

Color Matters More Than Shape: Effects of Within-Dimension Statistical Regularities of Distractor Features on Attentional Selection

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Abstract

In visual search tasks, search efficiency improves when distractor features remain constant, demonstrating that statistical regularities can enhance attentional selection performance. However, previous studies have employed inconsistent feature dimensions for targets and distractors, potentially confounding the effects of statistical regularities with attentional guidance differences attributable to dimensional variations. To investigate how target and distractor dimensions influence the effects of statistical regularities, Experiment 1—consistent with prior research—defined targets by shape and distractors by color, while Experiment 2 reversed these dimensional assignments. The results indicated that differences in defining dimensions between targets and distractors themselves interfere with the operation of statistical regularities. Consequently, Experiment 3 maintained consistent defining dimensions for both targets and distractors, simultaneously examining the influence of statistical regularities in shape and color dimensions on attentional selection. The findings revealed that after dimensional unification, whether in the shape or color dimension, reaction times to targets were significantly faster when high-probability distractors were present compared to low-probability conditions, thereby confirming the independent contribution of statistical regularities to attentional selection. More critically, in the color dimension, no significant difference emerged between high-probability and absent conditions, suggesting that statistical regularities in the color dimension exert stronger inhibitory effects, preventing distractors from capturing attention. Conversely, in the shape dimension, reaction times were slower in the high-probability condition, indicating that statistical regularities in the shape dimension produce weaker inhibition, with attentional capture persisting. This study disentangles confounds arising from stimulus-defining dimensions themselves and demonstrates that the visual system can optimize cognitive resource allocation through statistical regularities and search dimensions, thereby enhancing search efficiency.

Full Text

Preamble

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1. Does this study break new ground or offer unique perspectives?

The journal aims to publish research that is “both scientifically excellent and of particularly broad interest and significance.” Studies with only minor contributions, lacking attempts to open new areas of inquiry or propose innovative perspectives—especially those focusing purely on algorithms or techniques without clear psychological questions—have low acceptance probability.

Response:

1) **Logical progression:** To verify how the defining dimensions (color or shape) of targets and distractors influence statistical regularity effects, Experiment 1 replicated previous findings. Experiment 2 confirmed the critical role of defining dimensions through a reversal manipulation, and Experiment 3 resolved this key issue. The logic advances systematically and delves deeper at each step.

2) **Theoretical contribution:** This study pioneeringly identifies confounds arising from dimensional differences between targets and distractors, challenges previous findings, provides critical methodological improvements, and revises theories of statistical regularity effects.

3) **Rich data exploration:** Beyond conventional comparisons of statistical regularity effects, we examined temporal dynamics of statistical learning across different dimensions by segmenting the experiment into time periods.

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Please state both. Psychology studies often suffer from low statistical power due to insufficient sample sizes. We recommend explaining your sample size determination in the Methods section, based on justified effect sizes and desired power, and reporting the software used. Reference: <https://osf.io/5awp4/>

Response: The Participants section reports both planned and actual sample sizes. All three experiments had actual sample sizes larger than planned.

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(Report exact p-values except for $p < 0.001$. For Bayesian factors, report sensitivity to prior assumptions.)

Response: The paper complies with this requirement.

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If you excluded data, did you report: what was excluded, why, and how results would change with inclusion? How were missing data handled? Were any questionnaire items deleted? Were any variables not reported? Please indicate locations in the paper.

Response: Each experiment's Results section reports exclusion criteria (trials beyond 3 SDs from each condition's mean).

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Please attach them for review. Will you share these materials if published?

Response: No unreviewed materials were used.

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Please choose one:

- c) Raw data and programs have been shared on the Psychological Science Data Bank (✓) <https://www.scidb.cn/en/s/I7nI7r>*
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Response: No (✓). The study is a laboratory experiment but was not pre-registered.

11. Ethics approval for human/animal subjects?

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Response: Yes, approval has been sent.

12. English abstract?

Have you written a 400-500 word English abstract following our guidelines? Has it been reviewed by a native English speaker or professional editing service?

Response: The English abstract is included in the manuscript.

13. If first author is a student, has the supervisor emailed the editorial office (xuebao@psych.ac.cn) to confirm they have reviewed the paper?

Response: First author is not a student.

14. Confidentiality certificate?

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Response: Already sent.

Color Trumps Shape: The Impact of Statistical Regularities of Same-Dimension Distractor Features on Attentional Selection

Abstract

In visual search tasks, search efficiency improves when distractor features remain fixed, demonstrating that statistical regularities can enhance attentional selection performance. However, previous studies often employed inconsistent feature dimensions for targets and distractors, potentially confounding statistical regularity effects with attentional guidance differences arising from distinct dimensions. Color is considered to possess “undoubted guiding attributes” for attention, whereas shape represents a relatively weaker guiding feature. This dimensional difference may influence the effectiveness of statistical learning in visual search tasks. The present study investigated how target and distractor dimensions affect the efficacy of statistical regularities, and examined the influence of statistical regularities on attentional selection across both shape and color dimensions while controlling for consistent dimensional definitions. We hypothesized that statistical regularities would differentially affect attentional selection depending on the defining dimensions of targets and distractors.

Three experiments were conducted with university students. Experiment 1 replicated previous work by defining targets by shape and distractors by color. Participants searched for a specific shape (e.g., diamond) among non-targets while ignoring a color singleton distractor. Experiment 2 reversed these dimensional definitions, with targets defined by color and distractors by shape. Experiment 3 controlled for consistent dimensional definitions, examining statistical regularity effects across both shape and color dimensions. Participants completed two

blocks: one with shape-defined targets and distractors, and another with color-defined targets and distractors. Across all experiments, participants performed a visual search task identifying targets among distractors while we manipulated distractor feature probabilities (high-probability: 72%, low-probability: 12%, no-distractor: 16%). Response times and accuracy served as dependent variables. All experiments employed within-subjects designs with counterbalanced condition orders.

Experiment 1 found significantly faster response times in high-probability distractor conditions ($691 \pm 10\text{ms}$) compared to low-probability conditions ($605 \pm 10\text{ms}$), confirming color-based statistical regularity effects on attentional selection. No significant difference emerged between no-distractor ($587 \pm 10\text{ms}$) and high-probability conditions, indicating effective suppression of high-probability distractors. Experiment 2 showed no significant effect of shape-based statistical regularities when targets were defined by color, suggesting that dimensional differences between targets and distractors interfere with statistical learning. In Experiment 3, with unified target and distractor dimensions, response times were significantly faster in high-probability versus low-probability distractor conditions for both shape and color dimensions. Critically, in the color dimension, no significant difference appeared between high-probability ($565 \pm 57\text{ms}$) and no-distractor conditions ($563 \pm 57\text{ms}$), indicating stronger suppression effects. Both conditions were significantly faster than the low-probability condition ($580 \pm 63\text{ms}$). Conversely, in the shape dimension, response times were slower in high-probability conditions ($747 \pm 87\text{ms}$) than no-distractor conditions ($699 \pm 80\text{ms}$), suggesting weaker suppression and persistent attentional capture, though both were faster than the low-probability condition ($759 \pm 92\text{ms}$). Analyses of learning trajectories revealed that color-based statistical learning emerged earlier and remained more stable than shape-based learning.

This study clarifies confounds introduced by inconsistent stimulus-defining dimensions in previous statistical regularity research. The findings highlight how the visual system optimizes cognitive resource allocation through both statistical regularities and search dimensions, thereby enhancing search efficiency. The differential effects between color and shape dimensions suggest that statistical learning may be more effective for features with stronger attentional guidance properties. These results advance our understanding of how prior experience shapes current attentional processes and provide insights for improving visual search efficiency in applied settings such as educational environment design and visual display optimization. Future research should explore these findings in more complex real-world scenarios and investigate interactions between different feature dimensions in statistical learning processes.

Keywords: statistical regularities; attentional selection; attentional suppression; color; shape

Introduction

Every moment, vast amounts of information enter our visual system. Given limited cognitive resources (Broadbent, 1958; Lennie, 2003), we must select task-relevant information while ignoring irrelevant distractors. Fortunately, our environment is not random but follows regular patterns. For instance, teachers repeatedly emphasize key knowledge points while glossing over non-essentials. The regularity that certain knowledge is frequently mentioned helps individuals quickly focus on important content, enabling efficient learning. Such implicitly embedded stimulus presentation patterns constitute statistical regularities (张帆等, 2021). Statistical regularities affect stimulus processing: as stimuli repeatedly associate with spatial locations or features, attentional deployments change, creating persistent selection biases that influence attentional selection of targets or suppression of distractors with statistical regularities (Failing & Theeuwes, 2018; Theeuwes, 2019). Investigating how statistical regularities affect attentional selection thus illuminates how prior experience influences current attention and provides guidance for improving attentional control, designing effective educational environments, and optimizing advertising placement.

Attention is influenced by distractor statistical regularities (Failing & Theeuwes, 2020; Ferrante et al., 2018; Wang & Theeuwes, 2018a, 2018b). Manipulating spatial statistical regularities of distractors affects visual search performance. For example, in Wang and Theeuwes (2018b), participants searched for a specific shape (circle among diamonds) while ignoring a color singleton distractor that appeared in a particular location with 65% probability (high-probability location) versus 35% elsewhere (low-probability). Results showed significantly faster response times when distractors appeared in high-probability locations, suggesting easier suppression of distractors in frequently occupied positions. Beyond location, feature-based statistical regularities (e.g., color, size, shape) also influence attentional selection, enabling individuals to learn distractor statistics, reduce interference, and improve selection efficiency (Failing et al., 2019; Stilwell et al., 2019; Vatterott et al., 2018; 张帆等, 2021). For instance, Stilwell et al. (2019) used the additional singleton paradigm, requiring participants to search for a specific shape (circle among diamonds) while ignoring a color singleton distractor that was a particular color with 65% probability (high-probability color) versus 35% for other colors. Results showed faster responses when distractors were high-probability colors. 张帆等 (2021) similarly found stronger attentional suppression of high-probability color distractors when using feature search mode.

However, the inherent attentional guidance strength differs between target (shape) and distractor (color) dimensions, potentially confounding statistical regularity effects. Previous research typically defined targets by shape while manipulating color-based distractor statistics (Stilwell et al., 2019; Wang & Theeuwes, 2018b; Vatterott et al., 2018). Different features produce differential attentional guidance. Compared to target shape, color possesses “undoubted guiding attributes” for attention (Wolfe & Horowitz, 2017), showing advantages

in attentional selection (Theeuwes, 1992; Treisman & Gelade, 1980) and earlier perceptual processing (Clifford et al., 2003; Rentzeperis et al., 2014; White et al., 2014). As color dimension singletons, the unique distractors in previous studies strongly captured attention (Theeuwes, 1992; Bacon & Egeth, 1994). Therefore, whether statistical regularity effects persist when targets are defined by the strongly guiding color dimension and distractors by the weakly guiding shape dimension remains unclear. Experimental verification is needed to determine whether different target and distractor dimensions confound statistical regularity effects.

If dimensional effects exist, unifying target and distractor definitions could balance attentional guidance strength and isolate statistical regularity effects. Kim et al. (2023) defined both targets and distractors within the same dimension (targets: regular or inverted pentagons; distractors: regular or inverted triangles), finding stronger suppression of high-probability distractors. However, this study examined only the shape dimension without direct comparison to the commonly used color dimension. Glavan et al. (2020) used Systems Factorial Technology to demonstrate that color and shape information can guide attention in parallel, with temporally separate processing. Moreover, the neural pathways differ: color-based attention activates bilateral extrastriate cortex in dorsolateral occipital cortex (dLO), while shape-based attention activates parahippocampal gyrus (PhG) and temporal cortex around the superior temporal sulcus (STS) (Clark et al., 1997; Corbetta et al., 1990; Wei et al., 2023). Building on Kim et al. (2023), using consistent dimensions for targets and distractors while directly comparing statistical regularity effects across shape and color dimensions can provide further evidence for dimension-specific attentional guidance pathways.

To investigate how target and distractor defining dimensions affect distractor feature-based statistical regularities, we conducted three experiments. Experiment 1 maintained conventional dimensional definitions (target: shape; distractor: color) to validate statistical regularity effects on attentional selection—that is, reduced attentional capture and improved target identification with high-probability color distractors (Failing et al., 2019; Stilwell et al., 2019; Vatterott et al., 2018)—demonstrating cross-dimensional effects of color-based distractor statistics.

Experiment 2 reversed dimensional definitions (target: color; distractor: shape). If dimensional guidance differences exist, statistical regularity effects should shift accordingly. Building on Experiments 1 and 2, Experiment 3 unified target and distractor definitions within the same dimension (both color or both shape) to directly compare statistical regularity effects across shape and color dimensions while controlling for attentional guidance strength differences. We hypothesized that if same-dimension distractor statistics affect attentional selection, high-probability distractors would be more easily suppressed than low-probability ones, facilitating target identification. Furthermore, based on color’s “undoubted guiding attributes,” we expected stronger statistical regularity effects in the color dimension.

Experiment 1

2.1.1 Participants Using G*Power 3.1.9.7 (effect size $f = 0.25$, $\alpha = 0.05$, power = 0.8), the required sample size was 29. We recruited 31 university students from Tianjin (15 male, 16 female; mean age = 20.5 ± 1.3 years) with normal or corrected-to-normal vision. All provided informed consent and received compensation. The study was approved by the ethics committee.

2.1.2 Apparatus and Procedure The experiment was programmed in E-Prime 2.0. Stimuli were presented on a 14-inch monitor (resolution: 1920×1080 , refresh rate: 60Hz) viewed from 65cm . Each trial began with a gray fixation point ($RGB : 102, 101, 92; 13\text{cd/m}^2$, $CIE : x = 0.321, y = 0.34$) for $100\text{--}500\text{ms}$, followed by a search display [Figure 1: see original paper] containing four stimuli evenly distributed on a virtual circle 2° from center. Each stimulus contained a tilted 45° left or right. Participants responded to the line orientation as quickly and accurately as possible.

The search display contained one target, two non-salient distractors, and one unique distractor. The target was either an equilateral triangle ($0.9^\circ \times 0.9^\circ$) or diamond ($1^\circ \times 1^\circ$), fixed throughout the experiment. Non-salient distractors were gray circles (diameter 0.9° ; $RGB : 102, 101, 92$). The unique distractor was randomly red ($RGB : 205, 0, 0; 13\text{cd/m}^2$, $CIE : x = 0.64, y = 0.33$) or green ($RGB : 0, 118, 0; 13\text{cd/m}^2$, $CIE : x = 0.300, y = 0.600$), categorized as: high-probability color (72%), low-probability color (12%), or absent (16%). For example, if the target was a diamond, the high-probability distractor might be green and low-probability red, counterbalanced across participants. The experiment used a one-factor three-level within-subjects design (distractor type: absent, high-probability color, low-probability color) with response time and accuracy as dependent variables. The response window was 800 ms with a fixed trial duration of 1500 ms. Practice included 20 trials; the main experiment comprised 600 trials (96 absent, 432 high-probability, 72 low-probability), lasting approximately 15 minutes.

[Figure 1: see original paper] shows the search display for Experiment 1. Participants searched for a specific shape (diamond or triangle) and responded to the line orientation inside it. High- and low-probability distractors were red or green, counterbalanced across participants.

2.2 Results We excluded error trials (7.38%) and trials with response times beyond 3 SDs (1.03%). A repeated-measures ANOVA on mean response times revealed a significant main effect of distractor type, $F(2, 60) = 20.08$, $p < 0.001$, $\eta^2 = 0.401$ [Figure 2: see original paper]. Post-hoc comparisons showed no significant difference between absent (587 ± 10 ms) and high-probability conditions (691 ± 10 ms), $p = 0.074$. Both absent (587 ± 10 ms) and high-probability conditions (691 ± 10 ms) were significantly faster than low-probability (605 ± 10 ms), $p_s < 0.001$. These results demonstrate that color-based distractor statistics affect visual selective attention: high-probability color distractors receive greater suppression, reducing attentional capture.

[Figure 2: see original paper] shows response times for target identification across statistical regularity conditions when targets were shape-defined and distractors color-defined. Error bars represent standard errors.

To examine temporal dynamics of distractor suppression, we divided trials into six temporal bins and conducted a 3 (distractor type: absent, high-probability color, low-probability color) \times 6 (time bin: 1–6) repeated-measures ANOVA. Results [Figure 3: see original paper] showed no significant main effect of time, $F(5, 150) = 1.79$, $p = 0.119$, indicating stable response speeds across the experiment. The main effect of distractor type was significant, $F(2, 60) = 19.77$, $p < 0.001$, $\eta^2 = 0.397$: absent and high-probability conditions were significantly faster than low-probability ($ps < 0.001$), with no difference between absent and high-probability conditions ($p = 0.096$). The interaction was non-significant, $F(10, 300) = 0.84$, $p = 0.548$, with Bayesian factor $BF_{10} = 0.016$. As $BF < 0.03$ provides strong evidence for the null hypothesis (Wagenmakers et al., 2018), this indicates no significant differences across time bins for different distractor conditions. Participants learned distractor feature statistics rapidly, from the first temporal segment.

[Figure 3: see original paper] shows response times across temporal bins for Experiment 1 when targets were shape-defined and distractors color-defined.

Experiment 1 replicated previous findings, confirming that color-based distractor statistics affect attentional selection (Failing et al., 2019; Stilwell et al., 2019; Vatterott et al., 2018). However, if dimensional definitions are reversed—targets defined by the strongly guiding color dimension and unique distractors by the weakly guiding shape dimension—would shape-based statistical regularities still affect attention? Experiment 2 examined how dimensional reversal influences statistical regularity effects.

Experiment 2

3.1.1 Participants Using G*Power 3.1.9.7 (effect size $f = 0.25$, $\alpha = 0.05$, power = 0.8), required sample size was 29. We recruited 31 university students from Tianjin (15 male, 16 female; mean age = 20.5 ± 1.3 years) with normal or corrected-to-normal vision. All provided informed consent and received compensation. The study was approved by the ethics committee.

3.1.2 Apparatus and Procedure The experiment used a one-factor three-level within-subjects design (distractor type: absent vs. high-probability shape vs. low-probability shape). Apparatus and procedure matched Experiment 1, except the search display [Figure 4: see original paper] contained one color-defined target, two non-salient distractors, and one shape-defined unique distractor. The target was randomly red or green, fixed throughout. The unique distractor was randomly an equilateral triangle ($0.9^\circ \times 0.9^\circ$) or diamond ($1^\circ \times 1^\circ$), with high-probability shape (72%), low-probability shape (12%), or absent (16%). High- and low-probability shapes were counterbalanced across participants.

[Figure 4: see original paper] shows the search display for Experiment 2. Participants searched for a specific color (red or green) and responded to the line orientation. High- and low-probability distractors were diamond or triangle, counterbalanced across participants.

3.2 Results We excluded error trials (6.18%) and trials beyond 3 SDs (1.13%). A repeated-measures ANOVA showed no significant main effect of distractor type, $F(2, 60) = 1.81$, $p = 0.172$ [Figure 5: see original paper]. $BF_{10} = 0.398$ supported the null hypothesis: no significant differences across distractor types. Shape-based statistical regularities did not affect visual selective attention.

[Figure 5: see original paper] shows response times when targets were color-defined and distractors shape-defined.

Temporal analysis using a 3 (distractor type: absent, high-probability shape, low-probability shape) \times 6 (time bin: 1–6) ANOVA revealed a significant main effect of time, $F(5, 150) = 2.88$, $p = 0.016$, $\eta^2 = 0.087$. Response times slowed significantly in bins 4 and 5 compared to bin 1 ($ps < 0.05$). The main effect of distractor type was non-significant, $F(2, 60) = 2.42$, $p = 0.098$. The interaction was non-significant, $F(10, 300) = 1.17$, $p = 0.323$. Simple effects analysis showed that in bins 2 and 4, absent conditions were significantly faster than high-probability conditions ($p = 0.028$ and $p = 0.004$, respectively), and in bin 2, absent was faster than low-probability ($p = 0.001$). However, no significant differences emerged between high- and low-probability conditions at any time point. This indicates that after extended learning, distractors no longer captured attention, but statistical regularities had no significant effect.

[Figure 6: see original paper] shows temporal dynamics for Experiment 2 when targets were color-defined and distractors shape-defined.

Dimensional reversal eliminated shape-based statistical regularity effects, confirming that target-distractor dimensional differences influence statistical learning. Therefore, Experiment 3 unified target and distractor definitions within the same dimension to directly compare statistical regularity effects across shape and color dimensions while controlling for attentional guidance strength.

Experiment 3

4.1.1 Participants Using MorePower 6.0.4 ($\eta^2 = 0.15$, $\alpha = 0.05$, power = 0.8), required sample size was 30. We recruited 31 university students from Tianjin (13 male, 18 female; mean age = 20.2 ± 1.3 years) with normal or corrected-to-normal vision. All provided informed consent and received compensation. The study was approved by the ethics committee.

4.1.2 Apparatus and Procedure Apparatus and procedure matched Experiment 2. Experiment 3 used a 2 (search dimension: shape vs. color) \times 3 (distractor type: absent vs. high-probability vs. low-probability) within-subjects

design, comprising shape and color blocks. Dependent variables were response times and accuracy.

In the shape block [Figure 7A: see original paper], all stimuli were gray (RGB: 102, 101, 92; 13 cd/m², CIE: $x = 0.321$, $y = 0.34$). Non-salient distractors were circles (diameter 0.9°). Targets could be equilateral triangle (0.9°×0.9°), *diamond*(1°×1°), *irregularpentagon*(1°×1°). High- and low-probability distractors were the other two shapes. For example, if the target was a diamond, the high-probability distractor might be a triangle and low-probability a pentagon. Target and distractor shapes were fixed within blocks and counterbalanced across participants.

In the color block [Figure 7B: see original paper], all stimuli were circles. Non-salient distractors were gray (RGB: 102, 101, 92). Targets could be red (RGB: 205, 0, 0; 13 cd/m², CIE: $x = 0.64$, $y = 0.33$), green (RGB: 0, 118, 0; 13 cd/m², CIE: $x = 0.300$, $y = 0.600$), or blue (RGB: 0, 80, 255; 13 cd/m², CIE: $x = 0.161$, $y = 0.100$). High- and low-probability distractors were the other two colors. For example, if the target was green, the high-probability distractor might be blue and low-probability red. Target and distractor colors were fixed within blocks and counterbalanced across participants.

The response window was 1500 ms with a fixed trial duration of 2200 ms. Each block began with 20 practice trials. The main experiment comprised two blocks of 600 trials each (96 absent, 432 high-probability, 72 low-probability), lasting approximately 45 minutes.

[Figure 7: see original paper] shows search displays for Experiment 3. In the shape block (A), targets could be triangle, diamond, or pentagon, with high- and low-probability distractors as the other two shapes. In the color block (B), targets could be red, green, or blue, with high- and low-probability distractors as the other two colors. All counterbalanced across participants.

4.2 Results We excluded error trials (3.8%) and trials beyond 3 SDs (1.24%). A 2 (search dimension: shape, color) × 3 (distractor type: absent, high-probability, low-probability) repeated-measures ANOVA on accuracy showed a significant main effect of dimension, $F(1, 30) = 4.389$, $p = 0.045$, $\eta^2 = 0.128$, with higher accuracy for color (96.9 ± 0.6%) than shape (95.9 ± 0.7%), indicating an attentional advantage for color. Neither the main effect of distractor type, $F(2, 60) = 0.64$, $p = 0.487$, $\eta^2 = 0.021$, nor the interaction, $F(2, 60) = 1.59$, $p = 0.217$, was significant.

A 2 × 3 ANOVA on response times revealed significant main effects of dimension, $F(1, 30) = 182.14$, $p < 0.001$, $\eta^2 = 0.859$, with faster responses for color (569 ± 10 ms) than shape (735 ± 15 ms), and distractor type, $F(2, 60) = 41.74$, $p < 0.001$, $\eta^2 = 0.582$. Absent conditions (631 ± 10 ms) were significantly faster than both high-probability (656 ± 12 ms) and low-probability conditions (669 ± 13 ms), $ps < 0.001$. High-probability conditions were significantly faster than

low-probability, $p = 0.005$, demonstrating that distractor feature statistics affect visual selective attention.

Critically, the dimension \times distractor type interaction was significant, $F(2, 60) = 21.35$, $p < 0.001$, $\eta^2 = 0.416$. Simple effects analysis [Figure 8: see original paper] revealed that in the shape dimension, absent conditions (699 ± 80 ms) were significantly faster than both high-probability (747 ± 87 ms) and low-probability conditions (759 ± 92 ms), $ps < 0.001$, indicating attentional capture by shape distractors. High-probability conditions were significantly faster than low-probability, $p = 0.022$, showing reduced capture for high-probability shapes. In the color dimension, absent (563 ± 57 ms) and high-probability conditions (565 ± 57 ms) did not differ significantly, $p = 0.403$, but both were significantly faster than low-probability (580 ± 63 ms), $ps = 0.013$ and 0.005 , respectively. This indicates that low-probability color distractors captured attention, while high-probability color distractors showed virtually no capture.

[Figure 8: see original paper] shows target identification response times for shape and color statistical regularity conditions when dimensions were unified.

Temporal analyses divided trials into six bins for each dimension. In the shape dimension [Figure 9A: see original paper], time showed a significant main effect, $F(5, 150) = 5.57$, $p = 0.001$, $\eta^2 = 0.157$, with faster responses in bins 4–6 versus 1–3 ($ps < 0.05$). Distractor type also showed a significant main effect, $F(2, 60) = 46.72$, $p < 0.001$, $\eta^2 = 0.609$: absent $<$ high-probability $<$ low-probability ($ps < 0.001$ and $p = 0.033$). The interaction was non-significant, $F(10, 300) = 0.94$, $p = 0.468$, with $BF_{10} = 0.017$, strongly supporting the null hypothesis. Thus, statistical learning in the shape dimension did not change over time.

In the color dimension [Figure 9B: see original paper], time showed a significant main effect, $F(5, 150) = 2.40$, $p = 0.04$, $\eta^2 = 0.074$, with faster responses in bins 4–5 versus 1–3 ($ps < 0.05$). Distractor type was also significant, $F(2, 60) = 46.72$, $p < 0.001$, $\eta^2 = 0.609$: absent and high-probability $<$ low-probability ($ps < 0.001$). The interaction was significant, $F(10, 300) = 2.64$, $p = 0.016$, $\eta^2 = 0.081$. Simple effects showed no differences among conditions in bins 1–2 ($ps = 0.694$ and 0.309), but from bin 3 onward, absent and high-probability conditions were significantly faster than low-probability ($ps \leq 0.037$). This indicates that after initial learning (first two bins), participants gradually showed capture by low-probability color distractors (slower responses) but not by high-probability distractors (performance similar to absent).

[Figure 9: see original paper] shows temporal dynamics for shape (A) and color (B) dimensions in Experiment 3.

General Discussion

By controlling for confounds from inconsistent target-distractor defining dimensions, this study validated and extended previous findings through three experiments. Experiment 1 replicated prior work, showing faster target selection

with high-probability color distractors, indicating better suppression of high-probability distractors and confirming cross-dimensional effects of color-based statistics. However, Experiment 2's dimensional reversal eliminated shape-based statistical regularity effects, confirming that target-distractor dimensions significantly influence statistical learning. Importantly, Experiment 3, with unified dimensional definitions, simultaneously examined shape and color statistical regularity effects while controlling for attentional guidance differences. Results showed better suppression of high-probability distractors in both dimensions. Critically, in the shape dimension, high-probability conditions remained slower than absent conditions, whereas in the color dimension, no difference emerged between high-probability and absent conditions. This indicates that when statistical regularities operate on more strongly guiding dimensions (color), the resulting suppression is stronger. The study not only resolved confounds from dimensional differences but also directly compared statistical regularity effects across dimensions, revealing interactive effects between statistical regularities and search dimensions that extend our understanding of how history influences current attention and provide new evidence for optimizing visual search efficiency.

The study identified a key factor influencing statistical regularities: the defining dimensions of targets and distractors. Experiments 1 and 2 demonstrated that dimensional differences interfere with statistical regularity effects. In singleton search mode, target color possesses “undoubted guiding attributes” compared to distractor shape (Wolfe & Horowitz, 2017), showing attentional selection advantages (Theeuwes, 1992; Treisman & Gelade, 1980). When searching for color targets, shape distractors minimally impact performance, allowing rapid target finding without learning shape statistics (张帆等, 2021; Failing, Wang, et al., 2019; Stilwell et al., 2019; Vatterott et al., 2018). Thus, unifying target and distractor dimensions is crucial. This study provides important evidence regarding a critical methodological factor that previous research commonly used but should avoid, offering clear recommendations for future statistical regularity studies.

With unified dimensions (Experiment 3), distractor feature statistics still guided attention, extending previous findings by demonstrating that statistical regularities affect attentional selection across both color and shape dimensions when confounds are eliminated. This indicates that statistical regularity effects are broad and stable, independent of whether target and distractor dimensions match. The results support statistical regularities' core role in visual search: through learning, individuals predict distractor features and learn to ignore features highly associated with distractors, optimizing attention allocation and improving search efficiency, demonstrating the flexibility and adaptability of the visual attention system (Ferrante et al., 2018; Failing, Wang, et al., 2019; Stilwell et al., 2019).

Importantly, distractor statistical regularities primarily reduce or even eliminate attentional capture, with this relative suppression modulated by color and

shape dimensions. Specifically, when statistical regularities operate on more strongly guiding dimensions, suppression is stronger. In the shape dimension, high-probability conditions remained slower than absent conditions, indicating reduced but persistent attentional capture. This aligns with Kim et al. (2023) and Tsai et al. (2023), supporting the Dimension-Weighting Account (DWA), which posits that when searching for a salient target in a particular dimension, salient distractors in the same dimension cannot be easily ignored (Liesefeld et al., 2019). Traditional attentional capture theory also holds that salient stimuli automatically capture attention, slowing responses (Theeuwes, 1992). Even with extensive statistical learning, individuals may not fully eliminate bottom-up capture effects (Failing et al., 2019; Ferrante et al., 2018; Stilwell et al., 2019). For instance, Stilwell et al. (2019) found that high-probability conditions always remained significantly slower than absent conditions, indicating persistent capture. Thus, statistical regularities weakly suppress high-probability shape distractors, which still show attentional capture consistent with DWA and traditional theory.

Surprisingly, unlike shape, the color dimension showed no difference between high-probability and absent conditions, indicating that high-probability distractors no longer captured attention—color-based statistical regularities eliminated attentional capture. Previous elimination of capture effects was found only in feature search mode; for example, Wang and Theeuwes (2018c) showed that spatial statistical regularities eliminated capture. However, our study found that feature-based statistical regularities (for color) can also eliminate capture in non-feature search mode (singleton search mode), suggesting that attentional allocation is not solely driven by bottom-up stimulation or top-down goals but is also influenced by prior knowledge and experience of features. This challenges existing attentional capture theories. The differential suppression between color and shape dimensions may arise because color stimuli have higher contrast and discriminability and are perceived earlier, making color information easier to identify and use for attention allocation to reduce focus on color distractors (Clifford et al., 2003; Rentzperis et al., 2014; White et al., 2014). Shape is considered a more complex feature than color, with weaker attentional guidance effectiveness (Wolfe & Horowitz, 2017; Huang, 2020). Consequently, color-based statistical learning produces stronger suppression. Additionally, different processing mechanisms may contribute: color processing relies primarily on the ventral stream, particularly V4 and IT regions, which are highly sensitive to color information (Conway, 2009), whereas shape processing depends on both ventral and dorsal streams (Collins et al., 2019; Freud et al., 2013). Our surprising finding of dimension-specific modulation of statistical regularities provides evidence for dimension specificity. Future research should further investigate the applicability of statistical regularities across different tasks and more realistic environments, as well as the role of other dimensions and their interactions in attentional selection.

Finally, statistical learning trajectories differed between shape and color dimensions. For color, statistical regularity effects emerged gradually: no differ-

ences among conditions appeared in the first two time bins, but from the third bin onward, high-probability conditions became significantly faster than low-probability conditions. This aligns with previous research (Gaspelin & Luck, 2018; Vatterott & Vecera, 2012). During initial learning, attention is more stimulus-driven; as experience accumulates, top-down cognitive control based on statistical learning becomes fully established, making regularity effects more pronounced (Han & Kim, 2009). For shape, however, no clear learning trend emerged across time bins; high- and low-probability conditions never differed significantly across six bins, showing only an overall high-probability advantage. This may relate to working memory capacity: strongly guiding features like color can be stored with high precision in visual working memory, with capacity for approximately four stimuli (张帆等, 2021; Luck & Vogel, 1997), whereas shape storage is poor even for two stimuli (Sakai, 2005; Salmela et al., 2010). Thus, observers may need more time to accumulate sufficient information to form stable statistical regularities for shapes (Mu et al., 2024; Salmela et al., 2010). Low working memory capacity for shapes may hinder rapid statistical learning. Additionally, our shape manipulation used simple shapes; complex shapes require future investigation.

In summary, this study reveals that when target and distractor dimensions are unified, both shape and color statistical regularities significantly affect attentional selection. The strength of statistical regularity effects interacts with search dimension: when regularities operate on more strongly guiding dimensions (color), suppression is more pronounced, eliminating distractor capture. These findings demonstrate that the visual system uses dimensional regularities to optimize cognitive resource allocation, advancing our understanding of how prior experience influences current attention and providing important insights for improving visual search efficiency.

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