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Using feature preview to investigate the roles of top–down and bottom–up processing in conjunction search

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ABSTRACT

The venerable conjunction search paradigm is a widely used tool to investigate how we search for items of interest from among visually complex surroundings. Models of visual search have long predicted that standard conjunction search is guided primarily by top–down processing. Prior attempts to test this claim experimentally have done so by altering some aspect of the standard conjunction search, whether by manipulating the distractor ratio or by including a feature singleton. Although suggestive, these manipulations result in a task that differs slightly from standard conjunction search. To leave the standard conjunction search paradigm intact, we used the feature preview task developed by Olds and Fockler [Olds, E. S., & Fockler, K. A. (2004). Does previewing one stimulus feature help conjunction search? *Perception, 33*, 195–216]. Our results show that in standard conjunction search the effect of bottom–up activation is not necessarily detrimental to search performance as previously suggested by computational models of visual search. Instead, bottom–up activation limits the scope of search, thereby boosting the efficiency of standard conjunction searches. Subjects also showed a bias to group items by color rather than orientation even when color differences were reduced nearly to threshold, indicating that the salience advantage of color is complemented by a general bottom–up preference for color.

1. Introduction

Searching for food from among a complex and variegated environment is a task that must have routinely confronted our ancestors. To efficiently locate one item of interest from among many others, our visual systems must be able to home in on the features that define the items we seek. At the same time it is often important to respond to conspicuous objects such as an animal that has suddenly appeared or a ripe fruit among green leaves. Top–down processing refers to mechanisms that guide our attention toward objects that are likely to meet our long-term goals, whereas bottom–up mechanisms process raw sensory information, thereby guiding our attention to conspicuous objects regardless of the relevance of these objects to our pre-existing goals (e.g., Connor, Egeth, & Yantis, 2004). Here we investigate the roles of top–down and bottom–up processing in visual search.

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2. Standard conjunction search and models of attention

In the visual search paradigm (e.g., Treisman & Gelade, 1980), subjects search for a target defined by a unique feature (feature search) or combination of features (conjunction search) that distinguishes it from non-target distractors. In standard conjunction searches half the distractors share one of the target's features and the other half share the second of the target's features. Such experiments commonly find that in feature searches response times are relatively insensitive to increasing numbers of display items whereas in conjunction searches response times increase along with the number of items in the displays. Prominent models of attention such as FeatureGate (Cave, Kim, Bichot, & Sobel, 2005) and Guided Search (Wolfe, 2007) simulate visual search by calculating the sum of top–down and bottom–up activations for each item in the display, then selecting the item with the highest activation for further processing. Top–down activation is proportional to the similarity between an item's features and a set of target features, and bottom–up activation is proportional to the difference between an item's features and the features of other items; here define top–down and bottom–up processing as in the models. In feature searches the target enjoys both a top–down and a bottom–up advantage over all the distractors because it has the target's features and has one feature that distinguishes it from all the distractors. As a result, in feature searches the models efficiently locate the target regardless of the number of display items, just as human subjects do; in feature searches the most salient item 'captures' attention (e.g., Theeuwes, 1994), unless a top–down strategy is used to circumvent visual capture (e.g., Bacon & Egeth, 1994; Proulx & Serences, 2006; but see Theeuwes, 2004). In standard conjunction searches, the target enjoys the same top–down advantage as in feature searches because it has both of the target's features whereas each of the distractors has only one of the target's features. As for bottom–up activation, every item (including the target) is distinct from about half of the other items for each of its features, so if bottom–up activations were based on the presence of feature differences across the entire display, every item would have the same bottom–up activation as every other item. However, bottom–up activations are scaled by distance so that each item receives more bottom–up activation from nearby items than from distant items. Any distractors that are locally salient might thereby accumulate sufficient bottom–up activation to overwhelm the top–down advantage enjoyed by the target. Thus, these models suggest that in standard conjunction searches bottom–up activation serves primarily to draw attention away from the target and toward locally salient distractors. However, the results from one type of conjunction search show that bottom–up activations can boost the efficiency of conjunction search by limiting the range through which search proceeds.

3. The role of bottom–up processing in non-standard conjunction search

In distractor ratio conjunction searches the overall display size is held constant but the set size of each distractor type is varied. Generally search is most efficient when one or the other distractor group predominates and least efficient when the two distractor types are equally numerous (Poisson & Wilkinson, 1992; Shen, Reingold, & Pomplun, 2000; Zohary & Hochstein, 1989), suggesting that search proceeds through either the target-color group or the target-orientation group, whichever happens to be smaller in a given trial. Do subjects search through the smaller group because each item in the smaller group is on average more salient than items in the larger group (bottom–up), or because subjects have a top–down strategy to select the smaller group? In models of attention (Cave et al., 2005; Wolfe, 1994) the bottom–up explanation is sufficient to explain smaller-group search without needing to posit any extraneous top–down strategy. On this basis, Sobel and Cave (2002) argued that the bottom–up explanation for smaller-group search is more parsimonious, but because standard conjunction search uses equally sized distractor groups this argument does not extend to standard conjunction search.

Nevertheless, Proulx (2007) recently developed an attentional capture technique that yielded the first direct evidence for bottom–up influence in standard conjunction search. In his experiment, displays were generated as in the standard conjunction search paradigm, but each display also contained a single item that was distinct along some irrelevant feature dimension. For example, in a search for a conjunction of color and orientation, one item might have had a different size than all of the other display items. Responses were quicker when the target was the singleton than when a distractor was the singleton, suggesting that conjunction search can benefit from bottom–up salience. In light of Proulx's arguments, we were emboldened to extrapolate the results from distractor ratio conjunction searches in order to develop a hypothesis about standard conjunction search. In standard conjunction search there are no group size differences to drive bottom–up advantages for any items, but perhaps one *feature* enjoys a bottom–up advantage. In models of visual search (Cave et al., 2005; Wolfe, 2007) each item's bottom–up activation consists of the weighted sum of activations across all feature channels. That is, each item receives bottom–up activation in the color channel based on the difference between that item's color and other items' colors, then the color channel activation is weighted before being combined with the output from all other feature channels. If the color channel's weight exceeds other channels' weight, bottom–up processing would tend to confer an advantage to color over other features, which would then encourage top–down mechanisms to search through target-color items rather than target-orientation items. Here we sought to test the hypothesis that in standard conjunction search bottom–up processing selects a feature and top–down selects a particular value of that feature, with a task that was as similar as possible to a standard conjunction search.

4. The effect of a preview

Previous studies that had sought to reveal the roles of top–down and bottom–up processing in standard conjunction search have used displays that diverged somewhat from standard conjunction search displays, either by varying the size of each distractor set (e.g., Egeth, Virzi, & Garbart, 1984; Sobel & Cave, 2002; Zohary & Hochstein, 1989) or by inserting feature singletons in the search displays (e.g., Friedman-Hill & Wolfe, 1995; Lamy & Tsal, 1999; Proulx, 2007). In order to investigate the roles of top–down and bottom–up processing in an *intact* standard conjunction search, we used a feature preview technique developed by Olds and Fockler (2004). In their experiments, visual search displays were preceded by previews of one of the features (either color or orientation) of the items in the subsequently appearing search array. For example, in the color preview condition, a set of colored squares appeared, then after 1 s the flanks of each square disappeared, leaving a central rectangular section visible. Does the feature preview enable search to proceed more efficiently than without a preview? The results in Olds and Fockler were surprisingly equivocal. In one experiment the color preview had no effect on response times but in a second experiment the color preview speeded search, whereas the orientation preview actually *slowed* search in one experiment and had no effect on response times in a second experiment. To explain the results from Olds and Fockler, it may be worthwhile to consider a different kind of preview paradigm that has been studied more extensively; to distinguish it from the *feature* preview paradigm in Olds and Fockler, we will refer to it as an *item* preview.

In the item preview paradigm, half of the items in a conjunction search display appear, then after a brief delay the remaining display items (including the target) appear. Response time results suggest that subjects are able to completely ignore the previewed items and search exclusively through the newly appearing items. Three different kinds of mechanisms have been advanced as explanations of the item preview effect (Watson & Inglis, 2007). Perhaps a top–down, limited capacity mechanism visually marks the previewed items as non-targets (e.g., Watson & Humphreys, 1997). On the other hand, items may be grouped together in terms of the time of their appearance (e.g., Jiang, Chun, & Marks, 2002). Finally, the newly appearing items create luminance onsets that may afford them a bottom–up advantage over the continuously visible previewed items (e.g., Donk & Theeuwes, 2003). For our purposes it is important to realize that both the visual marking and the temporal synchrony accounts are presumed to be top–down processes and the luminance onset account is presumed to be a bottom–up process (Pratt, Theeuwes, & Donk, 2007). How might these three accounts of item preview be extended to feature preview?

Olds and Fockler (2004) argued that any benefit of a feature preview in their experiments was driven primarily by bottom–up factors. On the contrary, we argue that any benefit from a feature preview is due to a mechanism akin to visual marking, and thus is driven primarily by top–down processing. The temporal synchrony and the luminance onset accounts cannot be readily extended to describe the mechanism underlying feature preview, because (1) for item previews there are two temporally asynchronous groups of items, but in feature preview all preview items change to a search item at the same time, and (2) in item preview half of the items enjoy a luminance onset because they appeared after the previewed items had already been visible, but in feature preview there is no such luminance differential. Where the temporal asynchrony and the luminance onset accounts fail, a kind of visual marking can profitably be used to describe the mechanism underlying feature preview. Subjects can use information from the preview to speed search, but only if they have maintained access to that information. If feature preview can speed search, then why did Olds and Fockler find that color preview speeded search but orientation preview actually slowed search?

To answer this question we will draw on our hypothesis about standard conjunction search as noted above: in standard conjunction searches bottom–up processing selects an overall feature (e.g., color over orientation), and top–down processing selects a particular feature (e.g., target-color over non-target-color). Perhaps in Olds and Fockler's displays color had a bottom–up advantage over orientation, either because the target-distractor color differences were more salient than the target-distractor orientation differences, or the subjects' color channel weight was greater than the orientation channel weight. In any event, we believe that color had an advantage over orientation, so in the control condition search proceeded naturally through the target-color group without needing any prompting to do so. If subjects were provided with the locations of the target-color items beforehand (as in the color preview condition), they could get a head start on their search through the target-color group. When subjects were encouraged to search through the target-orientation group (as in the orientation preview condition), they would have been less efficient than if they could have just selected the target's feature that had a bottom–up advantage.

In summary, our hypotheses are as follows: in standard conjunction search bottom–up mechanisms select the more salient of two features and top–down mechanisms select the items that share that feature with the target. The feature preview developed by Olds and Fockler (2004) empowers the experimenter to manipulate the top–down setting in their subjects' minds. If the results from bottom–up processing are congruent with the top–down preference (e.g., color differences are more salient than orientation differences, together with a top–down preference for target-color items), then search will be faster than the control condition. On the other hand, if the output from bottom–up and top–down processing are incongruent (e.g., color differences are more salient, but top–down selects target-orientation items) attentional capture may reduce the preview benefit and even slow search relative to the control condition. We should acknowledge that while the search tasks we used were intact versions of standard conjunction search, the preview changed the subjects' top–down settings from what they would have been without a preview. Thus, our search task is not identical to standard conjunction search, but is as close as we felt we could get. In Experiment 1 we replicated the feature preview experiment from Olds and Fockler.

5. Experiment 1: standard conjunction search with feature preview

5.1. Method

5.1.1. Subjects

Ten undergraduate students participated for course credit. All reported having normal color vision.

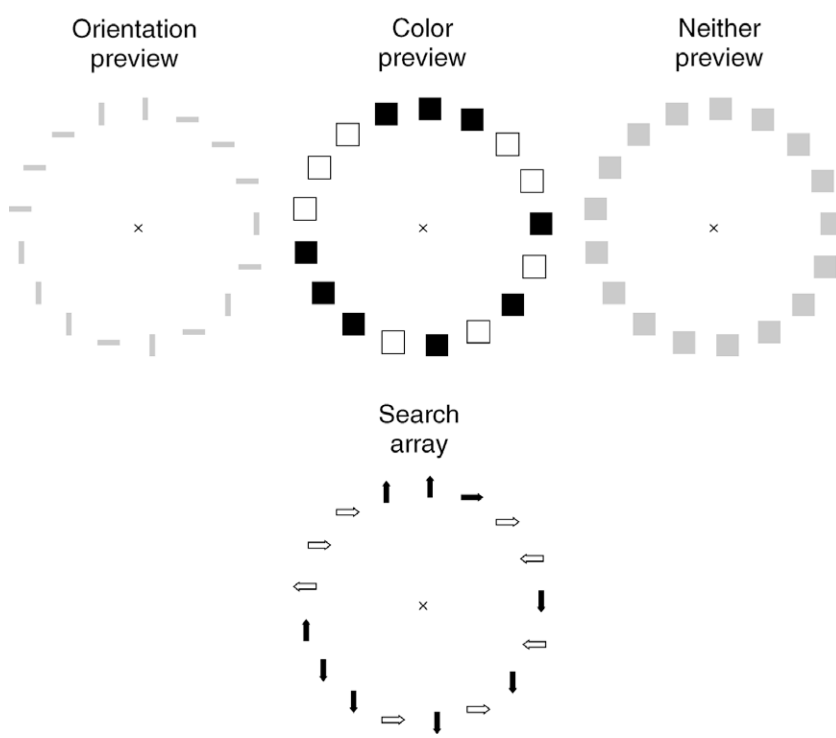

Fig. 1. Examples of preview and search displays for Experiments 1, 4 and 5 (in Experiment 2 there was no preview, and in Experiment 3 display items were arranged on a square grid). Red items are represented by filled shapes and green items are represented by open shapes. Each trial began with the presentation of one of the preview displays that remained visible for 1 s, after which it was replaced by the search display.

5.1.2. Apparatus

A program written in the RealBasic language and running on a Macintosh G4 computer presented search arrays and gathered responses.

5.1.3. Stimuli and procedure

Subjects viewed the computer screen from a distance of about 59 cm. A centered fixation cross (0.37° × 0.37°) was visible throughout the experiment. Search arrays consisted of a target (present on every trial) among varying numbers (4, 8, 12, 16 or 20) of distractors arranged on an imaginary, centered circle with a radius of 9.14°. The target was a red (Commission Internationale de L'Eclairage [CIE] *x*/*y* coordinates of .61/.33, with a luminance of 16 cd/m^2) horizontal arrow, 0.85° long × 0.26° wide, pointing either left or right. Half of the distractors were green (.28/.57, 16 cd/m^2) horizontal arrows and half were red vertical arrows, presented against a black background. The heading of each distractor arrow was determined randomly. The experimental program began by presenting a series of screens containing instructions and buttons labeled 'Previous' and 'Next'; subjects proceeded at their own pace, then the actual experiment began after the final instruction screen disappeared. In each trial a preview array appeared and remained visible for 1 s, then each item in the preview display was replaced by an item in the search display; for all experiments, the search display contained the same number of items as the preview display. Each item in the color preview was a red or a green square; each item in the orientation preview was a horizontal or a vertical gray (.29/.30, 16 cd/m^2) rectangle; each item in the neither preview was a gray square. An example of each of the three types of preview array (color, orientation, and neither) is depicted in Fig. 1, along with an example of the corresponding search array. After onset of the search array, subjects indicated the target's heading by pressing the right or the left arrow key as quickly and accurately as possible. Following response, the search array was erased for 1 s, leaving only the fixation cross (and the word 'Incorrect' on error trials).

There were five levels of display size (4, 8, 12, 16 or 20 distractors), three preview types (color, orientation or neither), two levels of target heading (pointing left or right), and four quadrants in which the target appeared (upper left, upper right, lower left, lower right). Every level of these variables (all manipulated within-subjects) was replicated three times, but because target heading and target quadrant were considered to be nuisance variables, there were effectively 24 (=3 replications × 2 target headings × 4 quadrants) replications of every level of display size and preview type, for a total of 360 (=24 replications × 5 display sizes × 3 preview types) trials. After every 72 trials, a screen appeared and indicated that 20% of the trials had just been completed and allowed a short break. The first three trials in the experiment and the first three trials following breaks were not analyzed.

5.2. Results and discussion

Fig. 2 depicts response times as a function of display size in all three preview conditions. A 2-way ANOVA indicated that the main effects of display size and preview type were significant. Response times increased with display size, $F(4, 36) = 61.9$, $p < .01$, and differed across the preview conditions, $F(2, 18) = 17.1$, $p < .01$, but the interaction was not significant, $F(8, 72) = 1.27$, $p = 0.28$. Planned pairwise comparisons showed that search was faster when subjects were shown a color preview than when previewing neither feature, $F(1, 9) = 6.32$, $p < .05$, but the color preview was not faster than the orientation preview, $F(1, 9) = 3.58$, $p = 0.07$, and the orientation preview condition was not faster than the neither preview condition, $F(1, 9) = 0.39$, $p = 0.54$.

We have argued that in standard conjunction search bottom–up processing selects the most salient feature (e.g., color) and top–down processing selects a particular feature value (e.g., target-color), so that standard conjunction search does not proceed through the entire display, but a feature-defined subset. Therefore, the difference between the color preview and neither preview conditions is *not* that search is restricted to a subset of items in the color preview and to the entire display in the neither preview condition. Instead, we believe that the color preview enables subjects to get a head start on preattentive processing, which is presumed to operate in parallel across the entire visual field (e.g., Treisman & Gelade, 1980). Thus, in standard conjunction search preattentive processing loads the color and orientation values into the appropriate feature maps, but in color preview the color map can be preattentively loaded before the search display appears. The fact that search was faster for the color preview than for the neither preview, together with the lack of an interaction supports this account of the benefit of a feature preview.

Although the color preview speeded search, the orientation preview did not. One explanation for these results is that for the color preview top–down and bottom–up processing work together, but for the orientation preview top–down and bottom–up processing are antagonistic to each other. An alternative explanation is that grouping by color is easier than grouping by orientation. One way to distinguish between these alternatives is to boost the strength of bottom–up activation. If there is a conflict between top–down and bottom–up processing in the orientation preview condition but not in the color preview condition, then boosting bottom–up activations should aggravate this conflict and thereby the difference between conditions. If instead our results are attributable to a top–down grouping advantage for color over orientation, then stronger bottom–up activations should have little effect on the difference between conditions.

We thought that packing items more densely in the search array should boost bottom–up activations. In models of visual search (Cave et al., 2005; Wolfe, 2007) bottom–up signals are scaled by distance so that nearby items contribute more activation than distant items. This constraint was included in the models in order to simulate the results from empirical studies showing that visual search is sensitive to local contrast. For example, Todd and Kramer (1994) found that the slope of response time as a function of display size was shallower when the target had a unique feature than when one of the distractors had the unique feature, and hypothesized that the salience of the unique feature increased along with

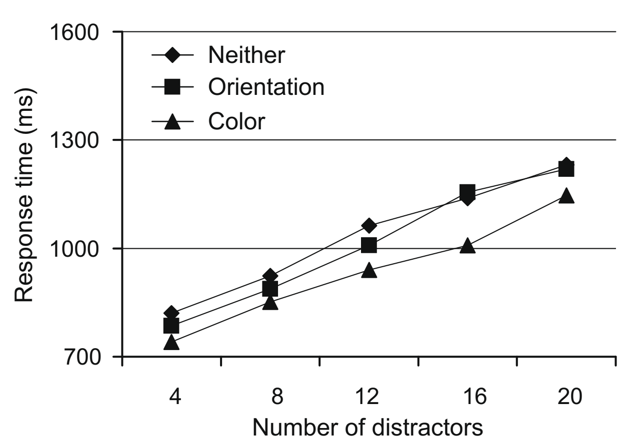

Fig. 2. Response times plotted as a function of the number of distractors across three preview conditions (neither, orientation, and color preview) from Experiment 1. Because a target was present on every trial, the display size equals the number of distractors plus one.

the number of neighbors. To verify this hypothesis they showed subjects an array of letters in which one was uniquely colored. When participants later named the letters that had appeared in the display, the uniquely colored letter was likelier to be named first when it was embedded in a large display than in a small display. In Bravo and Nakayama (1992) subjects searched for a uniquely colored target for which the color varied unpredictably across trials, so only bottom–up processing could locate the target. Response times decreased with increases in display density. Although both of these studies suggest that the proximity of neighbors boosts bottom–up salience, other researchers (Bacon & Egeth, 1991; Folk & Annett, 1994) have argued instead that display density promotes top–down grouping processes. In this context, we were motivated to develop a dense display that could be demonstrated to selectively boost the efficiency of bottom–up processing without affecting top–down processing.

6. Experiment 2: item density selectively boosts bottom–up processing

6.1. Method

Experiment 2 was identical to Experiment 1, with the following exceptions.

6.1.1. Subjects

Eighteen undergraduate students participated for course credit. None had participated in Experiment 1. The mean response time for one of the subjects was greater than the mean plus two and a half standard deviations of all the other subjects' response times, so this subject's data were removed and only the data from the remaining 17 subjects were analyzed.

6.1.2. Stimuli and procedure

Search arrays consisted of a target (present on every trial) among 15 non-target distractors arranged either on a circle as in Experiment 1, or in a square grid that was 6.72° wide × 6.72° tall. The target was an 'odd-one-out': it was the one item that had either a unique color or a unique orientation. If the target had a unique color it was either a red item among green items or a green among reds; if the target had a unique orientation it was either tilted 45° clockwise (CW) from vertical among items tilted 45° counterclockwise (CCW), or was CCW among CWs. When the target had a unique color, half of the items were randomly selected to be CW and half to be CCW, and vice versa when the target had a unique orientation. After onset of the search array, subjects indicated the target's tilt by pressing the right arrow key to indicate a CW target or the left arrow key to indicate a CCW target as quickly and accurately as possible.

The unique target feature was either the same for every trial in a block or randomized; every subject ran through three blocks of trials (unique color, unique orientation, and randomized) and the block order was counterbalanced across subjects. In the randomized block there were four levels of display features (red among greens, green among reds, CW among CCWs, and CCW among CWs), two display configurations (circular or square), and four quadrants in which the target appeared. Every level of these variables (all manipulated within-subjects) was replicated six times for a total of 192 trials in the randomized block. In the uniform blocks there were two levels of target feature (red among greens, green among reds in the unique color block; CW among CCWs, CCW among CWs in the unique orientation block), two display configurations and four target quadrants replicated six times for a total of 96 trials in each of the uniform blocks, for a total of 384 (=192 + 96 + 96) trials. After 192 trials, a screen appeared and indicated that half of the trials had been completed and allowed a short break.

6.2. Results and discussion

Fig. 3 depicts response times as a function of the display configuration and the type of processing available: top–down and bottom–up processing could be used in blocked trials, but in randomized trials only bottom–up processing could locate the target. A 2-way ANOVA indicated that both main effects were significant. Response times were faster for the square display than for the circular display, $F(1, 16) = 14.6$, $p < .01$, and were faster in blocked trials than in randomized trials, $F(1, 16) = 4.87$, $p < .05$. The interaction was not significant, $F(1, 16) = .055$, $p = .818$.

Search was more efficient when items were packed densely into the search array, but this effect was no stronger when subjects could use both top–down and bottom–up processing than when only bottom–up processing could be used. Having convinced ourselves that our square displays *selectively* boost the efficiency of bottom–up without affecting top–down processing, in Experiment 3 we used these square displays to determine whether the results from Experiment 1 were attributable to a conflict between top–down and bottom-processing in the orientation preview condition, or instead to top–down grouping by color being easier than grouping by orientation.

7. Experiment 3: preview search with dense arrays

7.1. Method

Experiment 3 was identical to Experiment 1, with the following exceptions.

7.1.1. Subjects

Ten undergraduate students participated for course credit. None had participated in either of the previous experiments.

7.1.2. Stimuli and procedure

Items were arranged in a square grid with the same density as in Experiment 2, but in order to accommodate as many as 21 items the grid included 25 locations arranged as a 5 × 5 grid.

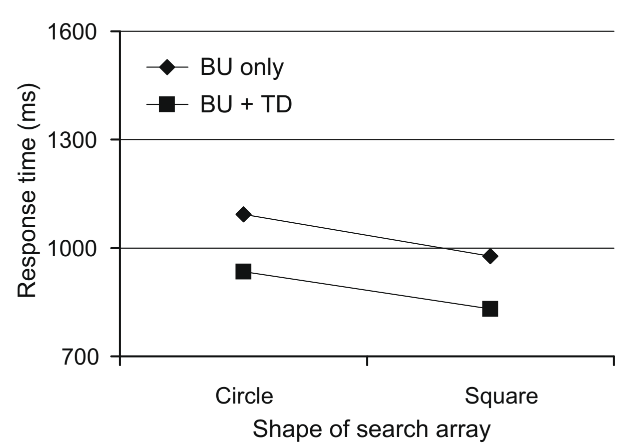

Fig. 3. Response times from trials using circular and square arrays in Experiment 2. The target was unique either by its color or by its orientation. The unique target feature was either the same across all trials in a block or was randomized; in blocked trials subjects could use both top–down and bottom–up processing to locate the target, but in randomized trials subjects could only use bottom–up processing.

7.2. Results and discussion

Fig. 4 depicts response times as a function of display size in all three preview conditions. A 2-way ANOVA indicated that the main effects of display size and preview type were significant. Response times increased with display size, $F(4, 36) = 20.3$, $p < .01$, and differed across the preview conditions, $F(2, 18) = 5.01$, $p < .05$, but the interaction was not significant, $F(8, 72) = 1.19$, $p = 0.32$. Planned pairwise comparisons showed that search was faster when subjects were shown a color preview than when previewing neither feature, $F(1, 18) = 10.6$, $p < .05$, and was faster for a color preview than for an orientation preview, $F(1, 18) = 15.4$, $p < .01$, but orientation preview was not significantly different from the neither preview condition, $F(1, 18) = 0.68$, $p = .43$.

Inspection of Fig. 4 suggests that not only is search slower for the orientation preview than for color preview, but also the difference between the two conditions inflates with display size. We carried out pairwise comparisons between the orientation preview and color preview at each level of display size, and found differences at the larger display sizes $F(1, 18) = 5.9$, $p < .05$ for 12 distractors, $F(1, 18) = 10.65$, $p < .05$ for 16 distractors, and $F(1, 18) = 45.3$, $p < .01$ for 20 distractors, but not at the smaller display sizes, $F(1, 18) = 0.92$, $p = 0.36$ for four distractors, and $F(1, 18) = 0.04$, $p = 0.85$ for eight distractors. In light of the fact that the contrasts between color and orientation preview increased with display size, we carried out the simple interaction contrast between color and orientation preview; the simple interaction contrast was significant, $F(1, 72) = 4.273$, $p < .05$. In the orientation preview condition, as item density increased with display size, the conflict between top–down and bottom–up processing grew increasingly more acute.

In Experiment 3, by packing the items more tightly in the display we expected that bottom–up salience would be amplified. If the results from Experiment 1 were due to a conflict between top–down and bottom–up processing with an orientation preview, search should be faster when top–down and bottom–up factors acted congruently to guide search toward the target-color group (color preview) than when top–down factors guided search toward the target-orientation group and bottom–up factors guided search toward the target-color group (orientation preview). Our expectations were confirmed; responses were faster when subjects were provided with a color preview than an orientation preview, whereas the difference between conditions was marginal in Experiment 1. The difference between these conditions was driven primarily by differences at larger display sizes, in which bottom–up activations were stronger than those at smaller display sizes, supporting our claim that top–down and bottom–up processing are antagonistic in the orientation preview condition.

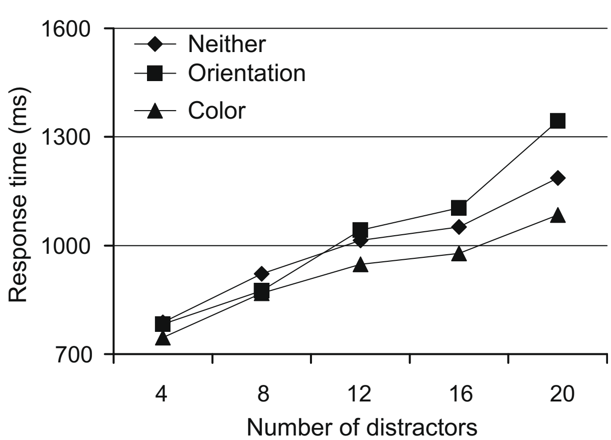

Fig. 4. Response times plotted as a function of the number of distractors across three preview conditions (neither, orientation, and color preview) from Experiment 3.

In our displays – and apparently also in the displays used by Olds and Fockler (2004) – the target-distractor color difference was more salient than the target-distractor orientation difference. Was color more salient than orientation merely because of the particular features that we chose, or do subjects confer a greater weight to the color channel than the orientation channel? To find out, in Experiment 4 we reduced the target-distractor color difference in an attempt to reverse the bottom–up advantage for target-color observed in Experiments 1 and 3.

8. Experiment 4: reduced color salience

8.1. Method

Experiment 4 was identical to Experiment 1, with the following exceptions.

8.1.1. Subjects

Ten undergraduate students participated for course credit. None had participated in either of the previous experiments.

8.1.2. Stimuli and procedure

Prior to carrying out the same visual search procedure as in Experiment 1, subjects first used a simple method of adjustment to determine an approximate value of their color difference threshold. In each trial for the method of adjustment, two color patches appeared for 500 ms, then after offset two buttons appeared on the computer screen, one labeled ‘Same’ and the other labeled ‘Different’. Subjects indicated whether the color patches had appeared to be the same or different by clicking the appropriate button with the computer mouse, after which the buttons disappeared and the next trial began with two more color patches. In the first trial the two color patches were the same colors as previous experiments. For each trial in which the subject clicked the ‘Different’ button, the RGB values of each color were moved equally far along the line connecting the points in color space to two new RGB values such that the new distance between colors was 0.18 log units less than the previous distance. The program proceeded through a series of trials until the first trial in which the subject clicked the ‘Same’ button, at which point the RGB distance was then returned to the value that it had had prior to eliciting the ‘Same’ response. The program then stepped through trials as before, but reducing distance by just 0.041 log units for each ‘Different’ response until the subject once again clicked ‘Same’. At this point the subject was finished with the method of adjustment and moved on to a visual search with preview task as in Experiment 1, using color values that had last elicited a ‘Different’ response.

8.2. Results and discussion

Fig. 5 depicts response times as a function of display size in all three preview conditions. A 2-way ANOVA indicated that only the main effect of display size was significant. Response times increased with display size, $F(4, 36) = 50.3$, $p < .01$, but the main effect of preview, $F(2, 18) = 2.65$, $p = 0.098$, and the interaction, $F(8, 72) = 0.37$, $p = 0.94$, were not significant.

In Experiment 4 the target-distractor color difference was reduced nearly to threshold as a way to make the target-distractor orientation difference more salient than the target-distractor color difference. Surprisingly, search was no faster when subjects were given an orientation preview than when given a color preview. Perhaps, then, the bottom–up advantage for the target-color group

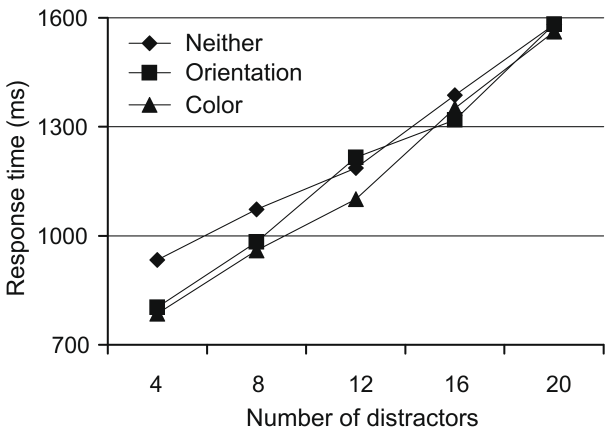

Fig. 5. Response times plotted as a function of the number of distractors across three preview conditions (neither, orientation, and color preview) from Experiment 4.

that was evident in Experiments 1 and 3 was not due to the fact that color just happened to be more salient than orientation in those particular displays, but may instead indicate that subjects have a bias for the color channel. Alternatively, maybe subjects are unable to use the orientation preview to increase top–down activation for orientation, so in Experiment 5 we sought evidence that subjects can use an orientation preview to guide their search to target-orientation items.

To do so, in Experiment 5 we combined the method of adjustment from Experiment 4 with a distractor ratio manipulation; display size was held constant but in some trials the target-color group predominated, in some the target-orientation group predominated, and in some trials the two groups were equally sized. In conjunction search experiments that manipulate distractor ratio like this, response times are typically plotted as a function of the size of one of the distractor types, as in the hypothetical plots of response time in Fig. 6. An inverted-U pattern of response times as in the left panel of Fig. 6 indicates that search proceeds through either the target-color group or the target-orientation group, whichever happens to be smaller. However, some experimenters have instilled a top–down preference for one of the target's features in their subjects. For example, in Bacon and Egeth (1997), for some subjects target-orientation items predominated across trials so restricting search to the target-color items was generally the most efficient strategy, whereas for other subjects target-color items predominated across trials so restricting search to the target-orientation was generally the most efficient strategy. Subjects tended to search through the less predominant feature, as in the middle and right panels in Fig. 6 (see also Kaptein, Theeuwes, & van der Heijden, 1995; Sobel, Gerrie, Poole, & Kane, 2007). As we have argued, a feature preview instills a top–down preference for the previewed target feature, so we expect when given a color preview response times should increase along with the number of target-color items as in the middle panel of Fig. 6, and when given an orientation preview response times should increase along with the number of target-orientation items as in the right panel of Fig. 6.

9. Experiment 5: manipulating distractor ratios

9.1. Method

Experiment 5 was identical to Experiment 4, with the following exceptions.

9.1.1. Subjects

Ten undergraduate students participated for course credit. None had participated in any of the previous experiments.

9.1.2. Stimuli and procedure

Subjects began with the same simple method of adjustment as in Experiment 4, but search arrays for the subsequent visual search task were generated differently than in any of the previous experiments. Display sizes were held constant across trials and contained one target along with 2, 5, 8, 11, or 14 red vertical distractors and 14, 11, 8, 5, or 2 green horizontal distractors.

9.2. Results and discussion

Fig. 7 depicts response times as a function of distractor ratio in all three preview conditions. A 2-way ANOVA indicated that both main effects and the interaction were significant. Response times varied across distractor ratios, $F(4, 36) = 11.3$, $p < .01$, responses were faster when subjects were given a feature preview than when they previewed neither feature, $F(2, 18) = 15.1$, $p < .01$, and the slopes of the distractor ratio functions varied across preview conditions, $F(8, 72) = 4.1$, $p < .01$. Planned contrasts intended to reveal the presence of quadratic trends indicated that there was a quadratic trend in all three conditions: for color preview $F(1, 36) = 47.8$, $p < .01$, for orientation preview $F(1, 36) = 23.2$, $p < .01$, and for neither preview $F(1, 36) = 8.1$, $p < .05$. The linear trend was significant only for the orientation preview condition, $F(1, 36) = 26.2$, $p < .01$, but not for color preview, $F(1, 36) = 2.73$, $p = 0.12$, or neither preview, $F(1, 36) = 1.58$, $p = 0.22$. Planned simple two-way interaction contrasts were carried out to compare the linear trends across the color preview and orientation preview conditions. The linear trend in the orientation preview condition

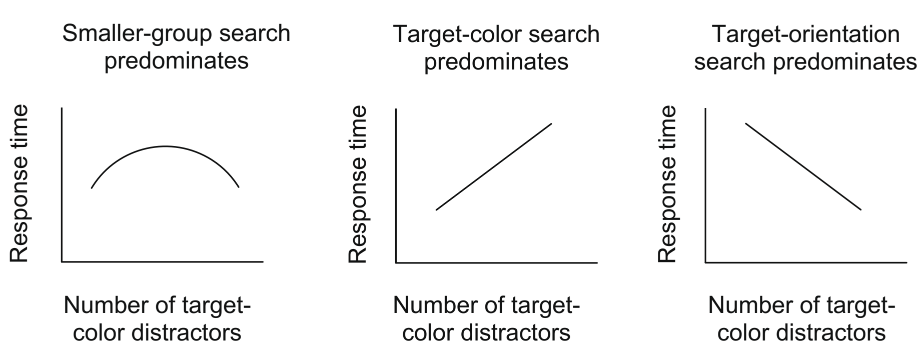

Fig. 6. Hypothetical response time curves resulting from visual searches in which display size is held constant but the relative contribution of two types of distractor is varied. An inverted-U pattern indicates search through the smaller group; monotonically increasing response times as a function of target-color items indicate target-color search; monotonically decreasing response times as a function of target-color items indicate target-orientation search.

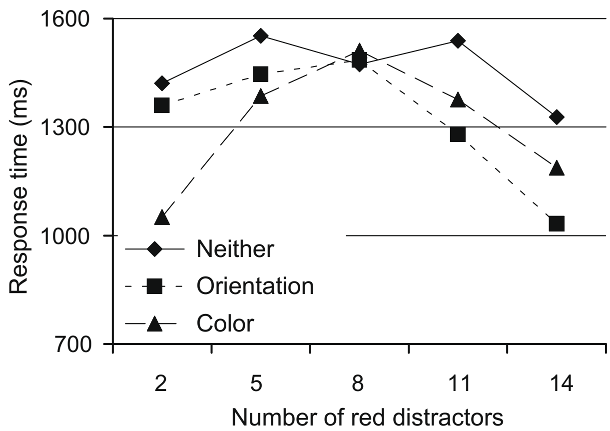

Fig. 7. In Experiment 5 the display size remained constant (16 distractors and one target in every display) but the number of each distractor type varied, so response times are plotted as a function of the number of red distractors across three preview conditions (neither, orientation, and color preview).

tended to increase in the opposite direction as in the color preview condition, $F(1, 72) = 20.3$, $p < .01$.

The presence of quadratic trends in all three conditions suggests that subjects searched through either the target-color group or the target-orientation group, whichever happened to be smaller in a given trial. When subjects were given an orientation preview, response times increased along with the number of target-orientation items, indicating target-orientation search blended with smaller-group search. These results nicely parallel those from Bacon and Egeth (1997). In Experiment 4 color differences were drastically reduced, but search was no faster in the orientation preview condition than in the neither preview condition, and we entertained the hypothesis that subjects are simply unable to use an orientation preview to increase their top–down activation for orientation. The results from Experiment 5 show that this hypothesis is untenable and so we are compelled to believe that in standard conjunction search there may be an inherent bottom–up bias for color over orientation.

10. General discussion

Models of visual search (Cave et al., 2005; Wolfe, 2007) suggest that search for a conjunction of features is driven primarily by top–down processing, and that bottom–up processing is essentially a hindrance. In contrast, recent conjunction search experiments that have altered the standard conjunction search procedure, either by varying the distractor ratio (e.g., Sobel & Cave, 2002) or by inserting singletons into displays (e.g., Proulx, 2007) have shown that search for a conjunction can benefit more from bottom–up processing than had previously been believed. Here we sought to extend these findings to an intact version of conjunction search; i.e., displays with equal distractor set sizes, and without any singletons. We hypothesized that in standard conjunction searches, bottom–up processing selects the most salient feature channel, and top–down processing selects the target feature from the channel with the bottom–up advantage.

For Experiment 1 color preview speeded search but orientation preview did not This effect may have been the result of a conflict between top–down and bottom–up processing in the orientation preview, or because grouping by color is easier than grouping by orientation. To distinguish between these alternatives, we needed a task that could manipulate bottom–up processing without affecting top–down processing. The results from Experiment 2 showed that our denser search arrays did just that, so in Experiment 3 the items were arranged in square grids. Amplifying bottom–up signals enhanced the effect from Experiment 1, implying that the orientation preview induces a top–down preference that is incongruent with a pre-existing bottom–up advantage for color. In Experiment 4 target-distractor color differences were reduced nearly to threshold to see if the color advantage occurred because the color differences were more salient than orientation differences, or because bottom–up mechanisms confer a higher weight to the color channel than to the orientation channel. The reduction in color salience failed to reverse the preference for color, suggesting either that the color channel enjoys an advantage over the orientation channel, or that subjects were unable to benefit from the orientation preview. In Experiment 5 orientation preview influenced distractor ratio search in an opposite direction as a color preview, lending support to the argument that the color channel may enjoy an intrinsic advantage over the orientation channel.

11. Visual search and working memory

Recent work has shown that working memory capacity (WMC) correlates well with performance on other tasks that require the controlled deployment of attention. For example, people with higher WMC are better able to avoid Stroop interference (e.g., Kane & Engle, 2003) and to ignore conspicuous words spoken in the unattended channel during dichotic listening (Conway, Cowan, & Bunting, 2001) than are people with lower WMC. Because models of visual search (Cave et al., 2005; Wolfe, 1994, 2007) had long predicted that standard conjunction search is guided primarily by top–down factors and that bottom–up processing serves mainly to guide attention away from the target, the efficiency of conjunction search seemed likely to correlate with WMC as well. In this context, Kane, Poole, Tuholski, and Engle (2006) designed a standard conjunction search experiment to test the correlation between individual differences in WMC and visual search efficiency, but were surprised to find that WMC was unrelated to search efficiency. Because we have shown here that bottom–up processing plays a more central role in standard conjunction search than had previously been believed, Kane et al.'s failure to find a correlation with WMC is less surprising than it had initially appeared.

12. What about other features?

We developed our hypotheses about standard conjunction search in general terms, expecting that bottom–up processing would select the more salient feature, and that while there might be a modest bias for one feature, this bias could be overcome if the disadvantaged feature could be made relatively more salient. Indeed, in distractor ratio search, color often enjoys a modest advantage over orientation, particularly in target-absent trials (e.g., Poisson & Wilkinson, 1992; Zohary & Hochstein, 1989), but the color bias can be reversed and orientation enjoys an advantage when target-distractor color differences are reduced (Sobel & Cave, 2002). Nevertheless, here we were compelled to conclude that the bottom–up bias for color in standard conjunction search was too great for us to overcome by reducing the salience of color. What about a search for a conjunction of other features? In a search for a conjunction of orientation and a non-color feature, would both kinds of preview speed search equally? If not, could the bias be reversed by reducing the salience of the feature that elicited the stronger preview effect? We look forward to trying to answer these questions. In so doing we will be able to inform builders of models of visual search how to assign weights to different feature channels.

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