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Task-Adaptive Changes to the Target Template in Response to Distractor Context: Separability Versus Similarity

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Abstract

Theories of attention hypothesize the existence of an attentional template that contains target features in working or long-term memory. It is frequently assumed that the template contains a veridical copy of the target, but recent studies suggest that this is not true when the distractors are linearly separable from the target. In such cases, target representations shift "off-veridical" in response to the distractor context, presumably because doing so is adaptive and increases the representational distinctiveness of targets from distractors. However, some have argued that the shifts may be entirely explained by perceptual biases created by simultaneous color contrast. Here we address this debate and test the more general hypothesis that the target template is adaptively shaped by elements of the distractor context needed to distinguish targets from distractors. We used a two-dimensional target and separately manipulated the *linear separability* of one dimension (color) and the *visual similarity* of the other (orientation). We found that target shifting along the linearly separable color dimension was dependent on the similarity of targets-to-distractors along the other dimension. The target representations were consistent with a post-experiment strategy questionnaire in which participants reported using color more when orientation was hard to use, and orientation more when it was easier to use. We conclude that the target template is task-adaptive and exploit features in the distractor context that most predictably distinguish targets from distractors to increase visual search efficiency.

Keywords

Attentional template; Visual search; Distractor context; Attentional shifting; Simultaneous contrast effect

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Xinger Yu served as lead for data curation, formal analysis, and validation and contributed equally to conceptualization, writing–original draft, and writing–review and editing. Raisa A. Rahim served in a supporting role for conceptualization, writing–original draft, and writing–review and editing. Joy J. Geng served as lead for conceptualization, funding acquisition, supervision, writing–original draft, and writing–review and editing.

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Introduction

The visual world is filled with numerous pieces of sensory information, but only a small fraction is relevant to behavior. How is our attention guided to objects of interest? Theories of visual search posit that this occurs by using information held within a memory representation (i.e., the *target* or *attentional template*) to bias sensory processing toward target features and serve as a decision boundary for target selection (Duncan & Humphreys, 1989a; Eimer, 2014; Geng & Witkowski, 2019; Wolfe, 2021). The target template has been largely assumed to contain a single, static, and veridical representation of what we are looking for, akin to a photograph of the target object. However, recent studies in which the search target appears predictably among linearly separable distractors (e.g., search for an orange tiger amongst yellower grassland “distractors”) have shown that the target template may not always contain veridical sensory features but instead shifts “off-veridical” away from distractors (Becker et al., 2013; Chunharas et al., 2022; Geng et al., 2017; Kerzel, 2020; Meeter & Olivers, 2014; Navalpakkam & Itti, 2007; Scolari & Serences, 2009; Tünnermann et al., 2021; Yu et al., 2022; Yu & Geng, 2019). It remains unclear, nevertheless, whether shifting away from distractors is due to a strategic adjustment that serves to increase the *representational distinctiveness* of targets from distractors and optimize attentional selection or due to a passive, automatic contrast effect in the visual system that alters the perception of targets.

Off-veridical target representations refer to the finding that target features are shifted, or distorted, away from distractors that are predictably linearly separable (Bauer et al., 1996; D’Zmura, 1991; Hodsoll & Humphreys, 2001; Navalpakkam & Itti, 2007). For example, when looking for an orange object among yellower distractors, the target is represented as being “redder” than the actual orange; this leads attention to be guided toward “orange-reddish” color values in the visual field. Similar shifting of target features has been found for varied stimulus dimensions, including size, shape, luminance, orientation, direction of motion, and even more complex facial expressions, and has been measured using a number of methods, including eye movements during visual search, irrelevant cues for attentional capture, working memory estimation probes, and two-alternative forced choice identifications (Becker, 2010; Becker et al., 2014; Geng et al., 2017; Kerzel, 2020; Scolari et al., 2012; Won et al., 2020; Yu et al., 2022). Interestingly, the impact of linear separability of distractors on target representations occurs only when this linear separability is predictable across trials (Yu & Geng, 2019).

Although there is clear evidence that the target representation shifts in response to linearly separable distractors, different underlying mechanisms have been proposed. One explanation is that shifting increases the representational distinctiveness of the target from concurrent search distractors, which then allows the target to be found more efficiently (Geng & Witkowski, 2019; Navalpakkam & Itti, 2007; Yu & Geng, 2019). For instance, Yu et al. (2022) found that observers who established more optimally shifted templates showed faster drift rates, reflecting easier discrimination of targets from distractors. Others have argued, however, that shifting away from distractors is caused by perceptual contrast effects between the highly similar search target and distractors (Hamblin-Frohman & Becker, 2021; Pouget & Bavelier, 2007). Perceptual contrast effects result from lateral inhibition between neighboring neurons and reflect the sensory environment independent of the current task demands. Simultaneous contrast may bias the perception of an orange target to make it appear redder (Brown & MacLeod, 1997; Singer & D'zmura, 1994) and these shifts in color perception would be encoded as a shifted target representation from the true color value. While a perceptual color shift might effectively increase the target-to-distractor distinctiveness, it is a perceptual mechanism that is agnostic to the task and goals of the observer.

The purpose of the current study was to determine whether shifting the target representation away from distractors is adaptive to the visual search task or whether it is purely a consequence of color contrast effects on perception. We addressed this question using a two-dimensional target (e.g., a 54° oriented, green-blue bar). The target was distinct from distractors in both *color* and *orientation* and therefore it could be identified based on either feature dimension. The critical manipulation was the distractor context in the visual search task across two groups (Figure 1B). The distractor colors in both groups were target-similar and were all from one direction on the color wheel (e.g., bluer than the target color). As a result, the linear separability of the distractor colors could be predicted from trial to trial in both groups. In contrast to *color*, the distractor orientations on each trial were linearly separable on a single trial (i.e., all rotated from the target clockwise or counterclockwise), but the direction of the distractors were unpredictable from trial to trial. Therefore, it was impossible to predict on a trial-by-trial basis the orientation of distractors, precluding the use of this feature for strategic search. The manipulation of making targets linearly separable from distractors in both *color* and *orientation* on a single display was employed to balance the perceptual effects of linear separability on a single trial. This manipulation also restricted attentional predictions to be made solely for *color* linear separability. Notably, even though the direction of distractor orientations was unpredictable across trials, the similarity of these distractor orientations to the target orientation was predictable. In the *high-orientation-similarity* group, the distractor orientations were always highly similar to the target orientation, while in the *low-orientation-similarity* group, the distractor orientations were substantially different. Distractor similarity is well known to affect the ease of visual search: when distractors are more perceptually dissimilar from targets, perceptual selection of the target is easier (Duncan & Humphreys, 1989b; Wolfe & Horowitz, 2017). If shifting of the target representation is a primarily task-adaptive mechanism to increase target distinctiveness in response to the distractor context, then we would expect color shifting to only occur in the *high-orientation-similarity* group when orientation is difficult to use and color information is more diagnostic of the target; but we would also predict that this does not occur in the *low-orientation-similarity* group because it will be easier to select the target based on *orientation*. On the other hand, if shifting is an automatic perceptual response to targets embedded within linearly separable distractors, the magnitude of color shifting should be similar in the two groups because the color distractors were identical. Nevertheless, it is also possible that the mechanism of shifting could be a combination of both task-adaptive and automatic perceptual processes, rather than a clear-cut choice between the two hypotheses.

Method

Participants

The sample size of 140 was determined by a power calculation (.8 power, .05 two-tailed significance) using results from Experiment 2 in Yu, Hanks, et al., (2022). Data were collected online using the Testable platform (https://www.testable.org/) until we obtained a sample of 140 participants after exclusion criteria were applied. 53 participants were excluded from the analysis because of poor performance in standard search trials (accuracy was below 70%). A large number of outliers was expected because the experiment was conducted online through SONA and course credit was not tied to performance. 140 students (self-reported females = 103, males = 32, non-binary = 5, left-handed = 8, age range = 18 – 30 years) from the University of California, Davis participated in partial fulfillment of a course requirement. They were randomly assigned into the *high-orientation-similarity* or the *low-orientation-similarity* groups (N=70 per group). All procedures were approved by the University of California, Davis Internal Review Board (IRB).

Transparency and openness

This experiment was not preregistered. Deidentified data and the data analysis scripts are available at https://osf.io/tkgj6/.

Stimuli

All oriented color bar stimuli were created in Illustrator, saved as PNG files, and uploaded to Testable.org. Bars were 35 pixels wide and 85 pixels long. All stimuli were presented against a mid-level gray background (RGB values: [128, 128, 128]). The colors of stimuli were selected from a color wheel defined in CIELAB color space that only varied in hue (coordinates: a = 0, b = 0; luminance = 70; radius = 38; from Bae et al., 2015). The color wheel was an approximation to the cited color space as individual monitors were not calibrated. Two conjunction targets (190° Color – 54° Orientation and 324° Color – 126° Orientation) were counterbalanced across participants. The noncanonical colors and orientations were chosen to avoid potential category effects on responses (Bae et al., 2015). Because the targets did not influence search performance ($ps > .13$), the data were collapsed in all subsequent analyses to maximize statistical power. The experiment consisted of two types of trials: *visual search* trials, which were used to establish expectations for the distractor context, and *memory probe* trials, which were used to measure the template contents independently of simultaneous distractor competition.

Visual search trials.—Of the total trials, 91% were visual search. Of those, 90% were “color standard search trials.” On standard trials, the target was always present and was located randomly at one of the 4 vertexes along an imaginary square (200 horizontal and vertical pixels from center to edge) while distractors appeared at the other 3 vertices (Figure 1A). In the *high-orientation-similarity* group, the distractor orientations were either positively (i.e., 6°, 12°, and 18°) or negatively (i.e., −6°, −12°, and −18°) rotated from the target orientation (Figure 1B). In the *low-orientation-similarity* group, the distractor orientations were less similar to the target and were either positive (i.e., 42°, 48°, and 54°) or negative rotations (i.e., −42°, −48°, and −54°) from the target orientation (Figure 1B).

We chose to make the distractor orientations linearly separable within a given trial, even though this separability was not consistently predictable across trials. This decision was made to control for potential perceptual adaptation effects within each feature dimension that might impact performance during a single trial. The distractor colors were always the same and were rotated by 6°, 12°, and 18° from the target color. We chose to only use *color* as the linearly separable feature because it commonly dominates visual search (Alexander et al., 2019; Huang, 2015; Hulleman, 2020), however, see Experiment 2 in the Supplemental Materials.

On the remaining 10% of visual search trials, the distractor colors were “reversed” (Figure 1B). The distractor colors on reversal trials were negative rotations from the target color (i.e., −6°, −12°, and −18°). If visual search for the target was based on a shifted color representation, reversal trials should produce a large performance decrement (lower accuracy, longer RT) because distractors would suddenly become closer to the remembered target feature than on standard trials.

Memory probe trials.—Memory probe trials occurred in 9% of the total trials. During these trials, participants were presented with either a color wheel or an orientation wheel (Figure 1A). The color wheel contained 60 feature segments of different colors, respectively, split into 6° bins. Each color segment was associated with a number from 1 to 60. Because the orientation space spans only 180°, the orientation wheel was reflected across the vertical axis to extend the range to a full 360° circle. This means that each orientation segment occurred twice, 180° apart. They were assigned the same number between 1 and 30 (see Figure 1). Participants were asked to report the number next to the remembered target feature. There were 8 possible rotations of the wheel.

Design and procedure

An example of the conjunction target was presented prior to the beginning of the experiment. On *visual search* trials (91% trials), participants searched for the predefined target and reported the number inside by pressing the button “U” for 1, “I” for 2, “O” for 3, or “P” for 4 with their right hand. Visual feedback (300 msec) was provided immediately following the response. On *memory probe* trials (9% trials), participants were required to type the number of the feature segment that best matched the target in memory in a response box at the bottom of the screen. Both the search and probe display remained on the screen until the manual response or up to 10 sec. After the response, a central fixation cross was presented for 800 – 1200 msec before the next trial started. Participants were instructed to fixate on the center cross until task stimuli were presented.

After receiving instructions, participants began with a practice block of 20 standard search trials. The main experiment was composed of 72 standard search trials, 8 reversal search trials, and 8 memory probe trials (50% color probe and 50% orientation probe). Trials were presented in 8 blocks, each containing 9 standard search trials, 1 reversal search trial, and 1 memory probe trial. The three types of trials were randomly interleaved within each block, with the limitations that the probe trials appeared only after the standard search trials and that there were no consecutive probe trials.

Following the main experiment, participants filled in a brief questionnaire, which was intended to gauge awareness of the strategic use of each feature dimension to discriminate the target from distractors. Two questions were posed simultaneously, “How frequently did you use *color* to find the target?” and “How frequently did you use *orientation* to find the target?” Participants answered each question by clicking on buttons corresponding to “Never,” “Rarely,” “Sometimes,” “Often,” or “Always.” Because the questionnaire was given at the end of the experiment, it could not influence performance on the visual search task.

Statistical analysis

Visual search trials with RT less than 250 msec or greater than 2500 msec were excluded from data analyses, which accounted for 3.55% of data. The extent of disparity between the probe responses and the actual target, measured at 6° intervals, serves as an indicator of how closely the target representations in memory align with the veridical target features. Probe trials with response errors beyond ±60° were excluded from data analyses, which resulted in the removal of 0.18% of color probes and 1.96% of orientation probes. These responses exceeding ±60° have already surpassed the defined boundaries for the two target colors (Bae et al., 2015). These outliers are unlikely to genuinely reflect memory representations (Störmer & Alvarez, 2014; Wang et al., 2015); rather, they are more likely due to accidental response errors. Despite the difference in the full range of the two wheels, the actual “response range” was similar and narrow in both feature dimensions. To ensure an adequate number of data points for fitting with a Gaussian function, we did not average the memory probe responses collected from each participant.[1] Instead, we aggregated the memory probe responses across all participants to create a frequency distribution (Figure 2), from which we estimated two parameters: μ, which represents the magnitude of template shifting away from the true target, and σ, which represents the precision of the template. Smaller σ values indicate higher precision.

All parameters from the Gaussian functions were estimated using a hierarchical Bayesian parameter (HBA) estimation method. To perform HBA, we used the R package, Bayesian Regression Models using “Stan” (brms) (Bürkner, 2017, 2018), and the probabilistic programming language Stan (Carpenter et al., 2017). Normal and Gamma distributions were used to set the hyperpriors of the normal mean ($\mu \sim$ Normal (0, 1)) and standard deviation ($\sigma \sim$ Gamma (5, 1)). The range of Gelman-Rubin statistics across all parameter estimates was between 0.99 – 1.01, suggesting satisfactory convergence. Goodness of fit was visually inspected with the posterior predictive check method (Figure 2).

In addition to using the Gaussian function, we also conducted a mixed 2 group (*high-orientation-similarity*, *low-orientation-similarity*) × 2 dimension (*color, orientation*) ANOVA to directly compare the mean of each participant’s memory probe responses. This analysis complements the analysis of μ from the Gaussian function by considering both within-subject and between-subject variance. The results of this analysis can be found in the Supplemental Materials.

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[1] Conventional frequentist statistics, where individuals were treated as a random factor, revealed similar results of a shifted mean in the *high-orientation-similarity* group, but only for the color memory probe task.

Results

Memory probe performance

Our main hypothesis was that shifting of the representation of the target color would only occur when orientation similarity was high and hard to use (*high-orientation-similarity* group). Under these conditions, target selection would be expected to rely more on *color*. However, when orientation similarity was low (*low-orientation-similarity* group), color shifting would be less adaptive because observers can easily use target orientation to select the target. To test this hypothesis, we looked at the posterior distribution of the mean parameter (μ) estimated from fitting each model. Figure 3 shows the distribution and marks the highest density interval (HDI) for each group and each dimension, which describes the 95% most credible values for the parameter (Kruschke, 2018). The fitted models estimated the value of μ_{col} to be −5.15° (HDI 95% = −5.81°, −4.50°) for the *high-orientation-similarity* group and −1.48° (HDI 95% = −2.36°, −0.60°) for the *low-orientation-similarity* group. We found that the μ_{col} of both groups was significantly shifted from the true target color (0°), probabilities > .99. Moreover, the fact that these intervals are non-overlapping (probability > .99) indicates that the *high-orientation-similarity* group shifted their color representation farther away from the target (in the direction opposite to distractor colors) than the *low-orientation-similarity* group. This result is consistent with the argument that target shifting has an adaptive function. In contrast to *color*, there was no difference between groups in the estimation of target orientation (*high-orientation-similarity* group: Mean = −0.11°, HDI 95% = −0.58°, 0.36°; *low-orientation-similarity* group: Mean = −0.90°, HDI 95% = −1.73°, −0.04°), probability = .09. The estimated central tendency of memory for the target orientation (μ_{ori}) was similar in both groups, and centered around the true value, as would be expected for a target flanked by distractors of both positive and negative rotations.[2]

Next, we assessed whether the standard deviations (σ) differed between groups (Figure 4). The results showed that the σ_{Col} estimated by the model was smaller in the *high-orientation-similarity* group (Mean = 7.36°, HDI 95% = 6.55°, 8.24°) compared with the *low-orientation-similarity* group (Mean = 9.89°, HDI 95% = 8.91°, 10.97°), probability > .99. This means that the *high-orientation-similarity* group had more precise memories of the target color than in the *low-orientation-similarity* group even though the central tendency of that color memory was more shifted. This indicates that shifting is not a result of poorer memory but rather an adaptive process that moves target representations away from distractor features when doing so is useful for visual search. Consistent with that interpretation, the σ of the orientation distributions did not differ between groups (*high-orientation-similarity* group: Mean = 9.57°, HDI 95% = 9.02°, 10.14°; *low-orientation-similarity* group: Mean = 8.82°, HDI 95% = 7.84°, 9.90°), probability = .14.

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[2] We divided the orientation memory probe trials based on preceding visual search trials, distinguishing between those with positively oriented distractors and those with negatively oriented distractors. No significant differences were found in the probe responses within both groups. This indicates that the orientation representation was not influenced by the local orientation linear separability in the immediately preceding trial, but rather by the cumulative evidence across multiple trials (see the Supplemental Materials).

Dimension reliance

Was color shifting associated with a stronger self-reported reliance on color representation to locate the target? To answer this question, we transformed each response option to a numerical value representing its relative frequency (i.e., "never": 1; "rarely": 2; "sometimes": 3; "often": 4; "always": 5). We performed a mixed 2 group (*high-orientation-similarity*, *low-orientation-similarity*) × 2 dimension (*color, orientation*) ANOVA on these frequency ratings (Figure 5), and post hoc t-tests were corrected with Bonferroni method. There was no effect of group, $F(1, 138) = 1.93$, $p = .17$, $\eta_p^2 = .01$, no effect of feature dimension, $F(1, 138) = 1.95$, $p = .16$, $\eta_p^2 = .01$, but there was a significant interaction, $F(1, 138) = 201.26$, $p < .0001$, $\eta_p^2 = .59$. The results revealed that the *high-orientation-similarity* group reported using *color* more often to find the target ($M = 4.51$, $SD = 0.79$), $t(69) = 11.87$, $p < .0001$, $d = 2.01$, whereas the *low-orientation-similarity* group reported using *orientation* more frequently ($M = 4.56$, $SD = 0.63$), $t(69) =10.55$, $p < .0001$, $d = 1.78$. Therefore, consistent with the probe data, self-reports of search strategies suggest that participants used *color* when *orientation* was difficult but switched to rely more on *orientation* when it was more dissimilar and presumably easier to use than *color* to find the target. This suggests that the ability to distinguish targets from distractors depends heavily on feature (dis)similarity but that shifting is employed when it is possible to use (i.e., when distractors are linearly separable) and confers an advantage (i.e. when perceptual similarity along other feature dimensions is high).[3]

Visual search performance

Accuracy (Figure 6) and RT (Figure 6) from the visual search trials were entered into mixed 2 group (*high-orientation-similarity*, *low-orientation-similarity*) × 2 trial type (*standard search, reversal search*) ANOVAs. For accuracy, there was a significant main effect of group, $F(1, 138) = 160.04$, $p < .0001$, $\eta_p^2 = .54$, a significant main effect of trial type, $F(1, 138) = 82.34$, $p < .0001$, $\eta_p^2 = .37$, and a significant interaction, $F(1, 138) = 81.56$, $p < .0001$, $\eta_p^2 = .37$. Post hoc t-tests found that the *high-orientation-similarity* group had significantly lower accuracy on reversal search trials ($M = .59$, $SD = .27$) than on standard trials ($M = .89$, $SD = .06$), $t(69) = -9.30$, $p < .0001$, $d = -1.11$. In contrast, accuracy in the *low-orientation-similarity* group was nearly at ceiling on both trial types (reversal search: $M = .96$, $SD = .06$; standard search: $M = .96$, $SD = .03$), $t(69) = -0.09$, $p = 1$, $d = -0.01$.

For RT, there was a significant main effect of group, $F(1, 138) = 22.33$, $p < .0001$, $\eta_p^2 = .14$, a significant main effect of trial type, $F(1, 138) = 92.87$, $p < .0001$, $\eta_p^2 = .40$, and a significant interaction, $F(1, 138) = 46.58$, $p < .0001$, $\eta_p^2 = .25$. Post hoc t-tests found that RT in the *high-orientation-similarity* group was significantly longer for reversal trials ($M = 1502$ msec, $SD = 331$ msec) than for standard trials ($M = 1131$ msec, $SD = 213$ msec), $t(69) = 9.42$, $p < .0001$, $d = 1.12$. Although RT significantly differed between reversal ($M = 1187$ msec, $SD = 218$ msec) and standard ($M = 1124$ msec, $SD = 176$ msec) trials

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[3] Participants in the *high-orientation-similarity* group were divided into three subgroups, depending on how often they reported using *color* and *orientation*. Among these subgroups, the one that relied more heavily on *color* had the most significant negative bias in color representation and showed the highest visual search accuracy. In contrast, the subgroup that relied primarily on *orientation* demonstrated no bias in color representation and performed the worst in visual search. These results provide additional support for the notion that target shifting is a task-adaptive mechanism (see the Supplemental Materials).

in the *low-orientation-similarity* group, $t(69) = 2.89$, $p = .01$, $d = 0.34$, the difference (63 msec) was much smaller than in the *high-orientation-similarity* group (371 msec). These results indicate that participants in the *high-orientation-similarity* group experienced more interference from the negative distractor colors on reversal search trials. This is consistent with the probe data showing that individuals in the *high-orientation-similarity* group shifted the representation of the target color more than the *low-orientation-similarity* group and also with the greater self-reported reliance on *color* in the *high-orientation-similarity* group.

In addition, we compared performance on standard search trials between groups. The accuracy of the *low-orientation-similarity* group was on average 7% higher than that of the *high-orientation-similarity* group, $t(138) = 9.15$, $p < .0001$, $d = 1.55$. There was no statistical difference in RT between the two groups, $t(138) = 0.22$, $p = .83$, $d = 0.04$. This suggests that visual search was easier when it could rely on orientation dissimilarity than when it relied on color shifting. Together, the accuracy and RT results indicate that shifting and sharpening the target representation away from expected distractors is done to effectively increase the psychological distinctiveness of the target from distractors to enhance performance (Yu & Geng, 2019) but that this only occurs when simpler solutions, such as relying on feature dissimilarity in another dimension, is unavailable.

General Discussion

The current study investigated the mechanisms by which the target template and attentional guidance are shaped by the distractor context. We used a target search task to create expectations of distractor context and a separate memory probe task to measure the representation of the target template. The critical question was whether the representation of the conjunction target's two dimensions would be affected by the utility of each dimension for localizing the target. We hypothesized that the use of target shifting, a mechanism that increases the distinctiveness of targets from linearly separable distractors, would only be employed when distractor similarity along the other dimension was high and therefore less useful for discriminating the target; however, when target-to-distractor similarity was low, target shifting would no longer occur to the same degree. Our results were consistent, demonstrating that target shifting is a task-adaptive mechanism and not just a passive perceptual outcome. Moreover, the target template is highly flexible and reflects the necessary information that best predicts what will distinguish targets from distractors based on previous experience.

Although target shifting in response to linearly separable distractors has been shown in different contexts, there remains a question of whether the effects are due to task-adaptive mechanisms or passive simultaneous contrast effects (Bauer et al., 1996; Chapman et al., 2023; Kerzel, 2020; Pouget & Bavelier, 2007; Yu & Geng, 2019). The current experiment addressed this long-standing question by manipulating the target-to-distractor similarity in *orientation* across groups while keeping the linear separability of targets and distractors in *color* constant (Figure 1B). Our findings showed that the memory representation of the target color was shifted further away from distractor colors in the *high-orientation-similarity* group; correspondingly, reversal trials only impaired visual search performance in the same group. Off-veridical color shifting in the target template was more pronounced when *color* was relied upon more to discriminate the target from distractors, illustrating that target shifting in visual search contexts cannot be attributed to that of simultaneous stimulus contrast alone. These data suggest that target shifting reflects a task-adaptive mechanism that serves to increase the representational distinctiveness of targets from expected distractors and improve visual search performance.

The off-veridical shift and high precision of the target color in memory in the *high-orientation-similarity* group replicate Yu and Geng (2019). When highly similar distractors come from only one side of the target space, the template shifts away and is more sharpened, increasing the efficiency of visual search performance (Kerzel, 2020; Lau et al., 2021). However, when the conjunction target was more discriminated along the orientation dimension, there was no longer a need to build a more distinct representation of the target color. Instead, participants could rely on the easier dimension, *orientation*, to locate the target, negating the need to adjust the color representation. One reason that shifting might not occur when distractor similarity is low (and search is easy) might be that shifting is an active internal mechanism to reduce competition that requires some form of cognitive effort but similarity is a perceptual property of the external display in which competition is already low. However, future experiments are necessary to precisely determine how to quantify the relative effortfulness of using different feature information.

This interpretation is consistent with the surprise self-report questionnaire at the end of the experiment. Participants in the *high-orientation-similarity* group reported using *color* more to find the target whereas participants in the *low-orientation-similarity* group reported using *orientation* more. The visual search accuracy and RT results converge with the self-report responses to strengthen our previous conclusions that shifting and sharpening are more effortful strategies that are only used when necessary to counteract pressure from competitive distractors (Geng et al., 2017; Lau et al., 2021; Yu & Geng, 2019). The adaptive use of feature information in attentional control is in line with the idea that visual search operates on the simplest, good-enough information to rapidly pick out targets with minimal cognitive effort (Draschkow et al., 2020; Droll & Hayhoe, 2007; Irons & Leber, 2018; Yu et al., 2023).

It should be pointed out that the color representation in the *low-orientation-similarity* group was also shifted away from the distractor colors, although the magnitude of this shift was only about −1.5°. This suggests that simultaneous contrast does play a role in creating a shift in the target representation, but does not account for the entire effect during visual search (see also Chapman et al., 2023). This result may superficially appear to be at odds with findings from Hamblin-Frohman and Becker (2021), in which they observed a strong perceptual color contrast effect when the target was surrounded by target-similar distractors. However, their task differed from ours on a number of dimensions, including the number and color homogeneity of the distractor set, as well as the size and distance of distractors. Perhaps more importantly, the task in Hamblin-Frohman and Becker (2021) was to report the unique color in the search arrays, which relied on color information generally but not on the representation of a specific color defining target identity. Additionally, our task gave participants the option to find the target solely based on *orientation*. It is still an open question how the exact stimulus configurations and task demands play a role in task-adaptive color processing versus color contrast effects. Nevertheless, our results demonstrate a case in which color shifting is reduced when color is used less to guide attention, illustrating conclusively that target shifting involves task-adaptive mechanisms.

Successful achievement of sophisticated visual search tasks requires the ability to selectively enhance goal-relevant information in variable distractor contexts (Gottlieb, 2018; Nobre & Stokes, 2019; Wolfe, 2021). The best approach to finding a target might seem to be to use all of its known features, but our results suggest that attentional control mechanisms compared the computations required to distinguish targets from distractors along each feature dimension and prioritized the more diagnostic one. Similar results have been found in other situations. For example, when distractors are more similar to the target in one dimension, the less similar dimension is prioritized (Barras & Kerzel, 2017; Boettcher et al., 2020; Lee & Geng, 2020; Liesefeld & Müller, 2019). Attention also prioritizes the more reliable target feature (Witkowski & Geng, 2019, 2022). These results fit well with the "dimension-weighting" account of visual attention, which hypothesizes that information from each target feature is weighted based on expectations of how informative each dimension will be (Müller et al., 1995; Tollner et al., 2012; Töllner et al., 2010; Weidner & Muller, 2013). Our current results go beyond to show those additional task-adaptive mechanisms, such as target shifting, are only activated when that dimension is currently prioritized for target selection.

Our findings suggest that target representations may lean more towards relying on statistics that predict the most efficient approach for selecting targets from distractors within the expected context, rather than an immediate computation of the current context. This observation is consistent with the statistical learning literature, which emphasizes that attention is highly sensitive to the anticipated (i.e., probable) perceptual context in which targets occur (Chun & Jiang, 1999; Fiser & Aslin, 2002; Geng & Behrmann, 2005; Hansmann-Roth et al., 2023; Jiang & Song, 2005; Rogers et al., 2021; Vickery et al., 2010). Future experiments will be essential to assess how the weighting of dimensions dynamically shifts based on the accumulated evidence learned across trials, and the present evidence within the ongoing trial.

Taken together, the present study provides strong evidence that the target template is task-adaptive and can be dynamically adjusted by distractor context. Expectations regarding the linear separability of the distractor set from the target produced a systematic shift in the target template away from distractors. However, this modulation is an adaptive mechanism to increase the representational distinctiveness of the target from distractors, even if it means compromising the precision of the template-to-target match. Nevertheless, when shifting is unnecessary for achieving the goal of distinguishing the target from distractors, it does not happen. Our work joins a growing literature that reframes the target template as a custom set of information that best differentiates the target from non-targets in the current environment (Geng & Witkowski, 2019; Lleras et al., 2020; Yu et al., 2023).

Constraints on generality

Our study includes mainly Asian and Caucasian undergraduates who are highly educated, with an overrepresentation of females. Thus, we advise being careful when generalizing our findings to other populations. However, we focused on examining fundamental characteristics of visual search that are typically explored across human subjects. As a result, we anticipate that the general principles we investigated here will not differ significantly between human subjects, including individuals of varying genders, ethnicities, or cultural backgrounds.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Public Significance Statement

Searching for a target object among perceptually similar distractor objects (e.g., finding an orange-colored pencil among yellow-colored pencils) is relatively difficult. In order to optimize the ability to distinguish targets from distractors, the target representation may shift “off-veridical” (i.e., prioritizing search for the reddish color within the orange target). The present study shows that this type of target shifting occurs more strongly when it facilitates the ability to find the target; it is greatly reduced when other properties of the distractor context, such as dissimilarity, make the target easier to find using another feature dimension. These results suggest that target shifting is a *task-adaptive* mechanism to increase the representational distinctiveness of targets from distractors during visual search and highlights the sensitivity of the target template to multiple features of the expected distractor context.

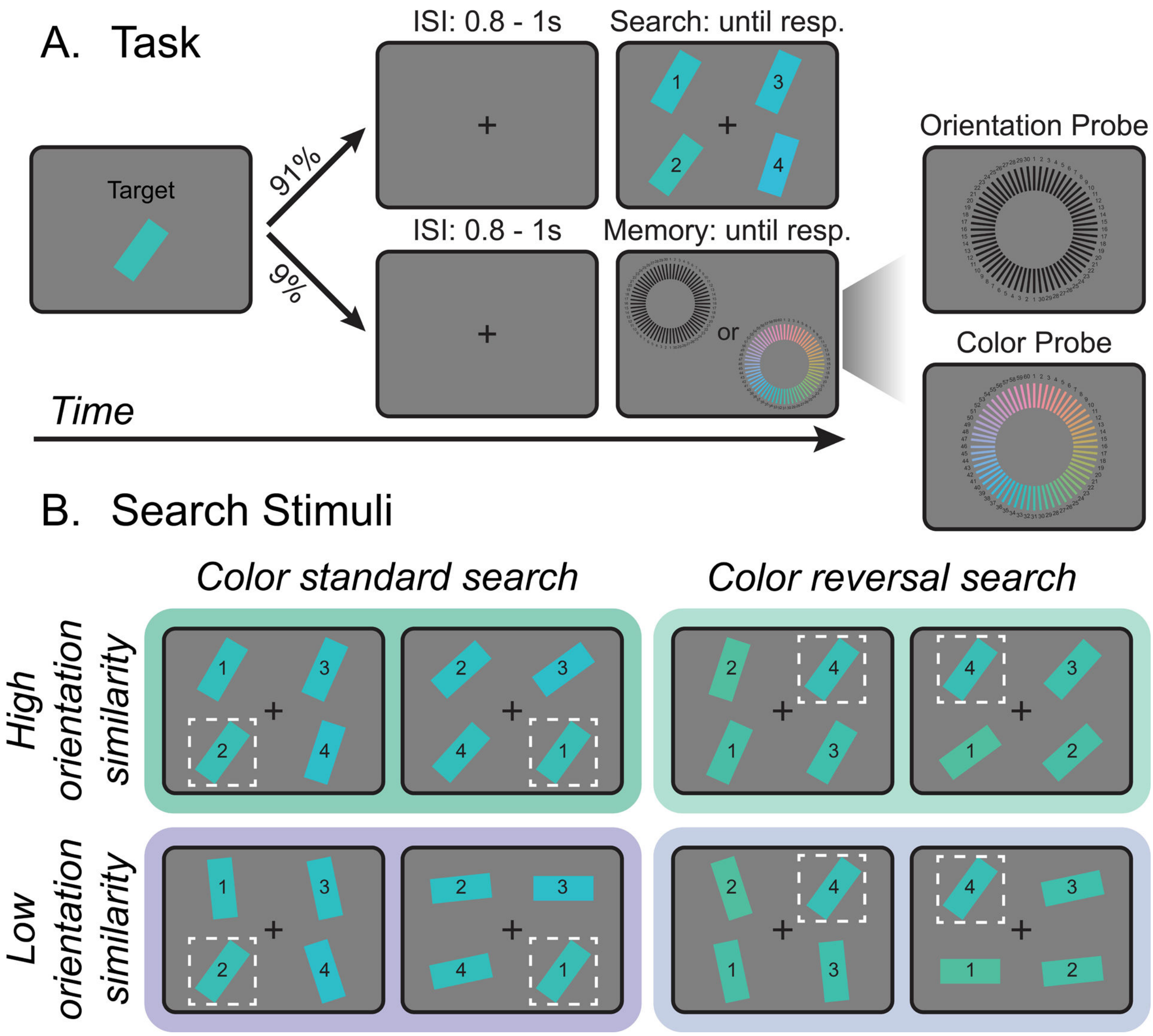

Figure 1.

Illustration of the Experimental Procedure

Note. A) Example visual search and memory probe trials. Prior to the start of the experiment, participants were shown an example of the conjunction target. On 91% of the total trials, participants performed a visual search task for a predefined target object and reported the number inside. The remaining 9% of the trials involved a memory probe task, where participants were presented with either a color wheel or an orientation wheel, and were asked to report the remembered target feature by selecting the number associated with that feature. B) Illustration of distractor sets on visual search trials. *Color standard search* (90% of search trials): The distractor colors were identical in the *high-orientation-similarity* and *low-orientation-similarity* groups. They were drawn from the positive side of the color wheel (i.e., bluer than the target color) and had a high degree of similarity to the target. However, while the distractor orientations were consistently either positively or negatively rotated from the target within a single trial, the direction was unpredictable across different trials. We anticipated that the predictable linear separability of *color* across trials would play a role in shaping the target template, whereas the local linear separability of distractor orientations, confined to a single trial, might have a limited impact. The distractor orientations in the *high-orientation-similarity* group were highly similar to the target, whereas they were more distant from the target in the *low-orientation-similarity* group. *Color reversal search* (10% of search trials): Distractors were the same as those on standard search trials, with the exception that now the distractor colors were negatively rotated from the target (i.e., greener than the target color). Here, the dashed white squares highlight the target but were not visible to participants. Colors are exaggerated for greater visibility.

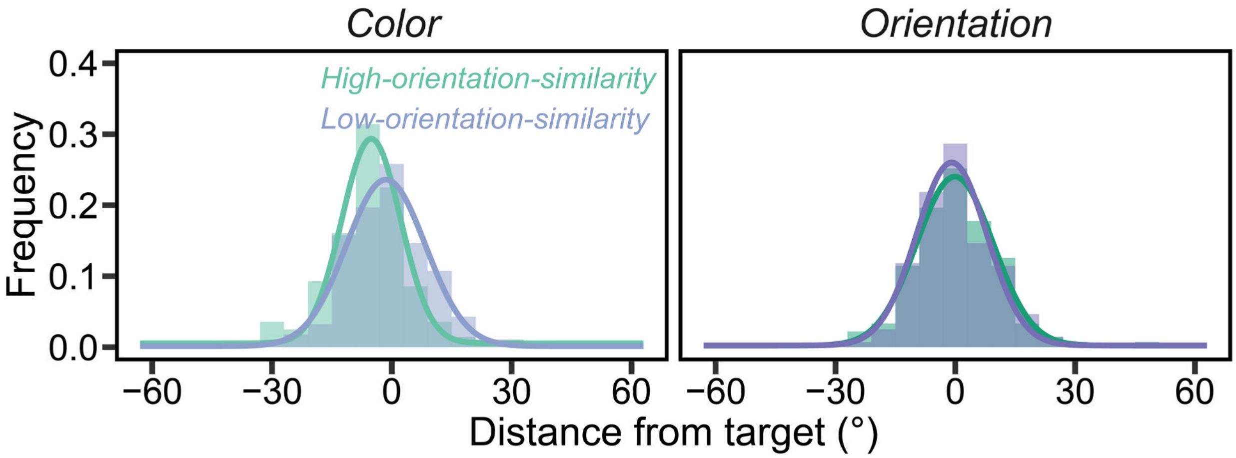

Figure 2.

Gaussian Model Fitting Overlayed on Memory Probe Responses

Note. Best fit Gaussian model for each group and each dimension (solid lines), overlayed on the distribution of actual responses (histograms). Distance from the true target value (0°) is in color and orientation degrees.

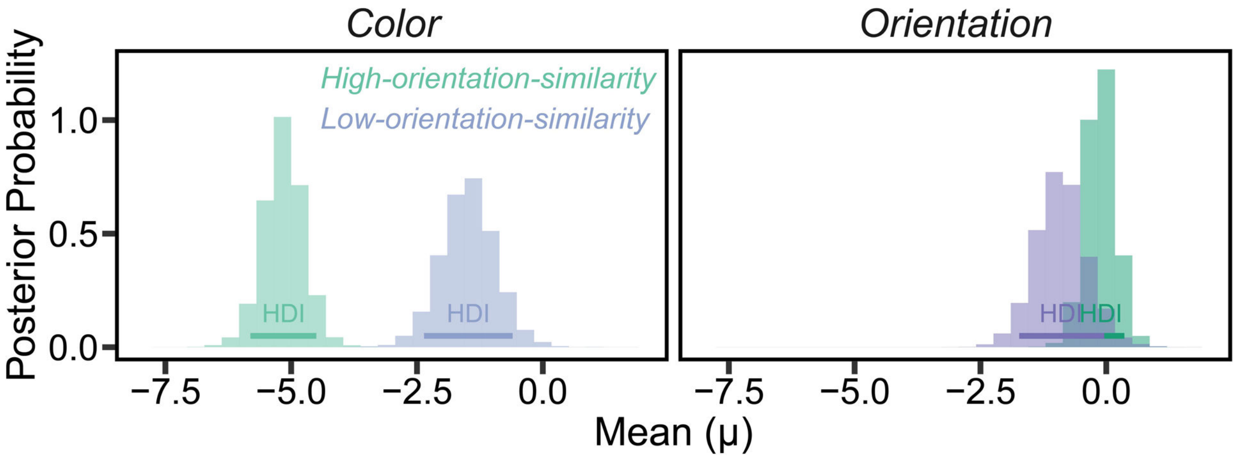

Figure 3.

Distribution of Posterior Estimates of the Mean Parameter

Note. Distribution of posterior estimates of the mean (μ) parameter for each group and each dimension. Colored bars at the bottom indicate the 95% HDI for each group and each dimension. The *high-orientation-similarity* group shifted their color representation farther away from distractors than the *low-orientation-similarity* group. However, there was no difference between groups in the estimation of target orientation.

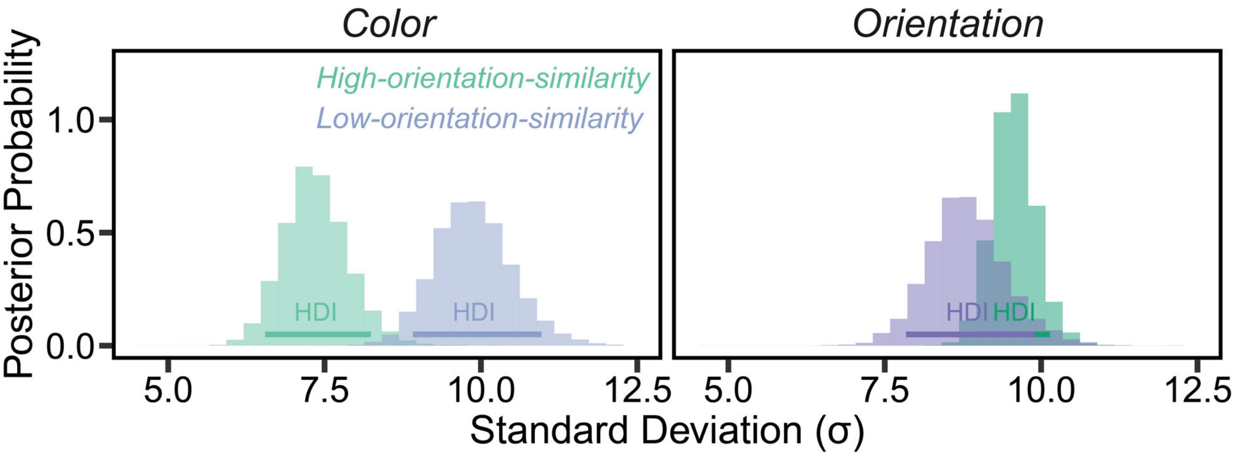

Figure 4.

Distribution of Posterior Estimates of the Standard Deviation Parameter

Note. Distribution of posterior estimates of the standard deviation (σ) parameter for each group and each dimension. Colored bars at the bottom indicate the 95% HDI for each group and each dimension. The representation of the target color was more precise in the *high-orientation-similarity* group than in the *low-orientation-similarity* group. In contrast, the precision of the target orientation did not differ between groups.

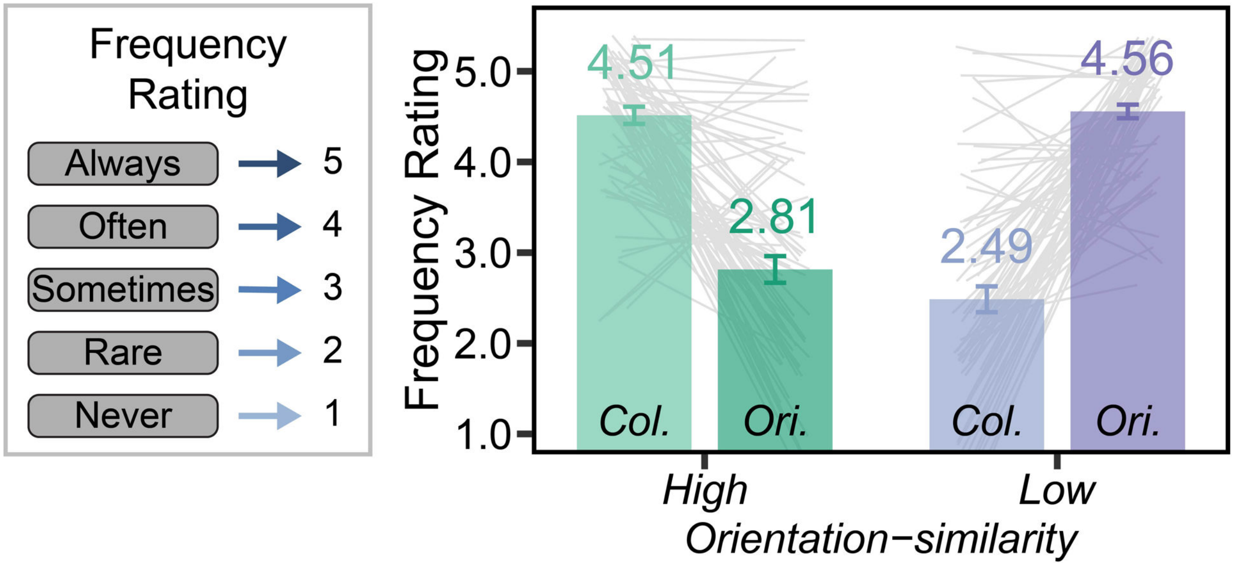

Figure 5.

Post-Experiment Questionnaire on Dimension Reliance

Note. Frequency ratings for the *high-orientation-similarity* and the *low-orientation-similarity* groups, shown separately for *color* and *orientation* dimensions. All error bars represent the standard error of the mean (SEM). The *high-orientation-similarity* group reported preferring to find the target using *color* but the *low-orientation-similarity* group opted to use *orientation*.

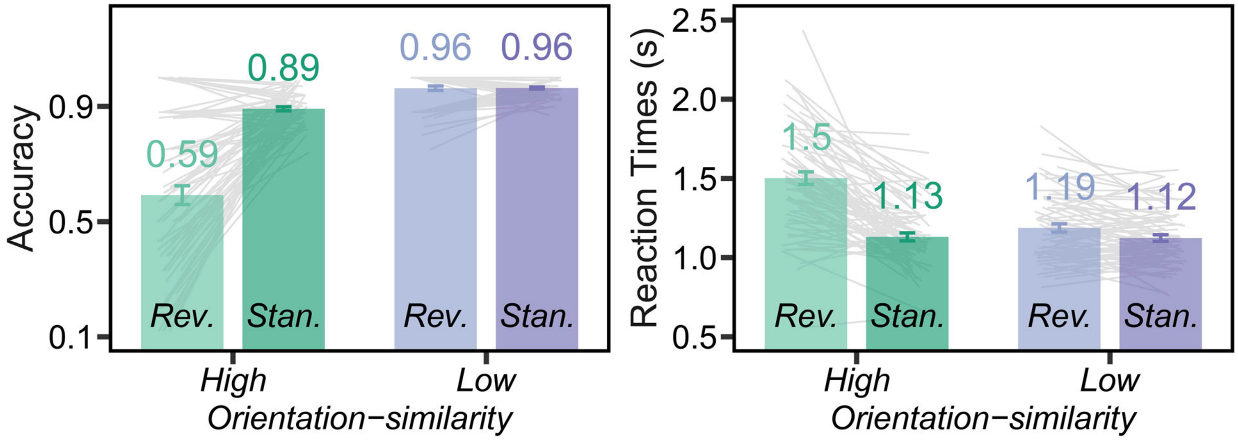

Figure 6.

Visual Search Accuracy and Reaction Times

Note. Visual search performance for the *high-orientation-similarity* and *low-orientation-similarity* groups, separated by *standard* search (90% of visual search trials, the distractor colors were positively rotated from the target color) or *reversal* search (10% of visual search trials, the distractor colors were negatively rotated from the target color). All error bars represent the standard error of the mean (SEM). Results show that the *high-orientation-similarity* group performed worse in reversal trials than in standard trials, whereas the *low-orientation-similarity* group did not. This is consistent with the use of adaptive shifting of target color in the *high-orientation-similarity* group but not the *low-orientation-similarity* group.