Orientation is different: Interaction between contour integration and feature contrasts in visual search

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Salient items usually capture attention and are beneficial to visual search. Jingling and Tseng (2013), nevertheless, have discovered that a salient collinear column can impair local visual search. The display used in that study had 21 rows and 27 columns of bars, all uniformly horizontal (or vertical) except for one column of bars orthogonally oriented to all other bars, making this unique column of collinear (or noncollinear) bars salient in the display. Observers discriminated an oblique target bar superimposed on one of the bars either in the salient column or in the background. Interestingly, responses were slower for a target in a salient collinear column than in the background. This opens a theoretical question of how contour integration interacts with salience computation, which is addressed here by an examination of how salience modulated the search impairment from the collinear column. We show that the collinear column needs to have a high orientation contrast with its neighbors to exert search interference. A collinear column of high contrast in color or luminance did not produce the same impairment. Our results show that orientation-defined salience interacted with collinear contour differently from other feature dimensions, which is consistent with the neuronal properties in V1.

Introduction

Forage is an important task in daily life. We search for our partner at a party, find our keys, or look for a particular document on our desktop. Usually salient items can guide searches, so we can increase the efficiency of searching for keys by putting salient decorations next to them. Conventionally, an item’s salience is determined by its feature contrast from its neighbors (Itti & Koch, 2001; Nothdurft, 1992, 2000; Treisman & Gelade, 1980; Wolfe, 2007; Wolfe, Cave, & Franzel, 1989), and a larger contrast leads to a higher salience regardless of feature dimension (Itti & Koch, 2001; Nothdurft, 2000). This salience is driven by visual inputs (bottom up or stimulus driven) rather than strategic plans (top down or task driven). Hence, salient targets typically elicit efficient search (Nothdurft, 1992; Treisman & Gelade, 1980; Wolfe, 2007), while salient distractors prolong search (see, e.g., Theeuwes, 1994, 2010). If a target is not salient by itself but is spatially overlapping with a salient item, like the keys with salient decorations, the target can also enjoy the benefit of salience (Turatto & Galfano, 2000, 2001; Turatto, Galfano, Gardini, & Mascetti, 2004).

Our previous work, however, has found that a salient item can slow search for a target placed on it if this salient item is part of a collinear group (Jingling & Tseng, 2013). We presented a search display (Figure 1) of regularly spaced white bars (in a black background); a randomly selected column was filled with bars perpendicular to all the background bars, making this column salient. The column could be collinear (snake shape, Figure 1A) or not (ladder shape, Figure 1B). The participants searched for a small black tilted bar (indicated by a red circle in

Figure 1) superimposed on one of the texture bars and discriminated the tilt direction. To avoid top-down expectations on target search, the target was designed to overlap with the salient column by chance. Even so, strong bottom-up salience of the column is predicted to facilitate visual search (Turatto & Galfano, 2000, 2001; Turatto et al., 2004). Nevertheless, responses were slower if the target overlapped with this salient collinear column (Figure 1A). When we reduced the number of the high-orientation-contrast bars in this salient column—that is, reduced the strength of collinear grouping—this impairment effect was eliminated. This impairment remained even when we rotated the display in Figure 1 by 90° to make a horizontal collinear structure, which allowed us to conclude that it was the collinear integration between bars, rather than the vertical orientation of individual bars, that was critical. In summary, a salient collinear structure impairs local visual search.

The unexpected search impairment for a target overlapping exclusively on the collinear column led us to consider the alternative view that the collinear column was not a salient distractor as we intuitively perceive it. Nevertheless, an earlier finding argues against this possibility. Jingling and Zhaoping (2008) compared perceptual salience of collinear borders (border bars were parallel to the border) and noncollinear borders between homogeneous and regular textures of iso-oriented bars. They found that participants were better at change detection on the former than the latter. This was taken as behavioral evidence to suggest that collinear borders were more salient. Our search display had a similar border, and according to Jingling and Zhaoping (2008) the collinear column (in Figure 1A) is more salient than the noncollinear column (Figure 1B). Another possibility is that the collinear column may be taken as a cutting edge of a surface or a background, giving targets overlapping with it a lower priority for search. However, data from eye-movement recording (Jingling, Tang, & Tseng, in press) has shown that saccadic latencies to overlapping targets are shorter than those to nonoverlapping targets, regardless of whether the salient column was collinear. In other words, in Figure 1A and B, participants saccaded to targets on the salient column more quickly than to targets in the background, showing that the salient column guided searches. Further study (Tseng & Jingling, 2013) has also revealed that such a collinear salient column still captures observers’ attention even if it never overlapped with a target and should be ignored (Theeuwes, 1994). Altogether, the data until now have supported the idea that the collinear column in Figure 1A is salient and captures initial attention.

In this study, we aimed to find out whether a collinear column, without a high orientation contrast as in previous work by Jingling and Tseng (2013), still impairs search for targets located on it. This question is theoretically important for our understanding of how perceptual grouping interacts with the selective-attention system. Grouped structure enjoys attentional priority over local items (see, e.g., Han & Humphreys, 1999; Navon, 1977, 2003) and is considered salient (W. Li, Piéch, & Gilbert, 2006). However, how perceptual organization is represented in a salience map is still unclear. According to one of
the most influential salience models (Itti & Koch, 2001), perceptual salience is the sum of separately computed feature contrast across different feature dimensions. In this case, collinear grouping makes little contribution to the final salience map. On the contrary, Zhaoping (2005; see also Z. Li, 2002) has proposed a salience computation based on neural mechanisms in the primary visual cortex (the V1 model of salience), which includes iso-orientation suppression, collinear facilitations, and general feature-unspecific suppression in computing salience in the orientation dimension. Iso-orientation suppression highlights locations of high orientation contrast, while collinear facilitation enhances neural responses to bars in a smooth contour. Finally, general suppression enables neural-response suppression from surrounding bars outside the receptive field. The final output of the V1 mechanism is predicted neuron-firing rates, and those areas with activations much higher than average indicate the most salient location. In this framework, collinear grouping and orientation contrast both contribute to the salience perception.

In this context, knowing whether the collinear column needs to be contingently salient in the orientation domain to impair visual search has significant theoretical implications. The findings in our previous work demonstrated a specific combination of collinearity and high orientation contrast, which leads to an end result opposite to what is expected in visual search: It impairs rather than facilitates search (Jingling, Tang, & Tseng, in press; Jingling & Zhaoping, 2008; Tseng & Jingling, 2012). Since reduction of collinearity can eliminate such impairment, it is possible that reduction of orientation contrast can also decrease impairment—if collinearity is computed with orientation contrast, as proposed by the V1 model of salience. The V1 model of salience also suggests that feature dimensions such as color or luminance do not interact with collinear contour as orientation does. If, on the contrary, collinearity affects selective attention separately from the bottom-up salience computation from all feature dimensions (Itti & Koch, 2001), then reducing orientation contrast should not affect the strength of collinear grouping. Given that salient items usually capture attention, reducing salience should lead to lower search priority and produce an even larger impairment effect. Further, the local contrast defined in any feature dimension should act the same as orientation contrast on this impairment effect in visual search.

In this study, we reduced the collinear column salience by dividing the search display into two regions, having collinear and noncollinear columns respectively, to enable us to examine the relative contributions from collinearity and local contrast. In Experiments 2 and 3, we examined how different local features (color and luminance) interact with collinearity. In summary, our data indicated that the search impairment only appears when the collinear column also contains high local orientation contrast, suggesting that salience computation considers collinear grouping together with orientation contrast.

**Experiment 1**

To study how orientation contrast interacts to produce search impairment on targets overlapping with a collinear structure, we designed a border configuration (Figure 2). More specifically, the search display was formed by two regions of uniform texture and a border in between. The border was the most salient area in the search display, and the perceptual salience decreased as the distance to the border increased. The border bars can be divided into two kinds: those parallel to the border direction (i.e., the vertical bars), which formed a collinear grouping at the border, and those perpendicular to the border (i.e., the horizontal bars at border), which did not group collinearly at the border. The two kinds of border bars should have similar degrees of orientation contrast (i.e., perceptual salience), with different degrees of collinearity. On the other hand, bars not at the border were all collinear in either the vertical direction or the horizontal direction; however, they were all not salient, for they did not have high orientation contrast to their neighbors. In total, we have three kinds of possible locations for target presence: border collinear bars, border noncollinear bars, and nonborder collinear bars. If collinearity is what instigates delayed search speed, we should observe longer response times when the target overlaps with collinear bars but not when it overlaps with noncollinear bars. On the other hand, if high orientation contrast (or perceptual salience) is a prerequisite for collinear structure to exert such impairment, then longer response times should be observed only for targets overlapping with border collinear bars, not with nonborder collinear bars.

**Participants**

Two experienced participants (ZL and JL) and four inexperienced participants (JC, AP, ZS, and KL) joined in this experiment. All had normal or corrected-to-normal vision. Inexperienced participants were paid 6 pounds per hour for the experiments.
Equipment and stimuli

The texture pattern was composed of $27 \times 21$ horizontal and vertical white bars against a black background. Each bar was $0.81 \times 0.18$ in the visual angle, placed on a regular grid with unit grid spacing of $1.04$ both horizontally and vertically. The target was a black line with dimensions $0.63 \times 0.11$, oriented either $45^\circ$ or $135^\circ$ from vertical and centered on a texture bar (Figure 2). A $0.18 \times 0.18$ white disk occupied the center of the screen in the fixation display.

The experiment was programmed in Matlab with the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). For AP, ZL, and JL, the stimuli were shown on a 19-in. Iiyama Pro 450 monitor, and for JC, ZS, and KL, they were shown on a 21-in. Sony GDM-F520 monitor. The luminance of the white bars on the Sony GDM-F520 monitor was $120.05 \text{ cd/m}^2$, CIE 1931 $x = 0.28$ and $y = 0.29$, while on the Iiyama monitor it was $103.08 \text{ cd/m}^2$, CIE 1931 $x = 0.28$ and $y = 0.27$. To make the apparent size of the stimuli approximately the same for these two monitors, the viewing distances were 60 cm and 67.6 cm for the Iiyama and Sony monitors, respectively.

Design

The search display, composed of $21 \times 27$ bars, is illustrated in Figure 2. Since the border was always vertical and changed along the horizontal axis from trial to trial, we called the horizontal direction the relevant dimension. The border was presented in one of the 16 possible locations, varying along the relevant dimension. The target was on one of the $9 \times 9$ central texture bars. In the relevant dimension, the target location was uniformly distributed on these nine possible locations, while in the irrelevant dimension it was randomly assigned. By independently varying the target location and salient border location, we ensured that there was no dependable correlation between border location and target location; in other words, the participants could not use the line location to predict the target location. Therefore, the salient line was irrelevant to the task. In total, each experimental session was composed of $16 \times 2 \times 8 \times 2 = 512$ trials. All participants completed three sessions—except JL, who completed five sessions—to include enough trials for later analysis. Although there were only six participants, the data and effects were robust enough to reach statistical significance.

Procedure

Each trial began with a fixation display for 800 ms, followed by the target display, which stayed on the screen until the subject gave a response by pressing left- or right-hand controls to indicate leftward and rightward tilted targets. There was no feedback, and the next trial followed immediately. The participants were informed about the area of the possible target location in advance and were encouraged to respond as fast as possible while maintaining accuracy. Fifteen randomly selected trials were used for practice at the beginning of each session before the real data collection. During experiments, a break was provided after every 60 trials. It took about half an hour to complete each
session. Participants usually completed one session a day.

Results

Figure 3 shows data from all six participants. The response time (RT) is plotted against the target-to-border distance in terms of number of texture-grid units along the relevant dimension. Negative numbers indicate that the target was on noncollinear columns (i.e., a horizontal bar), whereas positive numbers refer to a target on collinear columns (i.e., a vertical bar). For instance, distance 1 shows data when the target was at a border collinear bar, while distance −1 shows data when the target was at a border noncollinear bar. We observed a distance effect—that is, RT was on average 161.32 ms shorter for a target presented at the center of the screen (within the central four columns) than at the periphery (beyond four columns away from the center). This distance effect suggests that the participants usually started their search from the fixation position. To extract the effect of border and collinearity on response times, we needed to counterbalance the distance effect, so we only considered target-to-border distances that covered targets at all eccentricities. As a result, the range of target-to-border distance is −8 to 8 bar units along the relevant dimension (Figure 3). The
The accuracy was 93.12\% for nonsense (i.e., border collinear bars). The effect of orientation contrast (i.e., border collinear bars) was not significant. Therefore, a collinear structure only robustly delayed responses with sufficient orientation contrast (i.e., border collinear bars). The RT and its error $\sigma$ for this distance were then calculated as follows:

$$RT = \frac{\sum RT(e)}{N_e},$$

where $N_e$, the number of tested target eccentricities, is eight (eight possible target locations in the search display).

The effects of collinearity and orientation salience

To understand how collinearity grouping and perceptual salience (high orientation contrast at the border) affect responses, we divided responses into three categories: responses for trials when targets were at border collinear bars (distance 1), at border noncollinear bars (distance -1), and at nonborder collinear bars (distance from 2 to 8 and -2 to -8). Data are shown in Figure 2B. Results were submitted to a one-way repeated-measures ANOVA, and the main effect was significant, $F(2, 5) = 16.80$, MSE = 699.14, $p < 0.001$. A Tukey post hoc test showed that the responses were slower for targets on border collinear bars (724.23 ms) than on border noncollinear bars (646.45 ms) or on nonborder collinear bars (648.80 ms), ps < 0.05, while responses between the latter two did not reach statistical significance. Therefore, a collinear structure only robustly delayed responses with sufficient orientation contrast (i.e., border collinear bars). The accuracy was 93.12\%, 93.49\%, and 93.49\% for targets on border collinear bars, border noncollinear bars, and nonborder collinear bars, respectively. There was no significant effect in terms of accuracy.

The effect away from the border

From Figure 3 we found that there was a second peak of response time away from the border exclusively in the collinear-column region for four of our observers. The peak was when the target was at six bars away from the border for participants ZL, AP, and JL, and at five bars away for JC. This peak response is not due to specific response bias at a particular distance, since we collapsed data from all distances and averaged responses with the collinear region at the right and left side of the display. Analysis shows that the RT was significantly longer at the peak location than its adjacent neighboring locations (collapse two flanking distances) for participants AP, ZL, and JL [t(172) = 3.26, t(172) = 2.59, and t(288) = 3.08, ps < 0.05] and marginally longer for JC, t(172) = 1.39, $p = 0.08$. We cannot identify a peak for participants ZS and KL. The mean accuracy was 93.06\% and 94.01\% for the peak and next-to-peak locations, respectively; their difference is not statistically significant.

Discussion

In this experiment, we compared collinear and noncollinear structure at locations of various degrees of salience defined by local orientation contrast: The collinear structures next to the border between the two homogeneous regions were more salient than those not at the border. Results showed that a high-salience collinear structure impairs target search more robustly than a low-salience one. We conclude that search impairment from the collinear structure emerged only when the collinear structure possessed great orientation contrast with its neighboring elements. Therefore, a collinear structure per se is not enough to elicit impairment of target discrimination.

These findings support the V1 model of salience, which suggests that orientation contrast and collinear property compute on the same salience map, since we discovered that reducing a task-irrelevant distractor’s salience leads to the same effect as reducing collinear strength (Jingling & Tseng, 2013)—that is, removing the impairment effect to overlapping targets. If salience is separately computed with collinearity, a less salient structure should decrease attentional priority on it; combined with the original disadvantage, we should observe an even stronger impairment effect. To further confirm our observations, Experiments 2 and 3 were designed to test whether our observations are limited to the orientation dimension because collinearity only interacts with orientation computation but not with feature dimensions such as color or luminance (Hess, Hayes, & Field, 2003).

Another interesting finding in this experiment is the additional response delay when the target was presented on a bar several columns away from the border. This peak response was observed only in the collinear-texture region, suggesting that this effect may be a ripple after a very strong border as a result of dynamic neural computation in V1 (Popple, 2003; Zhaoping, 2003). The key assumption leading to such a ripple is that a more activated neuron produces larger suppression to its neighbors (general suppression). According to the V1 salience model, the collinear border in the experiment (Figure 2) earned the strongest neural activation because it received the least iso-orientation suppression and the most collinear facilitation. This strong activation thus suppresses neural activations of the neighbors, especially...
the iso-oriented ones, and the suppression can reach as far as the length of the lateral connection. Consequently, the neurons responding to a texture bar outside this border suppression region (i.e., the distance covered by lateral connections) are free from the suppression by the border, and additionally are less suppressed by the less active neurons within the border suppression region. As a result, a rebound could be observed adjacent to the border suppression region. A border noncollinear bar, on the other hand, did not elicit such strong neural activations and thus its ripple was undetectable.

Thus, it is possible that for participants ZL, JL, JC, and AP, the display somehow matched their neural scales, probably because of the way they fixated in the display, and thus a strong border effect produced a ripple. The display scales did not exactly match the neural scales for participants ZS and KL, and thus did not produce such a ripple. Note that those who exhibited the ripple effect only had their peak responses emerge in the collinear field and also tended to have a stronger border effect (Figure 3). Since individual differences can also be observed in contour-integration tasks (see, e.g., Dakin & Baruch, 2009; May & Hess, 2007), it is possible that the border effect was stronger or weaker in each individual, leading to a larger or smaller rebound peak away from the border.

**Experiment 2**

This experiment was designed to test whether a collinear column standing out by its unique feature other than orientation can also generate a masking effect on local target search. We modified the procedure from Jingling and Tseng (2013) and designed a search display that was filled with green collinear columns all over the display, with a randomly selected column displayed in red (Figure 4A). In this way the red collinear column was the most salient one among all. If it slowed the response more than the green collinear columns, it would help us to generalize the findings observed in the orientation dimension to other basic featural dimensions.

**Participants**

Twenty undergraduates from China Medical University with normal or corrected-to-normal vision joined this experiment. They were unaware of the goal of the study in advance, and received 50 New Taiwan dollars or extra course credit as compensation.

**Equipment and stimuli**

The experiment was carried out in a dimly lit room, and the participant sat with a chin rest to view the stimuli from a distance of 60 cm. The stimuli were shown on a 21-in. ViewSonic gamma-corrected monitor, driven by a dual-core CPU Acer personal computer. The screen-refresh rate was 70 Hz.

The search display consisted of 576 vertical bars arranged in 21 rows and 27 columns against a dark background (Figure 4A). Each bar was 0.81° × 0.18° in visual angle, placed on a regular grid with spacing of 1.04°. All the bars were green (CIE 1931 x = 0.544 and y = 0.390) except for the distractor bars, which were red (CIE 1931 x = 0.242 and y = 0.610), and all bars were at the same level of luminance (29.1 cd/m²). The target and the task were the same as in Experiment 1.

**Design**

The locations of the target and the salient distractor were manipulated to be independent in this experiment, following Jingling and Tseng (2013). The target location was fixed at the center row (11th row) and varied along the horizontal locations among seven randomly chosen locations in each trial (positions 8, 10, 12, 14, 16, 18, and 20 in the row of 27 bars). In each trial, a red column was independently and randomly chosen from the same seven possible locations, which made the location of the red line irrelevant to the task.

**Procedure**

Each trial began with a blank display for 500 ms, followed by the target display, which stayed on until the participant gave a response. After that, a blank display was shown for 800 ms and then the next trial started. Participants responded by pressing two keys (with markers) on a number keypad to indicate left- or right-tilted targets. Ten practice trials were given before the data collection. Participants were encouraged to respond as fast as possible while maintaining their accuracy. During experiments, a break was provided after every 75 trials. Each participant completed 196 trials, which took about 10 min.

**Results**

Results of response time are shown in Figure 4B. Correct trials within two standard deviations showed that a target overlapping with the salient column (899.44 ms) triggered similar response times as did a target overlapping with a nonsalient column (907.96 ms).
Discussion

We found that a collinear column in a unique color did not affect visual search. This result is opposite from what we observed from a collinear column unique in orientation and is not consistent with reports in the attentional-capture literature (Turatto & Galfano, 2000, 2001; Turatto et al., 2004). The lack of impairment might arise from two sources. First, collinearity is computed exclusively with orientation information, thus removing orientation contrast and reducing the effect of impairment. Second, the color singleton in our display may not have been as salient as the orientation contrast used in previous studies (Jingling & Tseng, 2013). The orientation contrast in Jingling and Tseng (2013) was at 90°, which is the largest contrast between two oriented bars. The color contrast used in this experiment, though it is distinctive, may not reach as high as the 90° orientation contrast. It was also evident by the longer RT in this (903 ms) than the previous study (854 ms), suggesting that Experiment 2 is harder than Experiment 1. It is possible that the feature contrast needs to be of a certain magnitude for a search impairment to emerge. To distinguish these two possibilities, in the next experiment we replicated Experiment 2 with salience defined in the luminance dimension, as luminance contrast is more salient and captures attention more easily than a color singleton (Rauschenberger, 2003).

Experiment 3

To further understand whether collinearity is affected by salience defined by features other than orientation, we used a luminance-defined collinear distractor to replace the color-defined distractor from Experiment 2. Thirteen undergraduates from China Medical University joined in this experiment, with 50 New Taiwanese dollars or extra course credit as compensation. They reported having normal or corrected-to-normal vision. The experiment was identical to Experiment 2 except that the bars in the display were all gray (luminance level 125 in 256 gray levels).
scale), and the salient column had brighter luminance (230 in gray scale), while the background was not black (77 in gray scale). An example of the search display is shown in Figure 4C.

Results

Only correct trials with RTs within two standard deviations of the mean were included for further analysis (Figure 4D). RTs were shorter for targets overlapping with salient columns (722.03 ms) than for ones overlapping with nonsalient columns (759.87 ms), t(12) = 3.16, p < 0.01. Salient targets (97.25%) also had higher accuracy than nonsalient targets (93.04%), t(12) = 4.27, p < 0.001. Thus, no evidence for a tradeoff between speed and accuracy was observed.

Discussion

In this experiment, we found that a collinear column facilitated—not impaired—visual search when it was salient in the luminance dimension. This facilitation is consistent with the attentional-capture effect by salient items found in the literature (Turatto & Galfano, 2000, 2001; Turatto et al., 2004). With high feature contrast, a collinear structure captures attention in Experiment 3 while it impairs visual search in Experiment 1 and our previous study (Jingling & Tseng, 2013). Table 1 summarizes the findings in this and the previous studies according to collinearity strength and degrees of salience. The search response was prolonged only when both collinearity and salience in the orientation dimension were strong. Reducing salience in the orientation dimension or reducing the strength of collinearity shortened responses. Strong salience value in the color or luminance dimension, however, did not produce the same impairment as in the orientation dimension; rather, strong luminance salience facilitated target search. This finding supports the idea that collinear grouping associates with orientation contrast but not other feature dimensions.

General discussion

In this study, we aimed to test whether the visual-search impairment effect on a salient collinear column, demonstrated in our previous work (Jingling & Tseng, 2013), only occurs when the collinear column is uniquely salient in a search display. In Experiment 1 we designed a two-texture display, with collinear and noncollinear columns either on the border (salient) or not (not salient). We found that a collinear column masked the target only when it was salient. Experiments 2 and 3 demonstrated that if the collinear column was salient in the color or luminance dimension, it did not impair search, and in fact facilitated it. Taken together (Table 1), high orientation contrast is required to enable a collinear structure to impair local visual search, and it cannot be replaced by high feature contrast in other dimensions. In other words, the unexpected impairment effect by a salient collinear column we found previously (Jingling & Tseng, 2013) is a specific combination result of collinear grouping and orientation contrast.

Our findings argue against the salience models that include computation of feature contrast in different featural dimensions in the same way (e.g., Itti & Koch, 2001; Nothdurft, 1992, 2000; Treisman & Gelade, 1980; Wolfe, 2007; Wolfe et al., 1989). The computational model of Itti and Koch (2001), for example, computes feature contrast using center-surround filters in order to highlight salient locations in visual scenes. They applied the same rule to all features—color, intensity, orientation, and ideally other features like motion, junctions and terminators, stereo disparity, shape from shading, and so on—and then produced the conspicuous maps for each feature. The final salience map is then obtained by combining with feature contrast in all dimensions. Accordingly, feature contrast in the orientation dimension should affect performance in the same way as feature contrast in the luminance dimension. Never-
theless, we found that a collinear column with high orientation contrast impairs visual search, while a collinear column with high color or luminance contrast facilitates visual search. On the other hand, our data are more in line with the V1 model of salience (Z. Li, 2002; Zhaoping, 2005), as it separates orientation from other feature dimensions in the consideration of collinear facilitation computation.

The observed strong links between collinear grouping and orientation contrast are also reported in the literature (see, e.g., Dakin & Baruch, 2009; Nothdurft, 1992; Jingling & Zhaoping, 2008; Popple, 2003; Wolfson & Landy, 1995). For example, Nothdurft (1992) reported that figure-ground segmentation in a texture of oriented bars depends on the direction of the bars: A rectangular figure is easier to segregate when the bars are parallel to the long axis of the figure region. In other words, a collinear border can define a figure more efficiently than a noncollinear border. Wolfson and Landy (1995) found that curvature discrimination of a texture border is better when the texture bars in one of the texture regions are parallel to the border. Popple (2003) reported a perceptual bias in the localization of texture borders toward the collinear texture region. The contour-integration literature also provides evidence that the immediate neighbors of the contour matter, and that this effect depends on the grouping strength of the contour. Dakin and Baruch (2009) put a smooth contour, either a snake or a ladder, with randomly oriented Gabors in a display while varying the orientation contrast between the contour path and the immediately neighboring Gabors from 0° (parallel to the path, low orientation contrast) to 90° (orthogonal to the path, high orientation contrast). Participants discriminated the configuration of the contour. To reach 82% correct performance, the display needed to present around 700 ms for a snake contour with randomly oriented neighbors (the baseline). However, with parallel neighbors, the threshold-presentation duration increased (approx. 1500 ms), and with orthogonal neighbors it decreased (approx. 400 ms). Thus, a high-orientation-contrast context can make a contour more salient. Interestingly, contextual modulation is less obvious in a ladder contour. Our study provides further information that such a collinear structure with high orientation contrast can produce a strong attentional masking effect on a local target.

One may explain our findings in another way: taking impairment of facilitation as a continued variation of feature-dimension strength. One may consider the impairment effect as being produced solely by collinear grouping of the structure, while the salience of the collinear structure can increase or cancel the impairment effect. For instance, salience in the luminance dimension might be the strongest at capturing attention and thus might overcome the impairment effect of the collinear structure and produce the facilitation effect. Relatively less salience in the color dimension, then, can only cancel the impairment; it is not strong enough to reveal facilitation. The least salient dimension, orientation, cannot cancel the impairment. This explanation is not favored for the following reasons. First, columns defined in the luminance (Figure 4C), color (Figure 4A), and orientation (Figure 1A) dimensions all popped out easily, and as singletons in a display they should all enjoy highest attentional priority regardless of feature dimensions. Behaviorally, our response-time results did not fully support the prediction that the luminance condition should be the easiest one, requiring the least processing time, followed by the color condition and orientation (741 ms, 903 ms, and 854 ms, respectively). Second, we did not find evidence in the literature showing that items of different degrees of salience can exert opposite effects in visual search. A salient distractor always prolongs responses, with more delay from more salient distractors (Theeuwes, 2010); a salient target always facilitates search, while a more salient abrupt onset leads to more efficient search, and a less salient color/shape singleton leads to less efficient search (Rauschenberger, 2003). Thus, it is more plausible that the impairment effect of the salient collinear structure was from a different mechanism than those capture effects.

Two additional remarks need to be made here. First, our manipulations in different feature dimensions did not answer why a collinear column slowed down target search, but very likely that effect is not originated by the salience computation, for two reasons: (1) Salience in the color and luminance dimensions did not produce the same impairment as orientation, and (2) salience usually guides rather than masks attention. It is likely to originate from a site where information of both collinearity and orientation contrast is available. Second, the unique impairment effect by the salient collinear column was observed under the condition that participants were required to search for a local target. When the task was to pay attention to the global structure, as in work by Jingling and Zhaoping (2008), then the salient collinear column facilitated performance. The exact mechanism of how a salient collinear column directs selective attention to hinder local target discrimination, however, is not yet clear. Several possibilities require further studies to test them. First, it is possible that collinear columns produce stronger crowding effects than noncollinear columns and thus mask target discrimination in visual search. The crowding effect, though, usually demonstrated in a simple rapid display, might be able to account for visual-search performance under the assumption that several saccadic eye movements are required in a visual-search display (Gheri, Morgan, & Solomon, 2007; Rosenholtz, Huang, Raj, Balas, & Ilie, 2012). Collinear
contour can produce a larger crowding effect than orthogonal contour (Chakravarthi & Pelli, 2011; May & Hess, 2007; Yeotikar, Khuu, Asper, & Suttle, 2011); thus it is possible that a target on a collinear contour suffers a stronger crowding effect and becomes more difficult to discriminate in our display. However, as the collinear columns are more salient and should attract initial gaze, the targets are more likely to be in the fovea rather than in the periphery. Also, crowding is negatively correlated with perceptual salience (Gheri et al., 2007; Livne & Sagi, 2007, 2010; Saarela, Sayim, Westheimer, & Herzog, 2009; Whitney & Levi, 2011), and our overlapping targets should be in a more salient region than nonoverlapping targets. Thus whether the crowding effect can account for the search impairment requires further testing.

Second, it is possible that a collinear structure elicits stronger filling in than does a noncollinear structure, which masks local target discrimination. Zhaoping and Jingling (2008) showed that a supra-threshold collinear context makes it easier to induce “yes” responses on target detection than does a noncollinear context. Yantis and Nakama (1998) also showed that target discrimination was delayed if the target was on the path of apparent motion, compared to a target not on the path. Both findings considered that perceptual filling in of collinear structures or of the path of apparent motion interferes with task performance. Our collinear structure might also generate strong filling in and thus make targets overlapping on it more difficult to detect.

Another possibility is that a salient collinear contour is integrated into a perceptual object, which enjoys high priority in visual attention (Driver, Davis, Russell, Turatto, & Freeman, 2001; Hillstrom & Yantis, 1994; Zhaoping & Guyader, 2007). Similar to the global-to-local interference effect (Navon, 1977, 2003), breaking down the global object in order to discriminate the local target in our display may prolong response times.

In addition to these possibilities, some top-down controls of attention may be involved in the search impairment. For instance, the collinear column did not predict target locations in our display, and it is much larger than the target, so it might have been inhibited, since it did not match the attentional-control setting generated by task demands. The types of targets may also matter. We have shown that an impairment effect can be observed for an oriented target. It is possible, however, that when participants are asked to find a color target, for example, this impairment can be abolished. Though the current study does not allow us to speculate about these possibilities, it provides some hints of the necessary and sufficient condition of the phenomenon: a collinear column with high orientation contrasts to the context.

In conclusion, we identified the necessary condition for a collinear column to impair local visual search. We demonstrated that such a collinear grouped structure needs to have a high orientation contrast to its background in order to produce a masking effect on the local target: High featural contrast in the color or luminance dimension did not produce such an effect. Further, feature contrast on the color or luminance dimension changed the effect of this collinear structure on visual search from impairment to facilitation. Our data suggest that salience computation needs to take collinear facilitation into account and individually consider its interaction with different feature dimensions rather than simply sum together contrast from every feature map. Further studies are required to investigate the actual mechanism that produces such impairment in visual search.

**Keywords:** collinear, salience, orientation, visual search, grouping

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**References**


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