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# Redundant coding assessed in a visual search task

Patrick Monnier\*

*Department of Psychology, The University of Chicago, Chicago, IL 60637, USA*

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## Abstract

Potential advantages for redundantly coded target elements were assessed using a latency visual search task. Search times for targets that differed from distractors in both color and orientation, color only, or orientation only were compared. The comparisons were performed at six levels of chromatic difference between the target and distractors and at two different levels of orientation discriminability. The results show redundant coding generally did not result in significantly faster search times compared to the other two conditions. Instead, response time for the redundant target was in large part determined by the most discriminable feature; orientation at low levels of chromatic difference and color at high levels of chromatic difference.

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## 1. Introduction

A target is redundantly coded when it is identifiable along two or more features or coding dimensions. For example, a red triangular target among green squares is redundantly coded because it can be identified by its unique color and/or unique shape. Redundant coding has the potential to facilitate search performance for several reasons. First, redundant coding can be used as a backup so that a target can be detected even if one of the features is ineffective. For example, color deficient observers might not be able to identify a color-coded target and would therefore benefit from redundant coding. Another way redundant coding may be useful is when the efficacy of a coding feature is affected by environmental factors, such as color under high levels of ambient illumination [1]. A third way redundant coding might be useful is if one of the features coding the target can be used to attentionally segment the display. For example, a coding dimension such as color might be used to restrict the search to a subset of elements and hence reduce search times [2]. A fourth way redundant coding might be advantageous is if it improves search performance above and beyond that achieved with a target

coded using either feature alone. Such an advantage may seem reasonable since a redundant target is detectable along multiple perceptual dimensions and may lead to faster detection performance. This prediction is supported by the concept of probability summation. Probability summation, as applied to redundant coding, stipulates that a target coded with multiple features ought to be more detectable than a single feature target, assuming the features are detected by independent neural mechanisms (e.g. a color-sensitive mechanism and an orientation-sensitive mechanism; see Ref. [3] for details).

On the other hand, it might be that coding a target redundantly does not offer an advantage beyond that achieved with the most discriminable feature. For example, a target that differs from the distractors in both shape and color might be detected by its unique color when the color difference between the target and distractors is highly discriminable. When the color difference is small, the target may be detected by the more discriminable shape difference.

While redundant coding is sometimes offered as an effective display design approach, clear empirical support for this recommendation has not been obtained. A potential source for this confusion is that redundant coding is not always tested thoroughly [4,5]. A complete test of redundant coding requires a comparison between the redundant condition in which the target is coded with multiple features and all of the conditions in which the target is coded with

\* Address: Visual Science Laboratories, The University of Chicago, 940 E 57th Street, Chicago, IL 60637, USA. Tel.: +1-773-702-9412; fax: +1-773-702-0939.

*E-mail address:* pmonnier@uchicago.edu .

each feature alone. For example, a performance advantage caused by the addition of color to a target that differs from distractors in orientation cannot necessarily be attributed to redundant coding. It might be that the added feature, in this example color, is more discriminable and is alone responsible for the improvement in performance. A complete test of redundant coding involves testing performance for the redundant condition as well as all of the single feature conditions. When such a complete comparison is performed, redundant coding does not seem to offer a clear advantage [6–8]. Instead, search performance appeared to be determined by the most discriminable feature dimension.

In the present study, potential advantages of redundant coding were investigated by comparing search latency (reaction time) for targets coded using both orientation and color, to targets coded using either orientation or color only. Comparisons were performed at multiple levels of color difference between the target and distractors, holding orientation discriminability constant. Varying the chromatic difference between the target and distractors has a dramatic effect on search performance [9,10] and allowed for a test of redundant coding at multiple levels of search difficulty. Furthermore, comparisons between coding conditions were repeated at two levels of orientation discriminability. Varying the relative discriminability of the two coding features is more likely to reveal an advantage of redundant coding. For example, it is possible that a large difference in discriminability between the two features will force an observer to only use the more discriminable feature. Also, as suggested by probability summation, the greatest advantage of redundant coding is expected when both coding features are near threshold [3]. Varying both the discriminability of the color difference and orientation discriminability between the target and distractors therefore maximizes the chance of observing an advantage of redundant coding.

Overall, the results show a target that differs from the distractors in both color and orientation is generally not detected more quickly than when coded using color or orientation alone. Comparisons between the three coding conditions at each level of chromatic difference revealed no significant advantage of redundant coding. That is, search performance for the redundant target was in large part determined by the more discriminable feature, orientation when the color difference between the target and distractors was small and color when the color difference between the target and distractors was large.

## 2. Method

### 2.1. Subjects

Two participants, ages 27 and 30, took part in the study (observer PM is the first author). Both observers had normal color vision as assessed with the Ishihara plates, had 20/20

acuity and were highly trained in similar visual search tasks. The second observer was naïve as to the purpose of the experiment.

### 2.2. Apparatus

An Apple Macintosh computer model 8500 was used to both generate the stimuli and collect responses. The stimuli were generated using an auxiliary board (Radius Thunder 30/1600) in 8-bit mode and were presented on a non-interlaced color monitor (model Nanao T2-17, at a resolution of 832 by 624 pixels, at 75 Hz). The monitor's gun outputs and chromaticities were measured using a Minolta Chromameter SC-100. The three guns were characterized by measuring their outputs at 15 gun values, linearly spaced over the operating range. These values were linearized and stored in lookup tables. Characterization was checked throughout the experiment and did not differ appreciably.

### 2.3. Displays

The displays were composed of 32 rectangular elements. Viewing distance was kept constant at 125 cm by having subjects position their heads on a chin rest. The 32 elements were presented in a circular area subtending approximately  $11^\circ$  of visual angle in diameter. The spatial location of each element was determined randomly following two restrictions: an element had to be presented within the  $11^\circ$  presentation area and had to be separated from another item by at least  $0.92^\circ$  of visual angle, center-to-center. The presentation of the 32 items on the monitor was done within one frame (14 ms). The 32 elements were presented on a dark background (approximately  $0.3 \text{ cd/m}^2$ ). The background chromaticity could not be measured reliably because of the low luminance level but appeared black.

Two element sizes were tested. In Experiment 1, the rectangular elements subtended  $0.18$  by  $0.28^\circ$  of visual angle, representing a length-to-width ratio of 1.56. In Experiment 2, the length of the elements was reduced to  $0.23^\circ$  of visual angle, decreasing the length-to-width ratio to 1.28. The orientation difference between the target and distractors was always  $90^\circ$ . The orientation difference between the target and distractors was therefore less discriminable in Experiment 2 due to the decrease in the elements' length.

In both Experiments, six levels of chromatic difference between the target and distractors were tested. The six levels were chosen to cover a large range of search performance (for example, the smallest difference resulted in search times of about 3 s while the largest difference produced search times of around 0.5 s). The distractor and target elements were always equal in luminance ( $11 \text{ cd/m}^2$ ) and either differed in both color and orientation (redundant condition), in color only or orientation only. In the redundant and orientation conditions, the target, when

present, was always vertically oriented while the distractors were horizontal. In the redundant and color conditions, the target differed in chromaticity as determined by one of the six preselected levels. In the color condition, both target and distractors were vertically oriented and differed in color only. Chromaticities are expressed in cone-excitation space [11] along the L direction, representing changes in the red-sensitive color-coding mechanism. An increase in chromatic difference roughly represents an increase in the target saturation in a reddish direction. The distractors appeared white (except in the orientation condition in which both target and distractors were identical in chromaticity).

#### 2.4. Design

A visual search task was used in which fifty percent of the trials contained a target element and the other fifty percent of the trials contained distractors only. The subjects' task was to determine whether a target was present or absent in a given trial. Response times were measured for detecting the presence/absence of a target. Search accuracy was kept at or above ninety percent accuracy by terminating and repeating a block of trials in which the error rate fell below the criterion. This technique avoids undesirable speed-accuracy trade-offs.

Three coding conditions were tested: redundant, color alone and orientation alone. Comparisons between the three conditions were made at six predetermined chromatic difference levels, at two levels of orientation discriminability. Both experiments were run in blocks of 60 randomly presented trials of which half contained a target and half contained no target. For each of the six chromatic difference levels, the three coding conditions were run in random order. Each block of trials was repeated twice, on separate days. Each data point represents a mean of two repetitions of 30 trials. The order in which the six chromatic difference levels was also determined randomly.

#### 2.5. Procedure

A typical block of trials began with a dark adaptation period of at least two minutes. After dark adaptation, an auditory warning indicated to the subject data collection was about to begin. Initially, five target-present trials were presented to familiarize the observer to the current condition. During the practice trials, the target was always presented at the center of the  $11^\circ$  field for easy identification. The target and distractors remained visible until the observer pressed the mouse button. Response times for the practice trials were disregarded. After the practice trials, an auditory signal warned the observer data collection was about to begin. First, a small fixation cross appeared at the center of the screen. The fixation point remained visible for a random time period (0.4–0.6 s). Next, the 32 elements were presented and remained visible until the observer pressed the mouse button indicating that he or she had made

a decision regarding the presence or absence of the target. The recorded response time consisted of the period of time between the display presentation and the observer's mouse button press. Next, the response display was presented which consisted of two fields. Subjects clicked on the right field for a 'target present' response or clicked on the left field for a 'target absent' response. Only correct trials were analyzed. After the response, a 1.5 s delay ensued, followed by the next trial. Search accuracy was fixed at 90% or higher. Error rates were computed for target present and absent separately. A total of six errors (three target present and three target absent errors) were therefore permitted within a block of trials. If the performance criterion was not maintained, the block was terminated and had to be run at a later time. Accuracy feedback was provided in the form of an auditory signal for a mistake. Observers usually collected data for about 2 h daily.

### 3. Results

Response times were measured for target elements that differed from distractors in both color and orientation (redundant condition), in color only or in orientation only. Response times for these conditions were measured at six levels of chromatic difference between the target and distractors. Two stimulus element sizes were tested. In Experiment 1, the elements subtended  $0.18$  by  $0.23^\circ$  of visual angle and  $0.18$  by  $0.28^\circ$  of visual angle in Experiment 2. The size difference made the orientation task easier in Experiment 2, and hence provided a test of redundancy at two levels of orientation discriminability.

#### 3.1. Experiment 1

Fig. 1 shows data for both observers for the larger element size ( $0.18$  by  $0.28^\circ$ ). Data for each observer and for target present and absent are shown separately. Log response times are plotted as a function of chromatic difference. Chromatic difference represents the difference in chromaticity between the target and distractors, except for the orientation condition in which target and distractors, within a level of chromaticity, were the same chromaticity. The open circles represent response times for the condition in which the target differed from the distractors only in color. For this condition, response times decreased with an increase in chromatic difference. As observed previously [9,10], response times can vary over a wide range of performance when the chromatic difference between a target and distractors is manipulated. The open triangles show response times for the condition in which the target differed from the distractors in orientation only. Response times for this condition are approximately constant across all six levels of chromaticity. This is not surprising and indicates that the elements' color did not affect the ability to perform the orientation task. Comparing response times for the color and orientation conditions (open circles vs. open

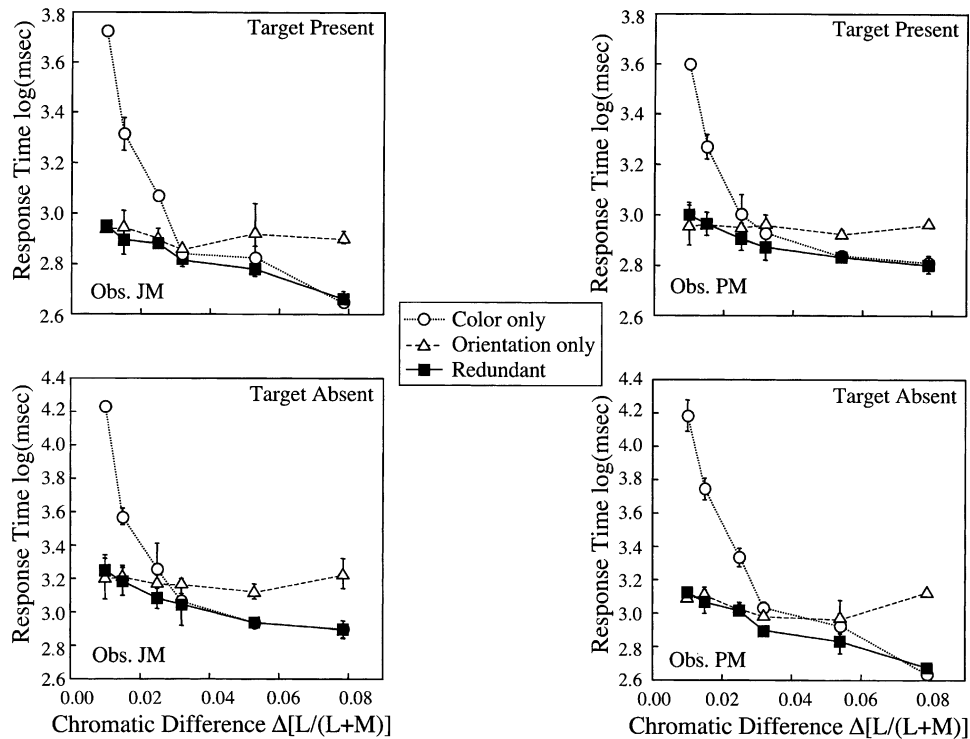


Fig. 1. Log response times are plotted as a function of the color difference between the target and distractors. Data for two observers and for target present and absent are shown in separate plots. Open circles represent response times for targets that differed from the distractors in color only. Open triangles represent response times for targets that differed from the distractors in orientation only. Solid squares represent response times for targets that differed from the distractors in both color and orientation. Error bars represent one standard error of the mean. In this experiment, elements subtended  $0.18$  by  $0.28^\circ$  of visual angle.

triangles) shows response times for the orientation condition were generally faster at lower levels of chromatic difference. This indicates the orientation difference was more discriminable than the color difference at low levels of chromatic difference. This relationship reversed at higher levels of chromatic difference where the color difference was more discriminable than the orientation difference. Finally, the solid squares represent response times for the redundant condition. Overall, response times for the redundant target were faster than for the color and orientation conditions although the critical comparison is between the three conditions at each level of chromatic difference. Redundant coding can be claimed superior only if the redundant target is detected faster than both single feature targets. Response times for the redundant target were faster than both color and orientation for a few conditions. A one-way ANOVA was performed for each observer and for target present and absent data separately. For both observers and for target present and absent data, the overall model was significant (JM target present:  $F(17, 35) = 34.38, p < 0.05$ ; PM target present:  $F(17, 35) = 22.66, p < 0.05$ ; JM target absent:  $F(17, 35) = 17.05, p < 0.05$ ; PM target absent:  $F(17, 35) = 47.93, p < 0.05$ ). Tukey's HSD post-hoc comparisons ( $p < 0.05$ ) between the three coding conditions at each level of chromatic difference showed redundant coding never was superior to both color and orientation. In this experiment, coding a target element with both color and orientation did

not improve search performance. Instead, search times for the redundant target were in large part determined by the more detectable or more salient feature. At low levels of chromatic difference, the redundant target was detected by its unique orientation, while at higher levels of chromatic difference, the target was detected by its unique color.

### 3.2. Experiment 2

Similar conditions to Experiment 1 were repeated with smaller stimulus elements ( $0.18$  by  $0.23^\circ$ ). The decrease in the length of the rectangular elements made the orientation difference between the target and distractors less discriminable. Fig. 2 represents data for the same two observers, for target present and absent data. The format is identical to Fig. 1. As in Experiment 1, response times for the color condition (open circles) decreased with an increase in chromatic difference between the target and distractors. The open triangles represent response times for the orientation condition and show no effect of the overall chromaticity of the elements. The overall response times for the orientation condition were slower than in Experiment 1, by approximately a factor of two. This confirms that the orientation difference was less discriminable in this experiment. The advantage trade-off between orientation and color can again be observed, although the level of chromatic difference at which the crossover occurs is different. In

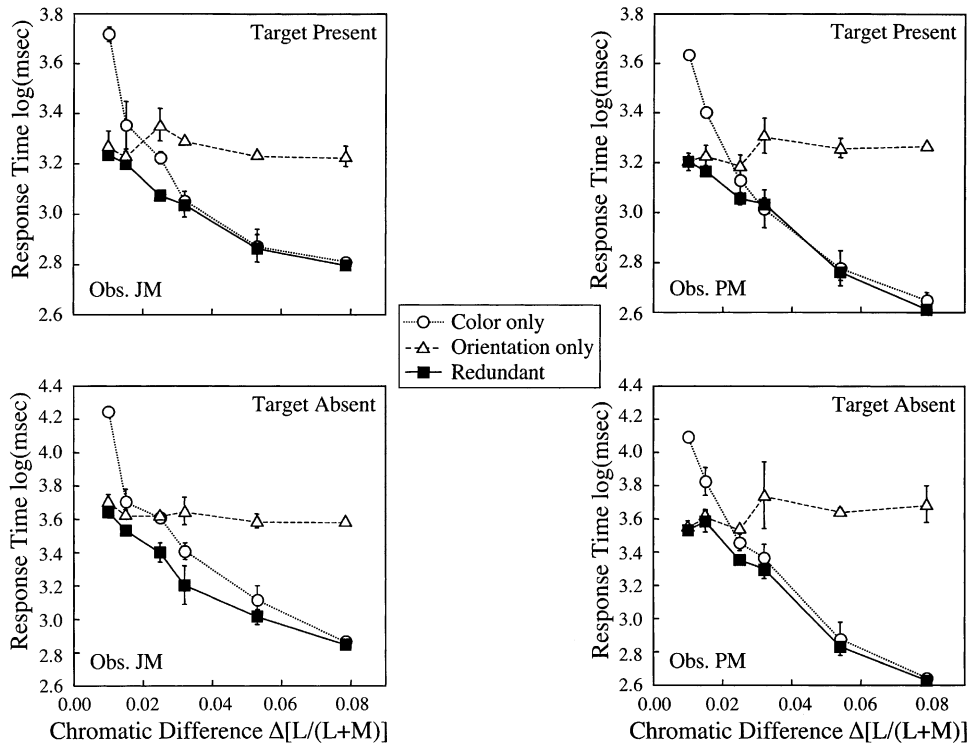


Fig. 2. Log response times are plotted as a function of the color difference between the target and distractors for elements that subtended 0.18 by 0.23° of visual angle. The format is identical to Fig. 1. Open circles represent response times for targets that differed from the distractors in color only. Open triangles represent response times for targets that differed from the distractors in orientation only. Solid squares represent response times for targets that differed from the distractors in both color and orientation.

Experiment 1, the crossover occurred between 0.028 and 0.043 L units while it occurred between 0.02 and 0.025 L units in Experiment 2. The solid squares represent response times for the redundant condition. As in Experiment 1, small advantages were present for the redundant condition compared to the color alone and orientation alone conditions. A one-way ANOVA was performed for each observer and for target present and absent data. For both observers and for target present and absent data, the overall model was significant (JM target present:  $F(17, 35) = 31.76, p < 0.05$ ; PM target present:  $F(17, 35) = 41.30, p < 0.05$ ; JM target absent:  $F(17, 35) = 47.03, p < 0.05$ ; PM target absent:  $F(17, 35) = 33.10, p < 0.05$ ). Tukey's HSD post-hoc comparisons ( $p < 0.05$ ) between the three coding conditions at each level of chromatic difference showed redundant coding never was significantly different than both color and orientation. The results of Experiment 1 were replicated at a second level of orientation discriminability, again suggesting performance for the detection of the redundant target was determined by the more discriminable feature.

#### 4. Discussion

Redundant coding can be an effective coding scheme when used as a backup. For example, redundant coding can ensure a target element will be detected even when one of

the coding features becomes ineffective. Environmental factors, or visual deficiencies of observers can render a coding feature ineffective. A more interesting question is whether redundant coding can improve search performance beyond that achieved with coding the target with either feature. To test for such an advantage, one must test search performance for the redundantly coded target as well as for a target coded using each feature alone. This is necessary because redundantly coding a target element by adding a feature such as color may lead to an improvement in performance simply because color is a more discriminable feature. It is therefore critical to compare performance between all conditions; the redundant as well as the single feature conditions. In the present study, search performance for a redundantly coded target that differed from the distractors in both color and orientation was compared to performance for a target coded using either color and orientation alone. Search performance for the redundantly coded target was statistically not superior to the performance for the target coded using either color or orientation. Instead, the more discriminable feature in large part determined search performance for the redundantly coded target. When the chromatic difference between the target and distractors was small, search performance was determined by the more discriminable orientation difference between the target and distractors. At larger chromatic difference levels, search performance was determined by the chromatic difference.

Although no statistically significant advantage of redundant coding was observed, search times for the redundant targets were never slower than either the color or orientation conditions. In fact, response times for the redundant condition were sometimes faster than the other two conditions, though these differences did not reach a significant level. It is possible that additional data, which would result in an increase in statistical power, would result in some statistically significant comparisons. Nonetheless, these differences are small and probably not significant from a practical point of view.

As mentioned in the introduction, a performance advantage for the redundantly coded target might have been expected according to probability summation. Probability summation is based on the assumption of independent neural mechanisms involved in the detection of the redundant targets. The redundant target in the present study differed from the distractors in orientation and color and therefore, might have been detected by separate orientation-sensitive and color-sensitive neural mechanisms. Channel independence is clearest for simple displays composed of stimuli near threshold. Such independence is less clear with displays that are more complex or when the stimuli are supra-threshold. It is therefore possible that the stimulus displays in the present study failed to tap into independent neural mechanisms.

Although response times for the redundant targets were never significantly faster than both targets coded with color or orientation alone, a trend in that direction can be observed at several levels of chromatic difference. Moreover, these differences occurred when the orientation and color difference resulted in similar and relatively slow search times. This trend is therefore qualitatively consistent with probability summation. To test the probability summation model more thoroughly (i.e. quantitatively), a similar experiment could be performed using an accuracy visual search task ([12,13]). Because the accuracy visual search paradigm was specifically developed to test threshold-like concepts, the task would provide a quantitative analysis of redundant coding.

In summary, search performance for a redundantly coded target was not significantly faster compared to conditions in which the target was coded with a single feature. Instead, search performance in the redundant condition was in large part determined by the more discriminable feature. These results are important because they suggest coding a target with multiple dimensions might not be the most efficient coding approach. Instead, choosing the most discriminable feature might result in good search performance with a less crowded display. The results also clearly demonstrate that stimulus features such as color, shape, or orientation should not be evaluated in absolute terms but should be regarded as lying along a performance continuum. For example, it is incorrect to assume color is always a superior coding feature since small color differences can result in

extremely slow searches [9,10]. Note that the efficiency of the color code was varied in the present study by changing the color difference between the target and distractors. There are more complex ways in which the efficiency of color, and for that manner other cues, can be altered. A complete understanding for the effective coding of visual information will therefore inevitably be complex.

From a practical point of view, the following recommendations can be made based on the present study. Color can be a very efficient way of coding information, though its efficacy depends on many factors, including the chromatic contrast between it and the distractors as well as the background. When the chromatic difference between the target and distractors is large, search times can be very fast. When the color difference is small, search times can be slow. The search time difference between the fastest and slowest condition varying only the chromatic difference between the target and distractors varied by a factor of at least six and as much as thirteen. Second, redundantly coding a target does not necessarily facilitate search performance. In the present study, a target that differed from the distractors in color and orientation was not detected faster than when it differed from the distractors in either color or orientation. The most discriminable dimension, color when the color difference was large or orientation when the color difference was small, in large part determined response time.

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