinction of learned attention over time.

Results

Experiment 1a: Learned target color

When 75% of targets appeared in one color (Fig. 2a), there was an effect of target color on mean RT, $F(2, 148) = 23.31$, $p < .001$, $\eta_p^2 = .24$. All conditions differed from each other as confirmed by dependent-samples t tests, with valid trials fastest (mean RT = 971 ms, SE = 21 ms), followed by neutral trials (mean = 1,005 ms, SE = 22 ms) and then invalid trials (mean = 1,049 ms, SE = 26 ms). Table 1 summarizes data and the results of statistical tests from training phases of all experiments.

Experiment 1b: Learned distractor color

When 75% of distractors appeared in one color (Fig. 2b), there was an effect of distractor color on mean RT, $F(2, 148) = 14.06$, $p < .001$, $\eta_p^2 = .16$. All conditions differed from each

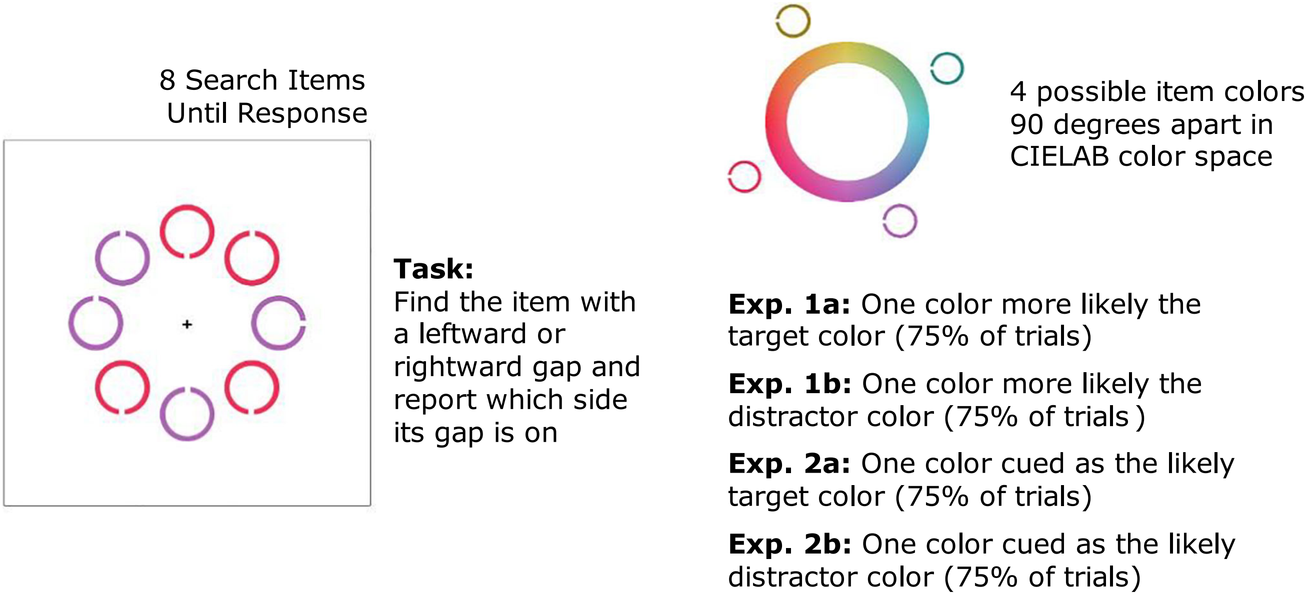

Fig. 1 Left: An example stimulus array. Participants searched among eight items for a target with a rightward or leftward gap and reported the gap location using the left and right arrow keys. Distractors had gaps on the top or bottom. Two colors appeared on each trial: the target and three distractors in the "target color" and four distractors in the "distractor color." Right: For each participant, a random color was chosen from a 360-degree wheel of CIELAB color space, which was used along with three other colors each 90 degrees apart from each other in color space. Then, one of these colors was chosen to frequently be the target color (Exp. 1a) or the distractor color (Exp. 1b), on 75% of trials. In Experiment 2, that frequent color was cued as the frequent target color to attend towards (Exp. 2a) or the frequent distractor color to ignore (Exp. 2b) and remained the same throughout the experiment for each participant. (Color figure online)

other as confirmed by dependent-samples *t* tests (Table 1), with valid trials fastest (mean RT = 994 ms, *SE* = 24 ms), followed by neutral trials (mean = 1,024 ms, *SE* = 24 ms), and then invalid trials (mean = 1,050 ms, *SE* = 27 ms). See Table 1 for a detailed summary of all results.

Discussion

Experiment 1 shows clear benefits for visual search when targets or distractors appeared in the more frequent target or distractor colors, respectively. This suggests that attention can

Table 1 Summary of the data analyses across all experiments

Experiment	*df*	Mean RT Difference (ms)	Test Statistic	*p* value	Effect size
Experiment 1a F-test	**2, 148**	**n/a**	**23.31**	**<10e-9*****	**.24**
1. Valid vs. Neutral	74	34	4.15	<10e-5***	0.48
2. Valid vs. Invalid	74	78	5.58	<10e-7***	0.64
3. Neutral vs. Invalid	74	44	3.85	<.001***	0.44
Experiment 1b	**2, 148**	**n/a**	**14.06**	**<10e-6*****	**.16**
1. Valid vs. Neutral	74	30	4.60	<10e-5***	.53
2. Valid vs. Invalid	74	56	4.51	<10e-5***	.52
3. Neutral vs. Invalid	74	25	2.17	.033*	.25
Experiment 2a	**2, 148**	**n/a**	**58.90**	**<10e-19*****	**.44**
1. Valid vs. Neutral	74	56	6.70	<10e-9***	0.77
2. Valid vs. Invalid	74	155	8.35	<10e-12***	0.96
3. Neutral vs. Invalid	74	100	6.78	<10e-9***	0.78
Experiment 2b	**2, 148**	**n/a**	**4.80**	**.010***	**.06**
1. Valid vs. Neutral	74	13	2.06	.043*	0.24
2. Valid vs. Invalid	74	24	3.12	.003**	0.36
3. Neutral vs. Invalid	74	11	1.22	.225	0.14

Effect sizes are partial eta squared for *F* tests and d_z for dependent-samples *t* tests. ***$p < .001$; **$p < .01$; *$p < .05$

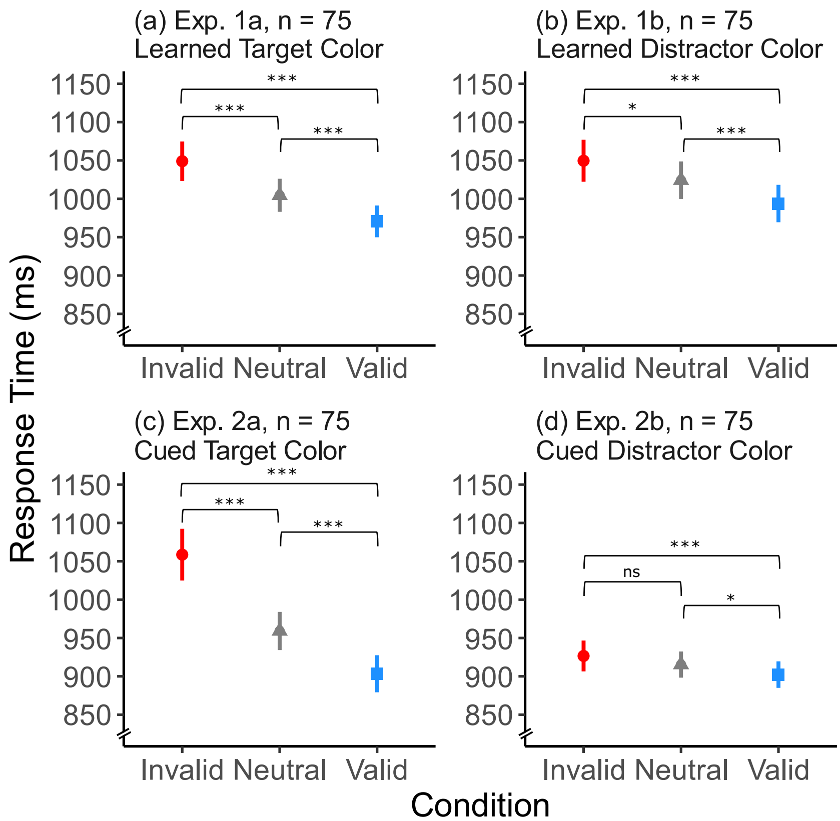

Fig. 2 Mean response times (RT) in milliseconds as a function of cue validity (Invalid = inaccurate cue; Neutral = cue color absent; Valid = accurate cue) for all experiments. In all experiments, we found evidence for benefits of selective attention on response times. **a** Experiment 1a, in which targets incidentally appeared in a certain color on 75% of trials. **b** Experiment 1b, in which distractors incidentally appeared in a certain color on 75% of trials. **c** Experiment 2a, which explicitly cued participants to upcoming target colors with 75% validity. **d** Experiment 2b, which explicitly cued participants to upcoming distractor colors with 75% validity. Asterisks denote statistical significance. ***$p < .001$; **$p < .01$; *$p < .05$; ns = not significant. (Color figure online)

be biased both toward and away from a specific feature based on incidental experience. An exploratory examination of the effects across block showed some growth of these effects across experimental blocks (see Fig. S2), indicating gradual effects of learning throughout the experiment. Notably, effect sizes (d_z) were similar across target and distractor learning: 0.64 for target learning and 0.52 for distractor learning (valid minus invalid RT, but this was also true across other validity comparisons, see Table 1). Quantitative comparisons of the magnitude of these effects are reported in the Cross-Experiment Analyses section below.

Experiment 2: Cued target selection and cued distractor ignoring

Experiment 2 tested how explicit cues to target colors (Exp. 2a) or distractor colors (Exp. 2b) affect visual search performance. The paradigm was identical to Experiment 1, except the frequent color was explicitly cued before each trial with a colored ring matching the high-probability color, and participants were instructed to use these cues to voluntarily attend towards that color (Exp. 2a) or away from that color (Exp. 2b). As in Experiment 1, the cue format (target vs. distractor cue) and cued color were held constant for each participant throughout the experiment, meaning that differences in cueing effects across experiments cannot be due to differences in the ability to switch attentional sets. This also means that we are likely assessing a mixture of both explicit, voluntary attention and learned attention through repeated exposure to certain color–target (Exp. 2a) and color–distractor (Exp. 2b) associations (more on this issue in the Results section of Exp. 2b and the General Discussion). We predicted that explicit color cues would benefit search performance for both target selection and distractor ignoring. The main question was whether the magnitudes of these effects would differ, and how potential differences would relate to performance differences in the learned attention experiments.

Method

Experiment 2 was not preregistered but included the same number of participants and followed the same design and analysis plan as Experiment 1.

Participants

We recruited 75 participants in each of Experiments 2a and 2b. We excluded data from 29 participants in Experiment 2a (five for taking longer than 90 minutes and 24 for low accuracy) and data from 27 participants in Experiment 2b (six for taking longer than 90 minutes, 20 for low accuracy, and one for greater than 10% of trials with outlier RTs). Experiment 2a included 50 women, 22 men, one nonbinary person, and two people who declined to report their genders, with a mean age of 20.3 (range: 18–28). Experiment 2b included 57 women, 17 men, and one person who declined to report their gender, with a mean age of 20.4 (range: 18–27).

Procedure

Experiment 2 was identical to Experiment 1 except for the addition of an explicit cue preceding each trial that predicted the target (Exp. 2a) or distractor (Exp. 2b) color. The cue was a centrally presented ring identical to one of the search items but with no gap. It appeared for 500 ms immediately after participants pressed the "down" arrow key to begin the trial and was followed by a 500-ms blank screen before the search array appeared until response. As in Experiment 1, this color remained constant throughout the experiment for each participant. The cue predicted the target (Exp. 1a) or distractor (Exp. 2b) color with 75% validity. On the remaining 25% of trials the cued color was either absent from the display (17%—neutral trials), or inaccurately matched the opposite item, i.e., as a distractor in Exp. 2a or a target in Exp. 2b (8%—invalid trials).

Results

Experiment 2a: Explicitly cued target color

When explicit cues predicted upcoming target colors with 75% validity (Fig. 2c), there was an effect of cue validity on mean RT, $F(2, 148) = 58.90$, $p < .001$, $\eta_p^2 = .44$. All conditions differed from each other as confirmed by dependent-samples t tests, with valid trials fastest (mean RT = 903 ms, SE = 24 ms), followed by neutral trials (mean = 959 ms, SE = 25 ms) and then invalid trials (mean = 1,059 ms, SE = 34 ms). Table 1 summarizes data and statistical tests from all experiments (see Supplementary Materials for discussion of the "testing" phase, which still used cues but to match Exp. 1's testing phase eliminated any relationship between cue and search display).

Experiment 2b: Explicitly cued distractor color

When explicit cues predicted upcoming distractor colors with 75% validity (Fig. 2d), there was a small effect of cue validity on mean RT, $F(2, 148) = 4.80$, $p = .010$, $\eta_p^2 = .06$. Response times on valid trials (mean RT = 902 ms, SE = 17 ms) were significantly faster than neutral trials (mean = 915 ms, SE = 17 ms) and invalid trials (mean = 927 ms, SE = 20 ms), which were not significantly different from each other (see Table 1). Thus, these data are consistent with a small but reliable effect of explicit distractor cues on search performance.

Discussion

Experiment 2 showed strong benefits of target cueing and much weaker, but reliable, benefits of distractor cueing. This pattern is consistent with many reports of less efficient distractor cueing than target cueing (Arita et al., 2012; Beck & Hollingworth, 2015; Carlisle & Nitka, 2019; Reeder et al. 2017). As stated above, one difference from other direct comparisons of target and distractor cues is that our experiment used the same target or distractor color throughout the experiment, rather than changing it from trial to trial. Thus, Experiment 2 combined potential effects of learning—and in fact learning that exactly replicated the learning of Experiment 1 in terms of proportion of trials in each condition—with effects of cueing. We opted to repeat the distractor color throughout the experiment to eliminate the possibility of other task switching costs (i.e., switching attention towards or away from a new feature on every trial) that could reduce the effect of distractor cueing. Thus, our experimental design allows us to quantify the maximum size of a possible distractor cueing effect for our search task. Even so, distractor cueing remained relatively inefficient, suggesting that explicit distractor cueing may have reduced—or potentially eliminated—the effects of learning (see also Stilwell & Vecera, 2019a). To better compare how different cue types and learning affect visual search performance, we next report cross-experiment analyses of the size of the effects across all experiments.

Cross-experiment analyses

Cross-experiment analyses were not preregistered.

Comparisons of attention effects across experiments

To compare the magnitude of explicitly cued and incidentally learned attentional biases, we conducted a three-way analysis of variance (ANOVA) on the effects of experiment (incidental learning or explicit cueing), type of predictability (target or distractor), and validity (valid, neutral, and invalid) on mean response time. The analysis showed a main effect of experiment, $F(1, 296) = 9.60$, $p = .002$, $\eta_p^2 = .03$, a main effect of validity, $F(2, 592) = 96.24$, $p < .001$, $\eta_p^2 = .25$, and no significant main effect of the type of predictability, $F(1, 296) = 0.94$,

p = .333, η_p^2 = .00. The three-way interaction of all factors was significant, $F(2, 592) = 11.68$, $p < .001$, $\eta_p^2 = .04$.

Because we were interested in whether the search RT effects differed across experiments (learned vs. explicitly cued) and type of predictability (target vs. distractor), we followed up on this three-way interaction by first computing a validity effect for each participant in each condition, measured by subtracting valid condition RT from invalid condition RT. This difference reflects a combination of costs and benefits of feature-based attentional cues in a single summary measure. We conducted an ANOVA on these validity effects with experiment (learned vs. explicitly cued) and type of predictability (target vs. distractor) as factors (Fig. 3). There was no main effect of experiment, $F(1, 296) = 2.73$, $p = .10$, $\eta_p^2 = .01$, a significant main effect of type of predictability, $F(1, 296) = 31.19$, $p < .001$, $\eta_p^2 = .10$, and a significant interaction, $F(1, 296) = 15.50$, $p < .001$, $\eta_p^2 = .05$. This interaction reflected similar effects of validity for both learned target colors (mean difference = 78 ms, SE = 10 ms) and learned distractor colors (mean = 56 ms, SE = 9 ms), $t(148) = 1.21$, $p = 0.228$, d_z = 0.198. This was verified by a Bayesian t test conducted with a default prior of 0.707, showing some evidence in favor of a null effect (BF_{10} = 0.34, reflecting about 3 times more evidence for the null hypothesis of no effect relative to the alternative hypothesis). In contrast, there was a considerably greater validity benefit for explicitly cued target colors (mean = 155 ms, SE = 13 ms) than explicitly cued distractor colors (24 ms, SE = 6 ms), $t(148) = 6.50$, $p < .001$, $d_z = 1.06$.

Finally, to directly compare the effectiveness of attention elicited by incidental learning and explicit cueing, we analyzed the effect of experiment (learning vs. explicit cueing) within each type of predictability (target vs. distractor color). Incidentally learned target selection (mean difference = 78 ms) was less effective than explicitly cued target selection (mean difference = 155 ms), $t(148) = 3.30$, $p = .001$, $d_z = 0.54$. The opposite pattern was found for distractor ignoring, with incidentally learned ignoring (mean difference = 56 ms) somewhat more effective than explicitly cued ignoring (mean difference = 24 ms), $t(148) = 2.15$, $p = .033$, $d_z = 0.35$. Overall, we found evidence for a large benefit of voluntary attention towards target features, moderate benefits of learned attention towards target features and away from distractor features that were comparable to each other, and small but reliable benefits of voluntary attention away from distractor features.

We also report detailed analyses of valid-neutral and neutral-invalid difference scores in the Supplementary Materials. These analyses have similar results to those of the valid–invalid difference. In our view, however, the valid versus invalid difference provides the clearest comparison because these conditions are closely perceptually matched, with on average the same search item colors on the display and differing only in which color includes the target. In contrast,

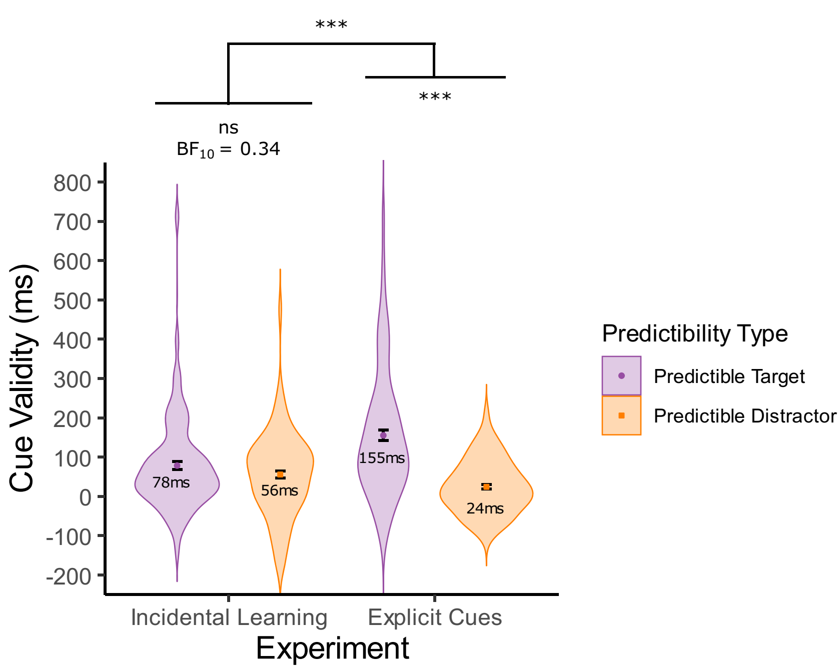

Fig. 3 Validity benefits (the mean RT difference between valid and invalid trials) from all experiments (N = 75 for each of the four experiments). Larger numbers indicate faster RTs on valid compared with invalid trials. The two leftmost violin plots show the data from Exp. 1 (incidental learning), and the two rightmost plots show the data from Exp. 2 (explicit cues). Higher target color probabilities are plotted in purple and higher distractor probabilities plotted in orange. Asterisks denote statistical significance, with Bayes Factors (ratio of evidence for the alternative versus the null hypothesis) also reported for nonsignificant tests. ***$p < .001$; **$p < .01$; *$p < .05$; ns = not significant. (Color figure online)

the neutral condition (17% of trials) is the only condition that doesn't have the frequent color as either target or distractor, potentially inducing an expectancy violation cost on top of any effects of feature-based attention (Retell et al., 2015).

Comparing effectiveness of constant cues and trial-by-trial cues

Experiment 2 was meant to examine the effects of voluntary attention, using cues that were always in the same color throughout the experiment because previous research has shown constant cues to be more effective than those that vary in identity from trial to trial (Cunningham & Egeth, 2016; Moher & Egeth, 2012). However, using constant cues may conflate learning and explicit cuing to some degree. Would we have found different effects if cues indicated a different target or distractor color on each trial? One of our previous papers used trial-by-trial cues in a very similar design, allowing us to address this question. That study (Addleman & Störmer, 2022, Exp. 1) differed only in varying the cued color pseudorandomly from trial to trial, including six cueing blocks instead of four (participants in that experiment did not complete an unbiased "testing" phase), and number of participants (48, rather than 75, participants). When comparing the effectiveness of constant and trial-by-trial cues across these studies we find strikingly similar effectiveness: the constant target cues of the present experiment (mean valid-versus-invalid difference = 155 ms, d_z = 0.78) were approximately as effective as trial-by-trial target cues (M = 159 ms, d_z = 0.77; BF_{10} = .20), and keeping distractor cues the same color had effects (M = 24ms, d_z = 0.36) comparable to varying them from trial to trial (M = 40 ms, d_z = 0.36; BF_{10} = .30). A three-way ANOVA on response time data with the factors of experiment (trial-by-trial versus constant cues), type of predictability (target or distractor), and validity (valid, neutral, invalid) confirmed this, showing a clear effect of validity (valid cues sped RT) that was greater for positive than negative cues, $p < .001$, $\eta_p^2 = .27$, but no interactions: three-way interaction, $p = .921$, $\eta_p^2 = .00$; two-way interaction between validity and experiment: $p = .79$, $\eta_p^2 = .00$. While this pattern diverges from other studies in which trial-by-trial distractor cues were ineffective (e.g., Cunningham & Egeth, 2016; Moher & Egeth, 2012; see General Discussion for why this may be the case), it shows that the results of the current Experiment 2 do not result from our use of the same cue color throughout the experiment.

Differences in overall response speed across experiments

We also conducted exploratory post-hoc analyses on an unexpected feature of our results, namely that overall response times were numerically faster for explicit cueing (Exp. 2) than incidental learning (Exp. 1), and particularly fast for the distractor cueing experiment (Exp. 2b). Participants were on average 97 milliseconds faster in the distractor cueing experiment than the distractor learning experiment, $t(148) = 3.26$, $p = .001$, d_z = 0.53. The same pattern was present but not statistically reliable for target selection experiments, with target cueing responses 57 milliseconds faster than target learning responses, $t(148) = 1.78$, $p = .077$, $d_z = 0.29$. These differences in response times were present despite similar, near-ceiling accuracy in all experiments (range: 96.9–97.8% accuracy), suggesting they do not reflect speed–accuracy trade-offs. One possible explanation of this difference is simply a longer time between participants' indication to start a trial by pressing a button and the actual search array onset: in Experiment 2, the introduction of the cue made this 1 second (500 ms of which was the cue), but in Experiment 1 it was only 500 milliseconds. It is well-established that, for relatively short durations between a readiness signal (e.g., a person's button-press) and a stimulus onset, longer readiness-stimulus durations ("foreperiods") cause shorter RTs (Näätänen et al., 1974; Niemi & Näätänen, 1981). Thus, Experiment 2 could have yielded faster overall RTs than Experiment 1 mainly because participants had longer before each search onset to prepare to respond.

We don't think these differences in overall RT affect our interpretation of the cueing effects themselves. This was verified by normalizing response times by dividing the mean RT for each participant in each condition (valid, neutral, invalid) by that participant's overall mean RT across conditions (e.g., valid/mean[all conditions]). This removes any influence of overall differences in RTs across participants and experiments. In all cases, analyses of these normalized data yielded the same statistical decisions (at an alpha of .05) as reported in the main text. Supplementary Fig. S3 shows the normalized data.

General discussion

This study reports a systematic investigation of the effects of feature-based attention towards and away from colors in visual search based on incidental learning and explicit cueing. We found similar effects whether participants incidentally learned to select a frequent target feature (Exp. 1a) or ignore a frequent distractor feature (Exp. 1b). In contrast, voluntary attention was much more effective when directed toward an explicitly cued target feature (Exp. 2a) than toward an explicitly cued distractor feature (Exp. 2b). These results reveal key differences in how learning and voluntary goals shape target selection and distractor ignoring. For one, explicit target cues (Exp. 2a) yielded the largest benefit compared with all other experiments, suggesting that unique mechanisms may support voluntary target selection. Furthermore, there was some evidence that learned distractor ignoring was more effective than voluntary ignoring, though these results ought to be interpreted with caution, as the evidence was relatively weak. The present results very clearly show that voluntary attention is much less efficient at ignoring features than selecting them, whereas learned attention yielded similar benefits whether selecting frequent target features or ignoring frequent distractor features. This is broadly consistent with an account where a single learning mechanism underlies both selection and ignoring that can either lead to the enhancement or suppression of features depending on context.

Mechanisms of distractor ignoring

Our results demonstrate that learned distractor ignoring has nearly equivalent benefits as learned target selection (Exp. 1), which stands in stark contrast with explicitly cued ignoring of distractors and the voluntary selection of targets, where the latter is much more effective than the former (Exp. 2). One plausible explanation of these findings is that the same statistical learning mechanisms can both up- and down-weight feature-based attentional priorities, such that similarly informative target and distractor learning yield similar benefits on search performance. Such a mechanism has been suggested for nonspatial features (Stilwell et al., 2019), and fleshed out in detail for spatial suppression (Ferrante et al., 2018). Even so, direct modulation of attentional priority is only one possible explanation of these search benefits, and future research should aim to distinguish between this account and accounts like secondary inhibition of distractors via enhancement of likely target features (Becker et al., 2015; Noonan et al., 2018).

In Experiment 2, responses were faster both when explicit cues validly predicted the upcoming target (Exp. 2a) or distractor (Exp. 2b) color relative to when that color was either absent from the display (neutral trials) or when cues were inaccurate (invalid trials). However, explicit target cues yielded far larger effects than distractor cues, consistent with previous studies (Arita et al., 2012; Carlisle & Nitka, 2019; Reeder et al., 2017; Zhang et al., 2020). What is unique about voluntary feature-based attention that makes selection based on explicit cues so much more effective than voluntary ignoring, a pattern not shared by learned attention? One possibility is the reliance of voluntary attention on active working memory, which itself has been associated with attentional selection (Desimone & Duncan, 1995; Downing, 2000; Soto et al., 2005). If participants are cued prior to the search array which color to subsequently ignore, as done in many paradigms investigating voluntary ignoring, any biases to prioritize perceptual information matching the contents of working memory must be overcome in order to suppress an explicitly cued distractor feature (an idea discussed in Carlisle, 2019). For instance, one recent study showed that providing a color cue to participants prior to an upcoming search task led to perceptual enhancement of the cue color in a target cueing condition as measured by rare, unpredictable probe trials, but no analogous suppression of the cue color in a distractor cueing condition (Addleman & Störmer, 2022, Exp. 2). This is consistent with suggestions that explicit distractor cueing is relatively ineffective because participants may use distractor cues to guide attention *towards* targets through relatively inefficient strategies, for instance by actively avoiding the spatial locations of items in the to-be-ignored color or recoding the distractor cue into one or more colors they should attend towards (Beck & Hollingworth, 2015; Becker et al., 2015; see also Vecera et al., 2014, for a discussion on certain contexts in which experience can lead to more effective goal-driven ignoring). In contrast, learned ignoring, which is often considered to be implicit and likely does not rely on active working memory representations in the same way as explicit cueing (Gao & Theeuwes, 2020; Wang & Theeuwes, 2018), may not suffer from inefficiencies related to biases to process information matching working memory contents. This distinction may underlie differences between the effects of voluntary and learned attention.

Explicit cueing using constant versus variable cues

Our results showed much smaller effects of explicitly cueing distractor features than cuing target ones. This was true even though participants were cued to the same feature throughout the experiment, which has been shown to increase the effectiveness of distractor cues relative to those changing in identity from trial to trial (Cunningham & Egeth, 2016; Moher & Egeth, 2012). As reported in our Cross-Experiment Analyses, we did not find any difference in our visual search paradigm when comparing the present Experiment 2's constant cues to previously published data using trial-by-trial cues (Addleman & Störmer, 2022, Exp. 1). Instead, constant cues and variable cues were nearly identical in their effectiveness. This is strikingly different from Moher and Egeth's (2012) finding that varying a cued distractor color from trial to trial *impaired* performance relative to providing no cue at all.

What might explain the divergence between our results showing little impact of varying distractor cue colors and those finding much greater benefits when holding distractor cues constant? Our Experiment 2 differs from other studies of explicit distractor cueing in the use of partially (75%) valid cues of the same format (target or distractor) for each participant, rather than 100% valid cues that varied in type (target, distractor, or no-cue) from trial to trial (Cunningham & Egeth, 2016). We chose this design to maximize similarity across learning and cueing experiments—the alternative of blocking both cueing type and learning type in all experiments would lead to confounded learning effects across blocks. This difference may itself explain why our results yielded benefits of distractor cueing both when cues were always the same color for a participant (Experiment 2) and when varying in color from trial to trial (Addleman & Störmer 2022, Exp. 1), whereas other studies have reported effective distractor ignoring only for consistent color cues (Cunningham & Egeth, 2016). In the latter case, even when distractor cue color remained constant, distractor cue trials were randomly intermixed with no-cue trials, meaning participants were still uncertain about the upcoming attentional set until the cue appeared, potentially reducing the size of their effects. Thus, another important consideration in the design of explicit cueing studies is not only whether the cued feature value varies from trial to trial, but also whether the cue type (target, distractor, or neutral) varies across trials, blocks, or participants.

Furthermore, in addition to allowing more direct comparisons across experiments, we also think that keeping the cue type (target, distractor, or neutral) constant within participants has the advantage of involving perceptually identical cues across conditions (rather than neutral or absent cues in some conditions) and thus identical preparatory processes prior to search onset. In this respect, it is similar to many studies of spatial cueing comparing valid to invalid trials to assess the effectiveness of voluntary spatial attention (Posner, 1980). It is important to consider this difference when comparing our results to those using 100% valid cues relative to a no-cue baseline, as the benefits of accurate versus inaccurate cues may be indexing a different set of processes than the benefits of accurate cues to search without cues.

Potential differences between feature-based and space-based suppression

Recent investigations of learned and voluntary suppression have been reported for both nonspatial features like color (Addleman & Störmer, 2022; Arita et al., 2012; Stilwell & Vecera, 2019b) as well as for location-based attention (Feldmann-Wüstefeld et al., 2021; Ferrante et al., 2018; Wang & Theeuwes, 2018). It remains an open question whether the present pattern of results using feature-based attention—with relatively inefficient voluntary ignoring and more efficient learned ignoring—also holds for spatial suppression. Recent studies have provided some evidence that attentional mechanisms may at least in part be shared across feature and location-based selection (Chapman & Störmer, 2021), including the inhibition of distractors (e.g., surround-suppression; Störmer & Alvarez, 2014). However, given that spatial attention may rely on premotor (Rizzolatti et al., 1987) and oculomotor mechanisms more so than feature-based attention, it also seems plausible that voluntarily suppressing locations is more efficient than ignoring visual features. Future research should explore the relationships between learned and voluntary selection and ignoring in spatial attention as well as feature-based attention, which would provide valuable insights into the mechanisms of suppression more broadly.

Conclusion

This study reports a systematic investigation of the relative benefits of voluntary and incidentally learned enhancement and suppression of visual features. We show that voluntary attention towards target features is by far the most effective form of feature-based attention, and clearly much more effective than voluntarily ignoring distractors. Most importantly, we also demonstrate that the difficulties of using voluntary attention to ignore distractor features are not present in learned attention. Instead, learned attention yielded similar effects whether selecting target features or ignoring distractor features. This divergence points to dissociable mechanisms supporting learned and voluntary feature-based attention and point towards an important role of prior experience in ignoring irrelevant and distracting information.

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Open practices statement Experiment 1's sample size, experimental design, and analysis plan was preregistered on AsPredicted (https://aspredicted.org/9ty9y.pdf). Experiment 2 was not preregistered but used the same analysis plan and sample size of Experiment 1. Cross-experiment analyses were not preregistered. Raw data, experimental code, and analysis code are available online (https://osf.io/a69h8/).

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