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Illusory Conjunctions Inside and Outside the Focus of Attention

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This article addresses 2 questions that arise from the finding that visual scenes are first parsed into visual features: (a) the accumulation of location information about objects during their recognition and (b) the mechanism for the binding of the visual features. The first 2 experiments demonstrated that when 2 colored letters were presented outside the initial focus of attention, illusory conjunctions between the color of one letter and the shape of the other were formed only if the letters were less than 1° apart. Separation greater than 2° resulted in *fewer* conjunction errors than expected by chance. Experiments 3 and 4 showed that inside the spread of attention, illusory conjunctions between the 2 letters can occur regardless of the distance between them. In addition, these experiments demonstrated that the span of attention can expand or shrink like a spotlight. The results suggest that features inside the focus of attention are integrated by an expandable focal attention mechanism that conjoins all features that appear inside its focus. Visual features outside the focus of attention may be registered with coarse location information prior to their integration. Alternatively, a quick and imprecise shift of attention to the periphery may lead to illusory conjunctions among adjacent stimuli.

Several different lines of evidence strongly indicate that during early vision, different features of each object are analyzed independently and the analysis is performed in parallel across the visual field. Features such as color, size, orientation, and direction of movement have been suggested as candidates for this stage. Because our own research is concerned with illusory conjunctions, we review only such studies here. Extensive reviews of the other lines of evidence are available elsewhere (e.g., Cohen, 1987; Livingstone & Hubel, 1987; Treisman, 1986b).

Synder (1972) briefly presented a circular array of 12 colored letters. Subjects were asked to name the one letter in the array that had a specific color (e.g., red). When the subjects made errors, they tended to choose one of the two letters that were adjacent to the correct one. This finding indicates that in many cases the features in the display (letters and colors) were correctly perceived but wrongly combined. Treisman and Schmidt (1982) reported a more sophisticated analysis of illusory conjunctions. They tachistoscopically presented a display that contained two small digits, one on each side of the visual field. Three colored letters were located between the digits. The letters and colors in each trial were selected from a pool of six letters and six colors. The primary task of the subjects was to report the two digits; in addition, they had to report as much information as possible about the rest of the display. The critical question centers on the errors. Treisman and Schmidt found that subjects tended to erroneously combine features of two different objects that were present in the display rather than select a feature that was not present at all in the display. These results and similar other findings (Prinzmetal, 1981; Prinzmetal, Presti, & Posner, 1986) indicate that different features are analyzed at some point separately and independently. Thus if the perceptual system is not given enough time to process the objects further, illusory conjunctions can be formed.

Two problems arise from these findings. The first problem concerns the nature of the mechanism for feature binding. The second problem concerns the accumulation of location information.

Mechanism for Feature Binding

The suggestion that objects across the visual field are parsed into features poses a difficulty for the perceptual system that would not have arisen had the objects been processed as whole units. Given that features from different dimensions (e.g., color, orientation) are registered independently, there must be a process by which objects are assembled by a conjoining of the appropriate features. What is the mechanism that enables the perceptual system to perform this binding? This binding problem seems to be central in perception (Savoy, 1987). Despite its certrality, little empirical work has been done on the topic.

Few theories for the solution of the binding problem have been proposed. Von der Malsburg (1985) proposed a temporal mechanism for the conjunction of features. According to this proposal, the focal attention mechanism scans the visual field, and at any given time, it is in some specific location. If features are present at that location, they will be coactivated

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(or inhibited). The features that are activated at the same time are conjoined. Crick (1984) also proposed a similar temporal mechanism. However, several tests of this hypothesis failed to obtain supporting evidence (Keele, Cohen, Ivry, Liotti, & Yee, 1988).

A more notable theory on the mechanism of feature conjunction is the feature integration theory of Treisman (1986a; Treisman & Gormican, 1988; Treisman & Schmidt, 1982). According to the feature integration theory, there are two main stages in object recognition. During the first stage, features from different dimensions are registered in different spatiotopic maps. During the second stage of processing, according to the feature integration theory, a focal attention mechanism conjoins the registered features in the focused locations. The mechanism of focal attention operates in the following way: In addition to the different feature maps, there exists a master map of locations with "hardwired" links to the feature maps. The focal attention mechanism selects a filled location in the master map, which in turn activates the features registered at that location in all the feature maps, and the activated features are conjoined. Focal attention does not need to activate a single location in the master map of locations. Instead, like a spotlight, it can spread over several locations in the master map and thus conjoin the features registered in all these locations. The notion of attention as a spotlight or a beam is not new and has been proposed by several investigators (e.g., Eriksen & Hoffman, 1972; Hoffman, 1975; LaBerge, 1983; Posner, Snyder, & Davidson, 1980). However, in their studies they were primarily concerned with the facilitatory and inhibitory effects of spatial attention, whereas the focal attention mechanism of the feature integration theory deals with the conjunction of perceived features. Therefore, the similarity between the attentional spotlight proposed by these investigators and the focal attention spotlight proposed by the feature integration theory should be viewed with caution (but see Prinzmetal et al., 1986, and Briand & Klein, 1987, for evidence of some relation between the two mechanisms). Nevertheless, the studies of Eriksen and Hoffman (1972), Hoffman (1975), LaBerge (1983), and Posner et al. (1980) indicate that the perceptual system can use mechanisms with spotlightlike properties.

Despite its widespread recognition as an important theoretical construct, the focal attention mechanism for feature conjunction has never been tested directly. There is no direct evidence for the proposed master map mechanism of focal attention, nor is there direct evidence for the spotlight properties of this mechanism. We return to this issue in the second part of the article.

Accumulation of Location Information

On the basis of the evidence reviewed earlier, there are at least two possible ways to account for the accumulation of location information. One possibility is that during the registration of features in the visual field, information about the location of these features is also registered. Alternatively, the information about the location of the objects may be processed only during the stage in which the conjunction of the features is performed.

There is some evidence that location information is available only at the time in which the features are conjoined. Treisman and Gelade (1980) found that when subjects had to detect a target composed of a single feature in a visual search task, they frequently could not localize it correctly (see also Nissen, 1985). When the target was composed of a conjunction of features, on the other hand, localization of the target was almost always accurate. However, search for a single feature is easier than search for a conjunction of features; thus in Treisman and Gelade's experiments, the feature search was either shorter or more accurate. It is possible that these differences caused the differential localization information.

Stronger evidence that location information becomes available only during the conjunction process was observed in Treisman and Schmidt's (1982) studies on illusory conjunctions. The tendency to form illusory conjunctions was not affected by the distance between the objects; that is, subjects exchanged features between relatively distant objects just as often as they did between adjacent objects. This finding suggests that features are not bound to any specific location.

Other studies, however, do not support the suggestion that features can be identified without location information. Eriksen and Rohrbaugh (1970) briefly presented to their subjects a circular display of letters. A bar marker pointed to one of the letters, and the subjects had to identify the letter. The authors found that when the bar was presented simultaneously with the letters or 50 ms later, subjects who failed to identify the correct letter tended to name an adjacent letter rather than a distant letter. This finding suggests that some information about the location of features is retained.

Several experiments on illusory conjunctions also indicate that some information about the position of features is available with their registration. As described earlier, Snyder (1972) found that illusory conjunctions occur primarily between adjacent locations. This preference for adjacent objects is easily explained with the assumption that some information about the location of the features is available to the perceptual system. Keele et al. (1988) reported similar findings.

The No-Location Hypothesis

Treisman and Schmidt (1982) argued that features are first perceived without their location information. More precisely, the features are perceived within spatiotopic maps, but the location information in the feature maps is implicit and is not available to the perceptual system. In some sense, the features are free floating before the stage in which they are conjoined. We refer to this view as the *no-location hypothesis*. Information about the features is available with their registration. However, information of the object location becomes available to the perceptual system only during the conjunction of the features. An additional important assumption of the no-location hypothesis is that although features are free floating, the conjunction mechanism is constrained to operate only on features that are present inside the focus of attention. Therefore, illusory conjunctions can occur only between objects that are either both inside the focus of attention or both outside it. The critical point with regard to the occurrence of illusory conjunctions is not the distance between the objects but whether both of them are inside or outside the focus of attention.

The no-location hypothesis is made less tenable by the results of Snyder (1972), Eriksen and Rohrbaugh (1970), and Keele et al. (1988). However, in all of these experiments, the subjects had to look at a fixation point at the center of the visual field, and the objects were presented in the periphery. There was no independent way to assess whether the subjects kept focusing their attention at the fixation point or whether they shifted their attention to the target with its appearance. According to the feature integration theory, one identifies multiple objects in succession by shifting attention from one object to the next. Therefore, shifts of attention have to be executed very fast by the visual system. It is possible, according to Treisman and Schmidt (1982), that the subjects had enough time to shift their attention to the cued area of the target. Because of time pressure, the attentional spotlight could not be focused enough and may have included adjacent objects. In these cases, illusory conjunctions could occur between the target and the adjacent stimuli that were inside the focus of attention, but not between the target and distant stimuli. As a result, illusory conjunctions in these experiments occurred primarily between adjacent objects.

The Location Hypothesis

An alternative explanation, which we call the *location hypothesis*, is that features are perceived with some coarse or partial information about their location. This information is not accurate enough to prevent confusion of features between adjacent objects, but it is sufficient to prevent confusion of features between distant objects. This explanation immediately accounts for the findings of Snyder (1972) and Eriksen and Rohrbaugh (1970). It does not, however, explain the findings of Treisman and Schmidt (1982) that illusory conjunctions can be formed between objects regardless of the distance between them. A possible explanation is that the primary task in Treisman and Schmidt's study required the subjects to spread their attention to the location of the two digits that were situated at the extreme display positions. The colored shapes were always presented between the two digits and thus could be considered to be inside the attentional spotlight. It is possible that inside the spotlight, there is a tendency to conjoin all the features regardless of the distance between them, whereas outside the spotlight, illusory conjunctions occur only between adjacent objects.

One of the key differences between the two views is the explanation for the findings of Snyder (1972), Eriksen and Rohrbaugh (1970), and Keele et al. (1988) that illusory conjunctions can occur only between adjacent objects. According to the no-location hypothesis, illusory conjunctions will occur only between adjacent objects because of a shift of attention to the stimuli area. The location hypothesis, on the other hand, does not assume such a shift. One way to evaluate the relative merits of these two explanations is to prevent the subjects from shifting their attention. The no-location hypothesis, as expressed by Treisman and Schmidt (1982), predicts that under these conditions illusory conjunctions will be formed regardless of the distance between the objects. The location hypothesis predicts that because of the availability of coarse location information with the registration of the features, illusory conjunctions will be formed only between adjacent objects.

In the first two studies we examined the occurence of illusory conjunctions in the periphery when the focus of attention was initially directed to the center of the visual field. The experiments were similar to the ones reported by Snyder (1972) with two differences. First, we used the technique originally introduced by Treisman and Schmidt (1982) to distinguish between errors in identifying basic features and errors in conjoining features. Second, the subjects were required to first identify a digit in the center of the screen.

Experiment 1

The purpose of the first experiment was to examine whether the occurrence of illusory conjunctions between objects outside the initial focus of attention is a function of the distance between the objects. Each trial began with the appearance of a fixation point in the center of the visual field. After that, the fixation point was replaced by a display that contained a white digit and two colored letters. After a short exposure period, the display was masked. This was done in an attempt to erase the display before the subjects could shift their attention from their original focus at the digit location (cf. Treisman & Schmidt, 1982). The digit was always presented in the center of the visual field in the exact position of the fixation point. The two letters were presented in two of eight possible positions that form an imaginary circle around the center of the visual field (see Figure 1).

The primary task of the subjects was to report the digit that appeared in the display. Subjects were told that the identifi-

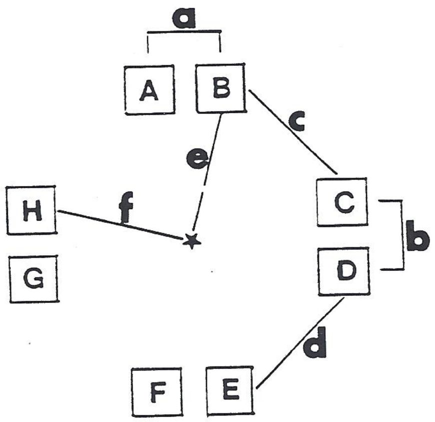

Figure 1. Possible locations of the stimuli used in Experiments 1 and 2. (The star represents the location of the digit, and it is located in the center of the visual field. The eight squares represent the possible locations of the two letters. The two right positions are symmetric to the two left positions, and the two top positions are symmetric to the two bottom positions. The lowercase letters represent the distance in visual angle between the stimuli. In Experiment 1, a = 0.77°; b = 0.99°; c = d = 2.86°; e = 2.64°; and f = 2.42°. In Experiment 2, a = 0.73°; b = 0.94°; c = d = 2.91°; e = 2.5°; and f = 2.71°.)

cation of the digit was the most important part of their task. This procedure was used to ensure that the subjects focus their attention on the center of the visual field.

The secondary task of the subjects is similar to that used by Prinzmetal et al. (1986, Experiment 3). One of the colored letters, the distractor, was always *O*, whereas the target letter could be either *X* or *F*. Two different colors were selected without replacement on each trial from a pool of four possible colors. The subjects' task was to report the color and identity of the target letter. For instance, if the display contained a green *O* and a blue *X*, the correct response was blue *X*.

Of principal interest is the type of mistakes that subjects made in the secondary letter task. According to the terminology used by Treisman and Schmidt (1982), there are two types of errors that can be made. The first type is a *feature error* in which the subject misperceived a single feature in the display. The subject could misidentify the letter (a letter feature error) or the color (a color feature error). For example, in a display composed of a green *O* and a blue *X*, a letter feature error would be a report of blue *F*. A color feature error would result from a report of pink *X*. A report of pink *F* would constitute both letter and color feature errors. Notice that in feature errors, subjects report a feature that was not present at all in the display. The second type of error is called a *conjunction error*. In this case the subject succeeded in identifying the features in the display but erronously combined features that belong to different objects. In the example just given a report of green *X* is a color conjunction error. Letter conjunction errors were not possible in this task.

The key question is whether the probability of illusory conjunctions is a function of the distance between the two letters. Because in this task there could not be letter conjunction mistakes, we could examine this question only by comparing the relative amount of color feature errors and color conjunction errors. The critical analysis would be the type of error that was made when the letter was correctly perceived and the color was misperceived. When the target color was not reported, there were three other colors that could be reported: the color of the distractor letter and the two colors that did not appear in the display. Thus if subjects did not see any color and simply guessed when they misperceived the color, they should have made twice as many feature errors as conjunction errors. A ratio of conjunction errors to feature errors greater than 1:2 indicates the presence of illusory conjunctions. A third possibility is that the ratio of conjunction errors to feature errors is smaller than 1:2. We extensively discuss this possibility and its possible cause in the *Results* section.

Method

Subjects. Eighteen undergraduate psychology students from the University of Oregon, all of them native English speakers, participated in the experiment as part of their course requirements.

Stimuli. The stimuli were presented on an Amdek color monitor controlled by an Apple IIe computer. Subjects viewed the display from a distance of 84 cm. The stimuli that were presented consisted of an asterisk, digits between 1–4, and the letters *O*, *F*, and *X*. An individual character in the display subtended approximately 0.88° of visual angle in height and 0.66° in width. The digit on each trial was randomly selected from the four possible digits. The display also included the letter *O* with either *F* or *X*. The selection of the letters was determined randomly. The letters were presented in four different colors that matched Munsell values 5RP 7/10 (pink), 10YR 8/14 (yellow), 2.5BG 8/6 (green), and 5PB 6/10 (blue). The colors of the letters on each trial were selected randomly and without replacement from these four colors. The two letters could appear in any two of eight possible locations (see Figure 1). The letters were considered adjacent if they both appeared in the top part (locations A and B, hereafter Pair AB), the right part (Pair CD), the bottom part (Pair EF), or the left part (Pair GH) of the screen. The location of the letters was determined in the following way: There were 28 possible pairs of locations. Adjacent locations were selected four times in a block of trials. The remaining pairs of positions were selected twice in a block. Thus each block of trials included 64 trials, of which in 16 the letters were adjacent. For any given pair, the target letter was equally likely to appear in either position. The display was masked by a random mixture of small squares in different colors that covered the whole screen. The distance in visual angle between the center of the visual field and each of the possible eight positions of the letters and the distance between adjacent positions in the display are presented in Figure 1. Because of a technical limitation, the distances of the top and bottom positions from the center were slightly longer than the distances of the left and right positions from the center. For the same reason, the distances between the two adjacent pairs in the top and bottom parts of the screen were somewhat shorter than the distances between the adjacent letters on the right and left sides of the screen.

Procedure. At the beginning of each trial, an asterisk, serving as a fixation point, was presented in the center of the screen. Subjects were instructed to keep their eyes on that location for the remainder of the trial. After 1,000 ms the asterisk was replaced by a display that consisted of a digit in the exact position of the asterisk and two letters, one of them *O* and the other either *F* or *X*. The display was presented for 200 ms during practice and for 67 ms during the test blocks. The display was masked for 100 ms. The subjects responded with a four-key device. Each one of the keys was assigned to a single digit and color. Two of the keys were also assigned to one of the target letters. The subjects had to first report the digit by pushing the appropriate key. Next, they reported the color and, last, the name of the target letter. The fixation point for the next trial appeared 1,000 ms after the last response. Subjects were told that it was most important to report the digit accurately. They were also instructed to guess in cases in which they missed any of the characters.

After one block for practice, each subject received five test blocks. No feedback with regard to performance was given during the experiment.

Results and Discussion

The primary task of the subjects was to report the digit that had appeared in the center of the visual field. The purpose of this task was to ensure that attention was focused on the center. Subjects reported the digit correctly in 96.3% of the trials.

Of more interest are the results of the secondary letter task. Only trials in which the digit was reported correctly were used in this analysis. As mentioned earlier, there were four adjacent pairs (AB, CD, EF, GH); all of the other possible pairs of locations were considered "far." The proportion of correct responses and proportions of the different types of errors that made in the adjacent and the far conditions are presented in Table 1.

Table 1
Average Proportions of Correct Responses and of the Errors Made in Letter Task: Experiments 1 and 2

	Experiment 1		Experiment 2	
Type of response	Adjacent	Far	Adjacent[a]	Far[a]
Correct	.535	.679	.608	.759
Color feature	.171	.160	.101	.101
Color conjunction	.135	.061	.130	.041
Letter feature	.063	.050	.074	.055
Letter and color feature	.052	.033	.047	.029
Letter feature and color conjunction	.044	.017	.039	.016

[a] Column does not add to 1.00 because of rounding errors.

The critical comparison was the relation between the feature errors and the conjunction errors. If subjects guessed a color when they missed the correct color, there should have been twice as many color feature errors as color conjunction errors. We refer to this proportion of feature to conjunction errors as the *baseline level*. There are two other possibilities: According to the no-location hypothesis, equivalent proportions of illusory conjunctions should be observed in both the adjacent and the far conditions. This interpretation is correct only if the digit task forced the subjects to focus their attention on the center until the appearance of the mask. Alternatively, the location hypothesis postulates that there should be more conjunction errors in the adjacent condition because location information may not be accurate enough to separate the two adjacent positions. Moreover, in the far condition there should be *fewer* color conjunction errors than expected according to the baseline level because when the target letter (either *F* or *X*) is perceived, coarse location information of that letter is registered as well. Similarly, when the color of the *distractor* letter is perceived, its coarse location is also registered. When the target and distractor are far from each other, the location information is sufficient to prevent the conjunction of the distractor color and the target letter. Thus when subjects identify the target letter and the distractor color but miss the target color, they have sufficient information to exclude the distractor color and consequently tend to make primarily color feature errors. A similar prediction would be made by the no-location hypothesis if the subjects were able to shift their attention to the periphery before the appearance of the mask.

The results are supportive of the location hypothesis. In the adjacent condition, the ratio of color conjunction errors to color feature errors was significantly higher than the predicted baseline level of 0.5, $t(17) = 5.22$, $p < .05$. In the far condition, this ratio was significantly lower than predicted by the baseline level, $t(17) = 1.954$, $p < .05$. Because the phenomenon of committing fewer conjunction errors than expected by baseline reflects a tendency to exclude the color distractor, it is hereforth called *exclusionary feature errors.*

The finding that illusory conjunctions occur in the adjacent condition and exclusionary feature errors occur in the far condition is also important for methodological reasons. In particular, it rules out the possibility that illusory conjunctions are due to either general strategic response or memory failure on the part of the subjects. Unlike our finding, general strategic response or memory failure should affect the adjacent and the far conditions equally. This methodological argument is also valid for the remaining studies reported in this article.

There may be a different interpretation of the results. One may argue that the difference in conjunction errors between the far and the adjacent conditions is primarily due to the difference in letter errors between the two conditions; that is, it is possible according to this argument that on many occasions the subjects did not perceive the letters but did perceive the colors. Not knowing which color belonged to the target, they simply reported one of the colors, thereby increasing the proportion of conjunction errors. Probabilistic considerations of the results, however, strongly indicate that this interpretation cannot account for the results. The details of this statistical analysis are presented in the Appendix.

Both the far and the adjacent conditions consisted of several pairs of locations for the two letters. Some of the pairs of locations in the far condition differed in the distance between the target and the distractor letters. For instance, as depicted in Figure 1, the two positions of Pair BC were closer than those of Pair BD, which in turn were closer than the locations of Pair BE. In fact, there were five distances between the target and the distractor. An analysis of variance (ANOVA) revealed that there were no significant differences between the five distances, $F(4, 68) = 0.3$, $p > .05$. Subjects committed exclusionary feature errors in all five distances. The conclusion implied by these findings is that above a distance of 2.5° of visual angle, there is a tendency to form the same amount of exclusionary feature errors, regardless of the exact distance.

In Table 2 we present the proportion of correct responses and the proportions of the different types of color errors made in the four different pairs of the adjacent condition. The results were surprising. The overall analysis had shown that subjects made illusory conjunctions in the adjacent condition. When that condition was decomposed into specific pairs, the result was obtained only for the top and bottom pairs. For the left and right pairs, subjects tended to make no more conjunction errors than expected by chance. There are a couple of possible explanations for this finding. First, the top and bottom pairs were separated horizontally, whereas the right and left pairs were separated vertically. Prinzmetal and Keysar (1989) recently demonstrated that there is a greater tendency to form illusory conjunctions between objects that are separated horizontally than between objects that are sep-

Table 2
Proportions of Correct Responses and of Color Errors Made in the Adjacent Condition: Experiments 1 and 2

Location	Correct	Color feature	Color conjunction
Experiment 1			
Top	.444	.165	.171
Bottom	.405	.196	.190
Right	.655	.164	.096
Left	.632	.159	.084
Experiment 2			
Top	.485	.107	.188
Bottom	.530	.116	.168
Right	.720	.105	.076
Left	.690	.078	.092

arated vertically. Another possible interpretation is that the separation in visual angle between the two locations in the right and left sides is bigger than the one in the top and bottom sides (1° of visual angle versus 0.77°). It is possible, therefore, that within a distance of 0.77°, the location information available with the registration of the features is not sufficient to distinguish between the two locations, and thus illusory conjunctions are formed. With a distance of 2.5° or more, the location information is accurate enough to distinguish between the two locations, and exclusionary feature errors are formed. However, with a distance of 1°, the accuracy of the location information is intermediate; that is, sometimes it is enough to distinguish between the two locations and sometimes it is not. We further discuss this issue in Experiment 2.

In the first experiment we examined only the effect of distances of less than 1° or more than 2.5°. To assess the effect of intermediate distances, we ran an additional experiment with 14 subjects. The design of this experiment was similar to the first experiment; the only difference was in the distance between the letters. In this experiment we examined distances of 1.5° and 2.17°, as well as larger distances. We found that with a distance of 1.5°, the amount of color conjunction errors in relation to color feature errors did not differ significantly from that predicted by the baseline level, $t(13) = 0.786$. The ratio of color conjunction to color feature errors in distances of 2.17° or more was lower than 0.5, $t(13) = 4.5$, $p < .05$.

In sum, the results demonstrate that when two objects are briefly presented outside the focus of attention, illusory conjunctions are formed only when the distance between the objects is less than 1° of visual angle. When the distance between the objects is more than 2° of visual angle, exclusionary feature errors are made. In intermediate distances of between 1° and 1.5° of visual angle, the ratio of color conjunction errors to color feature errors is about 0.5.

These results appear to support the assertion of the location hypothesis that features are registered with coarse location information. However, as mentioned earlier, the no-location hypothesis may still be able to explain the results as well. The location hypothesis assumes that because the subjects primarily had to report the digit in the center of the field, the letters were presented outside the focus of attention. Proponents of the no-location hypothesis may argue that this assumption is not justified. Visual search experiments have demonstrated that a search for a digit among letters can be done in parallel across the visual field (e.g., Duncan, 1983; Jonides & Gleitman, 1972). Therefore, it is possible that the subjects did not need to focus their attention on the center of the visual field. Instead, they may have shifted their attention to one of the letters that were presented in the periphery. This shift of attention could lead to the results obtained in the experiments. Experiment 2 was designed to further examine this possibility.

Experiment 2

The main purpose of this experiment is to replicate the results of the previous experiments with a more stringent control of the subjects' focus of attention. In order to achieve that, the primary digit task was changed. In this experiment, subjects were presented with two white digits in the center of the visual field and two colored letters in the periphery. The two digits were horizontal to each other. One of the digits was the same size as the letters, and the other digit was half of that size. In half of the trials the small digit was presented on the left side of the screen, and in the remaining half it was presented on the right side. The task for half of the subjects was to report the large digit; the other subjects were instructed to report the small digit. This modified primary task requires the subjects to report a conjunction of size and shape (the digit). Treisman and Schmidt (1982) showed that size and shape are independent visual features. Because conjunction discrimination requires focused attention (Treisman & Gelade, 1980), the subjects should have had to focus their attention on the center of the screen to be able to perform successfully in the primary task.

The letter task of the subjects was identical to the one used in the first experiment. The locations were nearly identical to those used in the first experiment (see Figure 1). The small changes were made necessary by the addition of the second digit in the center.

Another difference between this experiment and the previous one is in the exposure duration of the display. In the first experiment the exposure duration of the display was fixed for all the subjects at 67 ms. In this experiment the exposure duration was determined individually during the first phase of the session. This procedure was used to ensure that the subjects achieved a criterion level of performance in the digit task.

Method

Subjects. Eighteen undergraduate psychology students, all native English speakers, participated in the experiment as part of their course requirements. None of them had participated in the previous experiment.

Stimuli. Most of the stimuli are identical to the ones used in the first experiment. The only differences between the experiments were that in this one, subjects viewed the monitor from a distance of 87 cm; the letters, the asterisks, and the large digit subtended approximately 0.83° of visual angle in height and 0.62° in width; and the small digit was exactly half the size of the large digit. The distance in visual angle between the eight possible locations of the letters and their distance from the center is depicted in Figure 1.

Procedure. At the beginning of each trial, two asterisks appeared on the center of the screen for 1,000 ms. After that, a display that included two digits and two letters appeared on the screen. The digits were presented in the exact positions in which the asterisks had appeared. The two letters were presented in the periphery. The display was presented for an individually determined time, after which the pattern mask appeared for 100 ms.

The exposure time of the display was determined in the following way. First, a block of 20 trials in which the exposure duration of the display was 200 ms was run. This block was run to familiarize the subject with the task. Next, the exposure duration was reduced to 100 ms, and another block of 20 trials was run. If the subject was correct in responding to the digit task on at least 18 trials (the criterion of success), the exposure duration was reduced to 83 ms, and another block was run. If the subject again achieved the criterion level of performance, the exposure time was reduced to 67 ms, and a final block was run. The exposure time was not reduced below 67 ms because pilot studies had indicated that subjects were not able to perform the letter task at shorter exposures. The exposure duration of the last block in which the subject reached the criterion was set as the exposure time of the display in the experiment. The exposure time was 67 ms for ten subjects and 83 ms for eight subjects. After the determination of the exposure time, four experimental blocks were conducted.

Results and Discussion

The subjects correctly reported the target digit in 96.5% of the trials. This high level of performance indicates that, as instructed, the digit task was regarded as primary by the subjects.

The results of the letter task were analyzed only for trials in which the digit was reported correctly. The proportion of correct responses and the proportions of the different types of errors made in this task are presented in Table 1.

The pattern of errors in this experiment was basically similar to the one obtained in the first experiment. In the adjacent condition, the ratio of color conjunction to color feature errors was higher than predicted by baseline, $t(17) = 5.14$, $p < .05$. In the far condition, there was a tendency to form exclusionary feature errors. However, this tendency only approached significance, $t(17) = 1.38$, $p < .1$. Nevertheless, it is obvious that the patterns of results in the adjacent and in the far conditions were fundamentally different.

As in the first experiment, the far condition was divided into five groups according to the distance between the two letters. An ANOVA did not reveal any difference in the type of color errors between the various distances, $F(4, 68) = 1.56$, $p > .05$.

The adjacent condition was composed of four different pairs. The results for the different pairs are presented in Table 2.

As in the first experiment, more illusory conjunctions were made in the top and bottom pairs. However, unlike the first experiment, the number of the illusory conjunctions was above the amount expected by baseline even in the right and left pairs. There were minor differences between Experiments 1 and 2 in the arrangement of the right and left letters. The left and right letters in Experiment 2 were slightly more distant from the center of the visual field and slightly closer to each other. These differences could account for the differences in results of the two experiments. Obviously, when the letters are closer, it becomes harder to differentiate between them on the basis of location information. It is also possible that location information is less accurate when the letters are more peripheral. This explanation is in accord with the argument, mentioned earlier, that the difference in the adjacent condition between the top and bottom pairs and the right and left pairs is due to the fact that the two top letters, as well as the two bottom letters, are closer to each other than are the two right or the two left letters. Nevertheless, it is also possible that illusory conjunctions occur more often when the objects are horizontal to each other (see Prinzmetal & Keysar, 1989).

These results appear to support the contention of the location hypothesis that visual features such as color are registered with location information. The location information is not accurate enough to distinguish between the location of two neighboring features. However, it is accurate enough to prevent the migration of a perceived feature beyond a certain distance. Making the digit task more difficult did not change this pattern of results.

The no-location hypothesis must again hold that subjects shift their attention to the periphery. This interpretation cannot be entirely ruled out. The speed with which the attentional mechanism can shift its focus is not known. It is possible that the subjects had enough time to identify the digit and then shift their attention to the periphery. However, the increase in the difficulty of the digit task in the second experiment did not change the pattern of results of the letter task, in comparison with the first experiment. This finding is more readily explained by the location hypothesis. In addition, the method for determining the exposure time of the display was based on the time in which subjects were *just* able to perform the digit task correctly (see the *Method* section). This method was not sufficiently stringent to ensure that subjects would not have the time to shift their attention. Nevertheless, it indicates that this possibility is less likely.

Our findings appear to contradict the results of Treisman and Schmidt (1982) that illusory conjunctions between objects can be formed, regardless of the distance between the objects. There are several possible explanations for this discrepancy. First, there were some differences in the letter task used in the two studies. For example, Treisman and Schmidt presented three or four objects, whereas we presented only two objects. In addition, the types of response for the secondary task differed in the two studies. However, in pilot studies in which we used Treisman and Schmidt's digit task and our letter task, we replicated Treisman and Schmidt's results. Therefore, the explanation of the difference between Treisman and Schmidt's study and our study must lie in the different digit tasks that were used in these studies. Treisman and Schmidt presented two digits, one at each end of a row of three colored letters or shapes.[1] They asked their subjects to spread their attention to both digits and to report these digits as the primary task. As a result, the objects that the subjects reported for the secondary task were always presented inside the spread of attention. In contrast, the digit task of our experiments was designed to ensure that the letters of the secondary task were outside the focus of attention.

Why should the different digit tasks give rise to different patterns of results? A possible explanation, explored in this article, is based on the nature of the mechanism for the binding of visual features. The proposed mechanism is similar to the one suggested by Treisman and her colleagues and

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[1] We know of a single exception to this statement. Treisman and Schmidt (1982, p. 117) described a pilot study in which their subjects had to look at the center, and four colored letters were presented in the periphery. Treisman and Schmidt found that illusory conjunctions occurred regardless of the distance between the peripheral letters. These results are in contrast with the findings of our first two experiments. In Treisman and Schmidt's study, the subjects had to report four letters and four colors. This manipulation increases the load of attention and the load of memory. Unfortunately, the details of Treisman and Schmidt's study are not available, and thus we cannot settle the discrepancy between their results and ours.

reviewed in the introduction (Treisman, 1986a; Treisman & Gormican, 1988; Treisman & Souther, 1985). There are two important components to this mechanism. First, the boundaries of the focus of attention are used by the mechanism as the binding cues; that is, the mechanism tends to integrate all of the features that are present inside the focus of attention. Second, the focus of attention has spotlightlike properties: It can expand or shrink.

On the basis of the properties of this mechanism, it is possible to explain the different pattern of results with the different digit tasks. The digit task used in the first two experiments ensured that the colored letters were presented outside the focus of attention. Under these conditions, the feature integration mechanism is not operating, and the only cue that is used by the visual system is the location information of the features. The digit task used by Treisman and Schmidt (1982) forced their subjects to spread their attention across the area between the digits. Therefore, the objects reported in the secondary task were inside the focus of attention. We propose that the binding mechanism integrates all of the features inside the focus of attention, and thus illusory conjunctions may occur regardless of the distance between the objects. The purpose of the next two experiments was to test the proposed properties of the binding mechanism.

Experiment 3

Two related predictions of the spotlight binding mechanism were tested in this experiment. The first prediction is that when the distance between two objects is fixed, illusory conjunctions will occur only when the focus of attention spans both objects. The second, corollary prediction is that when the span of attention is fixed, illusory conjunctions will occur only between objects that are presented inside the attentional boundary, regardless of the distance between them.

The display in the experiment consisted of two digits and two colored letters. One digit appeared on the left side of the screen, and the second digit appeared on the right side. There were two alternative locations for the digits: They were either 3.3° or 6.6° of visual angle apart. The two letters appeared in two of six possible locations (see Figure 2): One of the letters appeared in one of the three left positions (positions A, B, and C in Figure 2), and the other one appeared in one of the three right positions (positions D, E, and F in Figure 2). Thus there were nine possible pairs of locations for the two letters. Two asterisks that appeared at the beginning of each trial cued the subjects about the exact location of the digits in that trial. No cuing was provided for the position of the letters.

The primary task of the subjects was to report the two digits. The purpose of this task was to manipulate the size of the focus of attention. The subjects were instructed to spread their attention at the beginning of each trial to the two locations marked by the asterisks. As before, the instructions emphasized the importance of the identification of the digits. To further increase the probability that the subjects would spread their attention to the location of the digits, the digits were presented 50 ms ahead of the letters and remained present with the letters until the termination of the display. The letter task was identical to the one used in all previous experiments. The target letter could be either *F* or *X*, and the subjects had to report its color and its name.

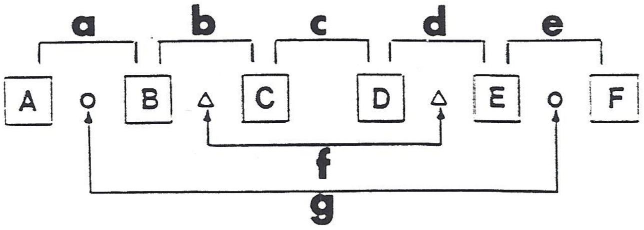

Figure 2. Possible locations of the stimuli in Experiments 3 and 4 and the distance in visual angle between them. (The circles represent the location of the two digits in the large spotlight condition. The triangles represent the location of the two digits in the small spotlight condition. The six squares represent the possible locations of the two letters. The stimuli were presented in the central row of the visual field. The lowercase letters represent the distance in visual angle between the stimuli. In Experiment 3, a = 1.54°; b = c = d = 1.61°; e = 1.7°; f = 3.3°; and g = 6.6°. In Experiment 4, a = 1.4°; b = c = d = 1.47°; e = 1.54°; f = 3°; and g = 6°.)

When the digits were close to each other (the small spotlight condition), there was only one possible pair of locations of the letters (Pair CD in Figure 2) that was between the digits. In the remaining eight possible pairs, at least one of the letters was not between the digits. When the two digits were far from each other (the large spotlight condition), there were four possible pairs of locations for the two letters that appeared between the two digits (Pairs CD, CE, BD, and BE).

Assuming that the digits mark the boundaries of the focus of attention, the hypothesis of the spotlight binding mechanism leads to the following predictions. First, in the small spotlight condition, illusory conjunctions will be formed only for Pair CD because this is the only case in which both letters are presented inside the focus of attention. In the large spotlight condition, illusory conjunctions should be made in the four pairs that are presented inside the spread of attention. Another interesting comparison is between the two spotlight conditions. Consider, for example, the case for Pair BD. In the small spotlight condition, illusory conjunctions between the two letters should not occur. In contrast, illusory conjunctions should be expected in the large spotlight condition. The point of interest is that the actual positions of the two letters, as well as their eccentricities from the fovea, are identical in both cases. The same comparison can be made with the Pairs CE and BE.

Method

Subjects. Twenty-four undergraduate psychology students, all native English speakers, participated in the experiment as part of their course requirements. None of them had participated in the previous experiments.

Stimuli. Subjects viewed the stimuli from a distance of 116 cm. All the characters subtended approximately 0.62° of visual angle in length and 0.46° in width. The distances in visual angle between the possible positions of the different characters are presented in Figure 2.

Procedure. At the beginning of each trial, two asterisks appeared on the two sides of the screen. The positions of the asterisks marked the exact positions of the digits at that trial. The asterisks remained on the screen for 1,500 ms and were replaced by two digits. Fifty milliseconds after the appearance of the two digits, two colored letters were added to the display. In addition to the two letters, a single white asterisk was presented in the middle of the display. The purpose of this asterisk was to ensure that in all conditions there will be at least a single object between the two letters. The display was presented for an individually determined time and was masked for 200 ms. The subject had to report the two digits and the color and name of the target letter. The next trial began 1,000 ms after the completion of the response.

The procedure for determining the exposure time of the display was identical to the one in Experiment 2. First, a block of 24 trials in which the display was presented for 200 ms was run to familiarize the subject with the task. The exposure time was then reduced to 150 ms, and another block was run. A criterion of at least 22 correct answers in the digit task was set. If the subject reached the criterion, the exposure time was reduced by approximately 17 ms, and another block was run. The last block in which the subject reached the criterion was determined as the exposure time in the experiment. The exposure time for the subjects ranged from 100 ms to 167 ms ($M =$ 118 ms). This procedure was followed by three experimental blocks. Each of the blocks included 72 trials, half of which were conducted under the small spotlight condition and the remaining half under the large spotlight condition. The possible pairs of locations for the two letters appeared equally often in both spotlight conditions. For any given pair, the target letter appeared equal numbers of times in the two locations.

Results and Discussion

Subjects reported both digits correctly in 94.9% of the trials in the small spotlight condition. They were less accurate in the large spotlight condition, in which they responded correctly in 89.0% of the trials.

The results of the letter task were analyzed for only the trials in which both digits were reported correctly. The question of interest was the number of color conjunction errors in relation to that of the color feature errors in the two conditions. The prediction of the spotlight binding mechanism is that there should be more illusory conjunctions in the large spotlight condition because in this condition the two letters appeared more often inside the span of attention. This prediction was confirmed by the results. The proportions of the color feature errors and the color conjunction errors in the small spotlight condition were 0.15 and 0.087, respectively. In the large spotlight condition, the proportions of color feature errors and color conjunction errors were 0.177 and 0.146, respectively. There was a significant interaction between the two spotlight conditions and the type of color errors made, $F(1, 23) = 17.02.$, $p < .05$.

Of more importance to the spotlight binding mechanism proposition is the distribution of errors as a function of the location of the letters within each one of the two spotlight conditions. There were nine possible pairs of locations for the letters (see Figure 2). Pairs that were symmetrical with regard to the center were grouped together to simplify the presentation. For example, the results for Pair AD were combined with those for Pair CF; similarly, Pairs AE and BF were combined, as were Pairs BD and CE. Consequently, there remained six types of pairs (see Table 3). In the top half of Table 3 we present the results of the letter task in the small spotlight condition as a function of the location of the letters. In the bottom half of Table 3 we present the corresponding results for the large spotlight condition.

As can be seen from the table, the results are generally supportive of the predictions derived from the assumptions of the hypothetical spotlight binding mechanism. In the small spotlight condition, there were more illusory conjunctions than predicted by the baseline level only for Pair CD $t(23) =$ 3.615, $p < .05$. There was no tendency to form illusory conjunctions in any of the other pairs. Our assertion has been that the difference between the pairs is primarily due to differences in the conjunction errors rather than differences in the feature errors. Analyses of variance confirmed this assertion. There was no significant differences among the six pairs with regard to color feature errors, $F(5, 115) = 0.86$. In contrast, there was a significant difference among the pairs

Table 3
Proportions of Correct Responses and of Errors as a Function of Letter Position in Spotlight Conditions: Experiment 3

	Pairs of letters						
Response	CD	BD–CE	BE	AD–CF	AE–BF	AF	Total
			Small spotlight condition				
Correct	.477	.651	.701	.590	.640	.609	.617
Color feature	.135	.132	.151	.143	.176	.168	.150
Color conjunction	.178	.074	.063	.087	.065	.088	.087
Letter feature	.093	.065	.055	.092	.065	.066	.073
Letter and color feature	.057	.039	.026	.040	.035	.047	.040
Letter feature and color conjunction	.060	.039	.004	.043	.020	.022	.033
			Large spotlight condition				
Correct	.331	.407	.479	.504	.507	.517	.461
Color feature	.162	.162	.158	.178	.205	.191	.177
Color conjunction	.200	.184	.125	.128	.123	.110	.146
Letter feature	.115	.097	.113	.073	.082	.089	.091
Letter and color feature	.077	.082	.060	.079	.046	.059	.068
Letter feature and color conjunction	.115	.069	.064	.038	.038	.034	.056

Note. Some columns do not add to 1.00 because of rounding errors.

with regard to color conjunction errors, $F(5, 115) = 8.198$, $p < .05$.

The pattern of results was different in the large spotlight condition. As in the small spotlight condition, subjects produced more illusory conjunctions in Pair CD than would be expected by baseline, $t(23) = 4.293$, $p < .05$. In addition, there was a significant tendency to make illusory conjunctions for Pairs BD and CE, $t(23) = 4.25$, $p < .05$. There was also a significant amount of illusory conjunctions in Pairs AD–CF, $t(23) = 2.157$, $p < .05$. The occurrence of illusory conjunctions in Pair BE only approached significance, $t(23) = 1.474$, $p < .08$. The proportion of illusory conjunctions was not significantly different from baseline for the other pairs. As in the small spotlight condition, the differences between the pairs were primarily due to the color conjunction errors, $F(5, 115) = 5.171$, $p < .05$. There was no significant difference between the pairs with regard to color feature errors, $F(5, 115) = .441$.

The results deviate from the prediction of the hypothetical spotlight binding mechanism in two of the pairs. We expected subjects to form illusory conjunctions in Pair BE and not to make these errors in Pairs AD–CF. However, the occurrence of illusory conjunctions was significant in Pairs AD–CF and only approached significance in Pair BE. Nevertheless, one can explain the results by assuming that the subjects failed to spread their attention to the *precise* location of the digits. A slight derivation either to the right or to the left would allow locations A or F to fall within the spread of attention.

The effect of the focus of attention can be further illustrated by a comparison of the same position of the letters in the two spotlight conditions. Consider Pairs BD and CE. In both spotlight conditions the letters were presented in exactly the same location and at the same eccentricity from the fovea. The only difference was in the position of the two digits. As is evident in Table 3, the patterns of the color errors in this position were very different in the two spotlight conditions. In the small spotlight condition, the amount of the conjunction errors was about half of the amount of the feature errors. In contrast, in the large spotlight condition, there were more conjunction errors than feature errors.

One aspect of the results did not entirely follow the predictions of the binding mechanism. In the large spotlight condition, there was a stronger tendency to form illusory conjunctions in Pairs CD and BD-CE than in Pair BE. In other words, when the distance between the two objects was larger, the tendency to form illusory conjunctions was weaker. On the basis of the spotlight binding mechanism prediction, there should be the same tendency in all these positions to form illusory conjunctions. These results can also be accounted for by the assumption that the spread of attention is not precise. A related explanation is that there may be a limit to the size of the spotlight. The distance between the two letters in Pair BE is too large to be inside the focus of attention, especially if there is a deviation of the focus of attention to one of the sides. This possibility was examined in the last experiment.

Experiment 4

This experiment was identical to Experiment 3 except for two differences. The first difference is that the distance in visual angle between the characters was shortened. We expected this change to eliminate the distance effect found in the large spotlight condition for pairs located within the two digits. Figure 2 depicts the distance between the characters in this experiment.

The second difference is that the exposure time of the display for the large spotlight condition was 17 ms longer than that of the display for the small spotlight condition. This change was added in an effort to decrease differences in the performance with the letters that were found in Experiment 3.

Method

Subjects. Twenty-three undergraduate psychology students, all native English speakers, participated in the experiment as part of their course requirement. None of them had participated in the previous experiments.

Stimuli. Subjects viewed the stimuli from a distance of 130 cm. All the characters subtended 0.56° of visual angle in length and 0.42° in width. The distances in visual angle between the possible positions of the different characters are presented in Figure 2.

Procedure. The procedure was identical to that in Experiment 3. The exposure time of the display for the small spotlight condition ranged from 100 ms to 150 ms ($M = 116$ ms). The exposure time for the large spotlight condition was 17 ms longer.

Results and Discussion

The results of the digit task were similar to those obtained in Experiment 3. The subjects reported both digits correctly in 93.6% of the trials in the small spotlight condition and in 87.8% of the trials in the large spotlight condition.

The results of the letter task were analyzed for only the trials in which both digits were reported correctly. The only clear difference between the two spotlight conditions was in the pattern of the color errors. The proportions of the color feature errors and the color conjunction errors were 0.14 and 0.089, respectively, in the small spotlight condition and 0.11 and 0.127 in the large spotlight condition. This is evident by the significant interaction between the spotlight conditions and the type of color errors, $F(1, 22) = 18.71$, $p < .05$.

The proportion of correct responses and the proportions of the type of errors as a function of position for the two spotlight conditions are presented in Table 4.

The results, with few changes, replicated those of Experiment 3. In the small spotlight condition, subjects made only illusory conjunctions for Pair CD, $t(22) = 2.719$, $p < .05$. This result was not observed for any of the other pairs in the small spotlight condition. The pattern of results was very different in the large spotlight condition. Subjects formed illusory conjunctions for Pair CD, $t(22) = 5.726$, $p < .05$; for Pairs BD–CE, $t(22) = 5.577$, $p < .05$; for Pair BE, $t(22) = 3.523$, $p < .05$; for Pairs AD–CF, $t(22) = 2.731$, $p < .05$; and for Pairs AE–BF, $t(22) = 3.2$, $p < .05$. Subjects did not commit illusory conjunction errors for Pair AF, $t(22) < 1$.

In general, these results are in accordance with the predictions of the spotlight binding mechanism. The strong prediction of the spotlight mechanism is that illusory conjunctions in the large spotlight condition should be formed only when both letters are between the digits. Thus illusory conjunctions

Table 4
Proportions of Correct Responses and of Type of Errors as a Function of Letter Position in Spotlight Conditions: Experiment 4

Response	Pairs of letters						Total
	CD	BD–CE	BE	AD–CF	AE–BF	AF	
	Small spotlight condition						
Correct	.444	.544	.630	.539	.599	.536	.552
Color feature	.131	.130	.113	.156	.151	.141	.140
Color conjunction	.135	.087	.088	.095	.067	.080	.089
Letter feature	.151	.124	.084	.107	.084	.110	.108
Letter and color feature	.097	.066	.038	.063	.061	.063	.067
Letter feature and color conjunction	.042	.050	.046	.040	.038	.049	.044
	Large spotlight condition						
Correct	.392	.468	.520	.526	.570	.567	.509
Color feature	.099	.097	.093	.134	.096	.154	.110
Color conjunction	.198	.129	.155	.100	.113	.087	.127
Letter feature	.122	.125	.124	.117	.111	.115	.119
Letter and color feature	.084	.065	.039	.072	.052	.038	.061
Letter feature and color conjunction	.106	.115	.074	.051	.057	.038	.075

Note. Some columns do not add to 1.00 because of rounding errors.

were not predicted for Pairs AD–CF and AE–BF. However, assuming that subjects could not fix the boundary of their focus of attention in the *exact* location of the digits, it is quite plausible that the subjects spread their attention to a slightly greater distance than was required. Given this assumption, the results conform to the predictions of the spotlight binding mechanism.

Two aspects of the results of this experiment are somewhat different from those obtained in Experiment 3. First, the occurrence of illusory conjunctions was significant for Pair BE. Second, unlike Experiment 3, illusory conjunctions were obtained with Pairs AE–BF. The main difference in the method between the two experiments is in the size of the focus of attention. These results suggest that there may be a limit to the size of the spotlight. In cases in which the required spread of attention is too large, the size of the spotlight may be smaller than required and will not include letters that are distant from each other. When the size of the focus is manageable, the subjects may even expand their focus of attention beyond the required distance.

The most striking aspect of the results involves the comparison between the two spotlight conditions. Consider Pairs BD–CE, for example. The proportions of color feature errors and color conjunction errors were 0.13 and 0.087, respectively, in the small spotlight condition and 0.097 and 0.129 in the large spotlight condition. Similar patterns of results were obtained for Pair BE, Pairs AE–BF, and, to some extent, Pairs AD–CF.

General Discussion

In this article we explored two questions. The first question concerned the accumulation of location information during the recognition of objects; the second question involved the mechanism for feature binding. The results of the first two experiments indicate that some coarse location information is registered with the identification of visual features during the early stage of perception. However, the possibility that these findings are due to a quick shift of attention cannot be ruled out. The findings of the last two experiments suggest that the visual features of each object are integrated by a focal attention mechanism. The boundaries of the focus of attention mark the edges of a specific area, and the features that are present in that area are integrated. The following discussion is divided into two sections. In the first section, we discuss the findings concerning the accumulation of location information; in the second, we discuss the findings on the mechanism for feature binding.

The Accumulation of Location Information

One of the assumptions of the feature integration theory (Treisman, 1986a; Treisman & Gormican, 1988; Treisman & Schmidt, 1982; Treisman & Souther, 1985) has been that during the registration of visual features, these features are free floating; that is, during that stage, the information about the location of the features is only implicit and is not available to the perceptual system. Our findings, together with earlier results by Snyder (1972), suggest an alternative possibility. We found that illusory conjunctions between two objects outside the focus of attention are formed only when the objects are adjacent. When the distance between the objects was sufficiently large, there was a tendency to avoid conjunction errors above what is expected by chance, a phenomenon termed *exclusionary feature errors.* One interpretation of these findings is that when visual features are registered, coarse location information may be available with it. This information is not accurate enough to prevent migration of the features to nearby locations, but it does prevent the features from moving to distant locations.

Several considerations are in accord with early availability of coarse location information. First, from an evolutionary point of view, it is reasonable to assume that location information would be available to the perceptual system with the registration of features. For example, quick detection of motion in many situations seems to be quite fundamental for survival. However, if the location of the moving entity is not available and the recruitment of attention is needed for that, most of the advantages of the quick detection of motion will be lost. The availability of some information about the location of the moving entity would enable an animal to respond quickly. The same logic applies to the detection of other features.

Our findings are also compatible with some computational suggestions made by Ullman (1984). Ullman suggested that one of the most basic operations of the visual system is the ability to start a computation from a specific location in the visual field. This operation, which Ullman termed *indexing*, enables the visual system to perform computations that are dependent on the starting spatial point. Ullman suggested that visual features such as color and orientation can serve as the trigger of the indexing operation. However, as Ullman acknowledged, location information has to be available with the registration of the features to be able to trigger the indexing operation. Our research indicates that this may be done by the perceptual system.

There is substantial physiological evidence that some location information is available to the visual system (e.g., Hubel & Wiesel, 1977). Cells in the visual system that are selective to a particular property, such as orientation, respond to that property only if it appears in a given area in space (the receptive field). Although the nature of the relation between a receptive field of a single cell and the location of visual features is not clear, it is likely that there exists some relation between the two phenomena. Also, in both cases the available location information is coarse and not precise.

The analogy between the receptive fields of single cells and the location information of visual features gives rise to additional consideration. In our experiments we found that illusory conjunctions outside the focus of attention occurred when the letters were less than 1° of visual angle apart. In addition, we found that when the distance between the two letters was more than 2°, exclusionary feature errors were formed. These findings may appear to indicate the level of precision of the location information that is registered with the visual features. However, one of the most ubiquitous findings on receptive fields (e.g., Hubel & Wiesel, 1962) is that their sizes increase as one moves from the center of the visual field to the periphery. It is possible that there exists a parallel phenomenon with regard to the location information of visual features. In this case one would expect to find more precise location information attached to features that are closer to the center of the visual field than to features in the periphery. Thus the parameters of the location information found in our research may be dependent on the distance of the perceived features from the center of the visual field.

As mentioned earlier, however, an attentional account of the results is also possible. According to this interpretation, subjects succeed in drawing their attention to the periphery after identifying the digits but before the display is erased by the mask. Such a shift of attention could lead to the results of the first two experiments. More research is needed to distinguish between the two possible hypotheses.

Mechanism for Feature Binding

In the last two experiments, we explored a possible mechanism of feature binding. The proposed mechanism, which is essentially identical to the one proposed by the feature integration theory (e.g., Treisman & Souther, 1985), works in the following way. First, focal attention is used to mark a specific area. The boundaries of the focus of attention serve as the markers of the boundary of the area. After that, the mechanism glues together the various visual features that are within that area. An important aspect of the mechanism is that it has a flexible focus of attention: The focus can expand or shrink like a spotlight.

The results confirmed the predictions of the spotlight mechanism. When the size of the focus of attention was manipulated so that in one condition it contained two letters inside the focus and in another condition it did not, the number of illusory conjunctions between the two letters was directly affected. Illusory conjunctions occurred primarily when both letters were inside the focus of attention. These results were obtained even when the locations of the two letters in the two conditions were identical.

We did not examine how the features inside the focus of attention are conjoined. One possibility, suggested by Treisman and Souther (1985; Treisman & Gormican, 1988) is that focal attention selects locations in a master map. Each location in the master map is connected to the corresponding locations in the feature maps. An activation of an area in the master map activates the corresponding locations in the feature maps, and all of the features registered in these locations are conjoined.

Questions regarding the operation of the spotlight mechanism remain. One such question concerns the nature of the factors that determine the boundaries of the focus of attention. Because the focus of attention is flexible, its boundaries have to be determined during the visual processing. In our paradigm, we manipulated the boundaries of the focus of attention by instructing the subjects to spread their attention to specific locations. The results indicated that it is possible to voluntarily determine the focus of attention. Obviously, natural situations are different. In some such situations there is no prior information about the locations of the boundaries of the focus. Yet, the occurrence of illusory conjunctions in these situations is extremely rare. There must be some clues in the visual scene that lead the spotlight mechanism to fix its boundaries in a proper way. It is important, therefore, to find these external factors. The research on this issue is scarce. There is evidence that some of the gestalt grouping principles may serve as cues for determining the boundaries. Prinzmetal (1981) showed that illusory conjunctions occur more frequently between objects that obey the gestalt principles of proximity and similarity. Prinzmetal and Keysar (1989) showed that subjective grouping also affects illusory conjunctions. Another candidate may be the edges or boundary contours of objects. Several students of perception (e.g., Marr, 1982) have emphasized the importance of edges in segregating the visual scene into objects. It is possible that the edges of objects also mark the boundaries of the feature binding mechanism. However, this possibility has not been investigated empirically.

In summary, our findings indicate that when visual features are registered, coarse location information of these features may be available as well. The visual features are conjoined by a spotlightlike mechanism that operates in the following way.

First, the boundaries of the focus of attention mark the boundaries of a specific area. Then, the features that are present inside that area are conjoined. The combination of these assertions indicates that there is a qualitative difference between objects that are presented inside and those presented outside the span of attention. The location information of visual features may be available to the perceptual system only when the features are presented outside the focus of attention. Inside the focus of attention, however, all the features are conjoined, and only location information of conjoined features is available. In some sense, the perceptual system recognizes the presence of an object (i.e., a particular conjunction of features) inside the focus of attention and the presence of individual features outside the focus of attention.

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Appendix

Three categories in Table 1 involve letter errors. The difference among these categories is in the type of color response: (a) *letter feature*, in which the color response was correct; (b) *letter and color feature*, in which there was also a color feature error: and (c) *letter feature and color conjunction*, in which there was a color conjunction error. The sum of these three categories is the total proportion of letter errors committed by the subjects. Thus the proportion of letter feature errors in Experiment 1 is 0.159 for the adjacent condition and 0.10 for the far condition. This difference is probably due to lateral masking. Because the probability of correctly guessing the letter is 50% it follows that subjects correctly guessed the letter without perceiving it in 15.9% of the trials in the adjacent condition and in 10% of the trials in the far condition, the difference between the two conditions being 5.9%. The ability of subjects to report the color of the distractor in the majority of these cases could account for much of the difference in color conjunction errors between the two conditions.

However, a closer examination of Table 1 strongly indicates that this explanation is not valid. The key point to notice is that the table provides an estimate of the proportion of the different types of color response made when the letter was misperceived. Consider, for instance, the type of response in the adjacent condition. Subjects misperceived the letter and wrongly reported it in 15.9% of the trials. As can be seen in Table 1, this proportion is composed of 6.3% of the trials in which the color was correctly reported (letter feature errors), 5.2% of the trials in which color feature error was made (letter and color feature errors), and 4.4% of the trials in which color conjunction error was done (letter feature and color conjunction errors). Presumably, about the same proportions of color response were made when the letter was misperceived and *correctly* reported. Thus the estimate of the proportion of color errors in the adjacent condition for the trials in which the letter was perceived rather than correctly guessed is 11.9% (17.1% − 5.2%) for color feature and 9.1% (13.5% − 4.4%) for color conjunction errors. Applying the same calculation to the far condition, the estimate of the proportions of the color errors is 12.7% (16.0% − 3.3%) for color feature and 4.4% (6.1% − 1.7%) for color conjunction errors. These estimates do not change the difference between the conditions, nor do they change the theoretical implications drawn in the article.

We did the same calculations for the remaining experiments reported in the article. As in the first experiment, these calculations did not change the type of results obtained with the total amount of color mistakes. Because it is easy to perform these calculations, we do not provide them here.

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