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Feature-based attentional control for distractor suppression

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Abstract

To investigate whether attentional suppression is merely a byproduct of target facilitation or a result of independent mechanisms for distractor suppression, the present study examined whether attentional suppression takes place when target facilitation hardly occurs using a spatial cueing paradigm. Participants searched for target letters that were not red, i.e., a negative color. On each trial, a target color was randomly chosen among 12 colors to prevent establishing attentional control for target colors and to reduce intertrial priming for target colors. Immediately before a target display, a noninformative spatial cue was presented at one of the possible target locations. The cue was rendered in a negative color, which was to be ignored, to detect targets or the reference color, which was never presented for target and non-target letters. Experiment 1 showed that negative color cues captured attention less than reference color cues, suggesting feature-based attentional suppression. The suppression effect was replicated when the temporal interval between the onsets of the cue and target displays was reduced in Experiments 2 and 3, suggesting proactive suppression. Experiment 3 directly confirmed no attentional control settings for target colors and intertrial priming. These findings suggest that distractor features can guide attention at the pre-attentive stage when target features are not used to attend to targets.

Keywords Visual search · Selective attention · Attentional capture · Attentional suppression

Introduction

Due to the limited capacity of the cognitive system, attention is needed to select task-relevant stimuli while filtering out task-irrelevant stimuli (Theeuwes, 2010). Information from the attended stimuli determines what we are aware of, and so guides our actions. Therefore, understanding the attentional mechanism is essential to designing devices and spaces for guiding behaviors appropriate in a given context (Beck et al., 2013; Cho & Proctor, 2001; Proctor & Cho, 2006). Recently, a growing body of research suggests that attention to distractors can be actively inhibited (van Moorselaar & Slagter, 2020). However, it remains to be resolved whether attentional suppression is always a byproduct of target facilitation or there is an independent mechanism for distractor suppression. Thus, the present study investigated whether attentional suppression operates when it is hard to utilize attentional control for target facilitation.

Attentional suppression

Physically salient distractors (e.g., a red object among green objects) tend to capture attention (Itti et al., 2001; Theeuwes, 1992). However, attentional capture by salient distractors can be reduced depending on the search mode (Gaspelin et al., 2015). For example, Gaspelin et al. found that attention was less frequently allocated towards salient distractors than non-salient distractors when participants searched for targets based on a basic feature (e.g., diamond shape) of the targets, suggesting that the feature-based search mode suppressed attention toward the salient distractors. However, attention was more frequently allocated towards salient distractors than non-salient distractors when they were based on the physical saliency of targets, suggesting that the saliency-based search mode did not suppress attentional allocation towards salient distractors. Note that non-salient distractors were used as a baseline to determine whether attentional suppression or facilitation to the salient distractors occurred (Gaspelin et al., 2015).

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The findings of attentional suppression were replicated and generalized by follow-up studies (Gaspelin et al., 2017; Gaspelin & Luck, 2018; Wang & Theeuwes, 2018; Won et al., 2019). Therefore, the presence of attentional suppression mechanisms is little questionable. However, it remains to be established whether attentional suppression can occur without target facilitation.

Independent mechanism for attentional suppression

Traditionally, it has been suggested that distractor suppression can occur as a result of target selection (Desimone & Duncan, 1995; Keele & Neill, 1978; Tipper, 1985). Particularly, according to the biased competition theory (Desimone & Duncan, 1995), distractor suppression is caused by competitive interactions between a target and distractors for further processing. In this regard, the suppression mechanism is merely a byproduct of the selection mechanism. However, a growing body of evidence suggests that the suppression mechanism is not unitary (Chelazzi et al., 2019; van Moorselaar & Slagter, 2020). Suppression can also occur based on mechanisms that are independent of selection (Hickey et al., 2009; Sawaki & Luck, 2010). For example, using event-related potentials (ERPs), Hickey et al. found that the magnitude of a suppression-related component, the distractor positivity (Pd), was modulated by distraction but was independent of selection (see also Kerzel & Huynh Cong, 2023).

The possibility that selection and suppression are served by at least partially distinct mechanisms has advanced based mainly on neurophysiological evidence rather than behavioral evidence (Chelazzi et al., 2019). This is because most behavioral research on attention had target-defining features and/or examined whether attentional suppression is dependent on target facilitation or not without a proper baseline (Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018; Kim & Beck, 2020; Kim & Cho, 2016; Won et al., 2019). This methodological limitation prevented the ability to explore the presence of independent suppression mechanisms. In line with this, Forstinger et al. (2022) developed a new experimental method to directly investigate the issue.

Forstinger et al. (2022) demonstrated that an independent mechanism operates for feature-based attentional suppression using a spatial cueing paradigm (Folk et al., 1992). In their visual search task, there was no target-defining color from task instruction. Instead, there was a distractor-defining color. For example, participants were instructed to search for the horizontal bar that was not red, and were presented with one red horizontal bar and two vertical bars on each trial. With the exception of the red horizontal bar, the other horizontal and two vertical bars had different colors, such as gray, blue, and yellow (potential target colors), and the colors were randomly determined on a given trial. That is, the color of the target could not be predetermined. Therefore, Forstinger et al. assumed that participants had to use the to-be-ignored color (red) and did not use the potential target colors to search for the target. To examine whether there was target-color facilitation and distractor-color suppression, one of three types of color cues was presented immediately before the onset of the target display: negative color cue, reference color cue, and positive color cue. A negative color cue was rendered in the color to be ignored. A reference color cue was in a color that was never shown from the four bars. A positive color cue was in one of the possible target colors. Forstinger et al. found that attention was allocated toward the negative color cue less than to the reference color cue, suggesting the attentional suppression of the to-be-ignored color. Furthermore, the authors suggested that there was no attentional control for target color because the positive cue produced a nonsignificant cue-validity effect: Response times were not significantly different between when a target was presented at the cued location, *valid cues*, and when it was presented at an uncued location, *invalid cues* (Folk et al., 1992; Forstinger et al., 2022; Kim & Beck, 2020; Kim & Cho, 2016; Posner, 1980).

Baselines for measuring attentional suppression and facilitation

In the spatial cueing paradigm, the magnitude of the cue-validity effect indicates the magnitude of attention toward a cue according to the net result of bottom-up saliency and top-down control factors (Folk et al., 1992; Schneider et al., 2022). Therefore, the presence/absence of the cue validity effect itself cannot determine whether feature-based attentional control facilitates or suppresses a cue. For example, in Forstinger et al.'s (2022) experiment, the reference, positive, and negative color cues were salient because the color at the cued location was unique relative to the color at the uncued locations. Therefore, the saliency of the cues can attract attention in a bottom-up fashion (Folk et al., 1992; Sawaki & Luck, 2010; Theeuwes, 1992). In addition to this bottom-up facilitation, the reference, positive, and negative color cues might have been suppressed due to dimension-based suppression. According to the dimension-based attentional suppression (Forstinger & Ansorge, 2023; Won et al., 2019), an attentional control system suppresses stimuli defined by a feature-dimension such as color. Therefore, it is unclear whether the cue validity effect reflects only feature-based suppression.

Instead, the judgment of whether feature-based attentional control for suppression or facilitation occurs should be based on the comparison with the validity effect of the reference color cue. The reference, positive, and negative color cues were in the same dimension and had the same saliency level. Therefore, the factors influencing attentional facilitation and suppression other than the feature-based attention factor can be controlled by comparing with the cue validity effect of the reference color cue.

In Forstinger et al.'s (2022) experiment, however, attention was allocated toward the positive color cue more than towards the reference color cue (a larger cue-validity effect for the positive than the reference color cue), suggesting attentional facilitation for target color. Therefore, it is possible that attentional suppression obtained in Forstinger et al.'s experiment resulted from the attentional facilitation of the target color rather than a suppression mechanism independent of the facilitation mechanism. The attentional facilitation to the target color could potentially be due to attentional control settings for the target colors and/or intertrial priming.

Attentional control and working memory capacity

Forstinger et al. (2022) used three target colors. Kerzel and Grubert (2022) suggested that simultaneous activation of three attentional templates is unlikely to occur. Nevertheless, Forstinger et al. observed a higher degree of attention directed towards the positive color cue than the reference color cue, indicating the possibility that participants established the attentional control settings for the three target colors. According to the dual mechanisms of control account (Braver et al., 2007; Braver et al., 2021), it is possible to concurrently activate three attentional templates, providing a potential explanation for the unexpected result.

The dual mechanisms of control account suggests that there are two kinds of control: proactive and reactive. The distinction between proactive and reactive control can be thought of as a distinction between early selection and late correction (Braver et al., 2007). Proactive control requires the goal information (e.g., establishing attentional control settings) to be actively sustained until the goal is accomplished. Therefore, proactive control allows an initial selection of a search target and an initial suppression of a distractor in the pre-attentive stage (Forstinger et al., 2022; Kim & Beck, 2020). In contrast, reactive control is activated by a trigger event. For example, attending to a distractor triggers reactive suppression so that attention is rapidly disengaged from the distractor to locate a target (Geng & Duarte, 2021; Moher & Egeth, 2012).

Critically, the sustained maintenance associated with proactive control uses working memory resources (Braver et al., 2007); accordingly, proactive control can occur when available working memory resources are sufficient for the control. In Forstinger et al. (2022), more attention to the positive than the reference color cue suggests that participants might have learned the three potential target colors to proactively guide attention toward the colors. Based on the dual mechanisms of control account (Braver et al., 2007), this was possible because three attentional templates are lower than the normal working memory capacity, which has been found around four (van den Berg et al., 2014; Vogel & Machizawa, 2004). That is, based on the dual mechanism, participants could have learned the three target colors to guide attention to the target by establishing attentional control settings for the target colors, allowing for attentional suppression by negative colors to occur.

Intertrial priming

Attentional facilitation can occur due to selection history such as intertrial priming (Awh et al., 2012; Maljkovic & Nakayama, 1994). Intertrial priming refers that distractors sharing the same feature as the target on the previous trial are attended more than those that do not share the same feature (Becker et al., 2009; Belopolsky et al., 2010). For example, when the color of a target is red, attention is facilitated toward red cues in the following trials. That is, in Forstinger et al. (2022), attentional facilitation to the target color (positive cues) might have occurred because the target color had been selected in the previous trial.

In summary, Forstinger et al. (2022) did not offer direct evidence that attentional suppression to the negative color was not driven by attentional facilitation to the positive color. The attentional facilitation could have occurred as a result of top-down attentional control for the target color and the intertrial priming in their experiment. The present study addressed this gap by examining whether an independent mechanism for proactive suppression operates when the attentional control settings for target colors and the intertrial priming are unlikely to occur.

Experiment 1

Using the spatial cueing paradigm based on the Forstinger et al.'s (2022) study, Experiment 1 was designed to test whether an independent mechanism for attentional suppression operates as in Forstinger et al.'s study. To prevent learning and establishing attentional control settings for target colors and the priming facilitation, however, a key difference from Forstinger et al. was that the experiment here used 12 different target colors, which was more than typical working memory capacities.

Specifically, a search target was Z or N that was not a negative color (see Fig. 1). On each trial, four letters were presented in the search display. Two of them were Z and Z, Z and N, or N and N, which were rendered in a negative color. With the other two letters, one was other than Z and N with a positive color, and the other letter was Z or N with a positive color. There were 12 possible target colors (positive colors), which were not disclosed to participants, and a target color was randomly chosen on each trial so that target colors were not predictable.

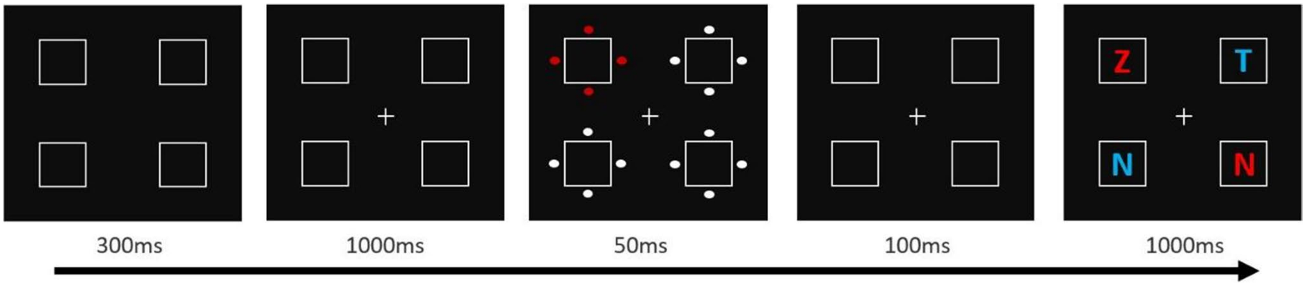

Fig. 1 An example of a trial in Experiment 1. In the example, a target is a Z or N that is not red; therefore, the cue is a negative color cue. The cue and target are presented at different locations (top-left for the cue, bottom-left for the target); therefore, the cue is an invalid cue

Therefore, to search for a target by facilitating the 12 target colors, participants should learn what the target colors are during performing a task and establish attentional control settings for the colors simultaneously. However, research in working memory and attentional control suggests that using this strategy is unlikely due to limited working memory capacities (van den Berg et al., 2014; Vogel & Machizawa, 2004) and attentional control abilities (Braver et al., 2007; Kerzel & Witzel, 2019; Thornton & Gilden, 2007; Wolfe, 1994). Therefore, it was assumed that participants should suppress the negative color to search for targets efficiently, and there was no attentional control setting for the target colors. Furthermore, participants were questioned after the visual search task about whether they used the target colors.

It was suggested that intertrial priming effects gradually decay and accumulate; therefore, the priming effects can be reduced when the same target color is presented infrequently (Brascamp et al., 2011; Maljkovic & Nakayama, 1994; Martini, 2010). The present study had 12 target colors so that each target color was presented less frequently than in Forstinger et al.'s (2022) study, which had three target colors. Accordingly, the reduced priming was assumed to be insufficient to produce attentional facilitation to the target colors.

If attention toward the negative color is suppressed, the negative color cue would capture attention less than the reference color cue. Therefore, the validity effect should be smaller for the negative than for the reference color cue. However, if the negative color is not suppressed, the negative and reference color cues would capture attention to a similar extent, leading to little difference between their cue-validity effects.

Method

Participants

Twenty-four participants (mean age = 21.9 years, SD = 2.2, 14 women and 10 men) with normal or corrected-to-normal visual acuity and color vision participated for payment of KRW 9,000 (about \$8). To determine the effect size, we referred to Forstinger et al.'s (2022) study, which had an effect size of 0.81 on average for detecting the difference in validity effects between cues. The G-power test with a power of 0.95, an alpha of 0.05, and an effect size of 0.81, showed a minimum sample size of 22.

Apparatus

Stimuli were presented on a 24-in. (16:9) LCD monitor. The viewing distance was approximately 60 cm but was not constrained. The experiment was programmed and administered using MATLAB R 2022b and Psychophysics Toolbox Version 3 software. Responses were recorded using a standard 101-key keyboard. The experiment was conducted individually in a dimly lit, sound-attenuated room.

Stimuli and procedure

Each trial presented a placeholder display for 300 ms, a fixation display for 1,000 ms, a cue display for 50 ms, a fixation display for 100 ms, a search display until a response, and a feedback display for 1,000 ms (see Fig. 1). The background of the screen was black (CIELAB: $L^* = 0$, $a^* = 0$, $b^* = 0$) for all displays. In the placeholder display, four placeholder-boxes (2.2° × 2.2°) with gray ($L^* = 49$, $a^* = 0$, $b^* = 0$) thin lines were presented in the up-left, up-right, down-left, and down-right. The distance from the center of the display to the center of each box was 6.0°. The fixation display consisted of the four boxes and a gray fixation cross. The cue display consisted of the fixation display with the addition of four cues. Each cue had four circles (0.6° × 0.6°) located around the boxes in a diamond configuration. The colors of the circles were the negative or reference color in the cued location and gray in the uncued locations. The search display consisted of the fixation display with the addition of a letter presented in each box. When a target color was non-red color, two of the four letters were red 'Z' or red 'N' ($L^* = 34$, $a^* = 74$, $b^* = 62$; see the color N in Fig. 2); on each trial whether each of the two letters was either 'Z' or 'N' was random. When a target color was defined by non-green

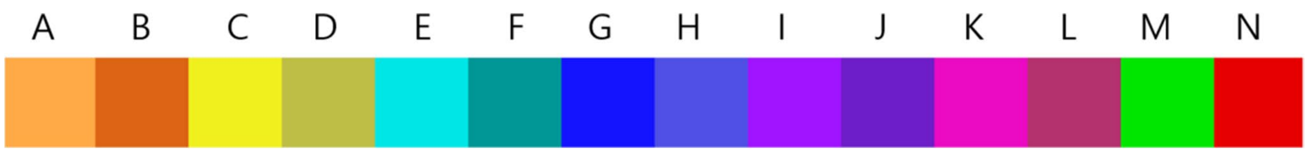

Fig. 2 In Experiments 1 and 2, the negative and reference cue colors were M and N (counterbalanced across participants), and the target colors were A–L. In Experiment 3, the negative, positive, and reference cue colors were G, M, and N (counterbalanced across participants). The target colors were A–F, H–L, and the positive cue color

color, two of the four letters were green ‘Z’ or green ‘N’ (L* = 70, a* = -79, b* = 76; see the color M in Fig. 2), such that each search display contained two green ‘Z’s, two green ‘N’s, or one green ‘Z’ and one green ‘N’. Therefore, in situations where there were two ‘Z’s and one ‘N’, a target was either ‘Z’ or ‘N’ depending on the colors of the letters. That is, participants should use the negative color to locate a target. On each trial, one of the remaining two letters was randomly selected between ‘Z’ or ‘N’, and the other letter was randomly selected from ‘T’, ‘S’, ‘H’, and ‘U’. Also, on each trial, the color of the two letters was randomly selected among 12 colors where there were not red and green (L* a* b*: 64 22 61; 35 43 60; 111 -20 87; 68 -15 58; 84 -44 -13; 32 -32 -9; 14, 70, -101; 17 45 -75; 22 83 -84; 11 64 -71; 43 86 -37; 33 56 -4, these colors are depicted in A~L, respectively, in Fig. 2). The search display was presented until a response was made; the letters disappeared if a response was not made within 1,000 ms, and only the placeholder boxes remained. The feedback display consisted of the placeholder display with the addition of the message “incorrect” and “too slow” in the center of the screen for an incorrect response and a slow and correct response (over 1,500 ms), respectively.

Search target was a letter ‘Z’ or ‘N’ that was not red for half of the participants and not green for the remaining half. They were instructed to search for a target by ignoring the negative color. Participants were asked to press the ‘Z’ key on a standard 101-key computer keyboard with their left index finger when the target was ‘Z’ and the ‘N’ key with their right index finger when the target was ‘N’ as quickly and accurately as possible. In the cue display, the color of the cue was equiprobably either the negative or reference color. When the negative color was red, the negative color cue and reference color cue were red and green, respectively; and vice versa when the negative color cue was green. Cues and targets were presented equiprobably at the four locations. The cue predicted target locations at a chance level; the target appeared at the cued location on 25% of the trials and at one of the uncued locations on 75% of the trials.

Participants had 32 practice trials and 384 experimental trials. Immediately after the experimental trials, participants were questioned about whether they had searched for a target by ignoring the negative color or by searching for any colors other than the negative color.

Results

Trials in which response time (RT) was shorter than 250 ms (0.08% of trials) or longer than 1,500 ms (1.32%) were excluded from the analyses. Then, incorrect-response trials were excluded (9.58%) from the RT analyses.

Response time (RT)

A within-subjects analysis of variance (ANOVA) with cue color (negative and reference) and cue validity (valid and invalid) as factors was performed on the mean RTs (see Fig. 3). The main effect of cue color was not significant, $F(1, 23) < 1$. The main effect of cue validity was not significant, $F(1, 23) < 1$. Importantly, the interaction of cue color and validity was significant, $F(1, 23) = 6.25$, $p = .02$, $\eta_p^2 = .21$. Post hoc analyses showed that neither negative, $t(23) = -1.75$, $p = .093$, Cohen’s $d = -.36$, nor reference color cue, $t(23) = .77$, $p = .45$, Cohen’s $d = .16$, produced a significant validity effect.

Accuracy

None of main effects or an interaction were significant: *F*s < 1.20, *p*s > .29 (see Fig. 4).

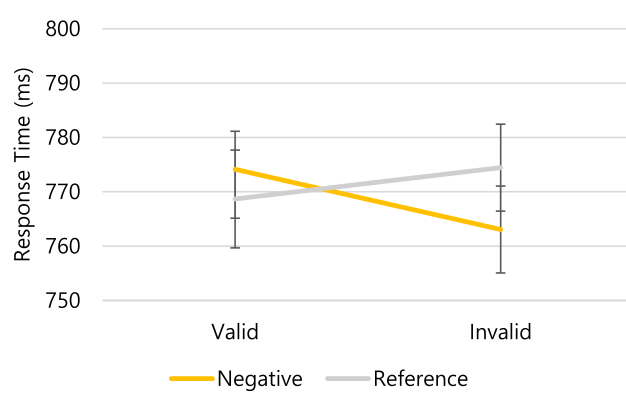

Fig. 3 Results of response times in Experiment 1. Error bars indicate 95% confidence intervals

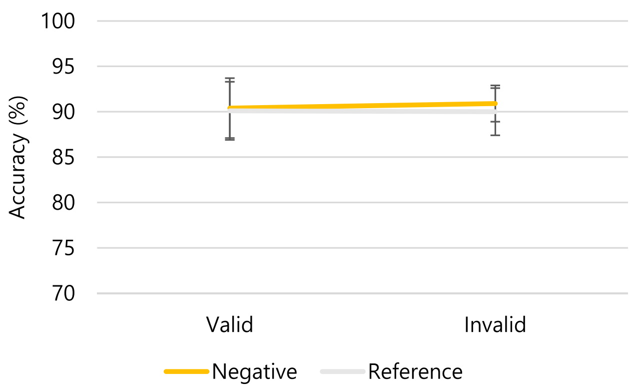

Fig. 4 Results of accuracy in Experiment 1. Error bars indicate 95% confidence intervals

Survey

All participants reported that they searched for a target by actively suppressing the negative color. No one searched for any colors.

Discussion

The magnitude of the cue validity effect was smaller for the negative color cue (-9 ms) than the reference color cue (6 ms). This implies that the negative colors were suppressed. Furthermore, the number of the potential target colors was beyond working memory capacities, and no-one reported that they searched for the target based on any color. These findings suggested that the attentional suppression effect (15 ms) was found when attentional facilitation for target colors was unlikely to occur. Therefore, Experiment 1 supported the presence of the attentional control mechanisms operating for distractor suppression without attentional control for target facilitation and intertrial priming.

Experiment 2

Experiment 2 investigated whether the attentional suppression of Experiment 1 occurred before or after initial attentional selection. Because the interval between the onsets of cue and target displays was 150 ms, there was a possibility that attention was rapidly disengaged from the negative color cue after the attentional capture by it, resulting in a smaller validity effect than the reference color cue (Geng & Duarte, 2021; Moher & Egeth, 2012). Therefore, in Experiment 2, the interval between the onsets of the cue and target displays changed to 50 ms, preventing the use of the rapid disengagement strategy (Forstinger et al., 2022). If the evidence for the attentional suppression obtained in Experiment 1 was due to the rapid disengagement from the negative color cue, the magnitude of the validity effect for the negative and reference color cues should be similar in Experiment 2. However, if it was due to proactive suppression of the negative color, a smaller amount of attentional capture would be found with the negative than reference color cue.

Method

The methods were identical to those of Experiment 1 except for the following changes. First, 24 new participants participated (mean age = 21.7 years, SD = 2.9, 18 women and six men). The stimulus onset asynchrony between the cue display and the search display was 50 ms.

Results

Trials in which RT was shorter than 250 ms (0.08% of trials) or longer than 1,500 ms (2.18%) were excluded from the analyses. Also, incorrect-response trials were excluded (8.73%) from the RT analyses.

RT

A within-subjects ANOVA with cue color (negative and reference) and cue validity (valid and invalid) as factors was performed on the mean RTs (see Fig. 5). The main effect of cue color was not significant, $F(1, 23) < 1$. The main effect of cue validity was not significant, $F(1, 23) < 1$. Importantly, the interaction of cue color and validity was significant, $F(1, 23) = 6.81$, $p = .016$, $\eta_p^2 = .23$. Post hoc analyses showed that neither the negative, $t(23) = -1.71$, $p = .101$, Cohen's $d = -.35$, nor the reference color cue, $t(23) = 1.67$, $p = .109$, Cohen's $d = .34$, produced a significant validity effect.

Accuracy

None of main effects and an interaction were significant: $Fs < .69$, $ps > .42$ (see Fig. 6).

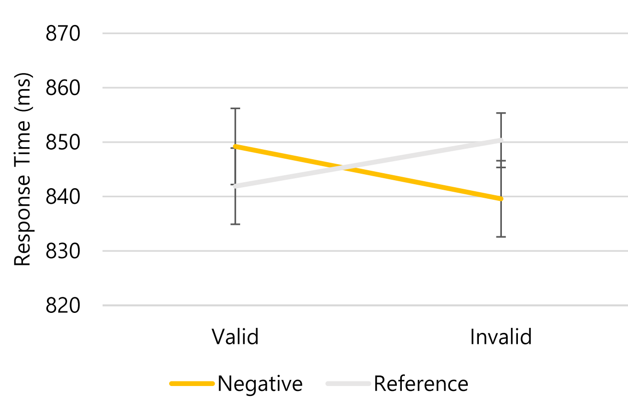

Fig. 5 Results of response times in Experiment 2. Error bars indicate 95% confidence intervals

Survey

All participants reported that they searched for a target by suppressing the negative color. No one searched for any colors.

Discussion

Although the temporal interval between the onsets of the cue and target displays was reduced to prevent the use of the rapid disengagement strategy after the negative cue capturing attention, the magnitude of the cue validity effect was smaller with the negative (-10 ms) than with the reference color cue (9 ms), as in Experiment 1. This finding suggests that attentional selection of the negative cue was suppressed in the pre-attentive stage, leading to the proactive suppression effect (19 ms).

Experiment 3

In Experiments 1 and 2, it was assumed that participants would not be able to learn and use the target colors for search and intertrial priming was not sufficient to produce attentional facilitation to the target colors. However, it was demonstrated that not only exact target color but also colors sufficiently similar to it can attract attention (Anderson & Folk, 2010; Ansorge & Heumann, 2003). For example, when participants searched for yellow, yellowish stimuli can also attract attention. Therefore, in Experiments 1 and 2, it was possible that participants might have merged some target colors into a single average color, allowing them to effectively search for 12 target colors. Although using this strategy appeared unlikely because all participants reported not employing such a strategy, we examined this possibility to ensure that there was no attentional facilitation for the target color compared to the reference color.

Experiment 3 directly confirmed whether participants searched for target colors by adding target color cues: positive color cues. If participants searched for target colors by forming the attentional control settings for the target colors and/or the priming produced attentional facilitation to the target colors, attentional capture should be stronger for the positive than for the reference colors, leading to a larger validity effect for the positive than for the reference color cue (Folk et al., 1992; Kim & Beck, 2020; Kim & Cho, 2016). If participants did not search for the target based on colors, the strengths of attentional capture by the positive and reference color cues would be similar, producing similar cue-validity effects.

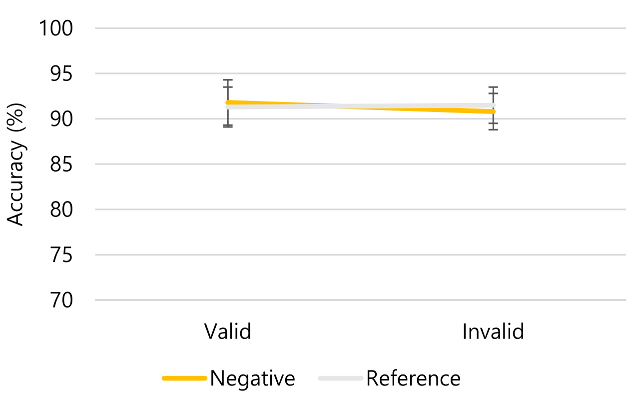

Fig. 6 Results of accuracy in Experiment 2. Error bars indicate 95% confidence intervals

Method

The methods were identical to those of Experiment 2 except for the following changes. First, there were three types of cues: negative, reference, and positive color cues. The color of positive color cues was randomly chosen among green, red, and blue (L* = 14, a* = 70, b* = -101; G in Fig. 2) for each participant; possible combinations of cue colors were 6, and they were randomly and evenly assigned to participants. The possible target colors were 11 of the colors appearing in A~F (L* a* b*: 64 22 61; 35 43 60; 111 -20 87; 68 -15 58; 84 -44 -13; 32 -32 -9) and H~L (L* a* b*: 17 45 -75; 22 83 -84; 11 64 -71; 43 86 -37; 33 56 -4) of Fig. 2 and a positive cue color. Furthermore, to detect attention to the cues, the numbers of participants and trials increased in proportion to the number of the cue types. That is, 36 new participants participated (mean age = 23.1 years, SD = 2.5, 24 women and 12 men), and the number of experimental trials became 576 trials. Considering an increase in the number of trials, the monetary reward for the participation was increased to KRW 10,000 (about $9).

Results

Trials in which RT was shorter than 250 ms (0.02% of trials) or longer than 1,500 ms (1.04%) were excluded from the analyses. Also, incorrect-response trials were excluded (7.62%) from the RT analyses.

RT

A within-subjects ANOVA with cue color (negative, positive, and reference) and cue validity (valid and invalid) as factors was performed on the mean RTs (see Fig. 7). The main effect of cue color was significant, $F(2, 70) = 5.77$, $p = .005$, $\eta_p^2 = .14$; post hoc analyses revealed a significant difference between the negative ($M = 765$ ms) and positive ($M = 776$ ms) cue, $t(35) = 3.54$, $p = .001$, but not significant differences between the negative and reference color cues ($M = 771$ ms), $t(35) = 1.73$, $p = .093$, and between the reference and positive color cues, $t(35) = 1.62$, $p = .115$. The main

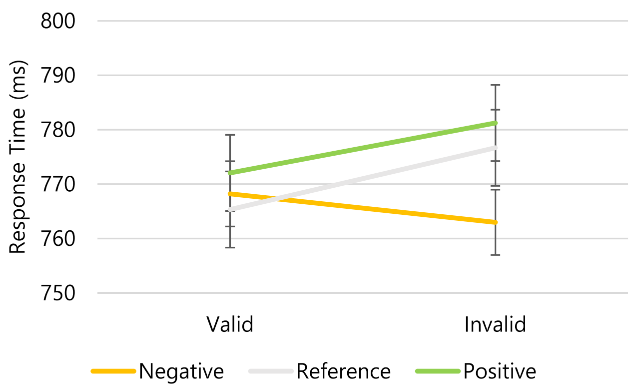

Fig. 7 Results of response times in Experiment 3. Error bars indicate 95% confidence intervals

effect of cue validity was not significant, $F(1, 35) = 2.06$, $p = .16$, $\eta_p^2 = .06$. The mean RTs were 768 ms when the target was presented at the cued location and 773 ms when it was presented at an uncued location. The interaction of cue color and validity was significant, $F(2, 70) = 4.14$, $p = .02$, $\eta_p^2 = .10$. To examine whether the interaction was due to attentional suppression and/or facilitation, ANOVAs were conducted in terms of between the negative and reference color cues and between the reference and positive color cues, respectively. The ANOVA with cue color and cue validity for the negative and reference color cues showed that the main effect of cue color was not significant, $F(1, 35) = 2.99$, $p = .09$, $\eta_p^2 = .08$. Furthermore, the main effect of cue validity was not significant, $F(1, 35) < 1$. However, the interaction of cue color and validity was significant, $F(1, 35) = 8.32$, $p = .007$, $\eta_p^2 = .19$, indicating attentional suppression of the negative color cue. The ANOVA with cue color and cue validity for positive and reference color cues showed that the main effect of cue color was not significant, $F(1, 35) = 2.61$, $p = .12$, $\eta_p^2 = .07$. The main effect of cue validity was significant, $F(1, 35) = 7.89$, $p = .008$, $\eta_p^2 = .18$. The interaction of cue color and validity was not significant, $F(1, 35) < 1$, indicating no attentional facilitation to the positive color cue when compared to the reference color cue.

Post hoc analysis showed that neither negative, $t(35) = -1.07$, $p = .29$, Cohen's $d = -.18$, nor reference color cues, $t(35) = 1.94$, $p = .061$, Cohen's $d = .32$, produced a significant validity effect. The positive color cue produced a significant validity effect, $t(35) = 2.12$, $p = .041$, Cohen's $d = .35$.

Accuracy

None of main effects and an interaction were significant: $F(2, 70) < 1$ for cue color, $F(1, 35) = 1.27$, $p = .27$, $\eta_p^2 = .04$ for cue validity, and $F(2, 70) < 1$ for the interaction between cue color and validity (see Fig. 8).

Survey

All participants reported that they searched for a target by suppressing negative color. No one searched for any colors.

Discussion

As in Experiments 1 and 2, the magnitude of attentional capture was smaller with the negative (-6 ms) than with the reference color cues (11 ms), suggesting that the negative color was proactively suppressed. Furthermore, the magnitude of attentional capture was not different between the reference (11 ms) and positive color cues (9 ms), supporting the assumption that participants did not learn to use target colors by establishing the attentional control settings for target colors, and intertrial priming did not occur or was too weak to produce attentional facilitation to the target colors.

Analyses of Experiments 1, 2, and 3

To examine whether the suppression effect obtained in Experiment 1 was due to reactive suppression, a shorter interval between the onsets of the cue and target displays was used in Experiments 2 and 3 (50 ms) compared to Experiment 1 (150 ms). Experiments 2 and 3 replicated the suppression effect obtained in Experiment 1, suggesting that the attentional suppression was proactive rather than reactive. However, if the suppression effects partially reflect reactive suppression, the suppression effects would be weaker in Experiments 2 and 3 than in Experiment 1. To investigate the possibility, a three-way ANOVA was conducted with cue color (negative and reference) and cue validity (valid and invalid) as within-subjects factors and experiments

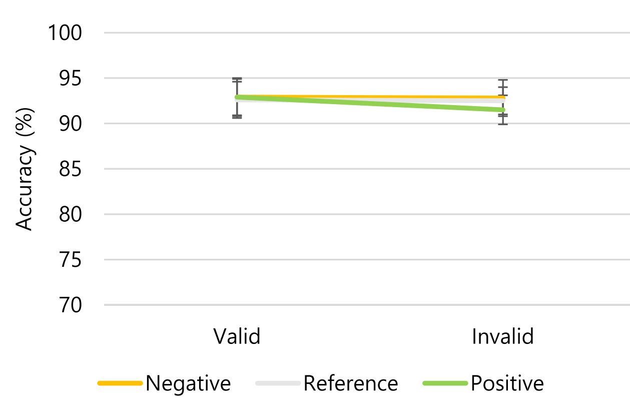

Fig. 8 Results of accuracy in Experiment 3. Error bars indicate 95% confidence intervals

(Experiments 1, 2, and 3) as between-subjects factors. The main effect of cue color was not significant, $F(1, 81) = 1.64$, $p = .20$, $\eta_p^2 = .02$. The main effect of cue validity was not significant, $F(1, 81) < .1$. The main effect of experiments was significant, $F(2, 81) = 5.17$, $p = .008$, $\eta_p^2 = .11$. A two-way interaction of cue color and experiments was not significant, $F(2, 81) < 1$. A two-way interaction of cue validity and experiments was not significant, $F(2, 81) < 1$. As expected, a two-way interaction of cue color and validity was significant, $F(1, 81) = 20.75$, $p < .001$, $\eta_p^2 = .20$, indicating attentional suppression. However, a three-way interaction of cue color, cue validity, and experiments was not significant, $F(2, 81) < 1$, implying that the magnitudes of the suppression effects were consistent regardless of the temporal intervals between the onsets of the cue and target displays. Therefore, it was unlikely that the suppression effects obtained in Experiments 1, 2, and 3 were due partially to reactive suppression.

Furthermore, t-tests revealed that the cue validity effect was significant for the negative color cue, $t(83) = -2.56$, $p = .012$, Cohen's $d = -.28$, and the reference color cue, $t(83) = 2.50$, $p = .014$, Cohen's $d = .27$. Importantly, the direction of the effects between the cues was opposite. That is, for the negative color cues, responses were slower when the targets were presented at the cued than at an uncued location. In contrast, for the reference color cue, responses were faster when the targets were presented at the cued than at an uncued location.

General discussion

The present study showed that attention to distractor colors can be suppressed when attentional suppression is necessary to accomplish a search task and the magnitudes of attentional facilitation for the target and reference colors are identical.

Independent suppression mechanisms or byproducts of facilitation

In Experiments 1–3, attentional suppression was found even though it was unlikely to form the attentional control settings for target colors and produce intertrial priming. There were 12 target colors, and one of the colors was randomly chosen on each trial. Therefore, to search for a target through attentional control for target color, participants should learn the 12 colors during the task and establish the attentional control settings for them. Previous research suggested that this strategy is unlikely to operate due to the limited capacities of working memory and attentional control (Braver et al., 2007; Kerzel & Witzel, 2019; Thornton & Gilden, 2007; van den Berg et al., 2014; Vogel & Machizawa, 2004; Wolfe, 1994). Also, the same target color was presented infrequently to minimize the intertrial priming effect of target colors. Moreover, in Experiment 3, it was demonstrated that the positive and reference color cues captured attention to a similar extent, providing direct evidence that there was no attentional facilitation for the target colors when compared to the reference colors. These findings suggested the independent suppression mechanism, consistent with Forstinger et al.'s (2022) suggestion.

Reactive suppression

It is unlikely that the attentional suppression effects obtained in the present study were due to reactive suppression. Specifically, the reactive suppression account suggests that after all cues (negative, reference, and positive color cues) captured attention, rapid disengagement occurred only for the negative color cues. The rapid disengagement consists of the processes of the attentional capture by cues, the recognition of cue colors, and the attentional shift to the fixation. The time required for the attentional allocation to a negative cue, its recognition, and subsequent disengagement seems longer than 50 ms (Egeth & Yantis, 1997; Ward et al., 1996), which was the temporal interval between the onsets of the cue and search displays in Experiments 2 and 3. Therefore, the findings that the negative color cue captured attention less than the reference and positive color cues in Experiments 2 and 3 suggested proactive rather than reactive suppression. Furthermore, there was no significant change in attentional suppression effects between Experiment 1 (150 ms interval) and Experiments 2 and 3 (50 ms interval). This finding further supported that the suppression effects of the three experiments were proactive not reactive.

Feature- and dimension-based suppression

The attentional suppression in the present study was not due to dimension-based attentional suppression. According to the dimension-based attentional suppression (Forstinger & Ansorge, 2023; Won et al., 2019), a cognitive system suppresses stimuli defined by a feature-dimension such as color dimension. In the present study, however, the negative compared to reference and positive color cues produced different magnitudes of attentional capture, inconsistent with the dimension-based suppression.

Instead, the attentional suppression in the present study was feature-based. According to feature-based suppression (Gaspelin & Luck, 2018), a specific color can be suppressed, allowing for less attentional capture by the negative than reference colors. Note that we do not argue that the dimension-based suppression mechanism did not operate. Rather, given that the reference cue, which was physically salient, did not produce a significant cue validity effect in all experiments, dimension-based suppression appeared to occur (Forstinger & Ansorge, 2023). We suggest that the suppression effect obtained in the present study was not due to the dimension-based suppression because if the dimension-based suppression but not feature-based suppression occurred, the negative and reference color cues should have been suppressed to a similar extent (Forstinger & Ansorge, 2023; Won et al., 2019). Furthermore, this is related to the reason for the reference color cue being used for detecting a feature-based attentional suppression effect.

Baselines for attentional suppression

There are various factors that influence attentional selection such as dimension-based suppression, feature-based suppression, task goals, and physical saliency of stimuli (van Moorselaar & Slagter, 2020; Wolfe, 2021). Accordingly, it was necessary to control factors other than feature-based suppression. The present study used a reference color cue as a criterion to assess whether negative colors were suppressed; therefore, each of the factors other than the feature-based suppression factor should have equal impact on the cues in attentional selection.

The cue validity effect, however, can be driven by the net result of top-down and bottom-up attentional effects. For example, the cue validity effect for the negative color cues (slower responses for valid than invalid cues, $t(83) = -2.56$, $p = .012$) might have reflected not only feature-based suppression but also dimension-based suppression. Furthermore, the cue validity effect for the reference color cue (faster responses for valid than invalid cues, $t(83) = 2.50$, $p = .014$) reflects the attentional facilitation by the cue saliency, which was stronger than the potential suppression mechanisms. Accordingly, to measure feature-based attentional facilitation and suppression, the baseline should be the reference color cue.

The magnitude of the suppression effect for the negative color was smaller in the present study (about 20 ms) than in Forstinger et al.'s (2022) study (about 30 ms). This might be because the search stimuli were letters in the present study and simple lines (horizontal and vertical) in the study by Forstinger et al. More attentional resources are required for identification of letters than line orientations (Treisman & Gelade, 1980). Therefore, available attentional resources for suppressing the negative color might have been greater in Forstinger et al. than in the present study.

Conclusion

Attentional suppression is a more effortful but less efficient mechanism compared to attentional facilitation. Therefore, attentional suppression is often considered a dispensable mechanism. However, this does not necessarily imply that attentional suppression mechanisms should not exist. In the present study, when suppressing distractor features became indispensable to accomplish tasks, attentional suppression occurred without establishing attentional control settings for target features. Thus, the present study supports that independent mechanisms of attentional suppression can operate in the pre-attentive stage.

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Data availability The data from the experiments are available at https://osf.io/dn2va.

Open practice statement None of the experiments were preregistered.

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