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If It's Not There, Where Is It? Locating Illusory Conjunctions

R. Eliot Hazeltine, William Prinzmetal, and Katherine Elliott
University of California, Berkeley

There is evidence that complex objects are decomposed by the visual system into features, such as shape and color. Consistent with this theory is the phenomenon of illusory conjunctions, which occur when features are incorrectly combined to form an illusory object. We analyzed the perceived location of illusory conjunctions to study the roles of color and shape in the location of visual objects. In Experiments 1 and 2, participants located illusory conjunctions about halfway between the veridical locations of the component features. Experiment 3 showed that the distribution of perceived locations was not the mixture of two distributions centered at the 2 feature locations. Experiment 4 replicated these results with an identification task rather than a detection task. We concluded that the locations of illusory conjunctions were not arbitrary but were determined by both constituent shape and color.

Several theories of object recognition assert that features, such as color and shape, are processed independently before being combined into the objects that people see (Cavanagh, 1990; Livingstone & Hubel, 1987; Treisman & Gelade, 1980; Zeki & Shipp, 1988). Therefore, when individuals look at a red apple, their visual systems may analyze its roundness separately from its redness. Before reaching consciousness, this information comes together, so that ultimately individuals perceive an integrated object (Treisman, 1988; Treisman & Schmidt, 1982). The present research addresses the question of what determines the perceived location of a complex object that is composed of several different features.

Both behavioral evidence and neuroanatomic evidence for the separate analysis of features exist. In their groundbreaking series of experiments, Treisman and Gelade (1980) showed that when individuals were asked to find target stimuli defined by a single feature (e.g., a red target in a field of blue and yellow distractors), reaction time was relatively independent of the number of distractors present in the display. In other words, targets possessing a single feature not shared by any distractors can be detected in parallel. However, when a target is defined by a conjunction of features (e.g., a red X or a yellow T in a field of yellow Xs and red Ts), reaction time is a linear function of the number of distractors. Furthermore, the slope of the function for trials in which no target is present is roughly twice the slope for those in which a target is present, a finding consistent with a serial self-terminating search. This pattern of results is in agreement with the proposal of Treisman (1988) that individual features are stored in separate feature maps that can be scanned in parallel. However, if features must be conjoined for the target to be detected, then a serial process is necessary to integrate the features.

A second source of behavioral evidence is the phenomenon of illusory conjunctions. When individuals are briefly presented a green X and a red O, for example, they report seeing a red X or a green O at a rate higher than that at which they simply misidentify a feature (e.g., report a green Y or a blue X). This result indicates that along with detecting features, there is the additional, fallible process of conjoining them (Treisman & Schmidt, 1982). In this report, we are concerned with the phenomenal location of these illusory percepts.

The picture presented by neuroanatomic data is murkier, but some general principles seem to be emerging. Recent developments have focused on the major pathways that may subserve the separate perception of shape and wavelength composition. Two classes of ganglion cells project to the lateral geniculate nucleus: (a) The parvicellular system is dominated by cells responsive to changes in wavelength composition, and (b) the magnocellular system is dominated by cells that are relatively insensitive to wavelength but respond more quickly and vigorously to small differences in contrast (Livingstone & Hubel, 1987, 1988). This distinction seems to be somewhat preserved in cortical visual areas beyond the lateral geniculate nucleus (DeYoe & Van Essen, 1988; Zeki & Shipp, 1988; however, see Desimone, Schein, Moran, & Ungerleider, 1985) and continuing into regions of V1 and then into V4 and the middle temporal area, which may process the wavelength composition and motion attributes of stimuli, respectively (DeYoe & Van Essen, 1988; Schiller, Logothetis, & Charles, 1990; Van Essen & Maunsell, 1983). Interestingly, these areas seem to be retinopically coded (Cowey, 1985; Desimone et al., 1985; Hubel & Wiesel, 1977). That is, the representation of space is encoded by the physical positions (in the brain) and, therefore,

R. Eliot Hazeltine, William Prinzmetal, and Katherine Elliott, Department of Psychology, University of California, Berkeley.

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Correspondence concerning this article should be addressed to R. Eliot Hazeltine, Tolman Hall, Department of Psychology, University of California, Berkeley, California 94720. Electronic mail may be sent via Internet to eliot@garnet.berkeley.edu.

neurons with similar receptive fields are located near each other in the cortex.

Although much has been done to establish the separation and independence of the information streams, little work concerns their reintegration. A question that has not been addressed is how different features are assigned a common location to become a complex object. It is difficult to determine what the various versions of feature integration theory propose, but the issue is an important one: How are locations assigned to complex objects? Illusory conjunctions provide an interesting test case for object location because the features that form the final percept come from different locations. The perceived location of illusory conjunctions should constrain theories of feature integration and location perception. We suggest that there are at least four possibilities for the phenomenal location of illusory conjunctions.

First, it has been proposed that "if attention to particular objects is prevented. . .the features of unattended objects will be *free-floating* [italics added] with respect to each other" (Treisman & Gelade, 1980, p. 100). Under these circumstances, in the absence of top-down constraints, some features will be "randomly conjoined" (Treisman & Schmidt, 1982, p. 111), leading to illusory combinations of features. It is difficult to derive a precise prediction from this version of the theory because it is unclear whether "free-floating" implies any constraints on object localization. For example, in the present experiments, individuals were presented a horizontal string of five colored letters and were asked to indicate the location of a target object. Free-floating might mean that the target could be located anywhere in perceptual space. It seems reasonable that individuals would constrain their localization responses to the computer screen and perhaps to the area of the computer screen in which the five stimulus letters appeared. In any case, free-floating implies considerable randomness with respect to where individuals will localize an illusory conjunction.

Treisman and Gelade (1980) proposed a second hypothesis. According to this view, correct feature integration occurs whenever the spotlight of attention is focused on a single display item. In our experiments, correct feature integration should occur when attention is directed to a single location that contains only one color and one letter. Illusory conjunctions occur whenever the spotlight of attention encompasses more than one letter and one color, that is, more than one letter position. According to Treisman and Gelade, individuals localize the illusory percept at a random position within this spotlight. For example, if an individual incorrectly combines the color and the letter from two adjacent locations into an illusory percept, the individual may localize the letter anywhere within the spotlight. The spotlight may encompass more than the two locations containing the target features, but it must encompass these two positions. Hence, over many trials, we predicted that the distribution of perceived locations of the illusory object would be highest in the region of the target features. However, within the region spanning the two target features, the distribution of perceived locations was expected to be rectangular.

A third possibility is that the perceived location of the illusory percept is determined by a single feature. For instance, the location could be determined by the color only. It has been found that over trials, the perceived localization of a single feature forms a symmetrical distribution around its actual location (e.g., Snyder, 1972; Tsal & Lavie, 1988). Therefore, if one feature determines the perceived location of an illusory percept, then the distribution of perceived locations should be centered on the actual location of that feature. A variant of this proposal, which was tested in Experiments 3 and 4, is that the perceived localization is a mixture of two symmetrical distributions centered on the two feature locations.

Finally, the perceived location of an illusory conjunction could be determined by an aggregation of information specifying the locations of the color and the shape. That is, a unitary perceived location is determined by combination of location information from both features. The logic of this theory is that individuals use whatever information is available about the locations of the features of an object to locate that object. One way of combining information would be a weighted spatial average of the locations of the two features making up the illusory percept. To understand location aggregation by a weighted spatial average, suppose the colored target could be located at one of several positions along a horizontal line. If the visual system has information that the color is located at display position 7 and the letter is located at display position 5, then the percept would be located at position $(7a + 5b)/2$, where a and b are weighting constants. The perceived locations of single features form a distribution around their veridical locations. By this notion, over trials the distribution of perceived locations would form a normal distribution (by the central-limit theorem), and the mean of this distribution would be between the positions of the two features.

We hoped that by studying the perceived locations of illusory percepts, we could shed light on how complex objects are generally located. The free-floating model obviously applies only to situations in which individuals make illusory conjunctions. However, the other integration theories described above provide general accounts of how complex objects are located: Learning where illusory conjunctions are perceived constrains theories of feature integration and demonstrates to some degree the comparative importance of different sources of information in determining the location of an object in the visual field.

Experiment 1

Typically the constituent features of an object come from the same region of the visual field, but when individuals make illusory conjunctions, the perceived location had two potential sources in our experiments: the color from one location and the shape from another. Hence, we could compare the relative importance of the two sources of location information and examine how they are combined.

In Experiment 1, participants were asked to locate the green letter in an array of five letters and to indicate whether the green letter was the letter O. We were particularly interested in the trials in which participants reported a green O but the display contained a green letter and the letter O of a different color (i.e., an illusory conjunction). Participants indicated the precise perceived location of the green letter with a computer pointing device (a mouse). In this way we were able to ascertain the perceived location with a measure more precise than those used in previous studies (e.g., Johnston & Pashler, 1990; Treisman & Gelade, 1980).

Method

Procedure. Each trial proceeded as follows. First, participants were presented with a fixation cross in the center of the screen for 500 ms. Next, the stimulus appeared. It consisted of a string of five differently colored letters, one of which was always green. The letters were presented for 57–143 ms. When the stimulus duration elapsed, the letters were replaced by a bright white mask that filled the screen for 57 ms. The mask was used to eliminate any cues provided by decaying phosphor traces. The mask was followed by a small arrow cursor that appeared in the center of the screen. The participant's task was to indicate the location of the green letter and also to indicate whether the green letter was the letter O. Responses were made on a three-button Logitech mouse. First, participants indicated the location of the green letter by moving the arrow with the mouse so that the tip of the arrow appeared in the position of the center of the green letter. Second, they indicated the identity of the green letter by pressing the left button if they thought the green letter was the letter O or the right button if they thought it was not the letter O. Immediately after the response was recorded, the computer would beep for 50 ms at a specified frequency indicating whether the identity response was correct (600 Hz) or incorrect (100 Hz). After feedback was given, the fixation cross would reappear and the next trial would begin. Participants were told to take their time and to be as accurate as possible. Reaction times were not recorded.

Participants attended two sessions conducted on separate days. There were two blocks of practice on the 1st day and one on the 2nd. Practice blocks consisted of 24 trials (12 with both features present and conjoined, 6 with both features present but not conjoined, and 6 with only the color feature present), which allowed a considerably longer glimpse of the stimuli than that used in the actual experiment to accustom the participants to the task. In the first block on the 1st day, the stimulus duration was 500 ms; the other two practice blocks had stimulus durations of 200 ms. During practice on location accuracy, the position of the participant's response, together with the actual stimulus display, was presented for 1,000 ms after each trial.

After practice, data were collected from three blocks of 160 trials each on each of the 2 days. Sessions were held on consecutive days. Each block took approximately 10 min to complete, and participants were allowed to rest between blocks. After completing each block, participants were told their average distance from the target stimulus and the percentage of correct responses. Error rates were used to determine the exposure duration for the next block. When errors occurred in less than 5% of color-only trials and in less than 20% of trials in which both features were present but not conjoined, the duration was shortened. When errors occurred in more than 8% of color-only trials, the duration was lengthened. The durations were kept within the range of 57–143 ms.

Design. There were three types of trials: target present, both present, and color only. One half of the 160 trials in a block were target-present trials. In these trials, the green letter was an O, and the correct response was the left button of the mouse. Twenty-five percent of trials were both-present trials, in which both target features were present but not conjoined. That is, both a green letter and the letter O were present, but the letter O was not green. In approximately two thirds of these trials, the target and the distractor were next to each other, whereas in the remaining one third, they were placed in Letter String Positions 2 and 4 with an intervening letter in Position 3. Thus, in both-present trials, even though the letter O was present, it was not green, and the correct response was the right button of the mouse. The remaining 25% of trials were color-only trials, that is, no letter O was present at any position in the display. The correct response for these trials was the right button of the mouse. This distribution of trial types meant that when the participant knew nothing about the content of the display, the probability of either response being correct was equal.

Stimuli. In each trial, one of four possible five-letter strings (LXIWF, MEHVZ, HTYLN, and IVZTE) was randomly selected. All of these letters are made exclusively of straight lines. In 75% of the trials, one of the middle three letters was replaced by the letter O. The viewing distance was approximately 70 cm, so that the letters subtended roughly 0.71° vertical by 0.54° horizontal (16 × 16 pixels) of visual angle and were separated horizontally by about 0.94° of visual angle (28 pixels) center to center.

The strings were centered randomly in one of two regions, located in the upper and lower halves of the visual field. The regions were 4.02° of visual angle wide (centered about the point of fixation) and extended from 0.88° to 1.76° vertically above or below the point of fixation. In a given trial, one of the two regions was chosen randomly and the center of the string was placed at a random (rectangularly distributed) point within that region.

The colors of the letters were determined in a manner similar to that used for the selection of the letters. One of the following four possible color sequences was chosen randomly: orange, blue, yellow, purple, and red; yellow, red, gray, orange, and blue; purple, orange, blue, yellow, and gray; and orange, red, purple, blue, and gray. This selection was independent of the letter string selection. In each trial, one of the middle three letters, selected randomly, was replaced with green. The Commission Internationale de l'Eclairage coordinates for the colors, as measured with a Minolta Chroma meter, were as follows: green—x = 0.311, y = 0.462, luminance = 44.2 cd/m^2; red—x = 0.499, y = 0.340, luminance = 27.5 cd/m^2; yellow—x = 0.437, y = 0.472, luminance = 67.7 cd/m^2; blue—x = 0.196, y = 0.165, luminance = 29.2 cd/m^2; purple—x = 0.282, y = 0.207, luminance = 28.5 cd/m^2; orange—x = 0.451, y = 0.455, luminance = 73.6 cd/m^2; and gray—x = 0.299, y = 0.313, luminance = 78.0 cd/m^2.

Participants. Eight college undergraduates from the University of California, Berkeley, were recruited for two 1-hr sessions. All participants were unaware of the purposes of the experiment. They were paid $5 per session, plus a bonus payment of up to $3 for responding accurately to the location of the target stimuli. The bonus was determined in the following manner. After each block, the mean distance between the green letter and the position of the participant's response would appear on the screen. The mean distance was computed with both the vertical and the horizontal deviations from the target. If the mean distance between the position of the participant's response and the veridical position of the target was less than 30 pixels, then a bonus of 25¢ for that block was given. If the mean distance was less than 20 pixels, then the bonus was 50¢.

Results and Discussion

Identification. Participants were most accurate in color-only trials, responding correctly in 95.7% of the trials; participants responded correctly in 81.5% of target-present trials; and both-present trials had the lowest percentage of correct responses, 74.9%. There was a significant effect of trial type on accuracy, $F(2, 6) = 22.55$, $p < .01$.

In the present experiment, illusory conjunctions could have resulted in false positives in both-present trials. However, not all false positives in both-present trials indicate true errors in feature binding. Triesman and Schmidt (1982) suggested that true illusory conjunctions are occurring if the proportion of false positives in both-present trials is higher than that in trials in which only one feature is present (e.g., color-only trials). In the present experiment, every participant made more false-positive choices when both features were present (on average, 25.1%) than when only color was present (on average, 4.3%), $F(1, 7) = 32.98$, $p < .001$. Thus, when participants were presented with a green letter but no letter O in the display, very few errors were made, suggesting that participants had little difficulty in discriminating the individual features. However, when a letter O was present, thus requiring correct feature integration, accuracy decreased dramatically.

The both-present trials were divided into two categories. In roughly two thirds of these trials, the target and the distractor were adjacent, with 28 pixels (0.94° of visual angle) between the centers of the two letters (termed near trials). In the remaining trials (termed far trials), the target and the distractor were placed at Letter String Positions 2 and 4, at a distance of 56 pixels (1.88° of visual angle). Many investigators have found that illusory conjunctions occur more often when features are located close together (e.g., Chastain, 1982; Cohen & Ivry, 1989; Gallant & Gardner, 1988; Keele, Cohen, Ivry, Liotti, & Yee, 1988; Prinzmetal & Keysar, 1989; Prinzmetal & Millis-Wright, 1984; Prinzmetal, Treiman, & Rho, 1986; Wolford & Shum, 1980).[1] The proportions of false positives for both the near and the far categories were computed for each participant and, on average, 29.8% of the near trials yielded illusory conjunctions, whereas only 16.1% of the far trials did so. This effect was highly significant, $F(1, 7) = 36.11$, $p < .001$. However, it is important to keep in mind that this design confounds the distance separating the target and the distractor with the factor of an intervening letter. In the far trials, a letter was placed in between the green letter and the letter O.

Location. We next examined the reported locations of the correct and illusory perceptions. Data for the locating task were divided into six categories: the three trial types by the two possible identification responses (correct and incorrect). However, contrasting the correct and incorrect responses within both-present trials is most critical. These trials provide a comparison between illusory and veridical percepts in the same trial type.

Although there were 160 trials in a block, only 40 of these were both-present trials in which the location of illusory conjunctions could be assessed. This means that for an entire block, there were often as few as five or six trials that could be included in the illusory conjunction category. For this reason, data for each participant were pooled over blocks before being analyzed. We were primarily interested in the variability along the x-axis, because all of the stimuli in any given trial were presented along the same horizontal position. Far trials, in which the two letters were separated by an intervening letter (e.g., target at Position 2 and O at Position 4), were eliminated from this analysis, so that in all of the remaining trials the distance between the target and the distractor was 28 pixels. This procedure resulted in a data set with means of 111 correct rejections and 47 illusory conjunctions per participant.

A difference score was calculated by subtracting the x coordinate of a participant's response from the veridical x coordinate of the target (the green letter). A correction procedure was used to normalize the response according to the position of the distractor: If the letter O in the trial was located to the left of the target, then the difference score was multiplied by -1; if it was located to the right, then no change was made. In other words, trials with the distractor on the left (at -28 pixels relative to the target) were flipped in this analysis, so that for all trials 0 represented the position of the target and $+28$ represented the position of the letter O. Negative values in this scheme mean that the percept was located on the side of the target opposite the distractor. The resulting number was called the normalized location score.

The normalized mean position for the correct rejections was 1.29 pixels. This position was close to and was not statistically different from the veridical position of the green target, $F(1, 7) < 1.00$, as expected. However, the perceived location of the illusory conjunctions, 13.7 pixels, differed significantly, $F(1, 7) = 9.67$, $p < .05$, from the position of the correct rejections and, importantly, was in the direction of the distractor O. The perceived location of the illusory conjunctions was almost exactly at the midpoint between the target and the distractor (i.e., 13.7 pixels vs. 14.0 pixels).

The mean standard deviation was calculated by averaging the participants' individual standard deviations. The mean standard deviations were 22.95 pixels for correct rejections and 23.21 pixels for illusory conjunctions. These values were not significantly different, $t(7) = 0.13$.

A graph of the two response types for the eight participants is shown in Figure 1. This graph was constructed from an aggregate of the data for the participants. Bins 5 pixels (0.17° of visual angle) wide were chosen for the graph, and the middle pixel was used to label each bin. For example, the bin labeled 0 represents responses between pixels -2 and $+2$, the bin labeled 5 represents responses between pixels 3 and 7, and so forth. The y-axis was defined as the

[1] To our knowledge, only Treisman and Schmidt (1982) have failed to find a significant effect of the distance between features on illusory conjunctions. Prinzmetal and Millis-Wright (1984), using stimuli that were nearly identical to those used by Treisman and Schmidt, found a significant effect of the distance between items. In each of the present experiments, the distance between features had a marked influence on illusory conjunctions.

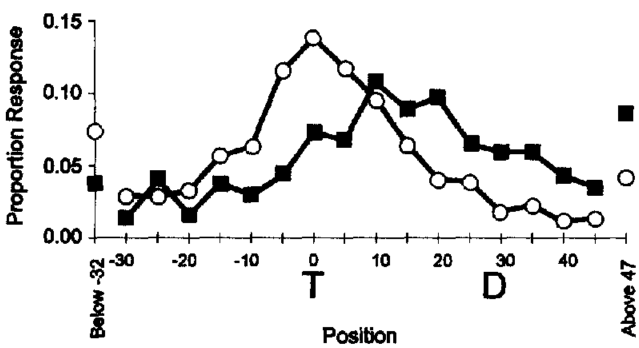

Figure 1. Distribution of perceived locations for correct rejections (circles) and illusory conjunctions (squares) in both-present trials in Experiment 1. The position of the green letter is indicated with a T; the position of the letter O is indicated with a D.

percentage of total responses, which means that the area under both curves is equal to 100%. The T in the figure marks the position of the green letter, which participants were instructed to locate; the D marks the position of the letter O, which was not green in these trials and therefore should have been ignored. The open circles represent correct responses, and the filled squares represent illusory conjunctions. The curves were roughly symmetrical for both response types; the skewness for correct rejections was 0.43, and the skewness for illusory conjunctions was 0.13. However, the positions and magnitudes of the modes were quite different. The mean of the correct rejections was centered at 0, the veridical position of the green letter. When the distribution of responses in the correct trials was examined, it seemed that the letter O had little influence on the perceived location of the green letter. The correct responses were fairly symmetrical around the veridical position of the target. However, the mean for the illusory conjunctions occurred between the two stimuli. In these trials, the perceived location of the illusory green O was strongly influenced by the positions of both the letter O and the green letter.

We also analyzed the location responses for feature errors. Some caution should be exercised in evaluating these data, as there were fairly few data points per participant. Also, because there was only a distractor and no target, we could make no specific predictions about the direction in which the perceived location should have been displaced. Therefore, no normalization procedure could be applied. The mean position was 1.49 pixels (0.05° of visual angle) to the right of and was not significantly different from the veridical position of the distractor, $t(7) = 0.36$. The mean standard deviation was 29.30 pixels (0.98° of visual angle), a value that was not significantly different from the value of 25.10 pixels obtained in nonnormalized illusory conjunction trials, $t(7) = 1.36$.

Finally, the vertical coordinates of the location responses also were calculated. The standard deviations of the vertical coordinates were smaller than those of the horizontal coordinates in all types of trials, but the difference typically was only marginally significant. For example, perception of the location of the green letter may have been categorical in that participants decided that the letter was part of the string of letters and constrained their responses to the location of the string (Huttenlocher, Hedges, & Duncan, 1991). However, because the theories that we were testing make no specific prediction with regard to this component, we confined our analysis to the horizontal component of the location, mindful of the fact that there were additional constraints on the perceived location of the object.

The results of Experiment 1 show that illusory conjunctions are not perceived at random locations. Furthermore, they suggest that both color and shape play a role in the determination of the location of an object. Unlike the results of trials in which the target was correctly identified, illusory conjunctions were located on average between the target and the green letter. Although the distribution of perceived locations was wider than that of correctly identified stimuli, the mode was between the target and the distractor.

The displacement of illusory conjunctions could have occurred for two reasons. First, location responses may have been centered between the two locations because the observed distribution is a mixture of two distributions, one centered at the target and one centered at the distractor. In illusory conjunction trials, participants may not have perceived the color of the target and the distractor at all but may have perceived the shape of the distractor O. Without any relevant color information, participants may have positioned the mouse on the O and responded that it was green. This strategy makes sense, because about two thirds of the green letters were in fact Os. The mean of this distribution may have been offset in the direction of the target by an additional proportion of trials in which the target was correctly located. Because participants made illusory conjunctions, letter feature errors, or incorrect mouse button presses, they responded that the targets were Os. In fact, an examination of Figure 1 hints that the distribution is bimodal—one peak occurring between the two stimuli and another occurring near the distractor. We address this possibility in Experiments 3 and 4.

Second, the perceived location of a stimulus may have been determined by a weighted aggregation of location information from each feature. This theory predicts that in each trial, a single perceived location was derived from both color and shape information. The two sources of location information can be aggregated by a spatial average to determine the perceived location of the illusory conjunction. Because the mean location of an illusory conjunction is almost exactly between the color source (the target) and the shape source (the distractor), the weightings of color and shape appear to be roughly equal.

The results that we obtained may have been affected by the fact that color and shape played different roles in Experiment 1: Participants searched for a color and then indicated its shape (Was it an O?). The asymmetry in the roles of color and shape may have influenced their importance in determining the perceived location of the object. On the one hand, if the perceived location were the result of a mixture, the proportions of that mixture would have been influenced by the asymmetry of the task. On the other hand, if the distribution of the perceived location were the result of a weighted spatial average, the weighting would have been affected by the asymmetry of the task. In Experiment 2, the roles of color and shape were reversed to test the generality of the symmetry of the distribution of perceived locations.

Experiment 2

In Experiment 1, the distractor (the letter O) contributed systematically to the perceived location of illusory conjunctions. Experiment 2 determined whether the same is true for distractors defined by color. The results that we obtained in Experiment 1 might have been influenced by the fact that color and shape played different roles in the experiment. In Experiment 2, participants were instructed to indicate the location of an item on the basis of shape (i.e., the letter O) and then report its color (i.e., Was it green?).

Method

Procedure. This experiment was identical to Experiment 1 except that the roles of color and shape were reversed. Each trial consisted of the same series of events and the stimuli were presented in the same regions of the screen as in Experiment 1. In this experiment, however, participants were asked to indicate the position of the letter O and to report whether it was green.

Stimuli. The letter string and color string sets used were the same as in Experiment 1, but in this experiment the letter O always replaced one of the middle letters. For one half of the trials, the letter O was green (target present); for one fourth of the trials, there was a non-green letter O and a different green letter in one of the two remaining middle positions (both present); and for the remaining trials, there was no green letter at all (letter only). No trial had more than one green letter, and all trials had exactly one letter O.

After presentation of the mask, participants moved the mouse to designate the position on the blank computer screen in which the letter O had appeared. They pressed the left button to indicate that they perceived the letter O as being green and the right button to indicate that they perceived the letter O as being another color. Immediately after they responded, they received auditory feedback regarding the identity of the target: a high-pitched beep for correct identifications and a low-pitched beep for incorrect identifications. No feedback about their estimates of the position of the target was given until the end of the block, when the stimulus duration was adjusted with the procedure described in Experiment 1. All other aspects of the experiment were identical to those in Experiment 1.

Results and Discussion

Identification. Participants were most accurate in the letter-only trials (95.5%) and in the target-present trials (88.8%). Participants were least accurate when both the color and the letter were present but were not part of the same stimulus (i.e., both-present trials, 78.9%). The effect of trial type on performance was significant, $F(2, 6) = 47.29$, $p < .001$. As in Experiment 1, the occurrence of true feature integration errors was assessed by comparing accuracies in both-present trials and color-only trials. For every participant, the color-only trials were easier than the both-present trials, $F(1, 7) = 110.33$, $p < .001$.

The percentages of false positives for the near and far categories of both-present trials were 26.9% and 10.6%, respectively. This effect was significant, $F(1, 7) = 58.33$, $p < .001$, replicating the distance effect of Experiment 1.

Location. The location responses for both-present trials were normalized as in Experiment 1 so that positive numbers were always in the direction of the distractor. Again, only near trials, in which the distractor and the target were adjacent, were analyzed. The mean normalized location scores were calculated for the correct and incorrect both-present trials. The mean position for the correct rejections was 4.20 pixels ($SD = 16.00$). This position was close to but was statistically greater than the veridical position of the green target, $F(1, 7) = 16.86$, $p < .01$. For false positives, the mean position was 17.87 pixels ($SD = 17.77$). As in Experiment 1, the perceived location of illusory conjunctions was significantly further toward the distractor, $F(1, 7) = 36.37$, $p < .001$, than the location of the correct rejections. On average, participants located illusory conjunctions near the midpoint between the veridical positions of the target and the distractor.

Figure 2 depicts the distribution of perceived locations for the two response types. Again, bins 5 pixels (0.17° of visual angle) wide were chosen, and the middle pixel was used to label each bin. The y-axis is defined as the percentage of total responses, which means that the area under both curves is equal to 100%. The curves were roughly symmetrical for both response types; the skewness for correct rejections was 0.97, and the skewness for illusory conjunctions was 0.07. However, the positions and magnitudes of the means were quite different.

We also analyzed the perceived locations of feature errors. The mean position was 2.68 pixels (0.09° of visual angle) to the left of and was not significantly different from the veridical position of the target, $t(7) = 0.77$. The mean standard deviation was 22.35 pixels (0.75° of visual angle), a value that was not significantly different from values obtained in nonnormalized illusory conjunction trials (26.82 pixels, 0.90° of visual angle), $t(7) = 1.20$.

As in Experiment 1, the distribution of perceived loca-

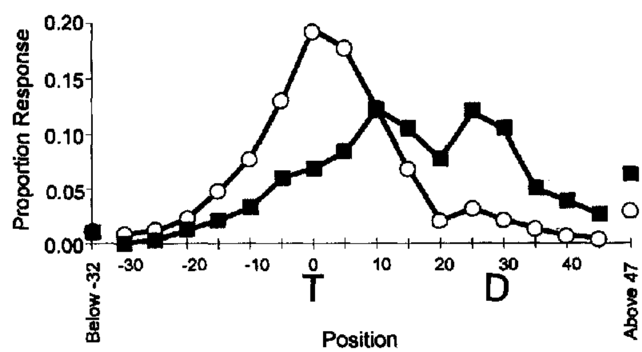

Figure 2. Distribution of perceived locations for correct rejections (circles) and illusory conjunctions (squares) in Experiment 2. The position of the letter O is indicated by a T; the position of the green letter is indicated by a D.

tions for illusory conjunctions showed considerable structure: Illusory conjunctions were not perceived in random locations. There was some indication of bimodality, which we explore in Experiment 3. The mean of the distribution was positioned near the midpoint between the veridical locations of the target and the distractor, suggesting that when participants were searching for a shape or a color, an illusory conjunction with another feature (shape or color) affected the perceived location of the illusory percept. Furthermore, this experiment demonstrated that the average location of the illusory conjunction between the two features was not an artifact of the task used in Experiment 1.

Experiment 3

Experiments 1 and 2 showed that both color and shape can influence the perceived location of an illusory conjunction, but this basic result can be interpreted in at least two ways. First, according to the mixture hypothesis, the resulting distribution of illusory conjunction locations may be the mixture of two distributions, one from the shape and one from the color. In trials in which features with different sources of location information are conjoined, one of the sources may be arbitrarily chosen to provide information about the location of the illusory percept. The perceived location of the illusory conjunction is generated by random selection of one location from one of the feature distributions in each trial. In some trials, the location of the shape determines the location of the illusory percept, and in others, the color determines the perceived location. The perceived location of each feature by itself forms a distribution over trials. The distribution of correct rejections for both-present trials provides some indication of the distribution of the perceived location of each feature by itself.

The second explanation is the aggregate hypothesis. In this hypothesis, the location of the illusory percept is determined by aggregation of location information from each feature. In one version of the aggregation model, the perceived location of the illusory conjunction is a spatial average of the two features. This spatial average account also presupposes that over trials, perceived locations for color and for shape form distributions around their actual locations. However, in each trial, the perceived location of the illusory percept is a unitary combination of color and shape location information. According to this theory, the perceived location of an illusory conjunction is generated by selection of the location from each of the feature distributions and averaging of the values.

In Experiment 3 we tested whether the perceived location of illusory conjunctions was the result of a mixture of two distributions. To simplify this test, we constrained participants' location responses. After presentation of the stimulus display, a row of boxes appeared. Participants indicated which box was in the position of the letter O and whether the letter O was green. The separation between boxes was exactly one half the distance between letters.

To understand our test of the mixture model, consider Figure 3. When participants responded on the box labeled

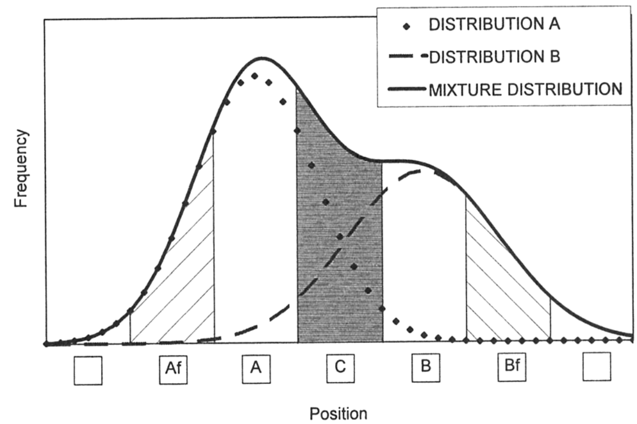

Figure 3. Explanation of the logic of Experiment 3. Two symmetrical distributions (indicated by the broken lines) are centered on A and B. Their mixture (indicated by the solid line) is divided into five regions of equal width. Region C represents the portion between the centers of the two distributions (i.e., the middle half of the distance between the edges of A and B. Af and Bf are the flanking regions. If the distributions add little to distant flanking regions (e.g., A does not extend significantly to region Bf), then the contributions of A and B to region C can be estimated with Af and Bf, respectively. That is, the shaded region C should equal the sum of the hatched regions Af and Bf.

C, they perceived the stimulus somewhere in the shaded region above the C. Assume that the distribution of the perceived location of one feature is symmetrical and is centered on A and that the other distribution is also symmetrical and is centered on B (i.e., the broken lines). Assume that the responses in region Af are mostly from feature A and that the responses in region Bf are mostly from feature B. If the two feature distributions are symmetrical, the proportion (p) of responses in region C must be equal to the sum of the proportions of Af and Bf responses:

$$p(C) = p(Af) + p(Bf). \quad (1)$$

If we relax the assumption that Af contains only responses from the A feature and that Bf contains only responses from the B feature, then Af and Bf will provide inflated estimates of the contributions from feature A and feature B, respectively. Thus,

$$p(C) \leq p(Af) + p(Bf). \quad (2)$$

Equation 2 represents the prediction of the mixture model. This model has two assumptions. First, the distributions of the perceived locations of the individual features must be symmetrical. Second, they must be centered around the veridical locations of the features. This test is valid even if the mean of the distribution of perceived locations is not exactly between the two features, as it was in Experiments 1 and 2. For example, in Figure 3 the mean for the mixture is not directly over C. The two assumptions of this test seem reasonable in the present experiments. As we showed in Experiments 1 and 2, the perceived locations of the correct rejections for the both-present trials were averaged near their actual locations, and the distributions were not skewed.

Responses falling under regions Af and Bf are flanking responses, because they lie on the flanks of the target–distractor pair. Note that the flanking responses could equal the central responses if the single-distribution model were in fact correct. That is, a failure to find significant differences between the central responses and the sum of the flanking responses is compatible with both assumptions, but the presence of significantly more central responses is incompatible with the two-distribution explanation and Equation 2.

The procedure used in Experiment 2 of locating the shape and identifying the color was chosen for Experiment 3 because it provided smaller location variance than the one used in Experiment 1.

Method

Procedure. This experiment used the same feature roles assigned to color and shape as in Experiment 2. That is, participants indicated where the letter O had appeared on the screen and whether it was green. The stimuli were also the same as in Experiment 2, except that the interletter distance was increased to about 36 pixels (1.21° of visual angle). An identical fixation cross and an identical mask were used; the duration of the stimuli varied from 57 to 143 ms as in the previous two experiments. The task was nearly the same, except that now a constraint was placed on the participant with regard to where the location response could be made. After presentation of the mask, a row of location boxes, each 0.17° on a side and separated horizontally by approximately 0.60° appeared on the computer screen. The separation distance was exactly one half that between the letter stimuli. One box was placed where the center of each letter had appeared, and one box was placed between adjacent letters. This spacing of boxes was continued across the entire screen to minimize cues about the veridical positions of the letters.

To register a response, participants had to place the mouse cursor on the box that appeared in the location previously occupied by the center of the letter O. As in Experiment 2, when the participants perceived that the letter O was green, they pressed the left button; when they perceived that the letter O was not green, they pressed the right button. The computer recorded these responses and proceeded to the next trial only when the mouse was placed within one of the location boxes. This procedure limited variations in participants' location responses to the horizontal axis because the boxes were placed in a row. Feedback was given as in the previous experiments.

Because of the location box methodology, the bonus payment scheme was altered slightly. For each trial, the number of boxes between the position of the participant's response and the veridical position of the target was calculated. If the participant correctly identified the box at the center of the target, this number was 0, if an adjacent box was chosen, the number was 0.5, and so forth. After each block, the mean absolute distance from the target was displayed. If the result was less than 1.00, then participants earned an extra 25¢; if the result was less than 0.75, then participants earned an extra 50¢. If there was sufficient time in the 1-hr session, participants went through an additional block of trials. This extra block was used to replace any block in which an insufficient number of illusory conjunctions had occurred.

Participants. Fifteen college undergraduates from the University of California, Berkeley, were recruited for two 1-hr sessions. One undergraduate was unable to accurately locate the target stimuli, so his data were eliminated from the analysis and a replacement undergraduate was selected.

Results and Discussion

Identification. As in the previous experiments, participants were most accurate in the feature-only trials. Participants were correct in 97.3% of the trials in which only the letter was present in the display. Participants correctly rejected the stimuli in 80.8% of the both-present trials. The target was identified in 87.4% of the target-present trials. There was a significant effect of trial type on accuracy, $F(2, 13) = 30.48$, $p < .001$, and participants performed significantly better in the letter-only trials than in the both-present trials, $F(1, 14) = 69.93$, $p < .001$. Analysis of the both-present trials alone revealed that participants were less accurate when the distractor was immediately next to the target (74.5% correct) than when the distractor was further away (89.2% correct), $F(1, 14) = 128.65$, $p < .001$.

Location. We confined the analysis of perceived locations to trials in which the target was not green but one of the letters immediately next to it was. Unlike the situation in the previous two experiments, location responses were now constrained to the locations of the boxes. The box located exactly where the target had appeared was assigned the score 0. Boxes to the left of the target box were given negative values in increments of 0.5, so that the box immediately to the left of the target box was −0.5, the box to the left of that was −1.0, and so forth. Likewise, boxes to the right of the target box were assigned positive scores according to the same scheme. If the distractor letter fell to the left of the target, then the value in that trial was multiplied by −1. Thus, a score of 1.0 always identified the veridical location of the distractor letter, and negative scores indicated positions on the opposite side of the target in all trials.

Figure 4 shows the distribution of the perceived locations for correct rejections and illusory conjunctions in the near trials. The mean perceived location of illusory conjunctions was 0.68 boxes ($SD = 0.55$), near the midpoint between the target and the distractor (i.e., 0.50 boxes). This mean location was statistically different from the veridical position of the letter target, $F(1, 14) = 88.55$, $p < .001$. The mean location of correct rejections in the both-present trials was 0.08 boxes ($SD = 0.53$), a value that was close to but was marginally significantly different from the actual location, $F(1, 14) = 4.33$, $p < .06$. The difference between the perceived locations of the target in illusory conjunction and correct rejection trials was significant, $F(1, 14) = 67.72$, $p < .001$. These results replicate similar findings from Experiment 2. Illusory conjunctions occurring with the target and distractor near each other can be compared to illusory conjunctions occurring in far trials, in which the distractor was at Position 2. In these trials, the mean location was 1.08 boxes, again approximately halfway between the target and the distractor. Although data from one participant had to be eliminated from the analysis because no illusory conjunctions were made in the far trials, illusory

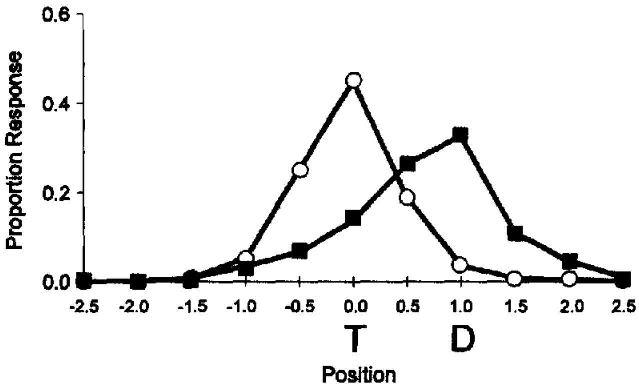

Figure 4. Distributions of perceived locations for correct rejections (circles) and illusory conjunctions (squares) in Experiment 3. According to the logic of the experiment, 0.5 corresponds to region C in Figure 3, −0.5 corresponds to region Af, and 1.5 corresponds to region Bf. The sum of the flanking regions is significantly smaller than the proportion of central responses, indicating that the distribution of illusory conjunctions is not a mixture of two symmetrical distributions centered between 0 (the position of the target [T]) and 1 (the position of the distractor [D]).

conjunctions in the near trials were perceived to be significantly closer to the veridical position of the target than were those in the far trials, $F(1, 13) = 5.82, p < .05$.

The critical test was to determine whether the distribution of perceived locations for illusory conjunctions in the near trials could be accounted for by two symmetrical distributions centered around 0.0, the location of the target, and 1.0, the location of the green distractor. Counts for each bin were converted to proportion of total responses for this analysis. To obtain estimates of the contribution of each putative distribution to the response count at position 0.5, we combined the outside flanking positions of the two potential distributions. So, for each participant, the sum of positions −0.5 and 1.5 generated a prediction, according to the two-distribution model, of the number of responses that should occur at position 0.5. The mean proportion for central counts was .34, and the sum of the proportions for flanking counts was .19; significantly more central responses than flanking responses were observed, $F(1, 14) = 8.54, p < .05$. Such a pattern of results was the opposite of that predicted by the two-distribution model.

Experiments 1 and 2 revisited. An analogous analysis was applied post hoc to the first two experiments. The procedure was altered as follows. All variation on the vertical axis was ignored. The proportion of central counts was computed by summing all the location responses in the region between the veridical positions of the target and the distractor; the region between the two stimuli was considered the central bin. Flanking bins extending a distance equal to that of the central bin were placed immediately to the left of and right of the target–distractor pair. Only trials in which the distractor and the target were next to each other were used in the analysis. According to the logic of Equation 2, if the distribution of illusory conjunction trials is a mixture of two symmetrical distributions centered around the target and the distractor, then the proportion of responses in the central bin should be no greater than the sum of the responses in the two flanking bins. This test was applied to the data from both Experiments 1 and 2.

For Experiment 1, the difference between the values for the central bin (0.48) and the sum of the flanking bins (0.41) was not significant, $t(7) = 0.972$, although the difference was in the direction not predicted by the two-distribution model. For Experiment 2, the proportion of location responses in the central bin (0.54) was significantly greater than the sum of the proportions of location responses in the two flanking bins (0.39), $t(7) = 3.271, p < .01$.

Taken together, Experiments 1, 2, and 3 suggest that location information obtained from both color and shape are integrated to determine the location of an object in the visual field. It can no longer be assumed that illusory conjunctions are seen either near the distractor or near the target, because the data do not support the mixture model. Hence, the difference in mean locations between correct rejections and illusory conjunctions suggests that in each trial, both features contribute to the perceived location of the illusory object.

Experiment 4

The three previous experiments all required participants to pay attention to two things: the letter O and the color green. Even though Experiments 1 and 2 reversed the roles of the two features, it is possible that in these experiments the participant's task was effectively the same: Participants may have searched for both a color and a letter in each experiment. Thus, the distractor, whether a color or a shape, may have been difficult to ignore and may have had an undue influence on location perception.

To alleviate this potential effect, we used multiple target colors and letters in Experiment 4. The participant's task was to indicate whether the display contained the target letter X or T and whether this target letter was red, yellow, or blue. If the display contained a red X and a yellow O, we classified responses of a yellow X as an illusory conjunction. Thus, in Experiment 4, if a participant perceived a red X, for example, there was no reason to search further for another color (or letter), as in the previous experiments. This procedure emphasized the detection of a complex target rather than the selection of two particular features (i.e., green and O). Furthermore, in the previous experiments, there was no way to determine whether the defining attribute of the target (green in Experiment 1 and O in Experiments 2 and 3) was perceived. Requiring participants to specify the shape as well as the color corrected this problem.

Experiment 4 introduced one additional change. Treisman and Schmidt (1982) stated that "an object can be as confidently seen when its conscious representation is generated from the color and size of one object and the shape and solidity of another as when it veridically matches the features of a physically presented stimulus" (p. 139). In their experiment, participants were asked to indicate how confident they were in determining whether a probe had been included in a briefly presented display. They compared the confidence ratings for three types of probes: target-present probes, which were actually present in the display; both-present probes, which were composed of features present in the display but not part of the same stimulus; and feature-only probes, which contained a feature not present in the display. Both-present probes tended to receive more "Sure yes" responses than features probes. However, the categories were defined by the type of probe, so that confidence was averaged across different types of trials. In Experiment 4, we did not use different types of trials (as we did in the first three experiments). Therefore, we could obtain confidence ratings when participants did or did not make illusory conjunctions without changing the type of trial.

Method

Procedure. This experiment included two possible target shapes (X and T) and three possible target colors (red, yellow, and blue). After presentation of the stimulus, participants first indicated where the target was located and then indicated which target (e.g., red X, blue T, and so forth) had appeared in the display. With each of these responses they gave a confidence rating.

Each trial proceeded as follows. First, a fixation cross appeared in the center of the screen for 500 ms, and then letters appeared for a variable interval of 57–143 ms. The stimulus duration was adjusted between blocks to maximize illusory conjunctions and to minimize other errors. The stimulus was followed by a 57-ms white mask. Next, a row of boxes separated by approximately 0.60° of visual angle appeared along the same horizontal axis as the stimulus, as in Experiment 3. The boxes were slightly larger than the ones used in the previous experiment, about 0.21° on a side. This modification was made so that responses did not require such fine motor control and could be made more quickly. The boxes were centered at the positions of each letter and halfway between each pair of consecutive letters. Additional boxes that maintained this spacing were placed across the entire display to ensure that the boxes provided no clues as to the position of the target.

Participants made two responses with the mouse. First, they moved the cursor to the position of the target and pressed one of three mouse buttons to indicate their confidence in the location judgment. They pressed the left button if they felt unsure, the middle button if they felt fairly confident, and the right button if they felt very confident. Participants were told that by using their confidence responses effectively, they could improve their accuracy scores and thereby increase their bonus payments, because more confident responses would be weighted more heavily than less confident ones. The computer would not register a response unless the mouse was correctly positioned over one of the location boxes.

After the location responses were made, six target identification boxes immediately appeared on the screen. These were arranged in two rows of three columns. Participants were told that the rows represented letter shape (top row = T and bottom row = X) and that the columns represented color (left = red, middle = yellow, and right = blue). To minimize the demands placed on the participants, we designed the boxes themselves to be colored so that the color response scheme would not have to be remembered. However, the letter shapes did not appear in the response boxes. To indicate that he or she perceived, for example, a blue X, the participant positioned the mouse in the bottom right box and pressed a mouse button. The three mouse buttons were assigned the same confidence values as for the location responses. Thus, for each trial, we obtained target location and identity responses, together with separate confidence ratings for the location and identity responses.

This procedure required more time than the previous experiments, so blocks were shortened from 160 to 100 trials. Participants performed one practice block of 24 trials and three experimental blocks on each of 2 days. This design meant that each participant generated 600 trials of data for analysis. After the completion of each block, the mean location and identification accuracies were displayed on the screen both with and without weighting responses by confidence. Participants were told before the experiment that if the unweighted score was higher than the weighted one, then the unweighted score would be used to compute the bonus payment (this outcome never occurred). The bonus payment was calculated in this manner so that participants would feel comfortable responding with both the high and the low confidence ratings. The bonus scheme was explained to participants before the experiment began and was as follows: For target location accuracy, each 0.01 under 1.00 in the mean box location difference generated an additional 2¢. For target identity accuracy, each percentage point over 50% in the accuracy score earned an extra 1¢. Participants typically earned an extra $2.50/hr.

If there was sufficient time in the 1-hr session, participants went through an additional block of trials. This block was used to replace any block in which an insufficient number of illusory conjunctions had occurred.

Stimuli. The stimuli were identical to those used in the previous three experiments, except that new distractor and target sets were used. For each trial, a string of five distractor letters was chosen from the set containing OSGCU, UGCSO, GCSOU, and SUOGC. One of the following four sets of colors was randomly chosen, and then each letter was initially assigned a color from the set. The four color sets were as follows: (a) orange, gray, green, purple, and pink; (b) green, pink, gray, orange, and purple; (c) purple, orange, green, pink, and gray; and (d) pink, green, orange, purple, and gray.

Once an array of differently colored letters had been created by combinations of color and letter strings, one of the middle three letters was selected randomly and replaced by the target. The shape (X or T) and the color (red, yellow, or blue) of the target were selected randomly. In addition, in every trial, one of the distractors in the middle three positions was assigned a different color from the target color set. For instance, if a red T was placed in Position 2, then the distractor in either Position 3 or Position 4 was colored yellow or blue. Thus, in each trial, only one of the possible target colors was not included in the five-letter array. As in Experiment 3, the letters were separated by about 1.21° of visual angle.

Participants. Eight college undergraduates from the University of California, Berkeley, were recruited for two 1-hr sessions. They were paid $5 per session, plus a $1 to $4 bonus payment for responding accurately to the location of the target stimuli (see above). Sessions for each participant were held on consecutive days. All participants were unaware of the purposes of the experiment.

Results and Discussion

Identification. There were six response categories, which can be thought of as a two-by-three array. One dimension of this array represents whether participants correctly identified the shape of the target. The other dimension represents whether participants reported the color of the target (correct response), reported a color that was not the target color but was present elsewhere in the display (illusory conjunction), or reported a color that was not present in the display (feature error). The six response categories can be broken down further into trials in which the distractor color was adjacent to the target letter (near trials) or separated from the target letter by one intervening letter (far trials). Table 1 shows the resulting 12 response categories.

Several aspects of the results in Table 1 should be noted. First, the overall accuracy (portion of trials in which participants correctly identified both color and shape) was about 84%, a value comparable to those obtained in the previous experiments. Second, not all of the responses labeled illusory conjunctions were the result of true feature integration errors. Some of these responses were probably attributable to guesses. Treisman and Schmidt (1982) proposed that true feature integration errors have occurred when the proportion of illusory conjunction responses exceeds the proportion of feature registration errors (for a discussion of the various criteria for true feature integration errors, see Ashby, Prinzmetal, Ivry, & Maddox, in press; Cohen & Ivry, 1989, 1991; and Prinzmetal, Henderson, & Ivry, 1995). The proportion of letter-correct illusory conjunctions was significantly greater than that of letter-correct feature errors for the near condition (12.4% vs. 3.0%), $F(1, 7) = 61.85$, $p < .001$; however, this difference was not obtained for the far condition (4.2% vs. 3.7%), $F(1, 7) < 1.0$.

Finally, it is interesting that the nearly 8% difference in letter-correct illusory conjunctions between the near and far conditions was entirely accounted for in the correct responses, for which there was also a significant effect of distance, $F(1, 7) = 54.81$, $p < .001$. Participants' responses were correct in 80.6% of the near trials and in 88.7% of the far trials. None of the other four response categories showed any significant effect of distance, $F < 1$ in all cases. This pattern of results—an increase in illusory conjunctions and a corresponding decrease in correct responses with no other changes—is consistent with a mechanism that is separate from feature detection processes and that conjoins features on the basis of proximity (Ashby et al., in press; Prinzmetal & Keysar, 1989). In other words, the fact that proximity of the target and the distractor affects conjunction errors but not feature errors suggests that feature detection and feature conjunction are separate processes. This topic is addressed in the General Discussion.

Table 1
Breakdown of Percentages for the Six Possible Responses in Experiment 4

Target identification	Response: Target color (correct)	Response: Color present (illusory conjunction)	Response: Color absent (feature error)
Near trials			
Letter correct	80.6	12.4	3.0
Letter incorrect	2.2	1.3	0.5
Far trials			
Letter correct	88.7	4.2	3.7
Letter incorrect	2.0	1.0	0.4

Location. The same procedure as that used in the previous experiments was applied to participants' location responses so that positive numbers always indicated displacement in the direction of the distractor. Only the near trials, in which the target and the distractor were next to each other, were analyzed for location because of limitations in the number of data points generated by participants for some of the six response categories for the far condition.

The mean response locations for each of the six response categories are shown in Table 2. We performed a two-tailed t test on each of the six response categories to determine which response locations were different from the target location, zero. The response location was significantly different from the actual location only for illusory conjunction letter-correct trials, $t(7) = 10.92$, $p < .001$. The mean location error approached significance for the illusory conjunction letter-incorrect trials, $t(7) = 2.20$, $p < .07$. This pattern of results means that only illusory conjunctions were systematically shifted from the veridical position of the target.

Distributions for correct and letter-correct illusory conjunction responses are shown in Figure 5. The test for a mixture model that was used in Experiment 3 was applied to the present location results. The central and flanking location responses were accumulated and converted into proportions for each participant (see Experiment 3). As in Experiment 3, the mean central proportion, .27, was greater than the mean flanking proportion, .17. However, this difference was only marginally significant, $F(1, 14) = 2.80$, $p < .15$. This difference was in the opposite direction of that allowed for by the mixture model. We interpret these results as demonstrating that the location distribution of illusory conjunctions was not a mixture of two distributions, each centered at the location of one of the features. Rather, the perceived distribution of illusory conjunctions depended on the locations of both the color and the letter.

When only location responses for targets identified with the most confident responses were analyzed, the difference between central and flanking responses increased. For these trials, central responses made up an average proportion of .32 of location responses, whereas flanking responses made up only .14 of location responses. This difference also approached significance, $F(1, 14) = 3.47$, $p < .15$.

Confidence. In general, both location and identity responses were more accurate when participants gave high rather than low confidence ratings. To examine the differences in perceived location as a function of confidence, we converted all values to their absolute distance from the veridical position of the target. Only trials in which the target and the distractor were next to each other were analyzed. The mean absolute distances for the three location confidence scores across the six response types are shown in Table 3.

Considerable caution was called for in the evaluation of trends in the last four categories, especially letter-error illusory conjunction and letter-error color-error categories,

Table 2
Mean Perceived Location by Response Type for Experiment 4

Trial	Response: Target color (correct)	Color present (illusory conjunction)	Color absent (feature error)
Letter correct	−0.041	0.660**	−0.054
Letter incorrect	0.008	0.317*	−0.233

* $p = .06$. ** $p < .01$.

because they were based on relatively few data points (see Table 1). Accordingly, only the correct and letter-correct illusory conjunction categories were analyzed. The trend for the location estimates to improve with increased confidence approached significance in correct trials, $F(1, 7) = 4.20$, $p < .1$, as well as in letter-correct illusory conjunction trials, $F(1, 6) = 4.56, p < .1$, although data for one participant had to be eliminated from the analysis because they were insufficient.

When we examined only the most confident location responses, the distributions of illusory conjunctions showed little change: The mean letter-correct illusory conjunction location was still between the target and the distractor. In fact, the mean location was closer to the midpoint between the target and the distractor color when only the highly confident location responses were considered than when all location responses were considered.

The mean confidence scores for the six target identity response categories are shown in Table 4. For the target identity confidence ratings, participants rated correct responses significantly higher than illusory conjunction responses, $F(1, 7) = 223.53$, $p < .001$. Among the five incorrect responses, differences in the mean confidence ratings were highly significant, $F(4, 6) = 10.59, p < .001$, although data for one participant had to be eliminated from

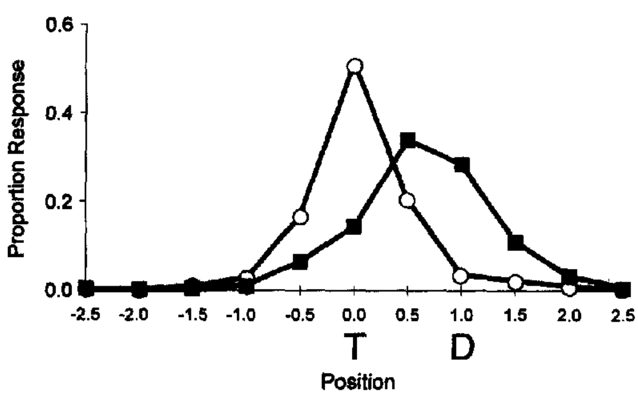

Figure 5. Distributions of perceived locations for correct responses (circles) and illusory conjunctions (squares) in Experiment 4. The sum of the flanking regions is smaller than the central region. T = target; D = distractor.

the analysis because no color-error letter-error responses were made.

The confidence levels for illusory conjunctions were not particularly high. The mean confidence rating for illusory conjunction responses was significantly lower than that for correct responses, $F(1, 7) = 53.96$, $p < .001$, and was not different from that for letter errors, $F < 1$. Although it was true that for approximately one third of illusory conjunctions responses were rated as most confident, this result was similar to that for letter and color errors. This finding was not inconsistent with results reported by Treisman and Schmidt (1982), who found that although on average confidence ratings for correct responses were higher than those for illusory conjunction responses, there was considerable overlap between the two distributions of confidence ratings. Most important for our purposes is that the confidence score data were consistent with the feature location average model: Even the most confidently located and identified illusory conjunctions were significantly displaced toward a point midway between the features.

The results of Experiment 4 were consistent with the conclusions drawn from the first three experiments. Changing from a detection to an identification task had little effect on the basic result that illusory conjunctions were displaced compared with correct responses, even though the identification task presumably diluted the significance of the distractor. The distribution of the perceived location of illusory conjunctions does not suggest that they are perceived either near the color or near the shape. Instead, both features exert influence on the perceived location of the integrated object.

General Discussion

In each experiment, there was considerable structure to the perceived locations of illusory conjunctions; the features were not free floating with regard to location. Furthermore, the distribution of illusory conjunctions appeared to show a peak between the locations of the two features. The model proposed by Treisman and Schmidt (1982) claims that when individuals make illusory conjunctions, the spotlight of attention encompasses both features, but that within this spotlight, these features randomly combine. Thus, according to their theory, perceived locations should form a rectangular distribution between the veridical locations of the two features. This prediction was not borne out.

The experiments demonstrated that the spatial distribution of the illusory conjunctions did not result from sampling one location in each trial from one of two distributions—one centered at the letter position and the other centered at the color position. Instead, the perceived location was an aggregation of information from both the color and the letter.

An alternative explanation is that feature errors contribute to the distribution of illusory conjunction locations in such a way as to cause the resulting distribution to fail the mixture test described in Experiment 3. Discounting this possibility is difficult given the current set of data. However, several observations lead us to believe that this expla-

Table 3
Mean Absolute Distance From Target by Location Confidence for the Six Response Types in Experiment 4

Score[a]	Correct	Illusory conjunction	Color error	Letter error	Letter error illusory conjunction	Letter error color error
1	0.45	0.87	0.65	0.65	0.83	0.63
2	0.38	0.84	0.54	0.56	0.93	0.55
3	0.28	0.73	0.48	0.43	1.00	None
M	2.39	2.04	1.90	1.94	1.84	1.73

Note. Values are boxes.
[a] 1 = least confident; 3 = most confident.

nation is somewhat unlikely. First, feature errors in the experiments were fairly rare. Second, the mean location of the feature errors was centered at the veridical position of the distractor, indicating no systematic deviation from the perceived locations of a feature error and its source. Third, the distribution of feature errors demonstrated no tendency to fail the proposed mixture test. It is clear that we were fairly underpowered when performing this analysis, but in each of the four experiments there was no indication of a trend in this direction. Histograms of feature error perceived locations in each of the experiments were made, and there were no multiple peaks at locations that might have induced a failure in the mixture test. It is impossible to predict the effect of the normalization procedure on the putative distribution of feature errors within the illusory conjunctions, but we saw no preliminary evidence that such a distribution was influencing our conclusions. On the basis of theoretical considerations and the inspection of the observed distribution of feature errors, the most likely distribution of feature errors is either rectangular across the array of letters or a mixture of exactly the types for which the test is designed. Adding a third distribution of one of these types to the mixture does not cause a failure in the mixture test. In fact, it has the opposite effect. Finally, in Experiment 4 it was possible to conduct the mixture distribution test for only the trials in which participants were most confident about the identity of the target. Less than 2% of these responses were categorized as letter errors or color errors (see Table 4). When the mixture distribution test was performed on these data, the trend toward failing the test strengthened.

There are many possible ways in which the information from the color and the letter could be combined. One way that information might be combined is by a weighted spatial average of the locations of the features. If the perceived location of an object is determined by the spatial average of the locations of its features, then over trials the perceived location of illusory conjunctions will form a normal distribution. Although we do not have enough data to adequately test this prediction, the distribution of illusory conjunctions shown in Figures 1, 2, 4, and 5 is consistent with a normal distribution. Furthermore, the spatial average rule for combining information can be applied to trials in which individuals make a correct response as well as an illusory conjunction. Again, the distributions of correct trials shown in the figures are consistent with a normal distribution. We have not displayed the distributions of correct responses for the target-present trials in Experiments 1 to 3, but these also appear to be normally distributed. However, to adequately fit the data to specific distributions, we would need many more trials per participant.

The present research was designed to investigate where participants perceive illusory conjunctions to help understand how complex objects are located. We have thus far not addressed the question of what causes illusory conjunctions. Indeed, it is possible that the mechanism that causes illusory conjunctions is not the same as the mechanism that determines their location. Hence, the present experiments might not shed light on the process of feature integration. However, at least one account of the phenomenon of illusory conjunctions is similar to our account of their perceived

Table 4
Breakdown of Target Identity Confidence Scores for the Six Response Types in Experiment 4

Score[a]	Correct	Illusory conjunction	Color error	Letter error	Letter error illusory conjunction	Letter error color error
1	0.47	0.26	0.12	0.07	0.06	0.02
2	0.72	0.18	0.05	0.02	0.02	0.01
3	0.93	0.04	0.01	0.01	0.00	0.00
M	2.71	1.93	1.71	1.94	1.43	1.32

Note. Scores are given as percentages. The mean is an abstract score.
[a] 1 = least confident; 3 = most confident.

location. Cohen and Ivry (1991) and Ashby et al. (in press) have proposed that features (i.e., colors and shapes) are extracted with some location information. There is noise in this process, so that the location associated with a particular feature may not exactly coincide with its veridical location. Over trials, there exists a distribution of feature locations for each letter and color. In a particular trial, participants perceive a letter in the color of the (color) feature that is closest to it. Usually, the color feature located closest to the letter feature is the correct color. Occasionally, a color associated with another letter is located closer to another letter, leading to an illusory conjunction. Ashby et al. found that this model provided excellent fits to performance in an illusory conjunction task.

The perceived location of features is critical for both the account by Ashby et al. (in press) of the occurrence of illusory conjunctions and our account of the perceived location of illusory conjunctions. Individuals combine a letter feature with the color feature that is closest to it, and they perceive this object (real or illusory) in a location that is the spatial average of the two features. It is therefore critical to have some notion of how the location of a feature is determined. The following account of feature localization is consistent with current knowledge of visual physiology. Suppose that each of a number of "feature detectors" is tuned for a specific feature (e.g., red). These feature detectors have receptive fields so that if the critical feature falls in the receptive field, the feature detector fires with some probability. The system has a certain amount of noise, so that there is a nonzero probability that a feature detector may not fire when the feature is in its receptive field or may fire even when the feature is not in its receptive field (i.e., background firing). In a given trial, a number of feature detectors fire, and the problem is how to combine this information to derive a single feature location. We suggest that one way to integrate the information from numerous feature detectors is to determine a spatial average of the locations signaled by the active feature detectors. The distribution of feature locations over trials will form a normal distribution.

On average, illusory conjunctions will occur in trials in which the feature location is relatively inaccurate, and the perceived location in correct trials will occur when the feature location is relatively accurate. Hence, the distribution of perceived locations of colored letters in correct trials should show a smaller variance than the distribution of perceived locations of illusory conjunctions. In every experiment, the variance of the perceived location distribution in correct trials was smaller than that for illusory conjunctions.

The general approach to feature integration and object location that we are advocating can also explain the effect of attention on illusory conjunctions without resorting to a spotlight. Several investigators have found that feature integration is affected by attention (Cohen & Ivry, 1989; Prinzmetal, Presti, & Posner, 1986; Treisman, 1985). If attention affects the perceived location of individual features, then it should affect the occurrence of illusory conjunctions. In support of this prediction, Tsal and Meiran (1993) reported that the localization of briefly presented dots was more accurate after presentation of a valid spatial cue than after presentation of an invalid spatial cue.

There is some physiological evidence for an effect of attention on the localization of features. Moran and Desimone (1985) measured the response properties in cells in V4 while rhesus monkeys attended to particular locations. They found that attending to a region narrows receptive fields within it. This result could be the mechanism responsible for the reduction of illusory conjunctions within attended locations: The reduction in receptive field size could represent an increase in the precision with which features are located, much like the account offered by Isenberg, Nissen, and Marchak (1990). Located with more precision, the features would be less likely to be assigned to the wrong stimuli, a process that would result in a decrease in the number of illusory conjunctions.

In this research, we examined where individuals perceive illusory conjunctions. Our results indicate that illusory conjunctions are not free floating but are located on average between separate features. Illusory conjunctions represent an interesting test case for understanding how the location of complex objects is perceived.

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