

# Deficits in Visual Feature Binding Under Isoluminant Conditions

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## Abstract

■ The contribution of the magnocellular stream to visual feature binding was examined psychophysically through the use of isoluminant stimuli. Subjects were presented with three briefly flashed colored letters arranged in an array and asked to identify the shape and color of the center letter. The rate of illusory conjunctions was much higher when the letters were isoluminant with a gray background, compared to when the letters were either brighter or dimmer. Over 90% of conjunction errors involved pairing the wrong shape with the correct

color, rather than vice versa. Directing attention to the target location with a nonisoluminant cue did not reduce illusory conjunctions. High rates of binding errors under isoluminance are interpreted here in terms of abnormalities in visual form processing rather than an attentional effect. In another experiment designed to examine the role of synchrony in feature binding, the rate of illusory conjunctions was highest when flanking letters were presented before the central target letter and not synchronously. ■

## INTRODUCTION

Visual objects can have various features, such as color, shape, and motion, whose processing may be distributed over different cortical areas (Felleman & Van Essen, 1991). If there are multiple objects in the visual scene, the question arises how the correct conjunction of features is bound together for each object, without crosstalk among features belonging to different objects. This is the essence of the “binding problem” (reviewed in Golledge, Hilgetag, & Tovée, 1996; Treisman, 1996, Treisman, 1998; Prinzmetal, 1995).

Errors in feature binding can be created under particular experimental conditions, as was first described by Treisman & Schmidt (1982). For example, if a green X and red T are flashed simultaneously, the subject may report seeing a green T. Such binding errors are called illusory conjunctions. One way to create illusory conjunctions is to flash the stimulus very quickly, while designing the task to divert the subject from attending fully to it. However, if the stimulus is moved away from fixation towards the periphery, where acuity and spatial localization are poorer, illusory conjunctions can be created with longer stimulus exposure times and lower attentional loads (Prinzmetal, Henderson, & Ivry, 1995). Illusory conjunctions have been reported under a wide variety of experimental conditions, among them, those of Moutoussis and Zeki (1997a), Moutoussis and Zeki (1997b), Tsal, Meiran, and Lavie (1994), Ivry and Prinzmetal (1991), Cohen and Ivry (1989), Keele, Cohen, Ivry, Liotti, and Yee (1988), Briand and Klein (1987), Prinzmetal, Presti, and Posner (1986), Prinzmetal and Keysar

(1989), Prinzmetal, Hoffman, and Vest, 1991, and Treisman and Paterson (1984).

In this study, we shall examine the effects of isoluminant stimuli on the rate of illusory conjunctions. By using isoluminant stimuli, we intend to selectively attenuate magnocellular contributions to processing in the visual system. Magnocellular units are insensitive to isoluminant patterns, unlike parvocellular units, which respond well under such conditions (Kaiser, Lee, Martin, & Valberg, 1990; Lee, Martin, & Valberg, 1988; Derrington, Krauskopf, & Lennie, 1984). Some effects of isoluminance on various psychophysical tasks have been reviewed by Livingstone and Hubel (1987).

There is a body of evidence suggesting that the visual system can be divided into two fundamental pathways: a dorsal pathway, leading ultimately to the posterior parietal cortex, dealing with spatial localization of stimuli and attention (the “where” pathway), and a ventral pathway leading to the inferotemporal cortex (IT), dealing with color and form (the “what” pathway) (Maunsell, 1995; Ungerleider & Haxby, 1994; Vaina, 1994; Baizer, Ungerleider, & Desimone, 1991; Morel & Bullier, 1990; Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Mishkin, 1982; Pohl, 1973). The dorsal and ventral pathways differ in the relative contributions that they receive from Magnocellular and Parvocellular streams (Maunsell, 1992). The dorsal stream appears to be dominated by M input (Maunsell, Nealey, & DePriest, 1990), although some P input to this pathway can be demonstrated as well (Sawatari & Callaway, 1996). The ventral pathway receives major

contributions from both the M and P streams, with mixing taking place within the striate cortex (Edwards, Purpura, & Kaplan, 1995; Ferrera, Nealey, & Maunsell, 1994; Nealey & Maunsell, 1994).

Since the magnocellular stream is the predominant input to the dorsal pathway leading to the posterior-parietal cortex, and since the posterior-parietal cortex is believed to be heavily involved in attention, one possibility, in the context of Treisman's feature integration theory, is that any disruption of feature binding under isoluminant conditions is the result of attenuated activation of structures involved in directing attention. However, since the magnocellular stream also makes a significant direct contribution to the ventral pathway, an alternative possibility, and one that we will favor below, is that the effects on feature binding presented here are due to abnormalities in form processing for isoluminant stimuli, abnormalities internal to the ventral pathway, and do not involve an attenuated or disrupted attentional mechanism.

One theory of binding that has received much attention lately suggests that different cortical unit processing attributes of the same object are bound together by synchrony in their spike timing (Singer & Gray, 1995; von der Malsburg, 1995). No evidence was found for a role of synchrony in binding in one experiment here, in which rates of binding errors were compared for stimuli whose elements were presented synchronously or asynchronously.

## RESULTS

First, it should be remarked that flashed isoluminant letters had a very different subjective appearance than nonisoluminant ones, even for the small .15 log unit luminance step used in the nonisoluminant cases. Isoluminant letters looked fuzzy, as if the color were bleeding past the contour boundaries. This effect was much stronger for flashed letters as used in the experiment, compared to steadily viewed ones. The fuzziness seemed strongest for green letters, and, to a lesser extent, blue ones, and weakest for the orange and magenta letters.

Moving to the quantitative aspects of the data, results from three subjects show that there was a much higher incidence of trials in the "conjunction error" category when the stimulus letters were isoluminant with the background, compared to when they were either brighter or dimmer than the background (Figure 1). The number of trials in the "feature error" category (reporting features completely nonexistent in the stimulus) also increased markedly under the isoluminance condition.

Examining the "conjunction error" results more closely, it turned out that for the three subjects, 91–97% of them were "shape illusions," getting the color right but misreporting the shape (Figure 2). One possible reason for this might be that a monochromatic mask was being

used, which masked shape but not color. However, when a colored mask was used, the overwhelming number of "conjunction errors" remained "shape illusions," with the percentage for subject PK dropping only slightly from 94% to 88%. Results in the "feature error" category were even more lopsidedly in favor of shape errors over color errors, being virtually 100% shape errors.

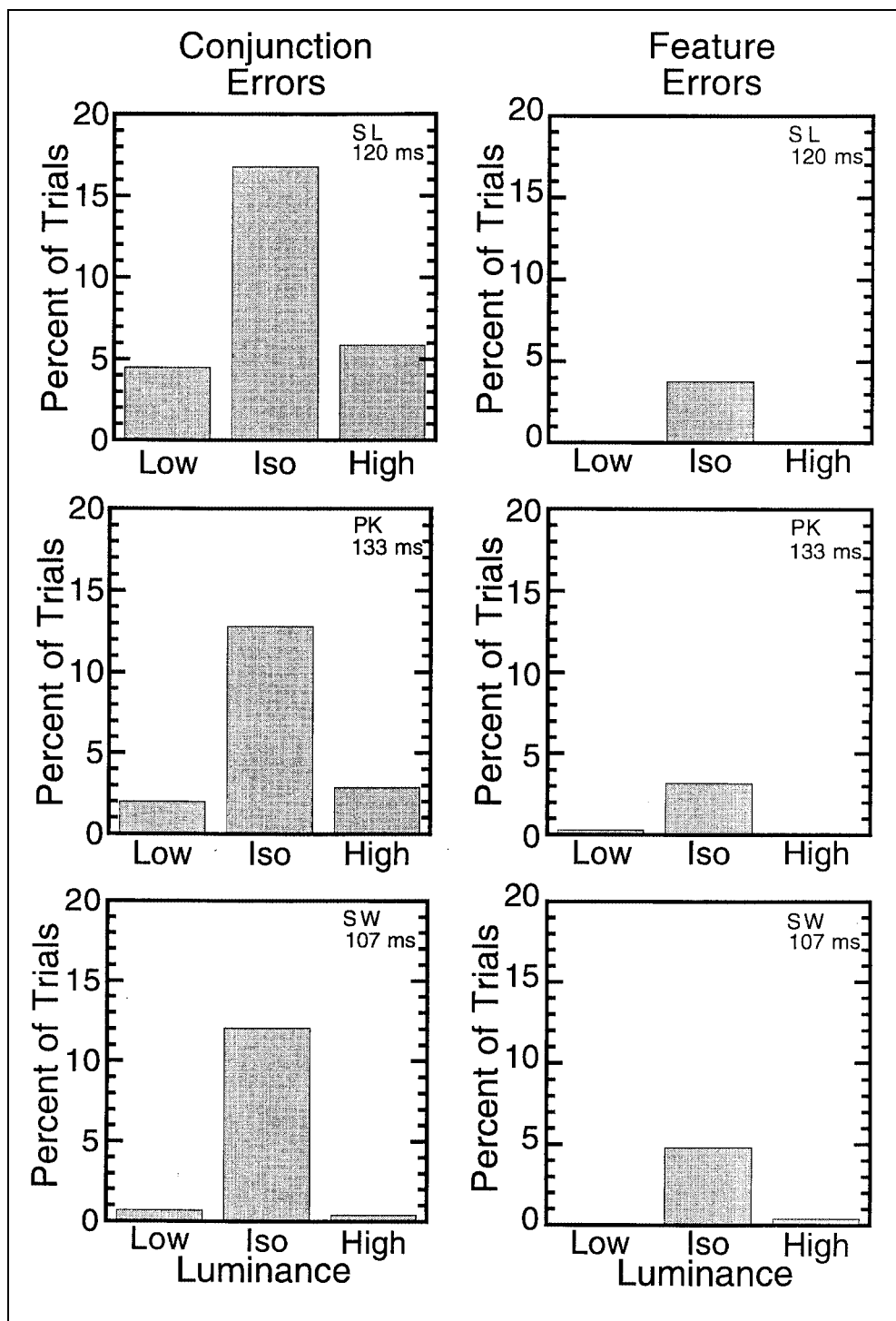
Because a trial fell in the "conjunction error" category does not mean that it actually was an illusory conjunction. The subject might not have seen a feature clearly at all (i.e., it was actually a feature error trial), but in guessing happened to report something that made it seem as if an illusory conjunction had occurred. If subjects were reporting features at random, merely by guessing, it is possible to calculate the ratio of "conjunction errors" to "feature errors." Responding by chance, a subject would be expected to report 1/16 correct trials, 8/16 conjunction error trials, and 7/16 feature error trials. That is a (conjunction error)/(feature error) ratio of 1.14. However, from Figure 2, we know that the subject almost always gets the color right. If we add the constraint that color reporting is 100% correct, then the chance distribution becomes 1/4 correct, 2/4 illusory conjunction, 1/4 feature error, or a (conjunction error)/(feature error) ratio of 2.0. We shall use the latter, more conservative ratio and count illusory conjunctions as occurring only if the (conjunction error)/(feature error) ratio is greater than 2.0. Anything lower, and the so-called "illusory conjunctions" could be attributed to guessing.

For the three subjects, the (conjunction error)/(feature error) ratios were: SL - 4.4, PK - 4.0, SW - 2.8 (these numbers are simply the ratios of the "isoluminance" bars in Figure 1 for the two categories of errors). This indicates a pattern of results that can reasonably be interpreted as demonstrating an elevated rate of illusory conjunctions under the isoluminant condition, and not just a higher feature error rate.

Magnocellular inputs are particularly prominent in the dorsal pathway, ultimately leading to the posterior-parietal cortex, which is important for attention. Perhaps, then, the problems identifying letters under the isoluminant condition reflect an inability to focus attention at an isoluminant target (even though the stimulus letter array always had nonisoluminant end markers). To test this, the position of the target letter was marked by a briefly flashed nonisoluminant cue, which preceded the target letter as described in the Methods. As seen in Figure 3, the rate of illusory conjunctions dropped only slightly when the target position was cued, from 13% to 11%. This suggests that the ability to direct attention to the target location was not a limiting factor underlying the effects of isoluminance seen in Figure 1.

Another issue is whether it makes a difference to the rate of illusory conjunctions if the target is presented synchronously or asynchronously with the flanking let-

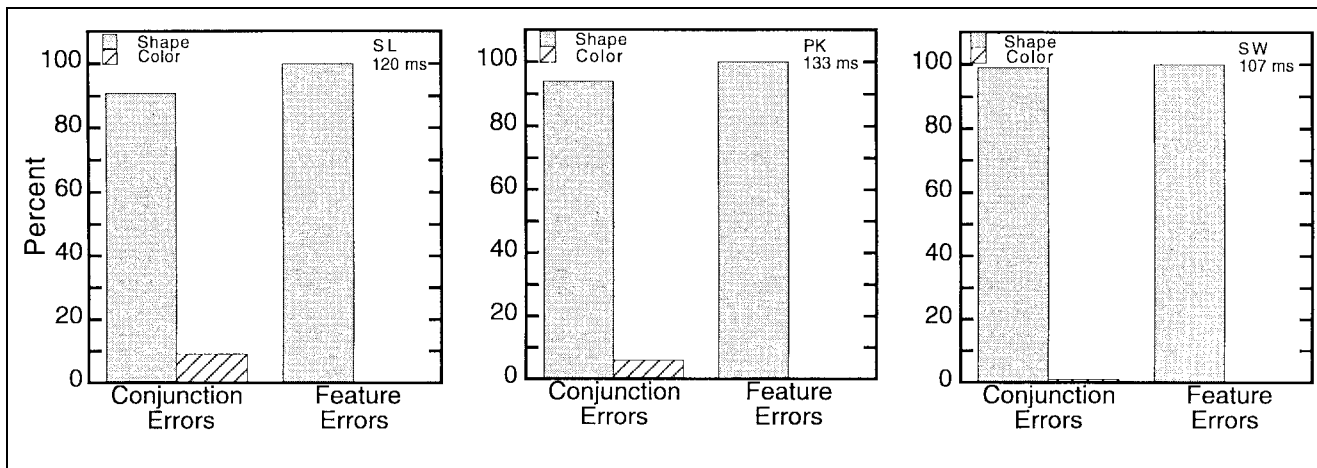
**Figure 1.** Percentage of conjunction errors (left column) and feature errors (right column) for three subjects. Within each graph, error rates are shown for the three luminance conditions, in which the stimulus letters had high luminance, isoluminance, or low luminance relative to background. These data show elevated rates of conjunction errors and feature errors during isoluminance.



ters. The motivation here is to examine theories postulating that feature binding involves synchrony of neuronal spikes in cortical areas processing various features of the stimulus (Singer & Gray, 1995; von der Malsburg, 1995). If this is so, one possibility is that there will be a higher rate of illusory conjunctions when multiple objects are presented synchronously. Figure 4 shows that this conjecture is not the case. The highest rates of illusory conjunctions occurred when the flanking letters

slightly preceded the target, rather than occurred simultaneously.

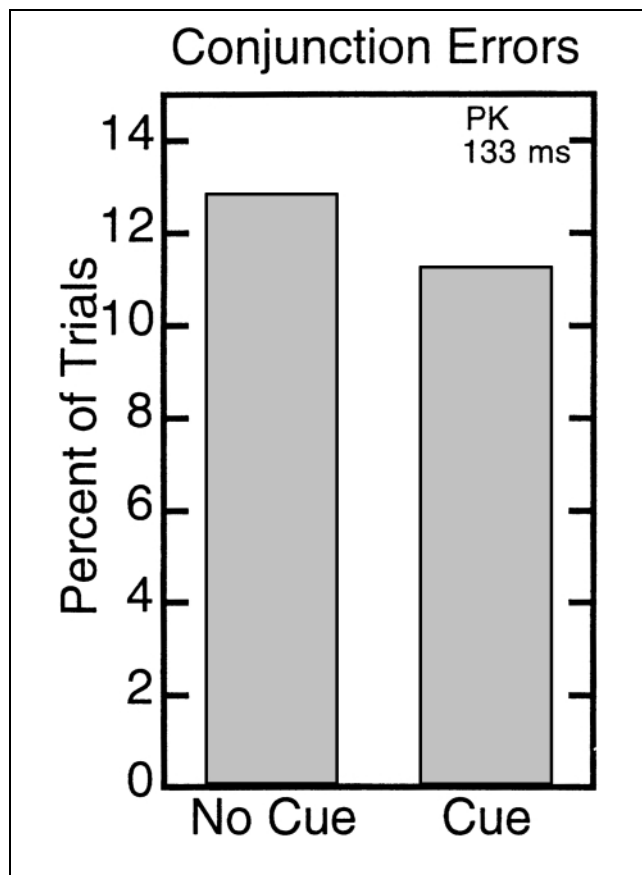
Finally, while we have been looking at various confusions and errors in observing an array of colored letters, it would be useful to look at letter recognition for a single letter in isolation under similar conditions. Recognition curves for color and shape as a function of stimulus duration are shown in Figure 5. These data show that color and nonisoluminant shape can be



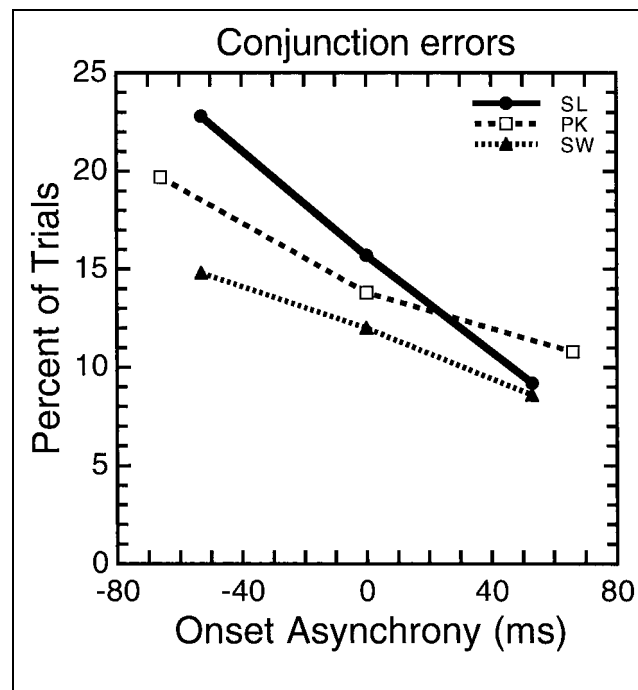
**Figure 2.** Percentage of errors in isoluminant stimuli which were either shape errors or color errors, for three subjects. Over 90% of conjunction errors and almost 100% of feature errors involved mistakes identifying shape and not color.

identified with approximately the same stimulus durations (about 30 msec for color, 40 msec for shape, at 75% recognition level). However, recognizing an iso-

luminant shape required twice the duration as for a nonisoluminant one, or 40 msec longer. Not only is the shape recognition curve shifted to longer stimulus durations, but its slope is less steep as well. There is no similar isoluminant effect for recognition of color. All three-color curves are roughly the same. What small differences do occur fall strictly in order of luminance, with recognition requiring progressively longer stimulus durations as luminance decreases. Intersubject dif-

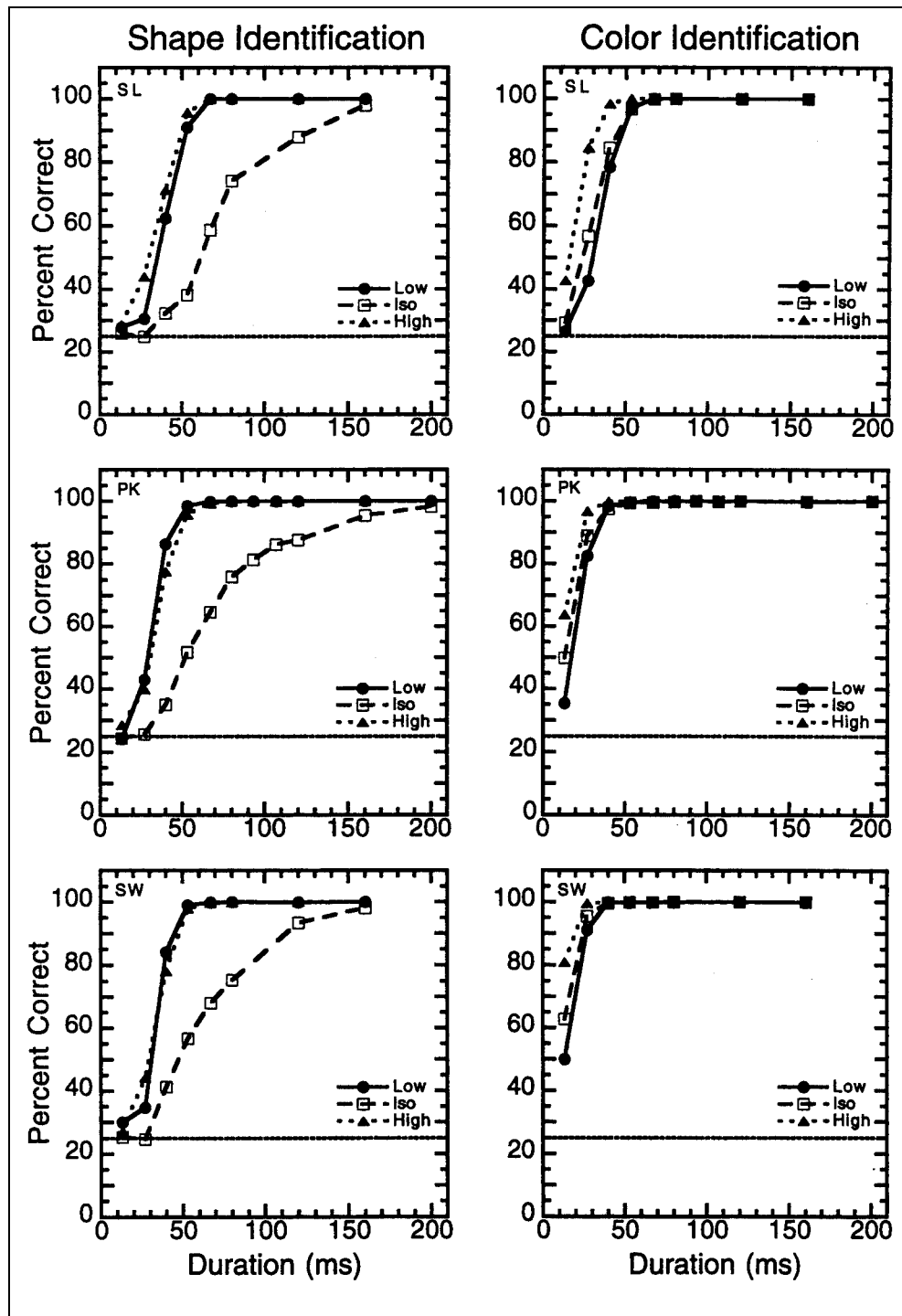


**Figure 3.** If the location of the target letter was indicated by a flashed nonisoluminant cue that preceded the target by a short time, the rate of conjunction errors did not decrease significantly. This suggests that an inability to shift attention to the isoluminant stimulus was not the cause of elevated error rates during isoluminance seen in Figure 1. Stimulus duration was 133 msec, and the cue lead time, or onset asynchrony between cue and stimulus, was 80 msec.



**Figure 4.** The rate of conjunction errors was measured when the two flanking letters in the three-letter experiment were presented before the central target letter, synchronously with the target letter, or after the target letter. The highest rate of conjunctions was not for the synchronous condition, but when the flankers preceded the target. These data are for isoluminant letters.

**Figure 5.** Percent correct identification of shape and color of a single flashed letter as a function of stimulus duration, for three subjects. The presentation conditions for this single letter was identical to that of the target letter in the three-letter experiment, except that duration was systematically varied here. These data show that color and non-isoluminant shape can be identified with roughly the same presentation times, but that isoluminant shapes require much longer than non-isoluminant shapes. Horizontal line indicates chance level.



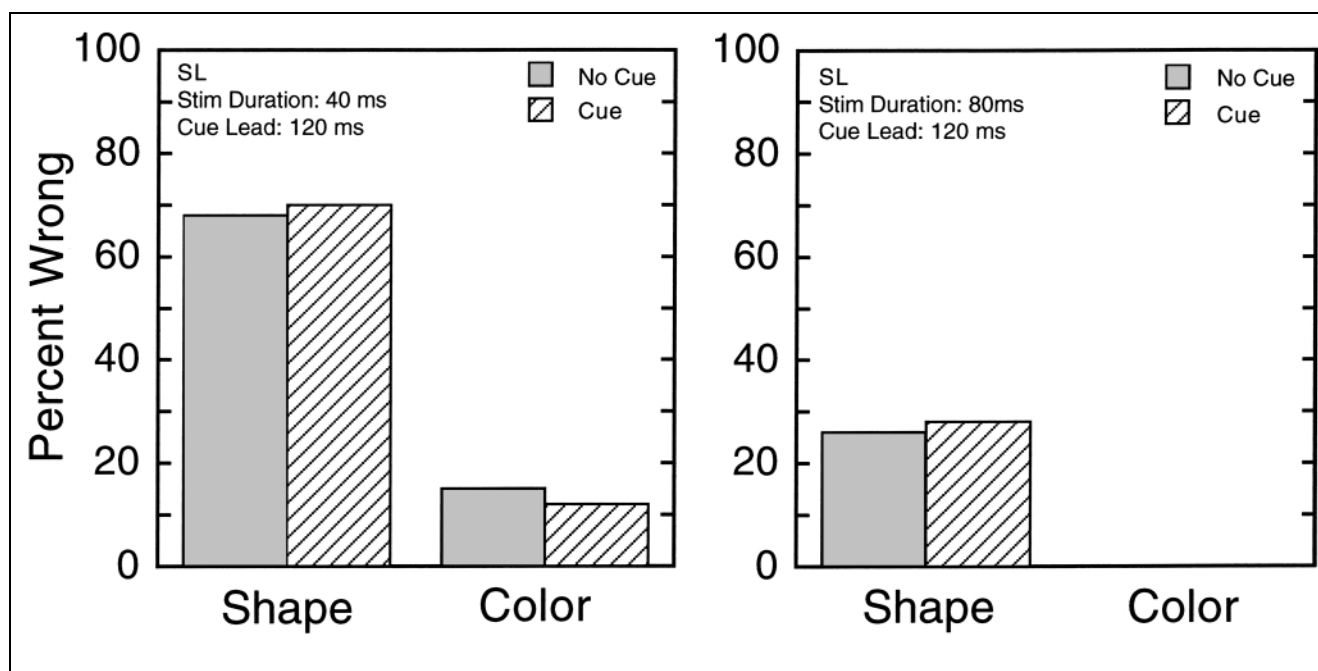
ferences in the color curves might arise from differences in perceived brightness of the stimuli, perhaps related to things like the optical density of the lens or macular pigments.

The effect of cueing target letter position was examined for this one-letter task (Figure 6). The results indicated that marking the target position in advance with a nonisoluminant cue did not improve the ability to identify flashed isoluminant letters. This suggests that the reduced ability to identify isoluminant shape is not

due to an inability to orient attention towards the target. The finding here in the one-letter experiment is the same as for the analogous three-letter cueing experiment shown in Figure 3.

## DISCUSSION

Isoluminant stimuli had elevated rates of illusory conjunctions compared to nonisoluminant stimuli (Figure 1). Directing attention to the location of the isoluminant



**Figure 6.** A nonisoluminant cue marking target location before the appearance of the target failed to change performance very much in the one-letter task. This again suggests that deficits in identifying isoluminant letters are not due to an inability to orient attention towards isoluminant targets, similar to what was shown for the three-letter task in Figure 3. Cue lead = the onset asynchrony between cue and stimulus.

target letter using a nonisoluminant cue preceding the target did not reduce the rate of illusory conjunctions to a major extent (Figure 3). Nor did such a cue improve identification of isoluminant single letters (Figure 6), buttressing the view that there is not a problem directing attention to an isoluminant stimulus. Overall, it does not seem likely that an inability to direct attention to the target location was the factor underlying higher rates of illusory conjunctions for isoluminant stimuli. Although Steinman, Steinman, and Lehmkuhle (1997) have reported psychophysical evidence of poor attentional orienting under isoluminance, this does not appear to be the case for the task at hand.

Isoluminant stimuli may have produced more feature-binding errors because the stimuli were poorly localized within feature maps for reasons unrelated to attention. Subjectively, briefly flashed isoluminant letters looked quite fuzzy, and objectively, presentation times for identifying shapes of isoluminant letters were about 40 msec longer than nonisoluminant ones (Figure 5). It may be that it takes a certain amount of time for activity within a feature map to become organized. Perhaps the dynamics of neural processing are such that it takes slightly longer under isoluminant conditions for an initially unfocused hump of activity within a feature map to organize into a more localized activity peak. If this were the case, then, for short presentation times, isoluminant stimuli would be spatially more poorly defined than nonisoluminant ones. From the perspective of feature integration theory, if for some reason activity in feature maps were delocalized, directing attention to a particular spatial

location in an entirely normal fashion might still lead to binding errors. Prinzmetal et al. (1995) have noted that stimuli presented relatively far from fixation still have high rates of illusory conjunctions even for long presentation times and low attentional loads. Since in the periphery, receptive fields are larger and feature maps are spatially more coarse-grained, this may be another example of binding errors occurring because of poor localization within feature maps rather than a deficit of attentional resources.

Thus, there may be two routes to producing feature binding errors, either deficits in directing attention to a particular locus within feature maps (based on data in the literature), or poorly localized activity within the feature maps themselves (based on our interpretation of the present data). If attention is deficient, there are binding errors, and if the neural substrate of what is being attended to is sufficiently disrupted, then there are also binding errors.

Over 90% of the conjunction errors involved “shape illusions,” in which the shape was misreported, but the color reported correctly (Figure 2). Mistakes in reporting the color of the target letter were rare. This corresponds with the data in Figure 5 showing that stimulus presentation times required for correct shape identification of single isoluminant letters were abnormally long, but presentation times for color were normal. In other words, longer processing times for a feature correlate with a higher incidence of binding errors for that feature. This is consistent with the suggestion made above that it takes a certain amount of time for activity

within a feature map to become organized, and if presentation times are limited, then activity within the map may be poorly localized, leading to feature binding errors. Feature binding is a dynamical process, typically cut short in midflight by short stimulus durations to produce errors. Anything that speeds up or slows down the dynamics of the process would be expected to change the rate of binding errors. (It is interesting to note here that Leonards & Singer, 1998, studying temporal dynamics of texture segmentation, found slower dynamics for isoluminant stimuli. This is another example of a complex perceptual organization process operating more slowly at isoluminance, similar to what is being suggested here for shape/color binding.)

The explanation being offered for binding errors in this particular task focuses on shape and color processing internal to the ventral pathway, rather than attentional effects emanating from the dorsal pathway. As was outlined in the Introduction, the magnocellular stream, whose activity is selectively attenuated for isoluminant stimuli, makes significant direct contributions to the ventral pathway. Effects of isoluminance on ventral extrastriate areas have not been studied physiologically, but it seems reasonable to believe that knocking out a major input could lead to perturbations in neural activity related to the perception of form.

Moving on to the issue of neural synchronization and feature binding, this theory was examined by seeing if the rate of illusory conjunctions depended on whether the flanking letters in the three-letter experiment were presented synchronously or asynchronously with the central target letter. It turned out that the highest rate of illusory conjunctions occurred when the flanking letters preceded the target (Figure 4), and not when they occurred synchronously. This agrees with the findings of Keele et al. (1988) that temporal synchrony does not enhance the rate of illusory conjunctions. These data suggest that neural synchrony generated externally by synchronous presentation of stimulus features is not critical to feature binding. It does not exclude the possibility that internally generated synchrony is important, possibly generated by a top-down segmentation or parsing process.

Other psychophysical reports looking at stimulus synchrony have used periodic stimuli and focused on temporal phase effects in figural grouping or texture segmentation. Some have shown positive results for synchronized stimulus elements (Alais, Blake, & Lee, 1998; Usher & Donnelly, 1998; Leonards, Singer, & Fahle, 1995; Leonards & Singer, 1998), and others have not (Fahle & Koch, 1995; Kiper, Gegenfurtner, & Movshon, 1991). A recent physiological study in V1 (Lamme & Spekreijse, 1998) failed to produce support for the idea that figural binding in texture segmentation is mediated by synchronous neural activity.

It may have been that the perceptual grouping induced by stimulus synchrony in some of the cases

mentioned above could actually have been the result of top-down processing, particularly given the long durations and periodic nature of the stimuli. In other words, it may not have been stimulus synchrony per se that caused binding, but a high-level process deciding that this pattern of input, recurrent over an extended period, was “interesting.” By using a single, quick, flashed stimulus instead of long-duration periodic stimuli, this study may have been better suited for capturing the effects of bottom-up processing less contaminated by top-down processing. In any case, the grouping of similar features at different locations, as studied in the investigations cited above, may simply be a different problem than binding completely different feature classes (color and shape) at a single location, as is involved in illusory conjunctions.

Overall, this study has demonstrated strong effects of isoluminance on the processing of shape information and the interaction of shape and color. Since isoluminance is known to affect particular neural populations through well-studied anatomical pathways, the potential exists for examining the physiological basis of these psychological observations, and expanding our understanding of the neural basis of feature binding.

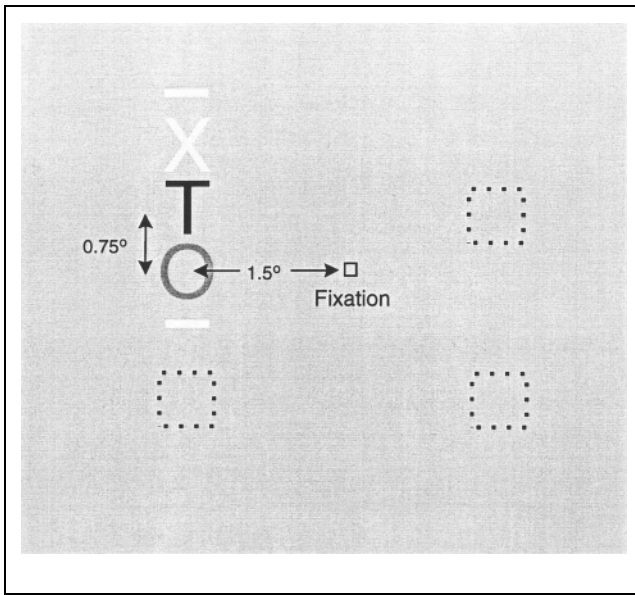
## METHODS

Three colored letters, arranged in a column against a gray background, were flashed on a computer screen at one of the four random locations (Figure 7). Subjects were required to identify the shape and color of the center letter. Error rates were tabulated for stimuli whose luminances were lower, the same, or higher than background luminance.

### Stimulus

Each letter had a different color and shape. Shapes were selected from the following four possibilities: X, T, O, R. The shapes were displayed in Helvetica 18-point type viewed at a distance of 44 cm, subtending a visual angle of about  $0.83^\circ$ . Spacing between letters, going from the bottom of one letter to the top of the next letter below, was  $.1^\circ$ . Colors were selected from the following four possibilities (with CIE color coordinates): orange (.50, .39), green (.30, .53), blue (.18, .16), and magenta (.29, .17). The top and bottom of the letter column were marked by short horizontal white lines for subjects SW and PK, and randomly chosen white numerals for the earlier experiments with subject SL.

There were three luminance conditions, in which the luminances of the colored letters were lower, equal, or higher than that of the gray background. The gray background had a luminance of  $15 \text{ cd m}^{-2}$ . The luminances of the colored letters for the three conditions were: (a) Low luminance:  $10.6 \text{ cd m}^{-2}$  ( $-.15 \text{ log units}$  relative to background); (b) Isoluminance:  $15.0 \text{ cd m}^{-2}$



**Figure 7.** Configuration of stimulus. Three colored letters arranged in a column (colors indicated by gray levels here) were flashed at one of four random locations  $.75^\circ$  vertically and  $1.50^\circ$  horizontally ( $1.67^\circ$  radially) from fixation. The task was to identify the shape and color of the central letter. The luminance of the three letters which were all the same during a given trial, could be higher, identical, or lower than the gray background for different trials. Nonisoluminant white markers indicated the top and bottom ends of the stimulus column. The rate of conjunction errors and feature errors was tabulated for each of the three luminance conditions. Dotted squares indicate possible stimulus locations, and were not actually part of the display.

(.00 log units); (c) High luminance:  $21.2 \text{ cd m}^{-2}$  (+.15 log units). The isoluminance point for the colors was set photometrically using a Minolta CS-100 meter. Within a single trial, all three letters had the same luminance. The white end-markers at the tops and bottoms of the stimulus columns were always nonisoluminant.

For each trial, the column of three letters would appear at one of the four random locations. Relative to fixation, the center of the column could be at  $\pm .75^\circ$  vertical and  $\pm 1.50^\circ$  horizontal. Following the flashed display of the letters, they were immediately masked by a black and white random checkerboard pattern. Each checkerboard square was four pixels across, placing them roughly in the same spatial frequency band as the stimulus letters.

### Task

The sequence of events for each trial was as follows. During the intertrial period, the screen was black. The subject started the trial by pushing a button. This caused a gray background square  $8^\circ$  across to appear. One second after the background appeared, a small light gray fixation spot appeared at its center. The fixation spot was displayed for 850 msec and then removed. Then, 150 msec after the fixation spot dis-

appeared, the three stimulus letters were flashed synchronously at one of the four random locations, and then masked. The duration of the stimulus was adjusted for each subject to bring the rate of correct trials down to around 80–85%, and was in the range 100–150 msec. This was sufficiently short so as not to allow saccades to the target.

Following presentation of the stimulus, a dialog box appeared on the screen, which allowed subjects to indicate the shape and color of the center letter. This dialog box had eight large buttons, four representing the possible colors and four representing the possible shapes. The subject responded by clicking one of the “color” buttons and one of the “shape” buttons with the computer mouse. The “color” buttons were labeled by simply being the appropriate color, and the “shape” buttons were labeled with the appropriate shapes in black. Reporting the characteristics of the central letter was the sole task of the subjects. There was no other attention-diverting task that had to be performed concurrently.

### Experimental Runs

An experimental run consisted of 240 trials, in which the three luminance conditions were randomly interleaved, so that there were 80 trials for each condition. It lasted for about 30 min. Data from 10 experimental runs were pooled, so that each data point reflects data from 800 stimulus trials. Every 60 trials, an announcement appeared on the screen indicating the cumulative percent of correct trials, pooled over all conditions, since the beginning of the run. This was intended to serve as a motivational device for the subjects. Every run started with 10 “warm-up” trials, automatically excluded from the data analysis, so that including these, there were actually 250 trials in a run.

Prior to the start of data collection, subjects were given 20 practice runs. This was done in an effort to reduce shifts in the data caused by perceptual learning by moving the learning to the practice phase. During the practice phase, after the subject had made a response for each trial, the actual three-letter stimulus used in the trial was displayed on a second video monitor to one side, which the subjects could inspect if they chose. This feedback was not available during the actual data collection.

### Colored Masks

In some cases, the monochromatic checkerboard mask was replaced by a colored checkerboard pattern. In these cases, the squares of the checkerboard were randomly assigned one of the four colors used in the stimulus display. The purpose here was to see if a colored mask disrupted processing of color more than a monochromatic one.



## Cues

One variant of this experiment was designed to test if effects of isoluminance were due to an inability to focus attention at the target location. For this variant, the location of the target letter was marked with a nonisoluminant cue preceding presentation of the stimulus. This cue was a hollow white square  $1.2^\circ$  across surrounding the position of the target letter. The cue was displayed for 40 msec, followed by an 80-msec blank period, at which point the letter display appeared. A 40-msec cue exposure plus an 80-msec blank period resulted in a 120-msec asynchrony between cue and target, or a 120-msec "cue lead time." The cue lead time was kept short so as not to allow a saccade to the stimulus. Long cue times might have confounded attentional effects with acuity effects as the subject foveated the target.

The data of Nakayama and Mackeben (1989) suggest that the cue lead times used here should be sufficiently long to produce a significant improvement in task performance, if indeed any cue-related enhancement effects exist for this task. While their optimal cue lead times varied with task and subject, 120 msec produced attentional effects within about 70% of the peak.

## Asynchrony

In another variant, which was designed to test the effects of synchronous and asynchronous presentation of features on binding, there were three timing conditions for the target and flanking letters. The two flanking letters could appear before, synchronously, or after the central target letter. The stimulus onset asynchrony between the center and flankers depended on subject, and was either 53 or 67 msec. The presentation durations of the three letters were identical, so that the offset asynchronies were the same as the onset asynchronies. Each letter was masked individually as soon as its presentation finished.

## Single Letters

Another experiment was designed to measure how well a single flashed letter could be identified. In this variant, only the central letter of the three was presented, and the subject indicated its shape and color. For these experiments, the white end bars marking the tops and bottoms of the stimulus were also removed, so that nothing appeared in the stimulus except the single flashed letter, at one of the four possible random locations.

## Possible Responses

Responses were placed into three categories: correct, conjunction error, or feature error. A correct response meant that the subject got both the color and shape of

the target letter right. A conjunction error occurred if the subject combined one feature of the central target letter (e.g., color) with one feature of a flanking letter (shape, in this case). If the wrong color was combined with the correct shape it was called a color illusion, and vice versa. If two features from the flanking letters were reported as belonging to the central character, this also was counted as a conjunction error. In practice this occurred fairly infrequently (around 7% of conjunction errors were double conjunction errors), so that these trials were not broken out into a separate category. A feature error occurred if the subject reported at least one feature that did not occur in the stimulus display at all. In principle, the feature error category could have been broken into three finer categories depending on the nature of the two features reported: nonexistent/correct, nonexistent/illusory conjunction, nonexistent/nonexistent. Again, in practice, the last two possibilities occurred so infrequently (under 1% of feature errors) it did not seem worth subdividing the feature error category.

## Subjects

Three subjects were used. SL, the author, was an experienced psychophysical subject, and was aware of the purposes of the experiment. PK and SW were novice psychophysical subjects, and had no knowledge of the purpose of the experiment. Both PK and SW were from India, and their native alphabet did not include the Roman characters used as stimulus patterns, though they were familiar with the Roman alphabet.

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