Statistical Regularities Based on Distractor Features Modulate Attentional Suppression

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Abstract

Employing a variation of the classic additional singleton paradigm, this study manipulated statistical regularities based on distractor color to investigate its effects on attentional suppression. The results revealed: (1) When participants were compelled to adopt a feature search strategy, response times were significantly faster in all singleton-present conditions compared to the no-color-singleton condition; (2) Response times were significantly faster in the high-probability color singleton condition compared to the low-probability color singleton condition. The findings indicate that the influence of statistical regularities on attention is not confined to stimulus location, and that statistical regularities based on distractor features also modulate the magnitude of attentional suppression effects.

Full Text

Preamble

The Influence of Feature-Based Statistical Regularities of Distractors on the Attentional Suppression Effect

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Abstract

This study employed a variant of the classic additional singleton paradigm to investigate how feature-based statistical regularities of distractor colors influence the attentional suppression effect. The results revealed that: (1) when participants were forced to adopt a feature search strategy, they responded significantly faster in all singleton-present conditions compared to the no-singleton condition; (2) responses were significantly faster in the high-probability color singleton condition than in the low-probability color singleton condition. These findings demonstrate that the influence of statistical regularities on attention is not limited to spatial location; feature-based statistical regularities of distractors can also modulate the magnitude of the attentional suppression effect.

Keywords: additional singleton paradigm, feature search strategy, statistical regularities, attentional suppression effect

Introduction

Every moment, countless pieces of information enter the visual system, yet we can only select a small fraction for further processing. This selection process requires the coordination of two attentional mechanisms: enhancing the processing of task-relevant information (i.e., target processing) and suppressing the processing of task-irrelevant information (i.e., distractor suppression). Attention can be actively allocated to task-relevant locations or objects (Folk et al., 1992), but it may also be automatically and unconsciously captured by salient task-irrelevant stimuli (Yantis & Hillstrom, 1994). Suppressing the processing of task-irrelevant stimuli to prevent attentional capture is crucial for improving search efficiency.

Numerous studies have demonstrated that participants can effectively suppress the processing of salient task-irrelevant stimuli, thereby improving search efficiency and producing "response benefits,"a phenomenon termed the "attentional suppression effect" (Gaspelin et al., 2015; Gaspelin & Luck, 2018a, 2018b; Gong et al., 2017; Hu et al., 2019; Lee et al., 2018). For instance, Gaspelin et al. (2015) investigated the attentional suppression effect using a variant of the additional singleton paradigm. In their experiment, multiple stimuli of different shapes were presented on the screen, and participants were required to search for a target of a specific shape. The target was never a singleton on any dimension, which forced participants to adopt a feature search strategy. In half of the trials, all stimuli were the same color, while in the other half, one distractor had a different color from all other stimuli (i.e., a color singleton distractor). The results showed that when participants were forced to adopt a feature search strategy, the presence of a color singleton did not produce the reaction time cost typically indicative of attentional capture (i.e., slower responses in singleton-present conditions). Instead, it produced a reaction time benefit, with significantly faster responses when a color singleton was present.

Additional evidence for this attentional suppression effect comes from electrophysiological studies (Eimer & Kiss, 2008; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018a; Jannati et al., 2013; Sawaki & Luck, 2010, 2011; Sun et al., 2018) and eye-tracking research (Gaspelin et al., 2017; Gaspelin et al., 2019). Jannati et al. (2013), using a variant of the additional singleton paradigm, found that in trials with faster responses, the salient color singleton elicited a PD (positivity contralateral to the distractor) component indicative of suppression, suggesting that participants suppressed the processing of the color singleton in these faster trials. In other words, effective suppression of the salient color singleton enabled rapid responses. Gaspelin et al. (2017) combined eye-tracking with the additional singleton paradigm and found that initial saccades were less likely to be directed toward salient color singletons compared to other non-singleton distractors, demonstrating that participants could suppress saccades to salient color singletons—a phenomenon also termed oculomotor suppression.

In addition to documenting the existence of attentional suppression, researchers have investigated factors that modulate this effect. Awh et al. (2012) proposed that priority maps are influenced not only by top-down goals and bottom-up physical salience but also by selection history. Selection history affects attention through trial history (Gaspelin et al., 2019), reward (Gong et al., 2016; Gong et al., 2017; 龚梦园 et al., 2018), and threatening stimuli (Nissens et al., 2017). Furthermore, statistical regularities (i.e., implicit regular patterns of stimulus presentation in experimental tasks) have been shown to influence attentional selection (Failing & Theeuwes, 2019; Ferrante et al., 2018; Wang & Theeuwes, 2018a, 2018b; Zhao & Luo, 2017). Research on statistical regularities has examined both target-based regularities (Jiang et al., 2013; Chun & Jiang, 1999; Geng & Behrmann, 2005) and distractor-based regularities (Failing et al., 2019; Wang et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). For example, in studies of target location regularities, Geng and Behrmann (2005) used a visual search task where the target appeared in one location with 75% probability (high-probability target location) and in other locations with 25% probability (low-probability target location). Responses were significantly faster when the target appeared in the high-probability location. Similarly, in studies of distractor location regularities, Wang et al. (2018a) required participants to search for a specific shape (a circle among diamonds or a diamond among circles) while ignoring a color singleton. The color singleton appeared in a specific location on 65% of trials (high-probability distractor location) and in other locations on 35% of trials (low-probability distractor location). The attentional capture effect was significantly reduced when the color singleton appeared in the high-probability location. Moreover, on trials without a color singleton, responses to targets were slower when they appeared in the high-probability distractor location.

While spatial statistical regularities affect the processing of subsequent stimuli at those locations (Failing et al., 2019; Stilwell et al., 2019; Wang et al., 2019), whether feature-based statistical regularities can influence attentional selection remains controversial. Maunsell and Treue (2006) noted that attention can be allocated not only to specific locations but also to specific features. Numerous psychophysical and neuroimaging studies have demonstrated that feature-based attention affects behavioral performance across the visual field (Sàenz et al., 2002; Sàenz et al., 2003; Kumada, 2001). Wang and Theeuwes (2018a) investigated how distractor location regularities affect attentional capture and found that whether the color of the high-probability distractor location repeated from the previous trial did not influence the capture effect. They concluded that the effect of statistical regularities on attentional capture was purely location-based and unaffected by feature-based factors. However, other researchers have found that distractor feature regularities can affect performance in visual search tasks (Vatterott et al., 2017). They observed that color singletons initially interfered with responses, but their impact on attention decreased when the same color singletons were presented consecutively, only to increase again when new color singletons appeared. Thus, there is no consistent conclusion regarding whether feature-based statistical regularities of distractors can modulate attention. Additionally, previous research has found that in the additional singleton paradigm, when participants adopt a feature search strategy, they can top-down suppress the processing of color singletons to facilitate search, producing a significant attentional suppression effect that only occurs when participants have specific knowledge about the singleton features (Gaspelin & Luck, 2018c). It remains to be investigated whether manipulating the statistical regularities of singleton features can overcome this top-down suppression.

The present study builds upon previous research on statistical regularities and attentional suppression to examine how feature-based statistical regularities of distractors influence the attentional suppression effect. Some researchers have noted that stimulus size affects perception and attention (Ono & Kawahara, 2007; Pronina et al., 2018; Louisa, 2017). For example, Louisa (2017) found that attention shift latencies were longest when large stimuli appeared at small eccentricities. However, previous studies on attentional suppression have not adequately controlled for stimulus size across different shapes (Gaspelin et al., 2015). Therefore, this study comprises two experiments. Experiment 1 used a variant of the additional singleton paradigm to investigate the attentional suppression effect while controlling for the influence of stimulus size on salience—that is, adding control for stimulus size to the design of Gaspelin et al. (2015). Experiment 2 built upon Experiment 1 by manipulating the statistical regularities of distractor features to examine their impact on the attentional suppression effect. Specifically, on trials where a color singleton distractor was presented, one color appeared with high probability while the other three colors appeared with low probability. If stimulus size has minimal impact on salience, we expected to observe significant attentional suppression effects in both experiments when stimulus size was controlled. If feature-based statistical regularities of distractors affect the attentional suppression effect, we expected a significant difference in the magnitude of attentional suppression between high-probability and low-probability color singleton conditions.

Experiment 1

2.1.1 Participants

Based on sample sizes reported in relevant studies (Gaspelin et al., 2015; Gaspelin & Luck, 2018a) and power analysis conducted using G*Power 3.1.7, the required sample size for Experiment 1 was determined to be 24. This calculation used a paired-samples t-test as the statistical method, with an effect size dz of 0.6, an alpha error probability of 0.05, and power (1-β error probability) of 0.8. The actual sample consisted of 60 undergraduate students from Soochow University (19 males, 41 females, mean age 20.8 $\pm$ 2.1 years) who were recruited randomly. All participants had normal or corrected-to-normal vision and passed the Wang Kechang Color Vision Test without showing color blindness or weakness. Participants provided informed consent before the experiment and received monetary compensation afterward.

2.1.2 Apparatus and Stimuli

The experimental program was developed using Matlab and the Psychtoolbox toolkit and run on a computer with Windows 7 operating system (graphics card: AMD Radeon(TM) R5 240). Stimuli were presented on a 19-inch LCD monitor (model: DELL P1914S) with a resolution of 1024\$×\$768 and a refresh rate of 75 Hz. Throughout the experiment, participants' heads were stabilized using a chinrest positioned 65 cm from the monitor. Responses were made using a keyboard (model: Dell KB212-B).

During each search sequence, the target and five distractors were evenly distributed on a virtual circle centered on a gray fixation point (radius: 4.5°, with 60° between adjacent stimuli and the fixation point). Each stimulus contained a black line segment (0.3° × 0.05°) randomly tilted 45° to the left or right. Participants were required to judge the orientation of the line segment within the target.

For each participant, the target was randomly assigned as either a diamond or a circle and remained constant throughout the experiment (diamond: 1.13° × 1.13°; circle: diameter 0.9°). Distractors could be three shapes different from the target, with no shape appearing more than twice in a search sequence. For example, when the target was a diamond, distractors could be circles, squares (0.8° × 0.8°), and regular hexagons (side length: 0.5°); when the target was a circle, distractors could be diamonds, squares, and hexagons. For half of the participants, the target was red (RGB: [171 0 0], 15.8 cd/m^2, CIE coordinates: x = 0.67, y = 0.32) and the color singleton was green (RGB: [0 98 0], 15.8 cd/m^2, CIE coordinates: x = 0.34, y = 0.59); for the other half, the target was green and the color singleton was red. Throughout the experiment, search sequences were presented on a black background. All line segments within stimuli were black, and stimulus colors could be red (RGB: [171 0 0]) or green (RGB: [0 98 0]).

Previous studies have not rigorously controlled stimulus size. For example, Gaspelin et al. (2015) used diamonds of 1.6° × 1.6° and circles with a diameter of 1.4°. Converting these to area on our monitor, the perceived circle (2.08 cm^2) was noticeably larger than the diamond (1.73 cm^2). In contrast, Wang and Theeuwes (2018c) used circles (1.06 cm^2) that were substantially smaller than diamonds (2.71 cm^2). Experiment 1 controlled for these size differences, which could bottom-up influence response speed, by equating stimulus size across all shapes (approximately 0.86 cm^2) while maintaining matched color luminance, thereby examining the attentional suppression effect with controlled stimulus dimensions.

2.1.3 Design and Procedure

Following previous research (Gaspelin et al., 2017; Gaspelin & Luck, 2018a), Experiment 1 employed a single-factor within-subjects design (color singleton presence: present vs. absent). For each participant, the target and the other five non-target distractors were the same color in half of the trials, while a color singleton was randomly presented at one non-target location in the other half.

The experimental procedure is illustrated in Figure 1 [Figure 1: see original paper]. Each trial began with a 500 ms blank screen, followed by a gray fixation point at the center of the screen for 500 ms to concentrate participants' attention. After the fixation point disappeared, the search sequence was presented. Participants were instructed to respond as quickly and accurately as possible by pressing keys to indicate the orientation of the line segment within the target (left arrow for left-tilted, right arrow for right-tilted). The search sequence disappeared after the response, and feedback was provided if the response was incorrect or exceeded 3000 ms.

Before the formal experiment, each participant completed 30 practice trials to familiarize themselves with the task and the different stimulus shapes. The formal experiment consisted of 240 trials in each of the two conditions (singleton present vs. absent), for a total of 480 trials divided into 8 blocks of 60 trials each.

Figure 1. Experimental procedure for Experiment 1. In the formal experiment, participants searched for a target of a specific shape (diamond or circle) and responded as quickly and accurately as possible to the orientation of the line segment inside it. During search sequence presentation, all stimuli were the same color in half of the trials (i.e., no color singleton), while a color singleton was present in the other half (dashed circle indicator; see color version in electronic edition).

2.2 Results and Analysis

Trials with reaction times greater than 2000 ms or less than 500 ms (2.32%) and error trials (1.39%) were excluded. A paired-samples t-test (color singleton presence: present vs. absent) was conducted on each participant's mean reaction time for the remaining valid trials.

As shown in Figure 2A, participants responded significantly faster in the singleton-present condition (947.40 ms) than in the singleton-absent condition (963.85 ms), $t(59) = -5.75$, $p < 0.001$, Cohen' s $d = 0.74$, 95% CI = [-22.18, -10.72]. This result indicates that the color singleton did not capture attention and produce a response cost; instead, it produced a response benefit, demonstrating an attentional suppression effect. Analysis of error rates revealed no significant difference between the singleton-present (0.75%) and singleton-absent (0.75%) conditions, $t < 1$.

To examine how participants' cognitive control changed over time, we divided all trials into quarters and conducted a 2 (time: first quarter vs. last quarter) × 2 (color singleton presence: present vs. absent) repeated-measures ANOVA on mean reaction times, following previous research methods (Gaspelin & Luck, 2017; Vatterott & Vecera, 2012). The results showed a significant main effect of time, $F(1,59) = 41.61$, $p < 0.001$, $^2 = 0.41$, a significant main effect of singleton presence, $F(1,59) = 11.70$, $p = 0.001$, $^2 = 0.165$, and a significant interaction between time and singleton presence, $F(1,59) = 5.62$, $p = 0.021$, $^2 = 0.087$. To further understand this interaction, simple effects analyses were conducted for each time period. In the first quarter, the difference between singleton-present (994.98 ms) and singleton-absent (1000.95 ms) conditions was not significant, $F(1,59) = 1.16$, $p = 0.286$. However, in the last quarter, the difference was significant, with faster responses in the singleton-present condition (917.98 ms) than in the singleton-absent condition (942.73 ms), $F(1,59) = 14.92$, $p < 0.001$. This suggests that participants could not effectively suppress the color singleton during the initial trials but gradually developed unconscious suppression of the singleton as the task progressed, thereby improving search efficiency. Furthermore, a paired-samples t-test comparing the magnitude of the attentional suppression effect (RT_{absent} - RT_{present}) between the first and last quarters revealed that the effect was significantly smaller in the first quarter than in the last quarter, $t(59) = -2.37$, $p = 0.021$, Cohen' s $d = -0.31$, 95% CI = [-34.64, 2.94], suggesting that the attentional suppression effect may involve an implicit learning process.

In this experiment, the color singleton had a fixed color feature. It remains unclear whether participants could still suppress the processing of color singletons and produce an attentional suppression effect if the singleton' s color features varied according to statistical regularities. To investigate the influence of feature-based statistical regularities on the attentional suppression effect, Experiment 2 manipulated the statistical regularities of singleton features, with singleton colors divided into high-probability and low-probability categories.

Figure 2 [Figure 2: see original paper] Mean reaction times under different singleton presence conditions in Experiment 1. Panel A shows overall reaction time results for Experiment 1. Panel B shows reaction time results for the first and last quarters under different singleton presence conditions.

Note: ***$p < 0.001$, n.s. $p > 0.05$

Experiment 2

3.1.1 Participants

Based on sample sizes reported in relevant studies (Wang et al., 2019) and power analysis using G*Power 3.1.7, the required sample size for Experiment 2 was determined to be 28. This calculation used repeated-measures ANOVA as the statistical method, with an effect size f of 0.25, an alpha error probability of 0.05, and power (1-β error probability) of 0.8. The participants were the same 60 undergraduate students from Soochow University as in Experiment 1 (19 males, 41 females, mean age 20.8 $\pm$ 2.1 years), recruited randomly. Participants provided informed consent before the experiment and received monetary compensation afterward.

3.1.2 Apparatus and Stimuli

The apparatus and experimental procedure were identical to Experiment 1. The key difference in Experiment 2 was that the color singleton could appear in one of four colors. When the target was red (RGB: [171 0 0], 15.8 cd/m^2, CIE coordinates: x = 0.67, y = 0.32), the color singleton could be green (RGB: [0 98 0], 15.8 cd/m^2, CIE coordinates: x = 0.34, y = 0.59), yellow (RGB: [89 89 0], 15.8 cd/m^2, CIE coordinates: x = 0.44, y = 0.50), blue (RGB: [0 0 255], 15.8 cd/m^2, CIE coordinates: x = 0.16, y = 0.05), or purple (RGB: [148 0 148], 15.8 cd/m^2, CIE coordinates: x = 0.31, y = 0.14). When the target was green, the color singleton could be red, yellow, blue, or purple.

3.1.3 Design and Procedure

Based on previous research (Wang et al., 2019; Wang & Theeuwes, 2018b, 2018c), Experiment 2 employed a single-factor within-subjects design (color singleton type: absent vs. low-probability color vs. high-probability color). In one-third of the trials, no color singleton was presented. In the remaining two-thirds, a color singleton appeared randomly at a location different from the target. Among singleton-present trials, the singleton appeared in one specific color on 50% of these trials (i.e., high-probability color, accounting for 1/3 of total trials). The other 50% of singleton-present trials were divided among three other colors (i.e., low-probability colors, each accounting for 1/9 of total trials). The high-probability color was counterbalanced across participants. Participants were instructed to respond as quickly and accurately as possible by pressing keys to indicate the orientation of the line segment within the target (left arrow for left-tilted, right arrow for right-tilted).

Before the formal experiment, each participant completed 30 practice trials to familiarize themselves with the task and the different stimulus colors. The formal experiment consisted of 120 trials in the no-singleton condition and 240 trials in the singleton-present condition (120 high-probability color singleton trials and 120 low-probability color singleton trials), divided into 6 blocks of 60 trials each.

3.2 Results and Analysis

To examine the effect of reaction time across different color singleton type conditions, trials with reaction times greater than 2000 ms or less than 500 ms (4.44%) and error trials (1.91%) were first excluded. A repeated-measures ANOVA (color singleton type: absent vs. low-probability color vs. high-probability color) was then conducted on each participant's mean reaction time for the remaining valid trials, F(2,118) = 13.91, $p < 0.001$, ^{2} = 0.19. The results are shown in Figure 3 [Figure 3: see original paper]. Further pairwise t-tests comparing the three color singleton type conditions revealed that participants responded significantly slower in the no-singleton condition (1033.61 ms) than in the low-probability color singleton condition (1022.98 ms), t(59) = 2.54, p = 0.014, Cohen' s d = 0.33, 95% CI = [2.24, 19.03]. They also responded significantly slower in the no-singleton condition (1033.61 ms) than in the high-probability color singleton condition (1010.69 ms), t(59) = 5.39, $p < 0.001$, Cohen' s d = 0.70, 95% CI = [14.41, 31.44]. These results demonstrate an attentional suppression effect when color singletons were present, indicating that participants could suppress singleton processing to produce reaction time benefits. Furthermore, responses were significantly faster in the high-probability color singleton condition (1010.69 ms) than in the low-probability color singleton condition (1022.98 ms), t(59) = 2.68, p = 0.010, Cohen' s d = 0.35, 95% CI = [3.11, 21.48]. This finding indicates that feature-based statistical regularities of distractors can modulate the attentional suppression effect—participants were better able to suppress high-probability color features compared to low-probability color features. A repeated-measures ANOVA on error rates across the three conditions showed no significant differences, F(2,118) = 1.04, p = 0.356.

Consistent with Experiment 1, to examine how the influence of feature-based statistical regularities on the attentional suppression effect changed over time, we divided all trials into quarters and conducted a 2 (time: first quarter vs. last quarter) × 3 (color singleton type: absent vs. low-probability color vs. high-probability color) repeated-measures ANOVA on mean reaction times, following previous analytical methods (Gaspelin & Luck, 2018a; Vatterott & Vecera, 2012). The results showed a significant main effect of time, with responses becoming significantly faster as the task progressed, F(1,59) = 11.17, p = 0.001, ^{2} = 0.159, and a significant main effect of color singleton type, F(2,118) = 13.64, $p < 0.001$, ^{2} = 0.188. The interaction between time and singleton type was not significant, F(2,118) = 0.68, p = 0.507, ^{2} = 0.011. However, because we were particularly interested in the effect of singleton type at different time points, we conducted further post-hoc comparisons. In the first quarter, there was no significant difference between the no-singleton condition (1062.16 ms) and the low-probability color singleton condition (1053.38 ms), t(59) = 0.99, p = 0.340. However, responses in the no-singleton condition (1062.16 ms) were significantly slower than in the high-probability color singleton condition (1037.42 ms), t(59) = 2.79, p = 0.007, Cohen' s d = 0.36, 95% CI = [7.00, 42.50]. In the last quarter, responses in the no-singleton condition (1027.82 ms) were significantly slower than in both the low-probability color singleton condition (1010.72 ms), $t(59) = 2.07$, $p = 0.043$, Cohen' s $d = 0.27$, 95% CI = [0.56, 33.63], and the high-probability color singleton condition (988.23 ms), $t(59) = 4.29$, $p < 0.001$, Cohen' s $d = 0.55$, 95% CI = [21.10, 58.08]. Crucially, unlike in the first quarter, responses in the last quarter were significantly faster in the high-probability color singleton condition (988.23 ms) than in the low-probability color singleton condition (1010.72 ms), $t(59) = 3.02$, $p = 0.004$, Cohen' s $d = 0.39$, 95% CI = [7.59, 37.40]. These results indicate that the attentional suppression effect differed across singleton feature conditions and was facilitated over time in all feature conditions. Moreover, participants acquired suppression of high-probability features more rapidly than suppression of low-probability features.

Figure 3. Reaction times under different singleton presence conditions in Experiment 2. Panel A shows overall reaction time results for Experiment 2. Panel B shows reaction time results for the first and last quarters under different singleton presence conditions.

Note: ***p < 0.001,*** *p < 0.01,* $p < 0.05$, n.s. $p > 0.05$

Discussion

The present study employed a variant of the classic additional singleton paradigm to investigate how feature-based statistical regularities of color singleton distractors influence the attentional suppression effect. In Experiment 1, after controlling for the influence of stimulus size, we still found that participants responded significantly faster when a singleton distractor was present compared to when it was absent, demonstrating a response benefit from suppressing distractors—a significant attentional suppression effect. Further analysis revealed that this effect emerged and increased gradually as the task progressed. Controlling for stimulus size was crucial because previous studies have shown that size differences can affect results (Wang & Theeuwes, 2018b). For example, in Wang and Theeuwes (2018b), participants searched for a 1° circle among 2° angular stimuli, and found that distractors that should have been suppressed actually captured attention. Building upon Experiment 1, Experiment 2 manipulated the statistical features of color singleton distractors to examine their impact on the attentional suppression effect. Consistent with Experiment 1, the results showed that when a color singleton was presented —regardless of whether it was a low-probability or high-probability color— participants responded significantly faster than in the no-singleton condition. Moreover, compared to the low-probability color condition, participants showed better suppression of high-probability color singleton distractors, producing a larger attentional suppression effect. This demonstrates that statistical regularities of singleton distractor features can influence the attentional suppression effect. Comparisons between early and late trials revealed that participants rapidly suppressed high-probability color singletons, while suppression of low-probability color singletons developed gradually over the course of the task.

Previous research has shown that location-based statistical regularities of distractors can affect visual attention (Failing et al., 2019; Wang & Theeuwes, 2018a; Wang et al., 2019). While spatial location has long been a central focus in attention research, attention can also be allocated to specific features (Maunsell & Treue, 2006). The present findings demonstrate that feature-based statistical regularities of distractors can similarly influence visual attention. At first glance, our results appear similar to previous location-based studies showing that high-probability locations or features receive more suppression (Failing et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). However, the underlying mechanisms differ. Previous location-based studies typically used the classic additional singleton paradigm, where the target was a shape singleton and participants adopted a singleton detection strategy—searching for the item that differed from all others. In this context, the color singleton automatically captured attention as a color dimension singleton, producing an attentional capture effect indexed by reaction time costs. The "suppression" observed when color singletons appeared in high-probability locations essentially meant that the attentional capture effect was reduced compared to low-probability locations. In contrast, Experiment 2 used a variant of the additional singleton paradigm with multiple different shapes, where the target was no longer a shape singleton. This forced participants to adopt a feature search strategy, resulting in top-down suppression of the color singleton and producing an attentional suppression effect indexed by reaction time benefits. In this case, suppression of high-probability color singletons meant an increase in the attentional suppression effect.

Some researchers have proposed that feature-based attention plays an important role in searching for stimuli with specific features. In visual search tasks, feature-based attention can enhance responses to target-related information, with many cortical voxels showing stronger responses to attended features than to other features (Gong & Liu, 2020; Maunsell & Treue, 2006). The present study extends this by demonstrating that feature-based attention also plays a crucial role in suppressing distractor processing. One possible explanation for why participants could simultaneously suppress multiple color features in our study relates to working memory capacity. Some researchers suggest that working memory capacity is linked to feature-based attention, with maintaining attention to a feature potentially involving the same neural resources as visual working memory (Sawaki et al., 2012; Sawaki & Luck, 2013). Feature-based attention can influence processing for a number of features that fits within working memory capacity. In Experiment 2, there were four different colors for high- and low-probability singletons, and participants were informed about the possible colors. When working memory capacity could accommodate this information, participants were able to suppress stimuli with specific features. However, not all research supports this view; some studies suggest that working memory capacity is independent of feature-based attention (Burnham et al., 2011; Fukuda & Vogel, 2011; Harris et al., 2020). For example, Harris et al. (2020) used three independent working memory tasks and found no correlation between individual differences in working memory capacity and individual differences in feature-based bias when processing distractors. Thus, the relationship between working memory and feature-based attention remains controversial, and future research is needed to investigate whether working memory capacity relates to how feature-based attention influences the attentional suppression effect.

Some researchers using a paradigm similar to our Experiment 2 have found that when color singleton location was manipulated, participants responded slower in low-probability location conditions than in no-singleton conditions, indicating that the singleton captured rather than suppressed attention (Wang & Theeuwes, 2018c). This differs from our Experiment 2 findings, and the discrepancy may be attributed to two factors. First, in our Experiment 2, color singletons had four possible color features, whereas Wang and Theeuwes (2018c) used location-based statistical regularities with eight possible singleton locations. The attentional resources allocated to each location may have been insufficient to produce greater suppression of high-probability locations. Second, our Experiment 2 used uniform stimulus sizes and required a strict feature search strategy, whereas Wang and Theeuwes (2018c) used 1° circles among seven 2° angular stimuli, potentially preventing participants from adopting a strict feature search strategy. Additionally, the reduced attentional suppression effect for low-probability colors in our Experiment 2 may reflect bottom-up influences from the occasional presentation of low-probability features, with bottom-up capture partially offsetting suppression of the singleton and thereby reducing the attentional suppression effect.

Gaspelin and Luck (2018c) explored the mechanisms of attentional suppression and found that participants could only suppress a singleton when they had prior knowledge of its specific features (what they termed "first-order features"). That is, telling participants to "suppress the red distractor" produced suppression and an attentional suppression effect, whereas telling them to "suppress a stimulus of a different color" did not. They called this the "first-order feature model." This account can explain our findings: participants who were informed about all possible color singleton features before the experiment could suppress them. Our study extends this model by showing that while previous experiments used a single, constant singleton color feature, our experiment used four randomly presented color features throughout the task, indicating that attentional suppression is highly flexible and robust. However, an alternative possibility is that when participants have knowledge of first-order target features, they automatically suppress any color singleton that does not match the target' s first-order features, regardless of the singleton' s feature information or number. Since the target color was single and constant for each participant in both our study and previous research, this possibility cannot be ruled out and requires further investigation.

The comparison between early and late trials in Experiment 1 revealed that the attentional suppression effect increased over time. Similarly, Experiment 2 showed that the attentional suppression effect for low-probability color singletons increased over time, and the difference in effect magnitude between high- and low-probability color singleton conditions also increased. These results demonstrate that the attentional suppression effect changes continuously throughout the task, consistent with previous findings (Gaspelin & Luck, 2018c; Vatterott & Vecera, 2012). This pattern may arise because cognitive control based on top-down information requires sufficient time to become fully established (Han & Kim, 2009). For example, Gaspelin and Luck (2018c) divided trials into four quarters and found no attentional suppression effect in the first quarter but significant suppression in the final quarter. Our Experiment 1 replicated this time course, indicating that suppression of color singletons is not automatic but rather subject to top-down attentional modulation that participants gradually learn to improve search efficiency. Building on Experiment 1, Experiment 2 found that low-probability color singletons could not be effectively suppressed in early trials, though their salience was insufficient to produce significant attentional capture. This may reflect a partial cancellation between bottom-up capture from low-probability color salience and top-down suppression. As the task progressed, participants gradually learned to suppress low-probability color singletons. Unlike Experiment 1, where color singletons could not be well suppressed initially, Experiment 2 showed that high-probability color singletons could be suppressed rapidly, demonstrating that feature-based statistical regularities influence the attentional suppression effect. The rapid suppression of high-probability color singletons, which increased further with task progression, may be due to the increased presentation frequency reducing the salience boost from occasional presentation, allowing participants to effectively suppress them soon after the experiment began.

However, this study has several limitations. First, we focused exclusively on statistical regularities based on color singletons and did not examine other types of salient stimuli (e.g., onset stimuli, emotional stimuli, semantic stimuli). Research shows that onset stimuli affect attention differently than color singletons (Franconeri & Simon, 2003; Jonides & Yantis, 1984), and emotional and semantic stimuli carry social meaning beyond their physical properties (王慧媛 et al., 2018). Future research should investigate how statistical regularities based on different stimulus types influence attention. Second, our color singleton features had identical luminance, preventing examination of interactions between statistical regularities and salience. Some studies have found that high-salience color singletons in high-probability locations produce smaller attentional capture effects than low-salience singletons in high-probability locations (Failing & Theeuwes, 2019). Future research should manipulate salience gradients across multiple color singletons to investigate interactions between feature-based statistical regularities and salience.

In summary, (1) after controlling for stimulus size effects, participants responded significantly faster when color singletons were present, indicating that the attentional suppression effect remains robust in the additional singleton paradigm when participants adopt a feature search strategy; (2) manipulating feature-based statistical regularities of distractors showed that participants responded significantly faster in high-probability color singleton conditions than in low-probability and no-singleton conditions, demonstrating that the attentional suppression effect is indeed influenced by feature-based statistical regularities of distractors.

References

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. Trends in Cognitive Sciences, 16(8), 437-443.

Burnham, B. R., Harris, A. M., & Suda, M. T. (2011). Relationship between WMC and contingent involuntary orienting. Visual Cognition, 19(8), 983-1002.

Chun, M. M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. Psychological Science, 10(4), 360-365.

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. Journal of Cognitive Neuroscience, 20(8), 1423-1433.

Failing, M., & Theeuwes, J. (2019). More capture, more suppression: Distractor suppression due to statistical regularities is determined by the magnitude of attentional capture. Psychonomic Bulletin & Review, 27(1), 86-95.

Failing, M., Wang, B., & Theeuwes, J. (2019). Spatial suppression due to statistical regularities is driven by distractor suppression not by target activation. Attention, Perception, & Psychophysics, 81(5), 1405-1414.

Ferrante, O., Patacca, A., Di Caro, V., Della Libera, C., Santandrea, E., & Chelazzi, L. (2018). Altering spatial priority maps via statistical learning of target selection and distractor filtering. Cortex, 102, 67-95.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. Journal of Experimental Psychology: Human Perception & Performance, 18(4), 1030-1044.

Franconeri, S. L., & Simons, D. J. (2003). Moving and looming stimuli capture attention. Perception & Psychophysics, 65(7), 999-1011.

Fukuda, K., & Vogel, E. K. (2011). Individual differences in recovery time from attentional capture. Psychological Science, 22(3), 361-368.

Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. Journal of Neuroscience, 34(16), 5658-5666.

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2015). Direct evidence for active suppression of salient-but-irrelevant sensory inputs. Psychological Science, 26(11), 1740-1750.

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2017). Suppression of overt attentional capture by salient-but-irrelevant color singletons. Attention, Perception, & Psychophysics, 79(1), 45-53.

Gaspelin, N., & Luck, S. J. (2018a). Combined electrophysiological and behavioral evidence for the suppression of salient distractors. Journal of Cognitive Neuroscience, 30(9), 1265-1277.

Gaspelin, N., & Luck, S. J. (2018b). The role of inhibition in avoiding distraction by salient stimuli. Trends in Cognitive Sciences, 22(1), 79–92.

Gaspelin, N., & Luck, S. J. (2018c). Distinguishing among potential mechanisms of singleton suppression. Journal of Experimental Psychology: Human Perception and Performance, 44(4), 626–644.

Gaspelin, N., Gaspar, J. M., & Luck, S. J. (2019). Oculomotor inhibition of salient distractors: Voluntary inhibition cannot override selection history. Visual Cognition, 27(3–4), 287-299.

Geng, J. J. & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. Perception & Psychophysics, 67(7), 1252–1268.

Gong, M., Li, S., & Yang, F. (2016). Reward association facilitates distractor suppression in human visual search. The European Journal of Neuroscience, 43(7), 942–953.

Gong, M., Jia, K., & Li, S. (2017). Perceptual competition promotes suppression of reward salience in behavioral selection and neural representation. Journal of Neuroscience, 37(26), 6242–6252.

Gong, M., Jia, K., & Li, S. (2018). Reward learning drives modulation on visual attention. Chinese Journal of Applied Psychology, 24(2), 99–112. [龚梦园, 贾珂, 李晟. (2018). 奖赏学习对视觉注意的调控. 应用心理学, 24(2), 99–112.]

Gong, M., & Liu, T. (2020). Biased neural representation of feature-based attention in the human frontoparietal network. Journal of Neuroscience, 40(43), 8386–8395.

Han, S. W., & Kim, M. S. (2009). Do the contents of working memory capture attention? Yes, but cognitive control matters. Journal of Experimental Psychology: Human Perception and Performance, 35(5), 1292–1302.

Harris, A. M., Jacoby O., Remington R. W., Becker S. I., Mattingley J. B. (2020). Behavioral and electrophysiological evidence for a dissociation between working memory capacity and feature-based attention. Cortex, 129, 159–174.

Hu, L., Ding, Y., & Qu, Z. (2019). Perceptual learning induces active suppression of physically nonsalient shapes. Psychophysiology, 56(9), e13393.

Jannati, A., Gaspar, J. M., & McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology. Journal of Experimental Psychology: Human Perception and Performance, 39(6), 1713–1730.

Jiang, J., Summerfield, C., & Egner, T. (2013). Attention sharpens the distinction between expected and unexpected percepts in the visual brain. Journal of

Neuroscience, 33(47), 18438-18445.

Jonides, J., & Yantis, S. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance, 10(4), 601-621.

Kumada, T. (2001). Feature-based control of attention: Evidence for two forms of dimension weighting. Perception & Psychophysics, 63(4), 698-708.

Lee, J., Leonard, C. J., Luck, S. J., & Geng, J. J. (2018). Dynamics of feature-based attentional selection during color-shape conjunction search. Journal of Cognitive Neuroscience, 30(12), 1773-1787.

Louisa, K. (2017). The effect of stimulus and eccentricity on attention shift latencies. Vision, 1(4), 25-34.

Maunsell, J. H. R., & Treue, S. (2006). Feature-based attention in visual cortex. Trends in Neurosciences, 29(6), 317-322.

Nissens, T., Failing, M., & Theeuwes, J. (2017). People look at the object they fear: Oculomotor capture by stimuli that signal threat. Cognition and Emotion, 31(8), 1707-1714.

Ono, F., & Kawahara, J. I. (2007). The subjective size of visual stimuli affects the perceived duration of their presentation. Perception & Psychophysics, 69(6), 952-957.

Pronina A. S., Grigoryan R.K., & Kaplan A.Ya. (2018). Objective eye movements during typing in P300 BCI: The effect of stimuli size and spacing. Moscow University Psychology Bulletin, 4, 120-134.

Sàenz, M., Buraĉas, G. T., & Boynton, G. M. (2002). Global effects of feature-based attention in human visual cortex. Nature Neuroscience, 5(7), 631-632.

Sàenz, M., Buraĉas, G. T., Boynton, G. M. (2003). Global feature-based attention for motion and color. Vision Research, 43, 629-637.

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. Attention, Perception, & Psychophysics, 72(6), 1455-1470.

Sawaki, R., & Luck, S. J. (2011). Active suppression of distractors that match the contents of visual working memory. Visual Cognition, 19(7), 956-972.

Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. Journal of Neuroscience, 32(31), 10725-10736.

Sawaki, R., & Luck, S. J. (2013). Active suppression after involuntary capture of attention. Psychonomic Bulletin & Review, 20(2), 296-301.

Stilwell, B. T., Bahle, B., & Vecera, S. P. (2019). Feature-based statistical regularities of distractors modulate attentional capture. Journal of Experimental

Psychology: Human Perception and Performance, 45(3), 419-433.

Sun, M., Wang, E., Huang, J., Zhao, C., Guo, J., Li, D., . . . Song, Y. (2018). Attentional selection and suppression in children and adults. Development Science, 21(6), e12684.

Vatterott, D. B., & Vecera, S. P. (2012). Experience-dependent attentional tuning of distractor rejection. Psychonomic Bulletin & Review, 19(5), 871-878.

Vatterott, D. B., Mozer, M. C., & Vecera, S. P. (2017). Rejecting salient distractors: Generalization from experience. Attention, Perception, & Psychophysics, 80, 485-499.

Wang, B. & Theeuwes, J. (2018a). Statistical regularities modulate attentional capture. Journal of Experimental Psychology: Human Perception and Performance, 44(1), 13-17.

Wang, B., & Theeuwes, J. (2018b). How to inhibit a distractor location? Statistical learning versus active, top-down suppression. Attention, Perception, & Psychophysics, 80(4), 860-870.

Wang, B., & Theeuwes, J. (2018c). Statistical regularities modulate attentional capture independent of search strategy. Attention, Perception, & Psychophysics, 80(7), 1763-1773.

Wang, B., Samara, I., & Theeuwes, J. (2019). Statistical regularities bias overt attention. Attention, Perception, & Psychophysics, 81, 1813-1821.

Wang H. Y., Sui, J., & Zhang M. (2018). Attentional capture is contingent on attentional control setting for semantic meaning: Evidence from modified spatial cueing paradigm. Acta Psychologica Sinica, 50(10), 1071-1082. [王慧媛, 隋洁, 张明. (2018). 语义关联的注意捕获——来自线索化范式的证据. 心理学报, 50(10), 1071-1082.]

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance, 10(4), 601-621.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. Journal of Experimental Psychology: Human Perception and Performance, 20(1), 95-107.

Zhao, J., & Luo, Y. (2017). Statistical regularities guide the spatial scale of attention. Attention, Perception, & Psychophysics, 79(1), 24-30.

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