

Visual search near threshold: Some features are more equal than others

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While searching for objects, we combine information from multiple visual modalities. Classical theories of visual search assume that features are processed independently prior to an integration stage. Based on this, one would predict that features that are equally discriminable in single feature search should remain so in conjunction search. We test this hypothesis by examining whether search accuracy in feature search predicts accuracy in conjunction search. Subjects searched for objects combining color and orientation or size; eye movements were recorded. Prior to the main experiment, we matched feature discriminability, making sure that in feature search, 70% of saccades were likely to go to the correct target stimulus. In contrast to this symmetric single feature discrimination performance, the conjunction search task showed an asymmetry in feature discrimination performance: In conjunction search, a similar percentage of saccades went to the correct color as in feature search but much less often to correct orientation or size. Therefore, accuracy in feature search is a good predictor of accuracy in conjunction search for color but not for size and orientation. We propose two explanations for the presence of such asymmetries in conjunction search: the use of conjunctively tuned channels and differential crowding effects for different features.

Keywords: conjunction search, feature search, color discrimination, orientation discrimination, size discrimination, crowding

Introduction

How do we combine input from visual modalities, such as color and orientation, when we search for information? Most current theories assume that individual visual features are first processed independently prior to some form of integration. This traditional idea finds support in earlier studies that suggested the existence of anatomically distinct pathways for color and orientation (Livingstone &

Hubel, 1984). Also, psychophysical evidence indicating that color is perceived before other features (Arnold, Clifford, & Wenderoth, 2001; Moutoussis & Zeki, 1997a, 1997b) is in line with the concept of independent feature processing.

However, other psychophysical findings do not support such a strict dissociation between single feature and conjunction search (Clifford, Spehar, Solomon, Martin, & Zaidi, 2003; Duncan & Humphreys, 1989; Eckstein, 1998; Findlay, 1997; Found, 1998; Nothdurft, 2000;

Pashler, 1987). In addition, color selectivity is suggested to be as frequent among orientation-selective neurons as it is among unoriented neurons (von der Heydt, Friedman, & Zhou, 2003). Recent physiological studies further indicate the presence of complex interactions between oriented and unoriented color cells of visual cortical areas V1 and V2 (Roe & Ts'o, 1999; Yoshioka & Dow, 1996). Altogether, these findings suggest an abundance of conjunctively tuned mechanisms in the visual cortex (Gegenfurtner, 2003).

Target selection in visual search is assumed to be mediated by saliency maps—integrated representations of bottom-up sensory information and top-down attentional modulation—that direct the gaze shifts to the most relevant locations (Treue, 2003). Although such saliency maps are generally modeled as independent, single feature maps, there is no reason why this should be so. Thus, visual mechanisms tuned to more than one feature could be used for conjunctively tuned saliency maps (Li, 2002).

The experiments discussed in this article were designed to further investigate the mechanisms underlying target selection in conjunction search. More specifically, we studied whether both features of a conjunction are processed symmetrically and contribute equally to target selection in visual search. Our hypothesis is that if features are processed fully symmetrically, then searching for a conjunction of two equally discriminable features should result in equal discrimination accuracy in conjunction search (although performance in conjunction search could be lower than in single feature search).

Classical theories such as Feature Integration Theory (Treisman, 1977; Treisman & Gelade, 1980; Treisman & Sato, 1990), Guided Search (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989; Wolfe & Gancarz, 1996), and Similarity Theory (Duncan & Humphreys, 1989) do not make specific predictions about possible interactions between features. Several findings have shown that when color is used in conjunction with other features, the visual system can use it more efficiently than other features (Luria & Strauss, 1975; Williams, 1966; Williams & Reingold, 2001), but other findings do not support such asymmetry in the processing of object features (Bichot & Schall, 1999; Treisman & Sato, 1990). Thus, despite decades of study and a very large knowledge base on visual search, we cannot be sure about what to expect.

An important point in our experimental design concerns the perceptual balancing of feature contrasts. The strength of perceptual segmentation can at least partly be explained by simple discriminability (Enns, 1986). Therefore, if discriminability of single features has not been matched, it is impossible to distinguish between biases resulting from saliency differences and those resulting from other effects. To the best of our knowledge, the balancing of features based on their discriminability has not been used so far to assess the (in)dependence of feature processing (however, see Nothdurft, 2000, for a comparable approach in a study on independence of salience mechanisms).

We conducted three experiments to investigate the presence of interactions between features in conjunction search. Search performance was measured in terms of accuracy and latency of the initial saccade. There is reason to believe that the initial saccade describes the allocation of visual attention (Beutter, Eckstein, & Stone, 2003; Deubel & Schneider, 1996). It is widely assumed that subjects fixate on one point of the display and use peripheral vision to decide which location would be the most relevant for the next fixation (Bloomfield, 1979; Williams, 1966). Decisions to sequentially foveate further areas of the display reflect the underlying attentional processing; initial saccade reflects which stimulus is assumed to be most likely the target at the beginning of the search where all stimuli are at equal distance from the fixation mark. In all cases and for each subject, we first measured target-distractor discrimination performance for each single feature used prior to the main experiment. On the basis of the resulting psychometric curves, we determined the feature contrast threshold necessary to obtain 70% correct responses. For all features, a single feature search task was then conducted using these contrasts. Subsequently, these same contrasts were used to assess performance for each feature in a conjunction search task. This procedure allowed us to compare search performance in single feature and conjunction search.

Experiment 1

Method

Subjects

Six subjects (three males, three females; age range, 18–23 years) participated in the experiment. All subjects had normal or corrected-to-normal vision.

Apparatus and stimuli

Stimuli were presented on a 20-in. CRT monitor and generated by a Power Macintosh computer. The software for experimental control was generated by Matlab (The MathWorks, Inc.), using the Psychophysics and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; see <http://psychtoolbox.org/>). The screen resolution was set to 1152 × 870 pixels with a refresh rate of 75 Hz. The background luminance of the screen was 25 cd/m². The luminance of the stimuli was 35 cd/m². The distance between the eyes and the screen was 40 cm.

The stimuli consisted of oriented bars in all experiments (Figure 1). The length of the stimuli was about 5.7 deg. Before the start of a trial, subjects were instructed to fixate on a central fixation mark and subsequently commenced the trial by pressing the space bar. Next, a cue representing the target color and orientation appeared at the center of the screen, disappearing after 500 ms. Subjects were

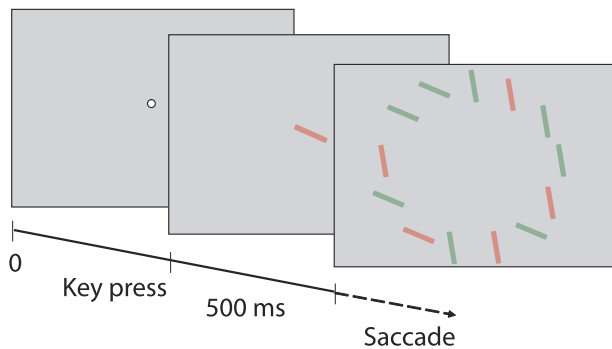


Figure 1. A schematic overview of the experimental paradigm of [Experiment 1](#). At 13 possible positions, objects were presented. One third of the distractors had the same color as the target, one third had the same orientation as the target, and one third had both a different color and orientation. In this example, the target is the red bar, rotated counterclockwise relative to 45 deg oblique. Distractors are green, counterclockwise-rotated bars; red bars rotated clockwise, and green bars rotated clockwise. (Note that for clarity, color contrasts and orientation differences have been exaggerated compared with the actual values used in the experiments.) Example is also linked as auxiliary [Movie 1](#).

asked to look at the target cue and to remember its characteristics. Thereafter, 13 equally spaced stimuli (1 target, 12 distractors) appeared along the circumference of a circle with a radius of around 17 deg and centered on the fixation mark. Subjects were instructed to make an eye movement to the target and to do this as fast and accurately as possible. In this first experiment, stimuli disappeared after a saccade was made and were replaced by small circles (<1 deg) at each of the locations of the stimuli. At the end of each trial, feedback about accuracy was given.

Eye movements were recorded at 250 Hz with an infrared video-based eyetracker (Eyelink I Gazetracker; SR Research Ltd., Osgoode, Canada). In further analysis, only trials in which subjects did not make any saccades while the cue was presented were included. Only the first saccade after target presentation was analyzed. An eye movement was considered as a saccade when the velocity of the eye was at least 25 deg/s with an acceleration of 9,500 deg/s² and a minimal amplitude of 1 deg. The experiments took place in a closed, dark room. Subjects rested their chin on a chin rest to prevent them from making head movements.

Single feature search for threshold determination

Prior to the main experiment, subjects performed single feature search with different target–distractor contrasts to determine individual thresholds for 70% discrimination for both color and orientation. Color contrasts (red/green) were created by increasing (decreasing) the luminance of the red (green) gun with a particular percentage (1.5%, 2.2%, 3.3%, 5.0%, 7.5%, 11%, 17%, 25%, 38%, or 45%)

and decreasing (increasing) the luminance of the green (red) gun with the same amount, such that total luminance stayed constant. Orientation contrasts were created by tilting the target—again, either positively or negatively—1.5, 2.2, 3.3, 5.0, 7.5, 11, 17, 25, 38, or 45 deg relative to a baseline orientation of 45 deg. Both tasks consisted of 260 trials (13 possible target positions \times 10 contrast levels \times 1 positive and 1 negative contrast). The threshold value was interpolated by fitting a cumulative Gaussian function to the data.

Main experiment: Single feature search task

After the 70% discrimination thresholds had been determined, each subject performed two blocks of a single feature search task both for color and orientation at this individual threshold level. One block consisted of 26 trials (13 possible target positions \times 1 positive and 1 negative contrast).

Main experiment: Conjunction search task

In the conjunction search condition, the 70% discrimination thresholds of both features were combined for a conjunction search task. Thus, the target could be either green or red and tilted clockwise or counterclockwise relative to baseline. Among the distractors, four had the same color as the target but different orientation, four had the same orientation but different color, and four had both different color and orientation. One block consisted of 52 trials (13 possible target positions \times 4 possible contrasts: 1 positive and 1 negative for color, 1 positive and 1 negative for orientation). Subjects started at random with either a feature or conjunction search task and then alternated between these blocks.

Analysis and statistics

Responses were classified into four categories:

1. Hit. The initial saccade was directed to the target.
2. Orientation correct. Initial saccade was directed to a distractor with correct orientation but different color.
3. Color correct. Initial saccade was directed to a distractor with correct color but different orientation.
4. Double error. Initial saccade was directed to a distractor with both different color and different orientation.

To eliminate potential reflexive eye movements, we filtered out all saccades initiated faster than 100 ms after stimulus presentation. For the analysis of search performance, we calculated the so-called feature hits. In single feature search tasks, we simply considered the hit responses. For conjunction search tasks, we distinguished between color hits (sum of hits and color correct) and orientation hits (sum of hits and orientation correct).

To determine if there were dependencies in conjunction search, we needed to verify two things. First, feature discrimination performance in single feature search should not differ for the two features. We used a paired Student's t test to check whether discriminability of single features was correctly balanced. Second, if the feature contrasts are correctly balanced, then independence of feature dictates that conjunction search feature performance should also be balanced. In other words, there should be no interaction between search type (single feature, conjunction) and feature (color, orientation). We used repeated measures analysis of variance to verify this. We also verified whether the finding was consistent with the result of a paired permutation test (Good, 2000). An alpha level of .05 was used for all statistical tests.

Besides examining the presence of discrimination asymmetries, we also wanted to directly compare absolute feature discrimination performance in single feature and conjunction search. This likely provides additional information about the mechanisms underlying feature processing in single feature and conjunction search, which is not immediately apparent from the raw data. To be able to do this, we first applied a correction to the raw data. The reason for this is that there is a discrepancy between the logged responses and the actual, underlying, target selection decision of the subjects. This discrepancy is not the same in single feature and conjunction search, making it hard to compare uncorrected results across tasks. There are two main sources for the discrepancy: different a priori guessing rates and a spatial bias in the error distribution. The first source is fairly obvious: Different distractor configurations in single feature and conjunction search result in different probabilities of correctly choosing a feature by mere chance. The spatial bias in the errors is less obvious, and we discovered its presence only after the experiments had been carried out. We found that in most experiments, many more errors resulted from selecting a distractor immediately neighboring the target than from selecting one at another location. This effect was especially apparent in single feature search and is, in hindsight, in line with previous findings (Findlay, 1997). Therefore, it appears that although subjects sometimes correctly noticed the presence of a feature discontinuity, they did not select the target but its immediate neighbor. We corrected for this by considering part of the error responses as correct responses, in such a way that the number of errors at immediately neighboring locations becomes the same as the mean number of errors at all other locations. For details about the correction procedure, we refer the reader to the Appendix.

To obtain better insight into the timing of the underlying processes, we also analyzed saccadic latencies. In this analysis, we only included trials in which either color

or orientation was correctly identified (in conjunction search, we thus excluded the hits).

Results

The descriptive statistics for this experiment are presented in the Table 1.

Feature discrimination performance

Figure 2 shows the percentages (mean and standard error) of correctly identified colors and orientations in feature and conjunction search. Figure 2A shows the uncorrected data, and Figure 2B shows the corrected data (for a description of the correction procedure, please consult the Appendix).

On the basis of the uncorrected data, we found that search type (single feature search task, conjunction search task) interacts with feature (color, orientation) discrimination performance, $F(1,5) = 23.96$, $p < .001$. This finding is supported by a paired permutation test. The performance difference between single feature and conjunction search is larger for orientation than for color, $p < .05$. Color and orientation discrimination accuracy in single feature search do not differ significantly, $t(5) = -2.22$, $p = .08$.

Analysis of the corrected data indicates that the average decrease in feature discrimination performance (difference

Response type	Proportion		Latency	
	M (%)	SD	M (ms)	SD
Single feature search				
Color search				
Hits	70.8	13.8	383	181
Errors	29.2	13.8	475	316
Orientation search				
Hits	74.6	13.2	417	192
Errors	25.4	13.2	553	338
Conjunction search				
Hits	46.9	19.5	679	316
Orientation correct	9.0	5.6	693	407
Color correct	39.4	16.0	691	428
Double errors	4.5	1.4	723	718

Table 1. Distribution and latencies of initial saccadic eye movements in Experiment 1. Note. $n = 6$. Hits, initial saccade to target; orientation correct, initial saccade to a distractor with correct orientation but wrong color; color correct, initial saccade to a distractor with correct color but wrong orientation; double error, initial saccade to a distractor with both wrong color and orientation.

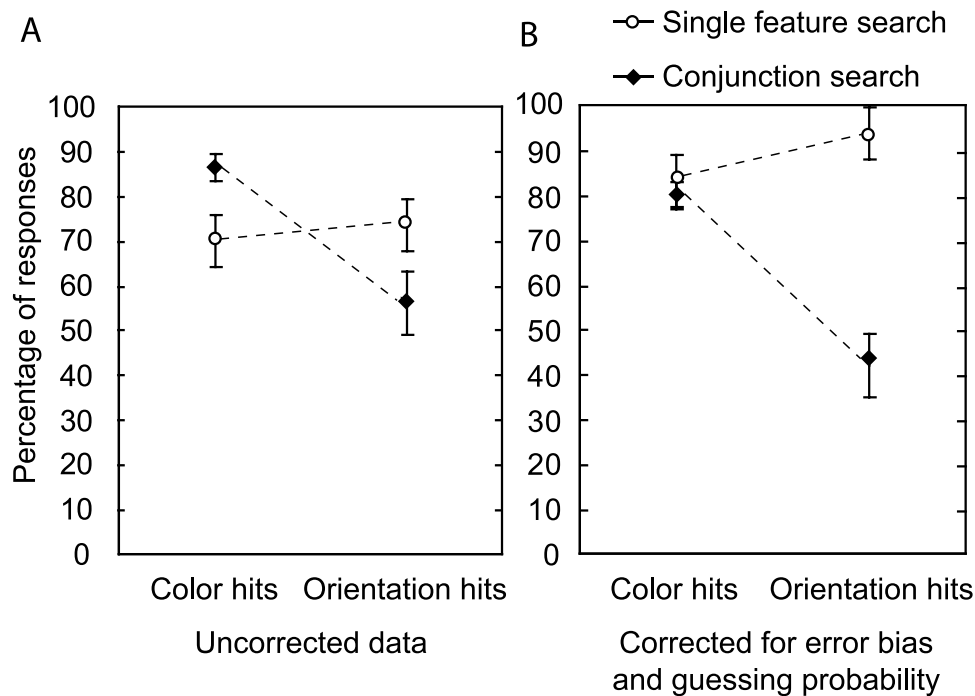


Figure 2. Mean response accuracy ($n = 6$) plotted as a function of the search task in [Experiment 1](#). Both percentages of uncorrected responses (A) and percentages of responses corrected for error bias and guessing probability (B) are presented. In conjunction search, the orientation discrimination accuracy decreased significantly compared with single feature search, whereas color discrimination accuracy remained approximately equal in both search tasks. Color hits, sum of hits and color correct; orientation hits, sum of hits and orientation correct. Bars show standard errors.

between single feature and conjunction search in absolute percentage) was 48% larger for orientation than for color (95% confidence interval: 17% to 80%). There was no significant difference between color discrimination performance in single feature and conjunction search, $t(5) = 0.60$, $p = .57$.

Saccadic latencies

In general, the shortest latencies appeared during correct performance in the single feature search task. Correct identification of color and orientation was significantly slower in conjunction search compared with single feature search ($p < .05$ for both features). In conjunction search, there is no significant difference between hit latencies of color and orientation discrimination.

Discussion

We find that feature contrasts that yield equal performance in single feature search result in a clear performance asymmetry in conjunction search. Due to the matched feature contrasts, accuracy of color and orientation discrimination performance in single feature search was approximately equal (uncorrected data). In conjunction search, color performance remained approximately at the

same level as in feature search, whereas orientation performance decreased substantially. In other words, feature contrasts that result in symmetric discrimination performance in single feature search did not result in symmetric performance in conjunction search. Therefore, relative search accuracy in terms of feature discrimination in single feature search appears to be a good predictor for accuracy in conjunction search for color but not for orientation.

Note that in the corrected data, it appears that the balance between color and orientation is no longer present. We do not see this as a problem. The slight imbalance is such that in single feature search, orientation performance has increased relative to color performance. If anything, this would only lead us to underestimate the size of the asymmetry that we find in conjunction search.

Importantly, the time needed to initiate a saccade to a stimulus with target color or target orientation in a conjunction search task was approximately equal. At first sight, this rules out a “speed–accuracy trade-off” explanation. However, comparing the latencies of color and orientation discrimination between single feature and conjunction search reveals significantly shorter latencies in both single feature search tasks. Therefore, a possible explanation of the asymmetry could be that the extra time in conjunction search is used more efficiently for color than for orientation discrimination (relative to the single feature

search). To investigate this, we conducted a second control experiment in which we limited inspection time.

Experiment 2

Method

Subjects

Four subjects (two males, two females) participated in the experiment; all of them had participated in Experiment 1.

Apparatus and stimuli

The experimental apparatus and stimuli were similar to those in Experiment 1. The only differences were that, now, the stimulus was presented for only a limited amount of time and was followed by a mask (consisting of a large number of randomly oriented bars on every stimulus location). Randomly, in one half of the trials, the stimuli were masked after 200 ms inspection time; in the other half of the trials, the stimuli were masked after 400 ms inspection time. The individually adjusted color contrast and orientation values of Experiment 1 were used for all subjects.

Tasks

Except for the stimulus time and masking, the tasks were identical to the single feature search and conjunction search tasks of Experiment 1. If subjects did not make a saccade toward a stimulus before the mask appeared, then they were asked to make a saccade to the location where they thought the target had been.

Analysis

The analysis was analogous to that of Experiment 1, except that we did not apply a permutation test. With four subjects, the number of possible permutations was too small to yield reliable results.

Results

The descriptive statistics are presented in Table 2.

Figure 3 shows the mean percentages of correctly identified colors and orientations in feature and conjunction search for both presentation times. Figures 3A and 3C show the uncorrected data, and Figures 3B and 3D show the corrected data. The analysis of the uncorrected performance data of the two inspection time conditions shows that the interaction between search type and feature was significant, $F(1,3) = 11.66$, $p < .05$. Feature discrimination performance of color and orientation in single feature search did not differ significantly, $t(3) = -1.70$,

Response type	Proportion		Latency	
	<i>M</i> (%)	<i>SD</i>	<i>M</i> (ms)	<i>SD</i>
Inspection time, 200 ms				
Single feature search				
Color search				
Hits	62.9	13.6	499	132
Errors	37.1	13.6	578	122
Orientation search				
Hits	74.7	9.4	480	109
Errors	25.4	9.4	591	134
Conjunction search				
Hits	36.6	15.3	605	104
Orientation correct	13.8	5.7	682	114
Color correct	41.1	16.0	676	182
Double errors	8.5	2.4	801	307
Inspection time, 400 ms				
Single feature search				
Color search				
Hits	76.0	16.1	546	125
Errors	24.0	16.1	593	135
Orientation search				
Hits	84.7	10.4	510	81
Errors	15.3	10.4	601	84
Conjunction search				
Hits	39.8	12.2	668	117
Orientation correct	8.4	3.5	802	119
Color correct	45.2	14.2	699	83
Double errors	6.7	1.9	831	216

Table 2. Distribution and latencies of initial saccadic eye movements in Experiment 2. Note. $n = 4$. Hits, initial saccade to target; orientation correct, initial saccade to a distractor with correct orientation but wrong color; color correct, initial saccade to a distractor with correct color but wrong orientation; double error, initial saccade to a distractor with both wrong color and orientation.

$p = .19$. There were no three-way interactions with inspection time.

On the basis of the corrected data, we found that orientation discrimination performance decreased 55% more than color performance in conjunction search (95% confidence interval: 0.4% to 110%). Color discrimination performance in single feature and conjunction search did not differ significantly, $t(3) = -0.19$, $p = .86$. Again, there were no three-way interactions with inspection time.

Discussion

Despite the fact that the subjects had only a short time to process the stimuli—200 or 400 ms, approximately the

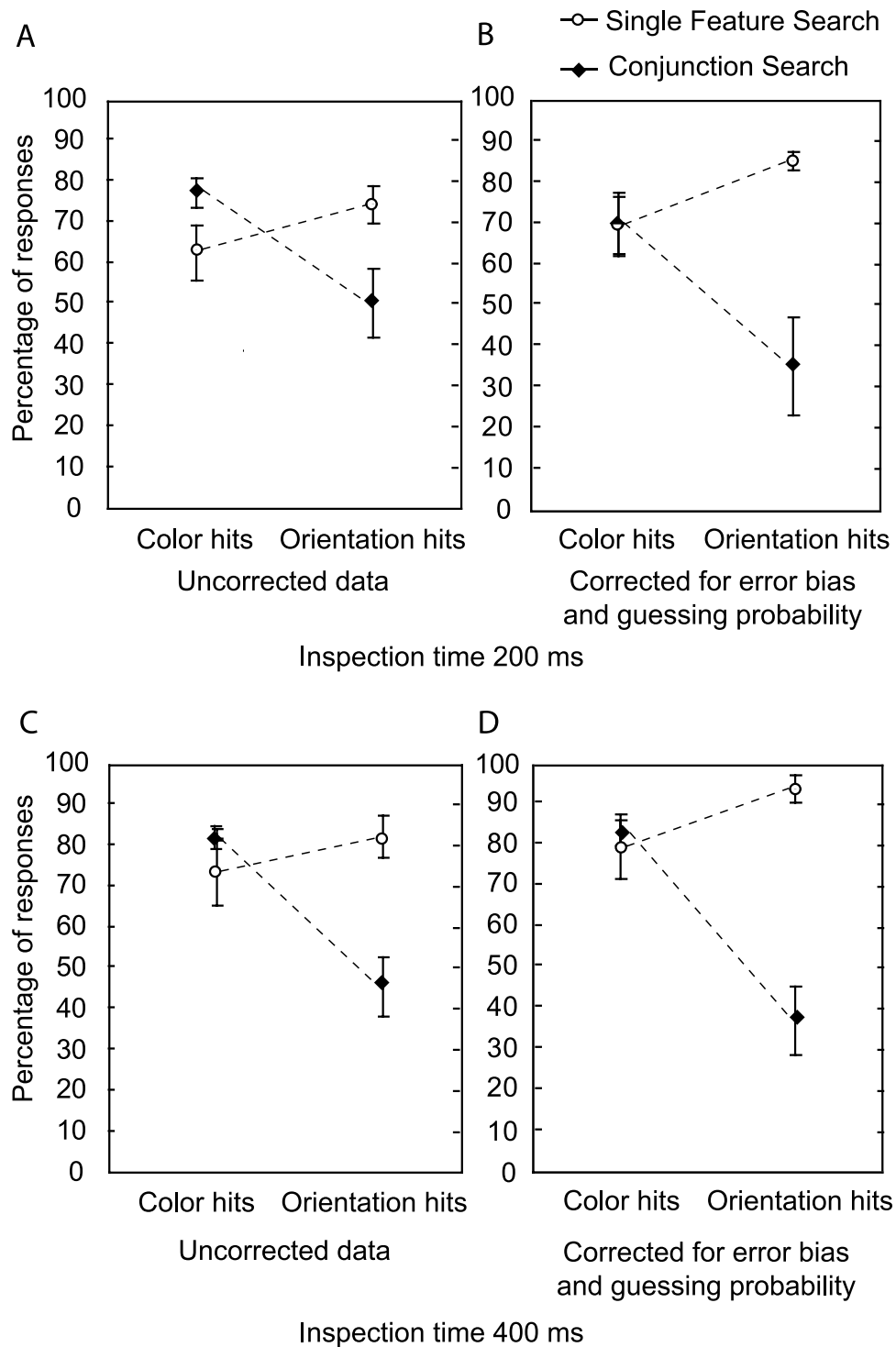


Figure 3. Mean response accuracy ($n = 4$) plotted as a function of the search task and inspection time in [Experiment 2](#). Panel A presents the uncorrected percentages of responses, and Panel B presents the percentages of responses corrected for error bias and guessing probability for an inspection time of 200 ms. Panel C presents the uncorrected percentages of responses, and Panel D presents the percentages of responses corrected for error bias and guessing probability for an inspection time of 400 ms. In general, in conjunction search, the orientation discrimination accuracy decreased compared with single feature search, whereas color discrimination accuracy was approximately equal in both search tasks. Color hits, sum of hits and color correct; orientation hits, sum of hits and orientation correct. Bars show standard errors.

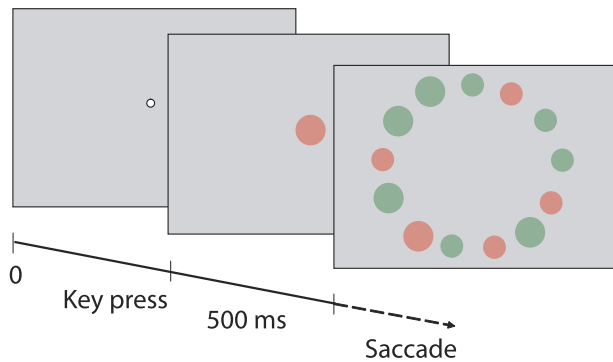


Figure 4. A schematic overview of the experimental paradigm of Experiment 3. At 13 possible positions objects were presented. One third of the distractors had the same color as the target, one third had the same size as the target, and one third had both a different color and size. In this example, the target is the large red disc. Distractors are large green discs, small red discs, and small green discs.

time needed to find a feature in a single feature search task—we were still able to find the feature discrimination asymmetry in conjunction search. Moreover, the effect size was of the same order of magnitude as what we found in the first experiment (although the 95% confidence interval of the effect size was larger, presumably due to the smaller number of subjects). In the next experiment, we wonder whether the feature discrimination asymmetry is present for the combination of color and another feature, namely, size, as well.

Experiment 3

Method

Subjects

Seven subjects (three males, four females; age range, 18–30 years) participated in this experiment. All subjects had normal or corrected-to-normal vision.

Apparatus and stimuli

The experimental apparatus was similar to the one used for the first two experiments, except for the fact that a different monitor and screen resolution were used (a 22-in. CRT monitor at a resolution of 2048×1536 pixels). The background luminance of the screen was approximately 7.5 cd/m^2 . The luminance of the stimuli was 10 cd/m^2 . The distance between the eyes and the screen was 50 cm.

The most important difference between this experiment and the previous one is that the stimuli were colored discs varying in size, instead of bars with an orientation. The base size of the discs was 2.4 deg.

The experimental procedure was the same as in the previous experiment. Subjects were presented with a central cue (500 ms), followed by 13 circularly arranged, equally spaced stimuli, of which 1 was the target (200 ms), followed in turn by a mask in which the stimuli were replaced by small position markers (<1 deg). Data were recorded when the subjects made an eye movement toward one of the small position markers (Figure 4). Eye movements were recorded at 250 Hz with an infrared video-based eyetracker (Eyelink II; SR Research Ltd.) and analyzed in the same manner as in the first two experiments.

Single feature search for threshold determination

Subjects performed single feature search tasks with different target–distractor contrasts to determine individual thresholds for 70% discrimination of color and size. Color contrasts were created in the same manner as in the first two experiments. Modulations of 0.7%, 1.0%, 1.3%, 1.8%, 2.5%, 3.3%, 4.5%, 6.0%, 8.1%, and 11% relative to base color were used (note that compared with the previous experiments, contrast levels are different due to the use of a different monitor). Size contrasts were created by modulating base size (defined by the radius) with 5.0%, 6.5%, 8.4%, 11%, 14%, 18%, 23%, 30%, 39%, and 51%.

Subjects performed 520 search trials (13 possible target positions \times 10 contrast levels \times 1 positive and 1 negative contrast \times 2 repetitions) for each feature, and the 70% discrimination thresholds were again determined by fitting a cumulative Gaussian to the results.

Response type	Proportion		Latency	
	<i>M</i> (%)	<i>SD</i>	<i>M</i> (ms)	<i>SD</i>
Single feature search				
Color search				
Hits	72.2	5.8	253	80
Errors	27.8	5.8	297	174
Size search				
Hits	75.7	12.1	256	46
Errors	24.3	14.1	291	110
Conjunction search				
Hits	55.1	8.7	296	78
Size correct	16.5	4.6	318	133
Color correct	26.8	6.9	335	140
Double errors	1.7	1.6	286	123

Table 3. Distribution and latencies of initial saccadic eye movements in Experiment 3. Note. $n = 7$. Hits, initial saccade to target; size correct, initial saccade to a distractor with correct size but wrong color; color correct, initial saccade to a distractor with correct color but wrong size; double error, initial saccade to a distractor with both wrong color and size.

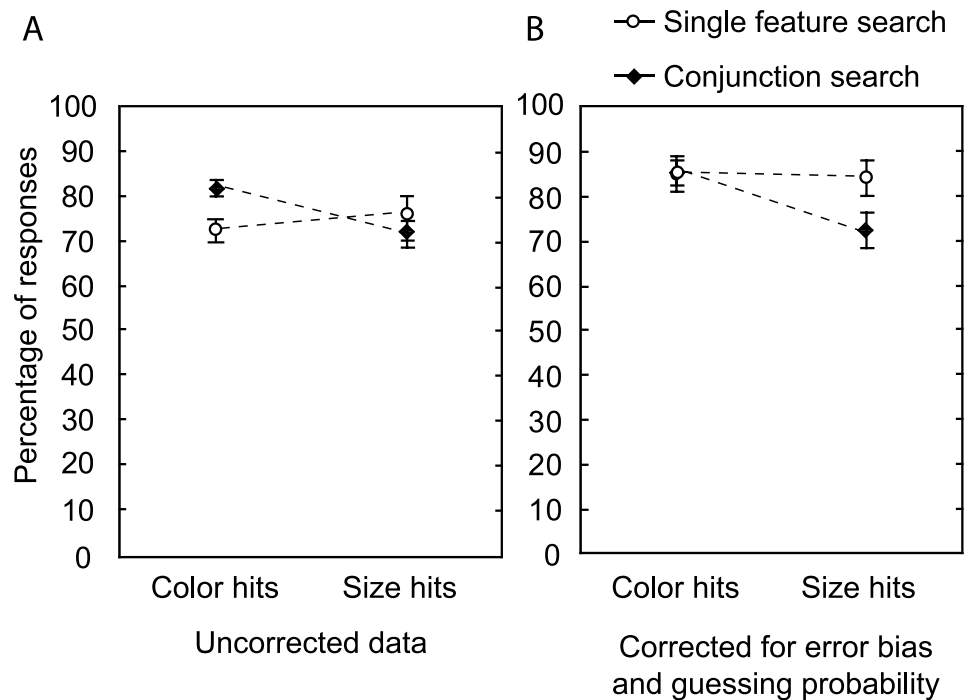


Figure 5. Mean response accuracy ($n = 7$) plotted as a function of the search task in Experiment 3. Both uncorrected percentages of responses (A) and percentages of responses corrected for error bias and guessing probability (B) are presented. In conjunction search, the size discrimination accuracy decreased significantly compared with single feature search, whereas color discrimination accuracy was approximately equal in both search tasks. Color hits, sum of hits and color correct; size hits, sum of hits and size correct. Bars show standard errors.

Past studies have shown that searching for a larger item among smaller distractors is easier than vice versa (Treisman & Gormican, 1988). This effect was also apparent in our data and was a reason for us to define two separate size discrimination thresholds: one threshold for targets larger than the base size and another threshold for targets smaller than the base size.

Main experiment: Single feature search task

After the 70% discrimination thresholds had been determined, subjects again performed blocks of single feature search tasks for both of the features with contrasts set to the thresholds determined in the first part of the experiment. One block consisted of 52 trials (13 possible target positions \times 1 positive and 1 negative contrast \times 2 repetitions) and each subject performed two blocks for each feature.

Main experiment: Conjunction search task

In the conjunction search task, stimuli were characterized by color and size. The distractor configuration was analogous to those in the other experiments: Four had correct color yet different size, four had correct size and

different color, and four had both different color and size. One block consisted of 52 trials (13 possible target positions \times 4 possible targets). Subjects began at random with either a feature or conjunction search task and then alternated between these blocks.

Results

The descriptive statistics are presented in Table 3.

Feature discrimination accuracy

Figure 5 shows the mean percentages of correctly identified colors and orientations in feature and conjunction search. Figure 5A shows the uncorrected data, and Figure 5B shows the corrected data. On the basis of the uncorrected data, we found that search type (single feature search task, conjunction search task) interacts with feature (color, size) discrimination performance, $F(1,6) = 10.209$, $p < .05$. This finding is supported by a paired permutation test. The performance difference between single feature and conjunction search is larger for size than for color, $p < .05$. Feature discrimination performance of color and size in single feature search did not differ significantly, $t(6) = -0.67$, $p = .53$.

Analysis of the corrected data reveals that the discrimination performance decrease in conjunction search (compared with single feature search) was, on average, 12% larger for size than it was for color (95% confidence interval: 2% to 22%). There was no significant difference between color discrimination performance in single feature and conjunction search, $t(6) = -0.10$, $p = .93$.

Saccadic latencies

There is no significant difference in latency for correct identification of color and size in conjunction search compared with single feature search $F(1,6) = 5.15$, $p = .06$. A paired-samples t test revealed a difference between the average saccadic latencies of color hit responses and size hit responses in conjunction search, $t = 2.60$, $p < .05$. On average, the saccadic latency of color correct responses was 16 ms longer than that of size correct responses (95% confidence interval: 1 to 31 ms). Given that the mean latency of color correct responses was 319 ms, this translates to an average difference of 5%.

Discussion

The results of this experiment show that color discrimination performance in conjunction search is better than size discrimination performance when using feature contrasts that have been matched for discrimination difficulty. This is in line with the results of the first two experiments. Again, the results cannot be explained by a speed–accuracy trade-off. Although there was a difference in saccadic latencies between trials that resulted in a color hit or a size hit, we believe that it is too small to be relevant in the explanation of performance asymmetry (to be consistent, we should have found a substantially larger difference in latency for orientation hits and color hits in [Experiment 1](#), but we found none).

General discussion

Despite carefully balancing the discriminability of features, we found a strong asymmetry in feature discrimination performance during conjunction search. Subjects much more often directed their first saccade toward the correct color than toward the correct orientation ([Experiments 1 and 2](#)) or correct size ([Experiment 3](#)) in conjunction search. The asymmetry in feature performance was present in the uncorrected data and, therefore, was clearly not a product of the correction procedure. To

compare absolute performance in feature and conjunction search, we applied corrections for guessing and spatial bias in the error distribution. Although the correction should not be considered as giving a 100% accurate picture of true performance, we nevertheless believe that the corrected data are useful for interpreting the results. A clear indication for this is that the results are consistent across experiments. On the basis of the corrected data, we can conclude that color search performance was approximately the same in feature and conjunction search, whereas orientation and size performance decreased in the latter.

The present results are in line with those of a previous study (Hannus, Cornelissen, Lindemann, & Bekkering, 2005). However, in this study, rather than for each individual, features were balanced at the group level, which we believe to be much less accurate. On the basis of this study, we can now exclude a speed–accuracy trade-off and compare absolute performance between single feature and conjunction search. Moreover, we have also demonstrated a similar bias for a conjunction of color and size.

Our findings are also in line with earlier reports about bias toward color processing when combined with other features. Williams (1966) showed that cueing the target color increases the probability that observers fixate objects of that particular color; cueing target size or shape results in a smaller increase. Using different methods, a bias toward color processing was also found in conjunctions of color and shape (Luria & Strauss, 1975), as well as in triple-conjunction search (Williams & Reingold, 2001). Recently, Nothdurft (2000) found a large overlap in the color and orientation saliency mechanisms used in conjunction search.

We present two types of explanation for these asymmetric performance results in conjunction search. The first resides in the existence of interactions between feature processing mechanisms. The second relates the asymmetries to relative differences in crowding, that is, the effect that neighboring elements in the surround have on a feature's discriminability. We will first discuss both types of explanation. Then, we will review classical visual search theories and indicate how these theories may need to be changed to accommodate our findings.

Discrimination asymmetries are due to interactions between feature processing mechanisms

If features are processed strictly independently of each other, we should have found equal discrimination performance in conjunction search (as discriminability of individual features was matched). Our finding could thus imply that features are not processed strictly independently. Interactions between features could come about in

three ways. First, independent feature maps may interact in a suppressive way, such as proposed by “winner-take-all”-type competition models of visual processing (Itti & Koch, 2000; Lee, Itti, Koch, & Braun, 1999). Such models predict that attention amplifies those visual filters better tuned to the stimulus and suppresses those more poorly tuned. However, because we matched color and orientation/size discriminability, this type of explanation does not answer the question why orientation and size, but not color, is suppressed.

Second, recent studies have suggested the existence of temporal asynchronies in the processing of features (Arnold et al., 2001; Moutoussis & Zeki, 1997a, 1997b). Color was generally processed faster, which could result in a selective bias toward this feature, and another way by which a form of competition could arise during conjunction search (with the fastest feature, color, being the “winner”). However, our results are at odds with what would be expected based on this idea. If subjects were to first select based on color and then on orientation or size, we would expect that orientation or size discrimination performance would actually be better than color discrimination performance. Selecting on color reduces the number of objects to search among for the correct orientation or correct size and, in principle, makes the task easier. Thus, an explanation in terms of a temporal asynchrony in feature processing is also inconsistent with our findings.

The third possibility relates to the possible involvement of conjunctively tuned filters in visual search. Different visual channels have been proposed for visual properties such as spatial frequency and orientation. During conjunction search, we may use a different set of “visual channels” than during single feature search. For orientation discrimination, this proposal suggests that we may shift from achromatic orientation channels used in single feature search to chromatically sensitive orientation channels in conjunction search. This idea in itself is not far-fetched. Color selectivity has been claimed to be as frequent among orientation-selective neurons as it is among unoriented neurons (von der Heydt et al., 2003). In line, orientation and color appear to be explicitly coded in combination at early stages. Moreover, theoretical work on image segmentation has suggested that conjunctively tuned channels might be beneficial in this realm (Burghouts & Geusebroek, 2006). If this is true, our data suggest that the color-orientation “conjunction channel” may have broader orientation tuning characteristics (making it harder to detect small orientation differences). In line, Beaudot and Mullen (2005) conclude that chromatic orientation discrimination is about 1.5–2 times worse than luminance orientation discrimination. Based on our psychometric functions for orientation discrimination, the latter translates approximately into the decrease in performance from feature to conjunction search that we

find here. Something similar could be the case for size. Spatial frequency discrimination is slightly worse for color than for luminance gratings (Webster, De Valois, & Switkes, 1990), which would indeed predict a small decrease in size discrimination performance when changing from feature to conjunction search.

A question that follows from the conjunction channel explanation is why the visual system would not use the more efficient luminance channel for orientation or size discrimination in conjunction search. A possible answer is that perhaps it cannot. This would be comparable to what has been found for spatial frequency channels; letters, for example, cannot be detected “off-channel” (Solomon & Pelli, 1994). Subjects are forced to turn to a specific channel based on the bottom-up signal and fail to use different channels for different masking noises (Majaj, Pelli, Kurshan, & Palomares, 2002). Similarly, subjects may be forced to use different channels for orientation or spatial frequency processing depending on whether color also needs to be discriminated.

Discrimination asymmetries are due to crowding

The second explanation for the asymmetry is that the influence of surrounding objects on feature discriminability, a phenomenon called “crowding,” differs for the different features used in our experiments. In the single feature search tasks, all distractors were uniform (e.g., in size search, all distractors had equal size and color was the same for both target and distractors). In contrast, in conjunction search, distractors were heterogeneous with respect to both features, possibly introducing crowding effects. From our (corrected) conjunction search results, it appears that color discrimination performance is the same as in single feature search, whereas orientation and size discrimination deteriorated. One possibility therefore is that orientation and size discrimination suffer substantially from crowding, whereas color discrimination does not or only very little. Theoretically, an increase in crowding effect in the conjunction display could be due to either an increase in variability in orientations or sizes present or the addition of color variation. Given that orientation discrimination deteriorates with increasing orientation variation of background elements (Nothdurft, 1993), we presume that the first option is the more likely one. While crowding has been studied extensively for letters or numerals, we are not aware of studies that have investigated crowding effects for basis features such as color and size. If crowding does indeed underlie the asymmetry, our results would imply that crowding effects are small for size and largely absent for color.

In summary, our results indicate that discrimination accuracy in single feature search does not necessarily

predict discrimination accuracy in conjunction search. Two plausible explanations are that an asymmetry exists in feature processing (e.g., different visual channels are used in feature and conjunction search) or that crowding introduced by the more variegated stimulus pattern in conjunction search has asymmetric effects across features. Note that the two types of explanation are not necessarily mutually exclusive (e.g., an increase in crowding could be related to the use of a conjunctively tuned channel) and could therefore both play a role. Our current data do not allow us to distinguish between these two lines of explanation.

A further aspect to note is that both explanations are in accordance with the idea that parallel and serial processing are not dichotomous. If there is a channel tuned to both color and orientation and one to both color and spatial frequency, it is no longer necessary to assume the existence of a serial binding stage, at least for these particular sets of features.

Similarly, if a feature's discriminability substantially decreases purely because of an increase in stimulus variability in conjunction displays, there is likewise no need for a specific serial stage to explain reduced search performance in conjunction search.

Classical visual search theories and their predictions

Our main premise questions whether classical models of visual search can predict asymmetry. According to the Guided Search model (Wolfe, 1994; Wolfe et al., 1989; Wolfe & Gancarz, 1996), preattentive processing takes place in independent maps that code features in terms of saliency. Attention is then guided to the most salient stimulus. Because the saliency of color and orientation/size was matched, we should have found, according to Guided Search, equal performance for both color and orientation/size in conjunction search. We do not find equal performance, and our results are therefore not directly interpretable by means of the Guided Search model. Nevertheless, it may be possible to accommodate our findings when slightly modifying this model. One option would be to change the model in such a way that in conjunction search, color is always preferentially guiding the attentional processes, at least when presented in combination with orientation or size.

One possibility is that despite matching of discriminability of features, subjects' ability to categorize them may not have been equal. In that case, the ability to use these features to guide visual search may not have been equal either. If so, we should find an explanation for why features matched in discriminability cannot be categorized to the same extent. Both explanations for the asymmetry given in the previous section could account for this. A

switch between channels could explain why color and orientation/size are differentially categorizable. We performed our feature matching on luminance bars and discs. If subjects use a less sensitive filter in conjunction search, it will also become harder to categorize a feature. Also, reduction in discriminability because of crowding could render a feature less easy to categorize. Such a "categorization stage" may need to become an integral part of models of visual search.

Similarity Theory (Duncan & Humphreys, 1989) suggests that attention is directed toward aspects of incoming information: At the first, unlimited capacity, parallel stage of processing, the visual representation of stimuli is segmented into structural units, which form a perceptual description of the visual input. Input descriptions are then compared with an internal template of the target, whereby the structural units containing some property of the template can get a higher weight and thus a higher probability of being selected. Hereby, attention could be directed to some aspects of the incoming information, for example, orientation or color of the structural units. Due to the matching of feature discriminability, interpreted in terms of this theory, color and orientation/size should have had equal weights. Yet, we find that in conjunction search, color outweighs orientation and also size. To bring Similarity Theory in line with these findings, it somehow should account for such asymmetries, for example, by assigning a larger a priori weight to the structural units with the correct color compared with the units with the correct orientation and size.

Finally, in its original form, Feature Integration Theory (Treisman, 1977; Treisman & Gelade, 1980; Treisman & Sato, 1990) does not predict our current findings either. This theory suggests that in the first step of processing, single visual features are processed and represented in separate feature maps, which are later integrated in a map of locations that can be accessed to direct attention to the most salient areas. For compatibility, our results would require that in the second cross-dimensional stage of processing, where feature maps activate specific locations in the master map, the activation due to the color map is amplified relative to the activation coming from the orientation or size map. In this way, the locations containing a stimulus with the correct color would become more active and saccades toward these locations would become more likely.

Conclusions

Our experiments indicate that equal feature discriminability in single feature search does not imply equal

discriminability in conjunction search. We propose that two explanations, not necessarily exclusive, may underlie this finding. First, in conjunction search, features may be processed by conjunctively tuned channels. An attractive aspect of this proposal is that it explains conjunction search without the need for a binding stage, at least for the feature combinations used in our experiments. The second explanation is that the influence of crowding because of the more variegated background in conjunction displays differs across features. Further research will be needed to determine the contribution of both effects to the observed asymmetry.

Appendix: Correction procedure

Close inspection of the data revealed that there was a significant spatial bias in the distribution of the errors. We found that many more errors were saccades to one of the immediate neighbors compared with more distant distractors, especially in single feature search. As will be explained below, this probably means that in part of the trials in which subjects successfully identified the target feature, they made a saccade toward one of the neighboring distractors. Because correction for this bias is expected to make the interaction effect only stronger (as explained at the end of this [Appendix](#)), we considered it justified to perform the statistical analyses on the raw data.

In addition to this spatial bias, the a priori probabilities of hitting a target feature were different in single feature and conjunction search. Because this difference was the same for all features, we also did not correct for this when we assessed interaction effects.

These two effects give a rather distorted picture of absolute performance and make it impossible to directly compare single feature search performance with conjunction search performance. This is the reason why we corrected for these effects. Below, we describe in detail how this was done. This procedure is identical for both color/orientation and color/size experiments, and we discuss here the former.

Spatial bias in errors

A close look at the spatial distribution of the errors revealed that it was not uniform. More specifically, many more errors were due to saccades toward distractors immediately neighboring the target than to more distant distractors ([Figure A1](#)).

If we define the distance between the target and its immediate neighbors to be 1, the distance between

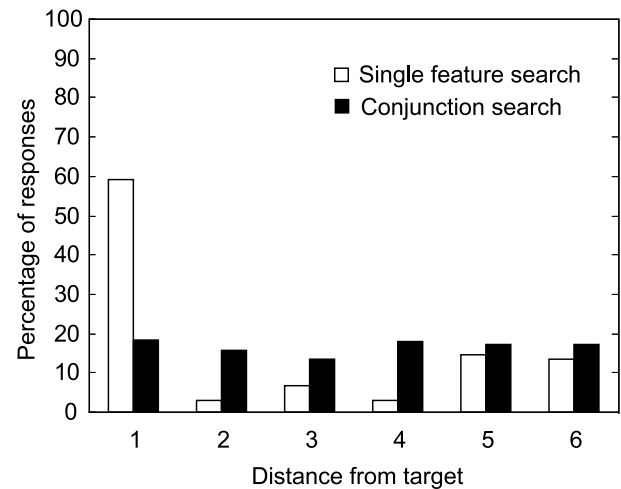


Figure A1. The spatial distribution of errors as a function of distance from the target in single feature search (color) and conjunction search of [Experiment 1](#). The immediate neighbors of the target have a distance of 1, whereas the most distant ones have a distance of 6. In single feature search, there is a bias toward the immediate neighbors of the target.

the target and the direct neighbors of its neighbors as 2, and so forth, then there was a large bias toward errors with a distance of 1 to the target compared with errors with a distance of 2, 3, 4, 5, or 6 to the target. In case of a uniform distribution, we should have found each distance to account for about 17% of the errors. However, we see that, on average, 56% of the errors in single feature search and 25% in conjunction search had a distance of 1, while the remaining errors with distances from 2 to 6 were more or less uniformly distributed. A large part of this bias can probably be explained by subjects searching for and making saccades to discontinuities, rather than specific items. However, because there was also a small bias in conjunction search (where searching for discontinuities does not help to solve the task), there must be other causes as well (e.g., inaccuracies in the planning of the initial saccade). For the purpose of comparing performance in single feature and conjunction search, we believe that it is reasonable to consider as hits part of the errors that have a distance of 1 to the target.

We transformed the data such that after correction, the resulting distribution of errors was uniform (i.e., after correction, each distance accounted for about 1/6th of the total number of errors). We first estimated how many of the errors with a distance of 1 were expected to be due to errors in discrimination (i.e., errors due to considering a distractor feature as a target feature) and how many were due to errors in saccade programming or made to a location representing local inhomogeneities in global

texture (i.e., errors due to saccades toward an immediate neighbor of the correctly identified target). Assuming that all errors with distances from 2 to 6 were discrimination errors, the average number of errors at these positions was used as an estimate of the number of discrimination errors at a distance of 1. The remaining errors at a distance of 1 are assumed to be saccade errors; correction consists of considering these as hits.

In single feature search, this correction consists of subtracting the estimated number of saccade errors at a distance of 1 from the total number of error responses and adding this to the correct responses. In conjunction search, the situation is slightly more complicated, because there are three types of error responses. As the amount of distractors was the same for each of these three types, each kind of distractor had the same probability to be a neighbor of the target. Therefore, the probability of a saccade error resulting in one type of error over another was the same for all three kinds of errors. Thus, correction of conjunction search data consists of adding the estimated number of saccadic errors to the correct responses and subtracting one third of this number from each error response type.

Guessing rate correction—Rationale

In single feature color search, the a priori probability of choosing an item with correct color is 1/13. The same holds for correctness of orientation in orientation search. In conjunction search, however, the a priori chance of having the color correct is 5/13 (the target as well as four of the distractors have the correct color). Also, the chance of having orientation correct is 5/13. This means that the a priori probabilities of a feature hit are different in single feature and conjunction search. To be able to compare single feature search results directly with conjunction search results, we need to correct for this. We have done this by making use of the following two assumptions:

1. If a particular feature was identified, then the selected item will possess this feature (i.e., subjects use the information they have). Thus, if a subject identified, for example, the target color, then we assume that the response was either “hit” or “color correct” in conjunction search and “hit” in single feature search (see [Analysis and statistics](#) section for details about response types).
2. If a particular target feature was not identified, then this feature does not play a role in the selection process (i.e., missing information is guessed). Thus, if, for example, a subject did not identify an item with the target color, he or she guessed with respect to color. For conjunction search, this means that if he or she also did not

identify the orientation, the response was purely random, but if he or she did identify an item with correct orientation, then the response will be either “hit” or “orientation correct” (with probabilities proportional to the number of “hit” and “orientation correct” items).

Guessing correction—Single feature search

From Assumption 2, it follows that in single feature search, in 12 of 13 times that a subject was not able to locate the target, this resulted in an “error” response, and in 1 of 13 times, this resulted in a “hit” response. In other words, the number of error responses reflects only 12/13 of the number of discrimination errors (we distinguish between “responses” and “discriminations.” The former refers to the response that has been logged, whereas the latter refers to information that a subject had at the moment of the saccade). Combining this with the first assumption—from which it follows that all discrimination hits resulted in hit responses—leads to the following two equations:

$$\text{error_responses} = \frac{12}{13} \text{discrim_errors}$$

$$\text{hit_responses} = \text{discrim_hits} + \frac{1}{13} \text{discrim_errors}$$

Rewriting gives:

$$\text{discrim_errors} = \frac{13}{12} \text{error_responses}$$

$$\text{discrim_hits} = \text{hit_responses} - \frac{1}{12} \text{discrim_errors}$$

These two equations were used to remove the effects of guessing from the single feature search data.

Response	Discrimination			
	Hit	Color correct	Orientation correct	Double error
Hit	1	1/5	1/5	1/13
Color correct		4/5		4/13
Orientation correct			4/5	4/13
Double error				4/13

Table A1. Probability distribution in conjunction search.

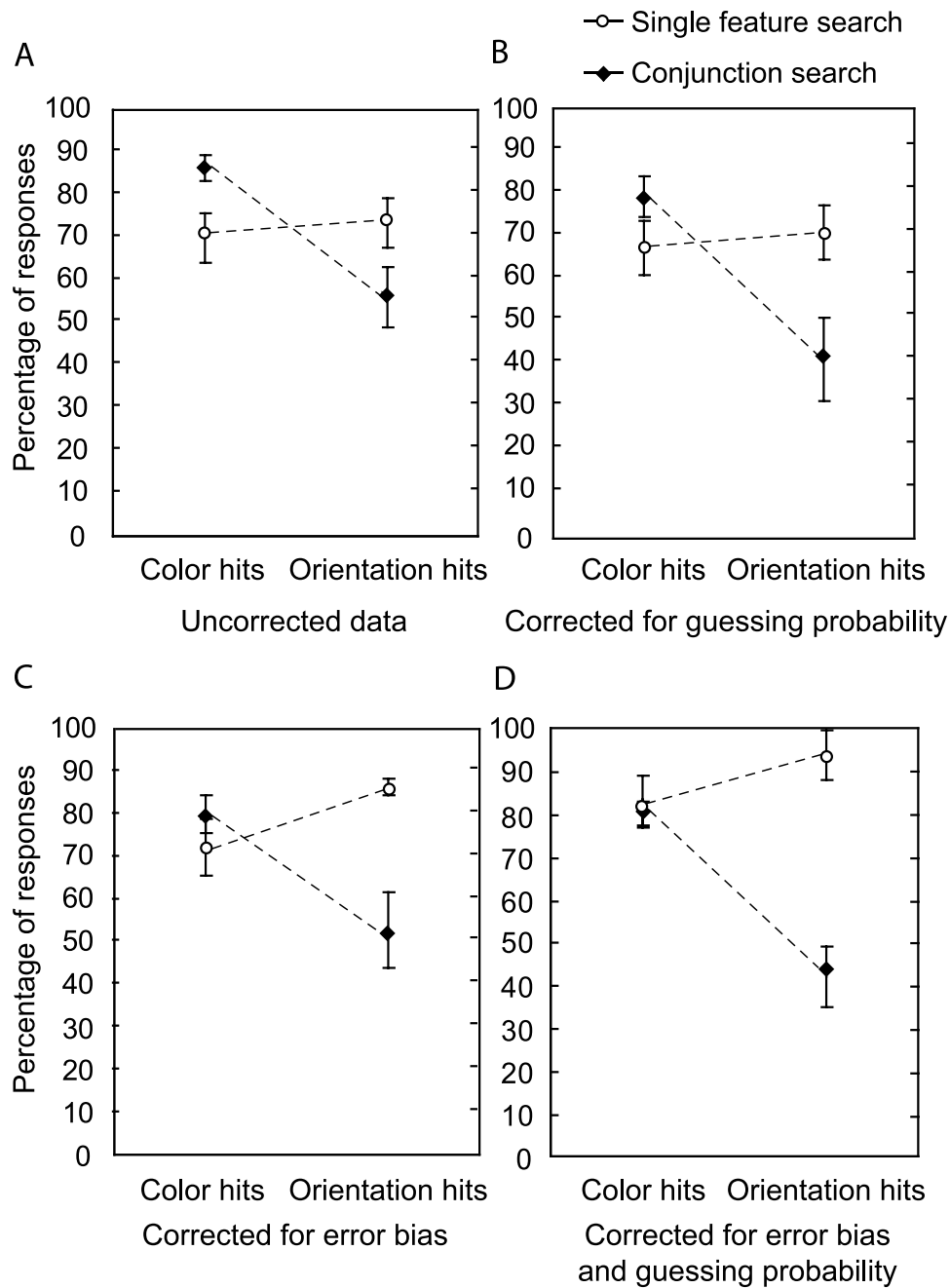


Figure A2. The effects of different corrections illustrated for Experiment 1. Panel A, uncorrected data; Panel B, data after guess correction; Panel C, data after correction for spatial bias in errors; Panel D, data after applying both corrections. Bars show standard errors.

Guessing correction—Conjunction search

In conjunction search, there are four instead of two possible types of discrimination (“hit,” “color correct,” “orientation correct,” and “double error”), as well as four corresponding types of responses. Assumption 1 implies that, again, a discrimination hit will always result in a hit response. However, from Assumption 2, it follows that in all other cases, a certain amount of

guessing is involved, making the response type probabilistic. For example, when only the correct color was identified, the probability that this resulted in a hit response was 1/5, and the probability that it resulted in a correct color response was 4/5. Table A1 gives an overview of the response probabilities for all discrimination types.

From this table, it follows that each of the response counts is a linear combination of one or more discrim-

ination counts. This gives us a linear system of four equations with four unknowns:

$$\begin{pmatrix} \text{hit_responses} \\ \text{correct_color_responses} \\ \text{correct_orientation_responses} \\ \text{double_error_responses} \end{pmatrix} = \begin{pmatrix} 1 & 1/5 & 1/5 & 1/13 \\ 0 & 4/5 & 0 & 4/13 \\ 0 & 0 & 4/5 & 4/13 \\ 0 & 0 & 0 & 4/13 \end{pmatrix} \times \begin{pmatrix} \text{discrim_hits} \\ \text{correct_color_discrim} \\ \text{correct_orientation_discrim} \\ \text{double_discrim_errors} \end{pmatrix}$$

By matrix inversion, we get

$$\begin{pmatrix} \text{discrim_hits} \\ \text{correct_color_discrim} \\ \text{correct_orientation_discrim} \\ \text{double_error_discrim} \end{pmatrix} = \begin{pmatrix} 1 & -1/4 & -1/4 & 1/4 \\ 0 & 5/4 & 0 & -5/4 \\ 0 & 0 & 5/4 & -5/4 \\ 0 & 0 & 0 & 13/4 \end{pmatrix} \times \begin{pmatrix} \text{hit_responses} \\ \text{correct_color_responses} \\ \text{correct_orientation_responses} \\ \text{double_error_responses} \end{pmatrix}$$

These four equations were used to remove the influence of guessing from the conjunction search data.

Results of corrections

The correction for the spatial bias in the error consists of redistributing correct responses over error responses. It therefore increases the count of correct responses and decreases that of error responses and, consequently, results in a performance increase. Given that this spatial bias was substantially larger in single feature search than in conjunction search, performance in single feature search increases more than performance in conjunction search. (Compare [Figures A2A](#) and [A2C](#), which show uncorrected and error bias corrected data, respectively.) Correction for differences in a priori chances has the

opposite effect: By decreasing the number of correct responses and increasing the number of errors, it results in a decrease in performance. Guessing chances in conjunction search were higher than in single feature search, and consequently, correction for guessing mostly affects conjunction search performance. (Compare [Figures A2A](#) and [A2B](#), which show uncorrected and guessing-corrected data, respectively.) After combining both types of correction ([Figure A2D](#)), we can directly compare performance in single feature and conjunction search.

Note that the corrections make the difference between orientation performance in single feature and conjunction search larger, whereas it makes the difference between color performance in these two types of search smaller. Therefore, although we found an interaction effect already in the uncorrected data, it is to be expected that the effect is even larger in the corrected data.

Acknowledgments

The two authors Hannus and van den Berg contributed equally to this article.

Commercial relationships: none.

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