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Loosening the Constraints on Illusory Conjunctions: Assessing the Roles of Exposure Duration and Attention

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Illusory conjunctions are the incorrect combination of correctly perceived features, such as color and shape. They have been found to occur using a brief exposure (under 200 ms) and a dual task designed to divert attention. The present study investigated the roles of exposure duration and attention in obtaining illusory conjunctions. Several mathematical models of the feature integration task were also assessed. Experiment 1 tested participants' accuracy at combining features using a long exposure and an attention-diverting task. Experiment 2 compared performance with and without the attention-diverting task. The final experiment compared performance using a brief (0.15 s) and a long (1.5 s) exposure duration without an attention-diverting task. Neither attention nor exposure duration had a significant effect on feature integration.

According to traditional theories of visual recognition, people identify an object through an analysis of the various visual features of that object. Proposed visual features include shape primitives (e.g., Selfridge, 1959), volumetric solids (Biederman, 1985), spatial frequencies (DeValois & DeValois, 1990), color (Treisman & Gelade, 1980), and so on. By this view, people would recognize an apple as such as a consequence of correctly perceiving its features, such as color, shape, and texture.

Treisman and colleagues have proposed that feature analysis, by itself, is not sufficient for recognition (Treisman, 1988; Treisman & Gelade, 1980; Treisman & Schmidt, 1982). For example, in a single scene observers are confronted with a multitude of objects. Simply being able to correctly register the features of these objects is not enough; observers must also be able to correctly combine the features of each object into a coherent whole. Incorrectly combining the features of different objects would lead to what Treisman has called "illusory conjunctions." Treisman and Schmidt (1982) introduced the notion of illusory conjunctions with the following anecdote: "A friend walking in a busy street 'saw' a colleague and was about to address him, when he realized that the black beard belonged to one passerby and the bald head and spectacles to another" (p. 109). In this instance, the correctly perceived features of a bald head and spectacles were incorrectly combined with a black beard to form an illusory face.

Treisman's theory of feature integration proposes that the different features of an object are identified automatically and in parallel, whereas actual object recognition takes place only after the different features have been put together in serial fashion. This second step—conjoining features—is said to require focused attention. If attention is not focused, features that have been correctly perceived may be incorrectly combined to form illusory conjunctions.

Treisman and Schmidt have demonstrated the existence of this phenomenon using a variety of tasks. For example, in a whole report task, Treisman and Schmidt (1982) presented participants with a stimulus consisting of three colored letters flanked by two black digits for an exposure duration averaging 120 ms. The participants' task was to report first the two digits and then as many of the colored letters as they could. The purpose of reporting the digits was to tax attention; the main results concerned the report of the colored letters. Participants reported incorrect combinations of colors and letters on nearly 40% of the trials. For example, if the display contained a red *T*, a blue *N*, and a green *X*, an illusory conjunction would have been the report of a blue *T*. Illusory conjunctions were twice as likely to be reported as errors involving the report of one feature (color or letter) present in the display combined with another feature not present in the display.

In addition to the whole report task, Treisman and others have obtained illusory conjunctions of color and shape using a presence–absence detection task, a same–different matching task, and a partial report task (e.g., Cohen & Ivry, 1989; Ivry & Prinzmetal, 1991; Keele, Cohen, Ivry, Liotti, & Yee, 1988; Prinzmetal, 1992; Prinzmetal, Hoffman, & Vest, 1991; Prinzmetal & Keysar, 1989; Prinzmetal & Mills-Wright, 1984; Prinzmetal, Presti, & Posner, 1986; Rapp, 1992; Treisman, 1988; Treisman & Schmidt, 1982). In addition to color and shape, illusory conjunctions have been found to occur with other features such as line segments and simple shapes (e.g., Fang & Wu, 1989; Gallant & Garner, 1988; Lasaga & Hecht, 1991; Maddox, Prinzmetal, Ashby, & Ivry, 1994; Prinzmetal, 1981; Treisman & Pater-

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son, 1984). For example, in a detection task, Prinzmetal found that participants perceived an illusory plus sign when they had been presented with both vertical and horizontal lines.

To date, every study involving illusory conjunctions has used a brief exposure (i.e., 200 ms or less). In addition, many of these studies have used a secondary task designed to divert attention from the stimulus. On the basis of Treisman's theory, many investigators assumed that the secondary task was necessary to obtain illusory conjunctions, because these errors were thought to occur only in the absence of focused attention. Nevertheless, illusory conjunctions have been obtained without a secondary attention-demanding task (e.g., Prinzmetal, 1992; Prinzmetal et al., 1991; Prinzmetal & Keysar, 1989; Prinzmetal & Mills-Wright, 1984; Rapp, 1992). In these experiments, stimuli were presented briefly in the periphery, and participants were not cued in advance as to where the stimuli would appear. It should be noted, however, that other researchers have found that it takes time for attention to be deployed to a stimulus location (e.g., see LaBerge & Brown, 1989; Posner, 1978; Reeves & Sperling, 1986; Tsal, 1983). If the time required to deploy attention is longer than the exposure duration, then participants may not have enough time to attend to the stimulus. Hence, with a brief exposure it is difficult to determine whether participants are making illusory conjunctions in the presence or the absence of focused attention.

If it is possible to obtain illusory conjunctions without diverting attention, a broader theoretical perspective may be necessary. One alternative to Treisman's theory of illusory conjunctions is the notion that these errors are due to poor location information (Ashby, Prinzmetal, Ivry, & Maddox, in press; Maddox et al., 1994; Prinzmetal & Keysar, 1989). By this account, if the red of one letter is perceived in the location of another letter, an illusory conjunction will occur. Thus, any factor that limits location accuracy might cause illusory conjunctions. Possible factors limiting the accuracy of spatial information might include diverting of attention (Prinzmetal, Presti, & Posner, 1986), but other factors, such as eccentricity, might also affect location accuracy and thus the occurrence of illusory conjunctions. The purpose of the present investigation was to determine whether illusory conjunctions could occur with relatively long exposure durations and without diverting attention, as the location theory suggests.

In previous studies, it has been difficult to establish whether responses classified as illusory conjunctions were the result of true errors of feature integration or were the result of merely guessing (e.g., Prinzmetal, Presti, & Posner, 1986). To address this problem, we needed a method of independently estimating the probability of correctly perceiving features from the probability of correctly joining them. We chose a new method developed by Ashby et al. (in press). This method, which is related to techniques developed by Batchelder and Riefer (1990; Riefer & Batchelder, 1988), is described only briefly here (a more rigorous development can be found in Ashby et al. (in press). This technique provided us with a rigorous way to determine whether participants were making true feature integration errors.

In the first of three experiments, we tested feature integration accuracy with a long exposure duration (1.5 s) while participants were engaged in an attention-demanding dual task. In the second experiment, we studied participants' accuracy at feature integration with and without the secondary task. The final experiment compared the occurrence of illusory conjunctions with long (1.5-s) and brief (0.15-s) exposure durations. In each experiment, participants made consistently more illusory conjunctions than all other errors combined. These results lead us to believe that illusory conjunctions are not limited to a few specialized laboratory conditions.

Experiment 1

There is a temptation to derive theoretical constructs on the basis of only a small sample of experimental manipulations. Cognitive psychologists have frequently assumed that certain perceptual phenomena will emerge only under conditions in which the information available to the visual system is limited by the use of a brief exposure. For example, it has been found that under conditions of a brief exposure and a poststimulus mask, participants are more accurate at identifying letters in words than in nonwords (word-superiority effect; Reicher, 1969). Hence, several theorists have proposed that a brief exposure and a poststimulus mask play a central role in the word-superiority effect (e.g., Massaro & Klitzke, 1979; McClelland & Rumelhart, 1981; Richman & Simon, 1989). Recently, however, Prinzmetal (1992; Prinzmetal & Silvers, 1994) has reported that the word-superiority effect can be obtained with an unlimited viewing time. Consequently, it can be concluded that manipulating exposure duration is one method for obtaining this effect, but it is not necessary.

A similar situation exists in the study of illusory conjunctions. Illusory conjunctions have always been obtained with a brief exposure, and therefore it is tempting to attribute a critical role to these exposure conditions. For example, Crick's (1984) account of illusory conjunctions made explicit mention of the idea that a brief exposure does not provide enough time for participants to allocate their attention to the stimulus.

Before a determination of whether taxing attention was necessary to obtain illusory conjunctions, it was important to establish whether illusory conjunctions would occur without a tachistoscopic exposure. In the first experiment, participants engaged in an attention-demanding rapid serial visual presentation (RSVP) task at fixation. Meanwhile, two colored letters were presented in the periphery for 1.5 s. We tested whether participants would incorrectly combine the color and letter-shape information.

Method

Procedure. Each trial lasted 5 s. During the trial, a rapid sequence of 30 digits was presented at the fixation point. Each digit remained in view for 167 ms. The participant's primary task was to press a button whenever the digit 0 appeared. The digits were presented in random order with the constraint that after a target 0, the next 2 digits could not be targets. Thus, there could be up to 10 target digits in each trial.

At the onset of the 20th digit, a string of four letters appeared at one of four locations in the periphery and remained in view until the onset of the 29th digit for 1.5 s (see Figure 1). The string of four letters consisted of a pair of colored letters flanked by two white *O*s. We used this flanking arrangement because Treisman (1982, Experiment 4) found that a similar one dramatically increased the proportion of illusory conjunctions obtained. One of the colored letters, the target letter, was *T, X,* or *L,* and the other colored letter, the noise letter, was always *O.* The participant's secondary task was to report aloud the identity and color of the target letter. For example, the participant would report "red *X*" or "green *T*." The experimenter then entered the response into a computer.

Most experiments studying illusory conjunctions have controlled individual participant accuracy by adjusting exposure duration. We controlled individual performance by adjusting eccentricity (see *Stimuli* section). The eccentricity was adjusted between blocks with the goal of obtaining 80% correct on the colored letter task. There were 48 trials in each block, 12 at each target position (see Figure 1). Each participant was tested for approximately 1 hr in two separate sessions. The first session was considered practice, and the data were not analyzed. Participants were tested for at least six blocks of trials during the second session.

Feedback. Participants were given the following feedback for the digit-detection task. If the participant correctly responded within 500 ms after the onset of a '0,' the computer immediately emitted a brief, high-pitched tone indicating a hit. If the participant did not respond or responded outside of this temporal window, the computer emitted a brief, low-pitched sound indicating a miss or false alarm.

The task was set up like a video game, complete with scoring system, to keep participants interested and motivated. Participants earned points, and their point total was displayed at the bottom of the screen. They earned 10 points for each digit hit and lost 10 points for each miss or false alarm. On trials in which participants made 100% digit hits and no false alarms, the computer emitted a sound like a ringing cash register, and the participant earned an extra 100 points. Participants reported that the RSVP task was both challenging and engaging.

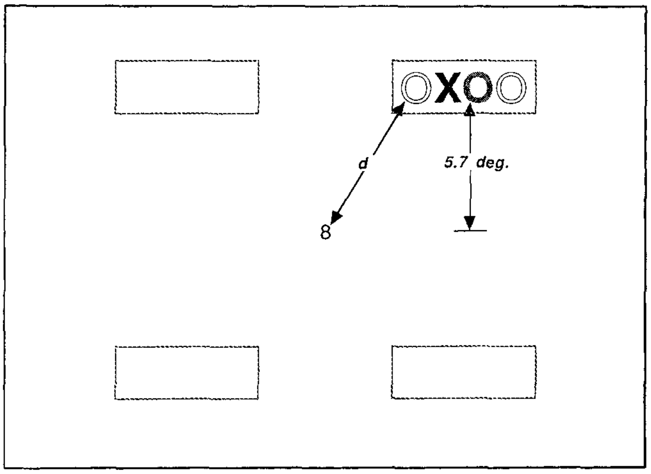

Figure 1. Stimulus display in Experiment 1. The rectangles mark the possible stimulus locations. The eccentricity was controlled by varying the distance (*d*).

Participants were given the following feedback for the color–letter identification task. After the last digit, participants responded with first the color and then the identity of the target letter. The experimenter entered this information into the computer sequentially, and the computer emitted a high-pitched tone for a correct response and a low-pitched tone for an incorrect response. Thus, two high-pitched tones indicated that both the color and identity were correct, a low tone followed by a high tone indicated that the color was incorrect but that the letter identity was correct, and so forth. Participants earned 10 points for each correct color or letter response. They lost 10 points for reporting an incorrect color or letter.

In keeping with the game format, every 10th trial was preceded with the words "next, bonus trial," together with a trumpet herald. Points earned on the bonus trial were doubled (i.e., points in the RSVP + target identification task). Participants' pay was not contingent on their points and performance (see later discussion). The points and sound effects were not directly related to the experiment except as a means of providing feedback and keeping participants motivated.

Stimuli. The displays were presented on a 33-cm (13-in.) Apple monitor controlled by a Macintosh II computer.[1] The monitor had a screen resolution of 72 pixels per inch (approximately 28 pixels per centimeter). Participants sat approximately 40 cm from the monitor. The stimuli were presented on a black background. The central digits for the RSVP task were white and drawn in 18-point Helvetica type. They subtended a visual angle of approximately 0.7° in height and 0.4° in width. The four letters were presented in uppercase 36-point Helvetica type and, as a string, subtended a visual angle of approximately 1.4° in height and 5.2° in width.

The target letter and two different colors were randomly selected on each trial. The two colors were from the set red, green, and blue. The target letter and the colored noise letter were flanked by two white *O*s. Whether the target was to the left or to the right of the noise letter was randomly determined on each trial, as was the location of the string of four letters.

The string of four letters appeared so that its nearest edge was always approximately 5.7° above or below the horizontal meridian (see Figure 1). The stimulus eccentricity was controlled by moving the stimulus either toward or away from the vertical meridian of the screen. The eccentricity of the four-letter stimulus string (*d* in Figure 1) was measured from the center of the screen to the nearest edge of the string and averaged 7.6° of visual angle (range = 7.2° to 8.2°).

The stimuli were viewed under normal (fluorescent) lighting conditions. The CIE coordinates were measured with a Minolta Chroma meter, model CS100 as follows: red, $x = .46$, $y = .33$; green, $x = .29$, $y = .49$; and blue, $x = .19$, $y = .13$. The luminance values were 42.4 cd/m^2 (red), 80.4 cd/m^2 (green), and 30.5 cd/m^2 (blue). (On the Macintosh computer, the RGB values were $FF00, $2C00, $2C00 [red]; $2A00, $F200, $2A00 [green]; $2C00, $2C00, $FC00 [blue].) The luminance of the white letters and digits was 120 cd/m^2, and the background of the monitor was 8.1 cd/m^2.

[1] The computer programs that were used in this research can be obtained from the authors. To receive the programs, please send a 3.5-in. double-density disk and a self-addressed, stamped envelope.

Participants. Six participants, 4 women and 2 men, were recruited at the University of California, Berkeley. Their ages ranged from 18 to 25, and they had normal or corrected-to-normal vision and no known visual deficits. Participants were paid $5 per hour.

Results

The results are presented in two sections. First, we present the direct analysis of the six response categories, and then we present and compare three models of the results.

Response categories analysis. The most critical results were obtained from the colored-letter task. There were six response categories. To illustrate the six possible types of responses, consider a stimulus consisting of a red X and a green O. The six response categories were as follows: correct (red X), conjunction report error (green X), color feature error (blue X), letter feature error (red L), letter feature–conjunction report error (green L), and color–letter feature error (blue L). These response categories are abbreviated C, CR, CF, LF, LFCR, and CLF, respectively. Figure 2 summarizes the categories for quick reference. The average proportions for each of the five error response categories are shown in Figure 3.

We use the label CR to make clear that not all of the responses in which the nontarget color was reported represented true failures of feature integration or illusory conjunctions. Some of these reports represented trials in which the participant did not perceive the color or identity of the target and guessed. Treisman and Schmidt (e.g., 1982, p. 115) inferred the existence of illusory conjunctions when the proportion of trials resulting in CRs exceeded the proportion of trials in which a participant combined one feature that was part of the display with one that was not. By this criterion, one can easily reject the notion that all of the CR were due to guessing. Participants averaged 16.95% CR errors (combination of noise color and target letter). However, the proportion of trials on which participants combined one display feature with a feature that was not part of the display was 6.0%. Each of the 6 participants had more CR errors than the total of all other errors. Certainly, by Treisman's criterion, participants made true feature integration errors without a brief exposure.

STIMULUS: X_{red} O_{green}

RESPONSE:	TYPE:
X_{red}	Correct (C)
X_{green}	Conjunction Report (CR)
X_{blue}	Color Feature Error (CF)
L_{red}	Letter Feature Error (LF)
L_{green}	Letter Feature - Conjunction Report (LFCR)
L_{blue}	Color Letter Feature Error (CLF)

Figure 2. Examples of the six response categories in the experiments.

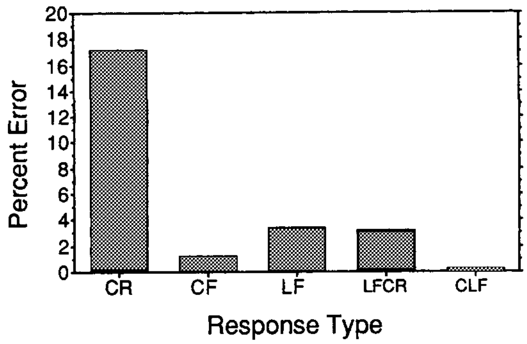

Figure 3. Results of Experiment 1. CR = conjunction report error; CF = color feature error; LF = letter feature error; LFCR = letter feature–conjunction report error; CLF = color–letter feature error.

Participants were extremely accurate at identifying the target color. The percentage of trials in which participants reported a color not present in the display was 0.52% (CF + CLF errors). Furthermore, participants were relatively accurate at identifying the target letter, erring on only 5.6% of the trials (LF + LFCR + CLF errors).

The probability of responding to the target digit in the RSVP task within 0.5 s of its onset (i.e., a hit) averaged .815. The probability of responding outside of this temporal window averaged .032 (i.e., a false alarm). It is possible that participants diverted their attention from the RSVP task when the colored letters appeared in the periphery. If this were the case, one might expect that during a trial in which participants diverted their attention to the peripheral letters, they might have missed the target digit. Hence, in a trial-by-trial analysis, the proportion of hits in the RSVP task would be negatively correlated with the proportion correct on the colored-letter task. For each participant, we correlated the hit rate with whether or not the participant was correct on the target identification task (coded 0 and 1). This correlation averaged only −.018. From this analysis, it appears that participants were not diverting their attention to the peripheral targets.

We have argued elsewhere that Treisman's criterion is not a sufficient method for assessing feature integration errors (Ashby et al., in press). Specifically, the method may overestimate the occurrence of such errors (see Ashby et al., in press). In the next section, we present three models that can be used to assess the occurrence of true feature integration errors.

Models. Previous investigators have used various methods to separate true illusory conjunctions from guessing. For example, Treisman has proposed that participants are making true illusory conjunctions when the proportion of CR exceeds the proportion of trials on which one feature from the display is combined with a feature that is not part of the display (Treisman & Schmidt, 1982). Alternatively, in an experiment such as the present one, Cohen and Ivry (1989) proposed that participants are making true illusory conjunctions when the proportion of CR errors exceeds the proportion of CF errors. It is difficult to compare these various methods because these investigators have not provided systematic derivations for their criteria. It is therefore unclear what assumptions are being made. Recently, Ashby et al. (in press) developed a formal method for analyzing feature integration data. This method requires theoretical assumptions to be specified explicitly, allowing for a rigorous comparison between models. In addition, the method allows one to separately estimate the probabilities of correctly perceiving and correctly joining features.

We analyzed our results using three models. The first two models assumed that participants did not make errors of feature integration but that the responses labeled CR errors resulted from guessing. The third model assumed that, on some proportion of trials, participants incorrectly perceived the target letter as being the color of the noise letter. The model that assumed that participants made true feature integration errors fit the results of Experiment 1 better than the alternatives.

The first step in our analysis was to represent all possible theoretical states and to show how they lead to specific response types given an explicit set of assumptions. Figure 4 depicts a simple two-parameter model (called Null 1) for our colored-letter task that assumed that participants did not make errors of feature integration. This model predicted that whenever a participant perceived the target color and the target shape, he or she correctly joined the features and made a correct response. The first parameter represented the probability that the participant correctly perceived the target letter (*TL* parameter), and the other parameter represented the probability that the participant correctly perceived the target color (*TC* parameter). The expressions $1 - TL$ and $1 - TC$ refer to the probabilities that the participant did not perceive the target letter and color, respectively. The constants (e.g., one third) are guessing constants dependent on the number of colors and target letters in the experiment. For example, suppose on a trial that a participant did not perceive the target letter ($1 - TL$) but did perceive the target color. Because there were three possible letters, there was a one-third chance that the participant would correctly guess

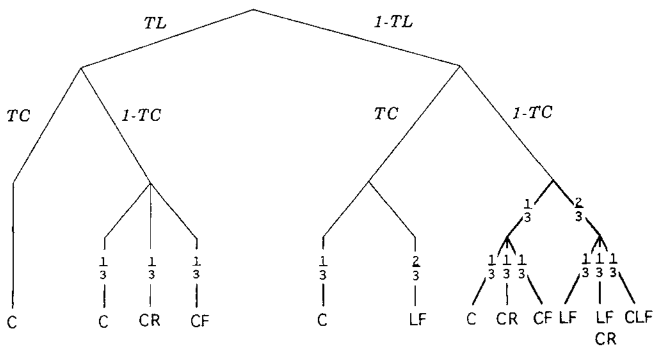

Figure 4. Null 1: a two-parameter model that does not assume true illusory conjunctions. *TL* = target letter parameter; *TC* = target color parameter; C = correct; CR = conjunction report error; *CF* = color feature error; LF = letter feature error; LFCR = letter feature–conjunction report error.

the target identity and thus make a correct response, and there was a two-thirds chance that the participant would guess a letter not included in the display, resulting in a letter feature error.

The predicted value for any response category was simply the sum of all paths that led to that response. For example, the predicted probability of a correct response was as follows:

$$p(C) = (TL \times TC) + [TL \times (1 - TC) \times 1/3] + [(1 - TL) \times TC \times 1/3] + [(1 - TL) \times (1 - TC) \times 1/9]. \quad (1)$$

Predictions for the other five response categories were made in the same manner. This model corresponds to the criteria for true illusory conjunctions proposed by Cohen and Ivry (1989). They proposed that true illusory conjunctions occurred whenever the probability of CR errors was greater than the probability of CF errors. The Null 1 model predicted that $p(CR) = p(CF)$. To the extent that this relation was violated, Null 1 (which assumed no true feature integration errors) did not provide a good description of the data.

We were not satisfied with the Null 1 model because it did not reflect the probability of perceiving the nontarget color. Consider the following scenario: The participant correctly perceived the two colors in the display but did not perceive the letters. The participant would naturally respond with one of the two colors he or she perceived. If the participant had correctly guessed the target letter, he or she would have responded with the target color on half of the trials but would have responded with the nontarget color on the other half. The Null 2 model was designed to capture this situation.

Null 2 is depicted in Figure 5. This model, like Null 1, assumed that participants did not make errors in feature integration. Hence, the left half of the diagram (*TL* branch) is identical to Null 1: If a participant correctly perceived the target letter and the target color, he or she would have correctly joined these features. The Null 2 model differs from Null 1 in the right half of the diagram ($1 - TL$ branch). This branch contains a third parameter, *NC*, the probability of perceiving the nontarget color. Consider the case in which the participant did not perceive the target letter ($1 - TL$) but did perceive both the target color and the nontarget color. There was a one-third probability that the participant would guess the correct letter and a two-thirds probability that the participant would guess an incorrect letter. The participant also must have chosen a color from one of the two that were perceived: In Figure 5, the circled ½s represent this probability. Finally, we assumed that if the participant did not perceive the target letter ($1 - TL$) and perceived only the target color or the nontarget color, but not both, he or she responded with that color. That is, participants would tend to use whatever information they had. Null 2 should have provided a good fit of the data except in cases in which participants made true illusory conjunctions. Note that unlike Null 1, Null 2 predicted that $p(CR) > p(CF)$

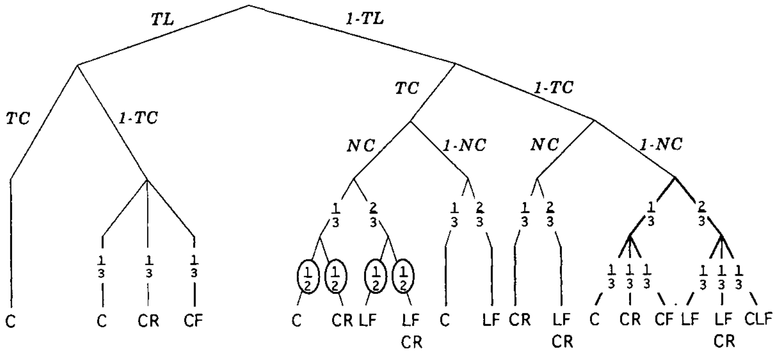

Figure 5. Null 2: a three-parameter model that does not assume true illusory conjunctions. *TL* = target letter parameter; *TC* = target color parameter; *NC* = nontarget color parameter; C = correct; CR = conjunction report error: CF = color feature error; LF = letter feature error; LFCR = letter feature–conjunction error.

without assuming that participants were making true illusory conjunctions.

The final model we considered with this data assumed that participants incorrectly combined the nontarget color with the target letter on some proportion of trials. We call this model alpha because it introduced a parameter, α, that is the probability of correctly binding the target color to the target letter. The alpha model is illustrated in Figure 6.

The $1 - TL$ branch of alpha is identical to Null 2, and so it has been omitted from Figure 6. To get a feel for this model, consider the four terminal nodes labeled A, B, C, and D (in circles). First, consider the situation in which the participant correctly perceives the target letter (e.g., *X*), the target color (e.g., red), and the nontarget color (e.g., green). The participant must bind one of the colors to the target letter. The probability of correctly binding the target color to the target letter is represented by the parameter α. This set of events results in Terminal Node A and is one way in which a correct response will arise. However, if a binding error occurs, represented by the $1 - \alpha$ branch, then the participant will erroneously join the nontarget color with the target letter (Terminal Node B). This CR error would reflect a true illusory conjunction.

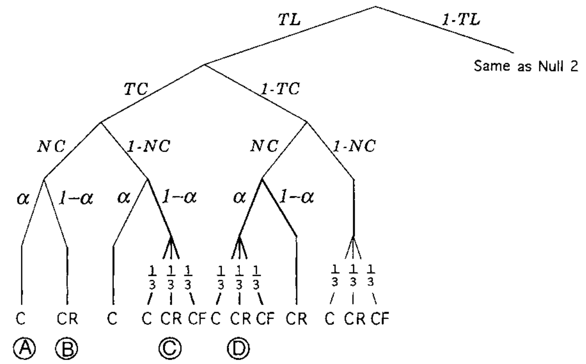

Figure 6. Alpha model: a model that does assume true feature integration errors with probability α. *TL* = target letter parameter; *TC* = target color parameter; *NC* = nontarget color parameter; *C* = correct; CR = conjunction report error; CF = color feature error.

Next, consider Terminal Node C, which represents a slightly more complex situation. The participant perceives the target letter and the target color but has failed to identify the nontarget color. The participant will correctly bind the target color with the target letter with a probability of α, resulting in a correct response. However, there is a probability of $1 - \alpha$ that the participant will incorrectly bind the target color to the nontarget letter. The incorrect binding of the target color to the nontarget letter leaves the target without a color. Phenomenally, the target might appear gray. In this case, the participant must guess a color for the target letter, and one third of these guesses will be CR errors.

Finally, consider Terminal Node D, which represents the situation in which the participant perceives the target letter and only the nontarget color. The participant correctly binds the nontarget color with the noise letter with a probability of α. The participant must then guess a color for the target letter, and one third of these guesses will be CR errors.

Note that the Null 2 and alpha models are actually different versions of the same model. If alpha equals 1.0 (perfect feature integration), then alpha becomes Null 2 (see Ashby et al., in press). Likewise, Null 1 is a special case of Null 2; if the *NC* parameter equals 0, then Null 2 becomes Null 1 (i.e., the nontarget color plays no role in responses).

We actually examined several variants of the three models presented here. For example, Null 2 and alpha assumed that participants did not use information from the nontarget letter to constrain their guess of the target letter. Because colors were not repeated in our experiment, participants might have excluded the nontarget color as a guess for the target color. For example, if a participant had perceived that the nontarget letter was green but did not perceive the target color, he or she might have excluded green as a guess of the target color. However, such an "exclusionary" model did not provide as good a fit of the present data as the models presented. In another variant model (opposite to the exclusionary model), when the participant perceived only the nontarget color, he or she would always guess that color. Ashby et al. (in press) discussed several other variants of these models. The models we present here are the best models we could find for the present data in terms of goodness of fit and reasonableness of the parameter estimates, although in other circumstances one of the other variants might provide a better fit.

Predicted values for all six response categories can be obtained from the models. We fit the data individually for each participant and model. Each fit was based on the 24 data points, because we did not combine the data over the four locations. We adjusted the parameters (e.g., *TL* and *TC*) with the method of gradient descent to obtain the best fit between the model-predicted probabilities and observed proportions. Different starting values for these parameters were used to ensure that the resulting fits were not local minima. Our criterion for goodness of fit between the model predictions and the 24 observed response proportions was log likelihood ($-ln$), defined as follows:

$$- ln = \sum_{i=1}^{24} (\text{FreqObs}_i)[ln(\text{ProbPred}_i)]. \quad (2)$$

FreqObs and ProbPred are the observed frequency and predicted probability for each of the six response categories at each of the four stimulus locations (i.e., 24 data points per participant). Log likelihood is always a negative value; the closer the value to zero, the better the model fit. The absolute value of $-ln$ depends on the goodness of fit of the model and the number of observations such that the value of $-ln$ is meaningful only when different models with the same data set are compared.

Models with different numbers of parameters such as these can be compared with Akaike's (1974) A information criterion (AIC). This statistic generalizes the method of maximum likelihood by penalizing models for each free parameter:

$$AIC = (-2 \times ln) + (2n), \quad (3)$$

where *ln* is the log-likelihood value obtained earlier and *n* is the number of parameters. Smaller AIC values indicate a better fit. The logic of AIC is as follows: The value ($-2 \times ln$) underestimates the expected value, $-2E(ln)$. The greater the number of parameters, *n*, the greater the bias. AIC corrects for this bias by adding 2*n*, which makes AIC an unbiased estimator. AIC is the only method of comparing models with different numbers of parameters that is general (i.e., models need not be nested). An excellent treatment of AIC has been provided by Sakamoto, Ishiguro, and Kitagawa (1986). Takane and Shibayama (1992) discussed several examples of psychological research involving AIC.

The goodness-of-fit (AIC) and parameter values are given in Table 1. For each of the 6 participants, the alpha model provided the best fit of the data.[2] Furthermore, the parameters of the null models did not accurately describe the results of the experiment. For example, from the raw data, *it is clear that participants* were more accurate in perceiving the colors than the letters. Yet, in the Null 1 model, the *TL* parameter was greater than the *TC* parameter for every participant. In the Null 2 model, the probability of perceiving the nontarget color was greater than the probability of perceiving the target color for each participant. This result seems unlikely given that participants should have more information about the color that they are asked to report than the color of the nontarget item. The parameters of the alpha model, on the other hand, seemed to capture the relative difficulty of the letter and color judgment components of the task. Because models that do not postulate true feature integration errors do not account for the data as well as a model that does, one can reject the idea that the CR errors observed in this task resulted from guessing.

Table 1
Model Fits From Experiment 1

Participant	*TL*	*TC*	*NC*	α	*ln*	AIC
			Null 1 model			
1	.927	.771			−209.6	423.2
2	.932	.802			−191.7	387.3
3	.896	.495			−323.9	651.7
4	.894	.731			−204.0	412.1
5	.870	.406			−357.3	718.7
6	.964	.875			−132.2	268.4
			Null 2 model			
1	.905	.857	.990		−184.2	374.4
2	.910	.886	.990		−167.1	340.2
3	.850	.583	.893		−309.1	624.1
4	.855	.846	.990		−183.6	373.2
5	.815	.522	.990		−334.4	674.7
6	.952	.910	.990		−125.2	256.4
			Alpha model			
1	.927	.986	.999	.897	−170.9	349.7
2	.932	.999	.999	.908	−152.6	313.1
3	.895	.982	.967	.690	−263.8	535.5
4	.894	.999	.999	.866	−166.7	341.4
5	.870	.872	.999	.694	−300.5	609.0
6	.964	.999	.863	.927	−116.4	240.8

Note. *TL* = target letter parameter; *TC* = target color parameter; *NC* = nontarget color parameter; *ln* = log likelihood; AIC = A information criterion.

Discussion

We used two methods to determine whether participants make true illusory conjunctions with a long exposure. First, we applied Treisman's criterion to the raw data. Second, we applied a more rigorous theoretical method developed by Ashby, et al. (in press) that involves all six response categories. With this approach, we were able to compare models that do not assume true feature integration errors with a model that does. In both cases, the evidence suggests that participants incorrectly combined features on a substantial proportion of trials.

[2] It is not inevitable that the alpha model will provide the best fit of the data. In cases in which participants do not make illusory conjunctions, the Null 2 model generally provides a better fit of the data. Ashby et al. (in press) reported such cases.

The probability of correctly joining features is estimated by the parameter α in the alpha model. If participants always correctly combined features, then α would have equaled 1.0 and the null models would have provided a better fit of the results (because of the penalty imposed by the AIC statistic for extra parameters). If features were truly free floating, then participants would have been as likely to combine the target letter with the nontarget color and α would have equaled .5. The truth appears to be somewhere between these extremes; α averaged .83. Thus, even with an engaging secondary task, features are not completely free floating, and feature integration is not perfect.

Experiment 2

In Experiment 1, we obtained feature integration errors with an exposure duration of 1.5 s. This is well within the time it takes to deploy attention to a nonfoveal location in the visual field (e.g., see Reeves & Sperling, 1986; Tsal, 1983). Of course, in Experiment 1 participants may have been prevented from shifting their attention to the location of the colored letters by the digit-detection RSVP task. In fact, the digit-detection task was explicitly designed to engage participants' spatial attention at the point of fixation and was similar to the attention-diverting task used by Treisman and others (e.g., Cohen & Ivry, 1989; Treisman & Schmidt, 1982). According to Treisman's feature integration theory, if the "spotlight" of attention is focused on the digits, the colors and letters will be outside the focus of attention and illusory conjunctions will occur.

In Experiment 2, we tested whether it is necessary to divert attention to obtain illusory conjunctions. In this experiment, there were two conditions. One condition was simply a replication of Experiment 1: Participants engaged in an attention-demanding task while the colored letters were presented in the periphery for 1.5 s. The second condition was the critical condition. Participants simply had to maintain fixation in the center of the monitor for 1.5 s while the colored letters were presented in the periphery. If illusory conjunctions are obtained in the second condition, then diverting attention is not necessary for the occurrence of illusory conjunctions.

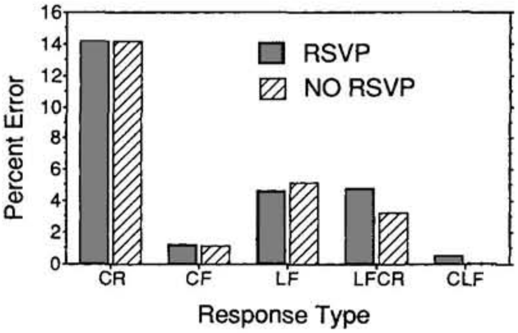

Figure 7. Results of Experiment 2. RSVP = rapid serial visual presentation; CR = conjunction report error; CF = color feature error; LF = letter feature error; LFCR = letter feature–conjunction report error; CLF = color–letter feature error.

Method

Each participant took part in two sessions. In one session, participants performed the RSVP digit-detection task while the colored letters were present. This session was essentially identical to Experiment 1. In the other session, participants had to maintain fixation only while the colored letters were presented in the periphery for 1.5 s (no RSVP task). Half of the participants performed the RSVP task first, and half performed the no RSVP task first. There was no practice session, but participants were given at least 36 trials of practice before each task.

The RSVP task session was identical to Experiment 1 except as follows: The digits were randomly selected from the set 1 to 9 (0 was excluded to avoid the possibility of participants confusing the flanking letter *O*s with digit 0s) and the target digit was a 1. Participants viewed the stimuli at approximately the same distance as in Experiment 1 (40 cm), and in addition, their heads were restrained with a chin rest. Eye movements were monitored with an Applied Science Laboratory eye movement monitor (Model 210). With this apparatus, in an independent test, we detected 3.6° diagonal eye movements with hit and false alarm rates of approximately .98 and .05, respectively. Whenever an eye movement was detected during a trial, the computer emitted a low-pitched tone for 2 s, and the participant was reminded to maintain fixation. Eye movements were detected on 4.08% of the trials. Although the results reported here include all trials, excluding the trials in which eye movements were detected did not affect the pattern of results.

In the no RSVP task, each trial lasted 1.5 s. At the beginning of the trial, a fixation dot changed to a small diamond (the same size as the digits in the RSVP task), and the string of letters was presented in one of four locations as before. After 1.5 s, the diamond was replaced by the fixation point, and the string of letters was erased. The participant had only to maintain fixation and report the identity and color of the target letter. Eye movements were monitored as described earlier.

Naturally, the RSVP task was much more difficult than the no RSVP task. To maintain the appropriate levels of performance for both tasks, we adjusted the stimulus eccentricity between blocks as in Experiment 1. Feedback was identical to Experiment 1, except that there was no feedback for digit detection in the no RSVP task.

Six participants, selected from the same population as before, took part in this experiment. The RSVP task took approximately 1.5 hr, and the no RSVP task took approximately 1 hr. Participants were paid $5 per hour.

Results

Response categories analysis. The RSVP and no RSVP tasks did not differ in terms of rates of correct reporting of the color and identity of the target letter. The mean percentage correct values for the RSVP and no RSVP tasks were 76% and 75%, respectively, $t(5) = 0.52$, *ns*. However, to obtain this equal overall performance, we used a significantly greater eccentricity in the no RSVP task than in the RSVP task. The eccentricities for the two tasks (*d* in Figure 1) were 8.4° and 7.6°, respectively, $t(5) = 7.38$, $p < .01$. It may have been that maintaining fixation in the no RSVP condition required some attention. Nevertheless, the RSVP condition was significantly more difficult than the no

RSVP condition. Hence, we know that the RSVP task effectively manipulated attention.[3]

The proportions of responses for each of the five error response categories are shown in Figure 7. What was striking about these results was how remarkably similar the response profiles were in the two tasks. There were no significant differences in any of the response categories between RSVP and no RSVP task conditions. The *t*-test values (with 5 degrees of freedom) ranged from 0.41 to 1.04; none approached significance.

According to Treisman's criterion, 5 of the 6 participants made true feature integration errors in both tasks. One participant satisfied Treisman's criterion in the no RSVP task but not in the RSVP task. In the no RSVP task condition there were 14.83% CR errors; the percentage for all other errors combined was 9.65%. In the RSVP task condition, the corresponding percentages were 14.13% and 11.21%. The averages for all color errors (CF + CLF) were 1.3% and 1.8% for the no RSVP and RSVP tasks, respectively. The averages for all letter errors (LF + LFCR + CLF) were 8.5% and 9.9% for the no RSVP and RSVP tasks, respectively. Thus, in comparison with Experiment 1, participants made more feature errors in both the no RSVP task and the RSVP task. The reason for this increase in feature errors may have been that participants received less practice before beginning Experiment 2.

The average hit and false alarm rates for digit detection on the RSVP task were .766 and .016, respectively. As in Experiment 1, we correlated RSVP task performance with whether or not participants were correct on a trial. The average correlation was .018, indicating that participants were probably not shifting their attention to the peripheral letters.

Table 2
Model Fits From Experiment 2: No RSVP Task

Participant	*TL*	*TC*	*NC*	α	*ln*	AIC
			Null 1 model			
1	.913	.712			−202.5	409.0
2	.839	.490			−351.0	705.9
3	.587	.649			−597.2	1,198.4
4	.781	.766			−275.6	555.3
5	.891	.661			−274.1	552.1
6	.901	.750			−233.0	470.1
			Null 2 model			
1	.883	.785	.929		−195.3	396.6
2	.813	.553	.539		−344.8	695.7
3	.551	.953	.928		−519.3	1,044.5
4	.718	.990	.990		−240.6	487.1
5	.851	.767	.990		−255.1	516.2
6	.871	.847	.990		−213.7	433.4
			Alpha model			
1	.912	1.000	.833	.816	−177.6	363.2
2	.837	.875	.642	.683	−326.7	661.4
3	.587	.982	.847	.912	−516.0	1,040.1
4	.781	1.000	.991	.926	−233.9	475.7
5	.891	.972	1.000	.826	−232.7	473.5
6	.901	.974	1.000	.888	−200.5	409.1

Note. RSVP = rapid serial visual presentation; *TL* = target letter parameter; *TC* = target color parameter; NC = nontarget color parameter; *ln* = log likelihood; AIC = A information criterion.

Table 3
Model Fits From Experiment 2: RSVP Task

Participant	*TL*	*TC*	*NC*	α	*ln*	AIC
			Null 1 model			
1	.850	.662			−243.4	490.8
2	.828	.484			−356.5	716.9
3	.964	.896			−119.4	242.9
4	.781	.854			−230.9	465.8
5	.865	.688			−276.3	556.6
6	.932	.677			−246.0	495.9
			Null 2 model			
1	.798	.822	.990		−214.9	435.7
2	.801	.567	.662		−346.7	699.3
3	.952	.926	.875		−115.1	236.3
4	.769	.982	.714		−202.7	411.4
5	.846	.747	.539		−269.3	544.7
6	.915	.729	.831		−235.9	477.9
			Alpha model			
1	.850	1.000	1.000	.838	−196.7	401.3
2	.828	.833	.651	.718	−333.6	675.1
3	.964	1.000	1.000	.941	−104.7	217.3
4	.782	1.000	.783	.985	−202.1	412.3
5	.862	.927	.681	.837	−259.2	526.5
6	.932	.949	.877	.827	−218.4	444.8

Note. RSVP = rapid serial visual presentation; *TL* = target letter parameter; *TC* = target color parameter; *NC* = nontarget color parameter; *ln* = log likelihood; AIC = A information criterion.

Models. We separately fit the data from the RSVP and no RSVP tasks to the three models described earlier. Our goals in this analysis were to find the best-fitting model and to compare model parameters in the RSVP and no RSVP tasks.

For the no RSVP task, the alpha model fit the data better than the Null 1 and Null 2 models for each participant (see Table 2). For the RSVP task, the alpha model provided the best fit for 5 of the 6 participants (see Table 3). One participant's data did not pass Treisman's criterion for illusory conjunctions; also, this participant's data did not fit the alpha model as well as they fit the Null 2 model.

Finally, we compared parameters for the alpha model with those for the RSVP and no RSVP task conditions. None of the differences in parameter values for the RSVP and no RSVP tasks approached significance according to a *t* test. The probabilities of correctly binding the target color to the target letter (α) were .842 for the no RSVP task condition and .858 for the RSVP task condition. (Eliminating the participant whose data did not have the best fit for the alpha model, these values were .825 and .833, respectively.) A lower α value indicates more errors of feature integration. Thus, the evidence for feature integration errors

[3] We attribute our attention manipulation to spatial attention, as opposed to a number of other varieties of attention, such as a general processing load. It could be that our digit-detection task and Treisman and Schmidt's (1982) digit-report task also affect other types of nonspatial attention.

without an attention-demanding task is at least as strong as that obtained with diverted attention.

Discussion

There were three main findings in Experiment 2. First, we replicated Experiment 1 in that both the RSVP and no RSVP tasks resulted in illusory conjunctions with long exposure durations. Second, considering only the no RSVP task, participants made illusory conjunctions even in the absence of an attention-demanding task. This claim was supported by both Treisman's criterion for illusory conjunctions and by our more rigorous formal method. These illusory conjunctions occurred even though there was plenty of time to allocate spatial attention to the colored letters (cf. Crick, 1984). Finally, a comparison of the RSVP and no RSVP tasks demonstrates that there are experimental manipulations that can be as effective as diverting attention in eliciting illusory conjunctions. We were able to obtain identical performance by trading off attention and eccentricity.

Although we are arguing that diverting attention is not necessary for feature integration errors to occur, we are not arguing that attention is irrelevant for feature integration. In fact, several studies indicate that attention may affect feature integration in several ways (Cohen & Ivry, 1989; Kleiss & Lane, 1986; Prinzmetal, Presti, & Posner, 1986; Treisman, 1985; but see Tsal, Meiran, & Lavie, 1994). For example, Prinzmetal, Presti, and Posner (1986) demonstrated that cuing a stimulus location affected the probability of correctly registering and joining features. Attention has also been shown to affect feature integration via its effect on perceptual organization in the following way: Attention affects perceptual grouping such that features within a perceptual group are more likely to be joined than features in different perceptual groups (see Prinzmetal & Keysar, 1989). Thus, although attention may be a factor in feature integration, Experiment 2 demonstrates that it is not a necessary component. In the General Discussion section, we present a framework for understanding how attention, along with a host of other factors, may influence feature integration.

In addition to demonstrating that diverting attention is not necessary to obtain illusory conjunctions, Experiment 2 also provides evidence that feature integration errors are not due to limits in memory. Illusory conjunctions in a detection task, such as the one we used, cannot be attributed to limitations in short-term memory capacity because participants are asked only to remember one color and one letter. However, participants might have trouble encoding this information with a brief exposure. The 1.5-s exposure duration in the present experiment provided ample time for participants to encode one letter and one color into memory.

Experiment 3

In the final experiment, we compared a long exposure duration (1.5 s) with a more traditional brief exposure duration (0.15 s) to determine whether there were any obvious qualitative differences between the two conditions that would limit the generality of our results.

Method

Each of 6 participants, selected as before, took part in two sessions. In one session, participants were tested with a long exposure duration. This condition was an exact replication of the no RSVP task in Experiment 2. The other session was identical, except that the exposure duration was only 0.15 s. Half of the participants were tested in the long exposure condition first, and half were tested in the brief exposure condition first. Eye movements were monitored only during the long exposure condition; movements were detected on 5.5% of the trials. Again, the results reported here include all trials, although inclusion of the trials in which eye movements were detected did not change the pattern of results. As in the previous experiments, eccentricity was manipulated so that performance was approximately 75% correct in each condition.

Results

Response categories analysis. The two exposure conditions did not significantly differ in terms of rates of correct reporting of the identity and color of the target letter. The mean percentage correct values for the long and brief exposure conditions were 73.61% and 71.18%, respectively, $t(5) = 1.30$, *ns*. For this equal overall performance to be obtained, the stimulus string had to have a significantly greater eccentricity with the long exposure than with the brief exposure condition. The eccentricities for the exposure conditions (d in Figure 1) were 9.1° and 6.7°, for the long and brief exposure conditions, respectively, $t(5) = 13.78$, $p < .01$.

The proportions of responses for each of the five error response categories are shown in Figure 8. The results were markedly similar across the two tasks. There were no significant differences in any of the response categories between long and brief exposure durations. The t-test values ranged from 0.002 to 1.47; none were significant.

For the long exposure condition, each participant reported more CR errors than all other errors combined. The mean

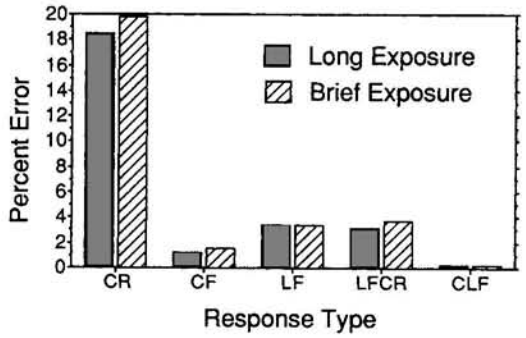

Figure 8. Results of Experiment 3. CR = conjunction report error; CF = color feature error; LF = letter feature error; LFCR = letter feature–conjunction report error; CLF = color–letter feature error.

percentage of CR errors was 18.46%, whereas the mean percentage for the sum of all other errors was 7.93%. This condition, combined with the identical condition in Experiment 2 (no RSVP), resulted in 12 of 12 participants meeting Treisman and Schmidt's (1982) criterion for true illusory conjunctions with a relatively long exposure duration and no distracting task. The results for the brief exposure condition were similar. Each participant reported more CR errors (19.8%) than all other errors combined (8.97%).

Models. We separately fit the data from the long and brief exposure duration conditions to the three models described earlier. The alpha model provided the best fit for the data from both the long and brief exposure conditions (see Tables 4 and 5). None of the estimated parameter values from this model significantly differed with exposure duration. The probabilities of correctly binding the target color to the target letter (α) were .798 for the long exposure duration and .805 for the brief exposure duration.

Discussion

We found no indication of differences in performance between the brief and long exposure conditions in feature integration. In both conditions, participants made feature integration errors as determined by both Treisman's criterion and our formal models. The finding of feature integration errors without diverted attention and with relatively long exposures (long exposure condition) replicated Experiment 2. We are not arguing that brief and long exposures will always be equivalent when adjusted for overall accuracy, however. It is plausible that as exposure duration is decreased, the amount of feature information available to the participant will decline. This should be reflected in the *TL, TC,* and *NC* parameters. Alternatively, as eccentricity is increased, the amount of feature information, particularly color information, will decline. In Experiment 3, the similarity of results in the brief and long exposure conditions might have resulted because both conditions enabled participants to accurately perceive the features. Given the scarcity of feature errors, it is reasonable to assume that errors in both tasks were related to processing (i.e., resource) limits rather than to data limits (Norman & Bobrow, 1975).

We were interested in determining whether the occurrence of illusory conjunctions in the two tasks seemed phenomenally similar. After each participant took part in the experiment, we asked him or her in what ways, if any, the two conditions seemed different. Most of the participants believed that the two conditions were more similar than different and were surprised by the question. Three of the participants said that the longer exposure seemed easier (even though they evidenced equivalent overall performance). In both tasks, participants were often very sure of their responses only to receive negative feedback. We have taken part in hundreds of trials with both brief and long exposures. Our experience of CR errors was similar: On some of the trials, we were quite confident of perceiving a red *T*, for example, only to have the computer give feedback indicating that the percept was an illusory conjunction.

Table 4
Model Fits From Experiment 3: Long Exposure Duration

Participant	*TL*	*TC*	*NC*	α	*ln*	AIC
		Null 1 model				
1	.958	.542			−274.8	553.6
2	.927	.599			−276.6	557.2
3	.885	.578			−305.0	613.9
4	.901	.698			−254.9	513.8
5	.917	.672			−256.8	517.5
6	.865	.729			−259.4	522.7
		Null 2 model				
1	.943	.571	.847		−271.6	549.2
2	.911	.663	.922		−257.4	520.9
3	.834	.694	.990		−282.6	571.1
4	.872	.779	.850		−241.3	488.7
5	.884	.750	.990		−245.6	497.3
6	.840	.829	.834		−241.6	489.2
		Alpha model				
1	.958	.999	.798	.677	−235.4	478.9
2	.927	.861	.928	.840	−245.3	498.5
3	.885	.999	.999	.755	−244.3	496.5
4	.900	.978	.911	.836	−221.7	451.4
5	.917	.999	.892	.795	−219.7	447.4
6	.864	.948	.823	.887	−233.9	475.9

Note. TL = target letter parameter; *TC* = target color parameter; *NC* = nontarget color parameter; *ln* = log likelihood; AIC = A information criterion.

Table 5
Model Fits From Experiment 3: Brief Exposure Duration

Participant	*TL*	*TC*	*NC*	α	*ln*	AIC
		Null 1 model				
1	.839	.563			−330.4	664.9
2	.865	.714			−265.9	535.8
3	.958	.599			−257.1	518.3
4	.891	.656			−276.0	555.9
5	.906	.583			−292.9	589.9
6	.870	.599			−305.6	615.1
		Null 2 model				
1	.807	.670	.801		−312.2	630.5
2	.845	.799	.767		−251.9	509.7
3	.941	.641	.990		−246.0	498.0
4	.858	.761	.990		−252.9	511.8
5	.875	.663	.896		−277.0	559.9
6	.815	.712	.950		−294.0	594.0
		Alpha model				
1	.837	.874	.818	.804	−300.0	607.9
2	.864	.920	.750	.883	−245.9	499.7
3	.958	.956	.999	.773	−212.9	433.8
4	.891	.942	.999	.847	−236.7	481.5
5	.911	.953	.999	.781	−252.3	512.6
6	.870	.999	.887	.741	−261.1	530.1

Note. TL = target letter parameter; *TC* = target color parameter; *NC* = nontarget color parameter; *ln* = log likelihood; AIC = A information criterion.

General Discussion

From the present research, it is reasonable to assume that illusory conjunctions are a more ubiquitous phenomenon than previously supposed. We were able to obtain feature integration errors with long exposure durations and without diverting attention. Furthermore, we obtained as many illusory conjunctions with a long exposure duration as with a brief exposure duration, with or without diverting attention.

Our results should not be interpreted as indicating that exposure duration and attention do not affect illusory conjunctions (e.g., see Cohen & Ivry, 1989; Kleiss & Lane, 1986; Prinzmetal, Presti, & Posner, 1986), as previously mentioned. There may be situations in which the exposure duration must be brief, attention must be diverted, or both. For example, with foveal presentation, it is unlikely that illusory conjunctions could be obtained without a brief exposure and perhaps diverting attention. However, without compelling theoretical or empirical reasons, it would be unparsimonious to propose a different theory of illusory conjunctions for foveal and nonfoveal conditions. Because we have shown that illusory conjunctions readily occur without diverting attention, Treisman's feature integration theory must be considered incomplete.

We have hypothesized that illusory conjunctions are the result of poor location information (Ashby et al., in press; Maddox et al., 1994; Prinzmetal & Keysar, 1989). Phenomenally, misperceiving the location of features can lead to illusory conjunctions. For example, one of us, while testing a new computer program, complained that the colored letters were occasionally presented in the wrong positions (e.g., ends of the strings). The perceived location of the color was, of course, illusory. In general, if the color of one letter is perceived at the location of another, the result will be an illusory conjunction. Poor location information could be a consequence of peripheral presentation, brief exposure duration, or diverted attention. There is evidence to support the idea that errors in perceived feature location can affect feature integration. The incorrect perceptual location of visual features has been well documented (e.g., Chastain, 1982; Estes, 1975; Wolford & Shum, 1980). For example, Wolford and Shum briefly presented squares with "tick" marks bisecting one side. Participants had to report the location of the tick marks. It was found that the tick marks tended to migrate to adjacent squares. Furthermore, location information has been shown to decline with eccentricity (Klein & Levi, 1987; Levi & Klein, 1989) and diverted attention (Tsal & Meiran, 1993). One advantage the location theory has over Treisman's feature integration theory is that it expands the number of factors that can affect feature integration.

Although attention and other factors can affect feature integration, our view of attention differs sharply from Treisman's feature integration theory in at least three ways. First, according to feature integration theory, attention is like a spotlight. Items within the spotlight will be randomly joined, as will items outside the spotlight; however, a feature will not cross the spotlight border. We believe that attention does not need to have a sharp boundary for correct feature integration to occur (LaBerge & Brown, 1989). Second, according to feature integration theory, attention does not affect the perception of features that are detected "preattentively." For us, there is simply more information from attended objects and locations than from unattended objects or locations. That information may include information about feature identity and location. Finally, for feature integration theory, features outside of attention are doomed to remain unconscious or to be randomly combined with other features. For us, location information does exist outside of attention, although there may be less information in nonattended locations and therefore more illusory conjunctions (Prinzmetal, Presti, & Posner, 1986). Thus, although illusory conjunctions are a real phenomenon, they are not inevitable outside of attention. In our experiments, participants were fairly accurate in combining features. Across all experiments and conditions, the model parameter, α, averaged about .85, which means that when participants had perceived at least one color and letter, they correctly combined this information on about 85% of the trials, regardless of conditions.

An advantage of our location theory is that it is in perfect accord with what is known about the physiology of the visual system (see Prinzmetal & Keysar, 1989). Neurons in the visual cortex are "tuned" for specific stimulus attributes, such as shape or direction of motion. That is, a neuron will fire differentially if it detects the presence of a particular attribute in its receptive field. Hence, neurons are performing an analysis of stimulus "features," although neural features and psychological features need not be the same. Receptive fields vary in size from less than a degree of visual angle to nearly a whole hemifield. Therefore, the precise location of a stimulus attribute or feature cannot be discerned from the response of a single neuron. On the other hand, if many neurons with overlapping but not identical receptive fields fire in the presence of a feature, the increase in information constrains the possible location of the feature. It must necessarily be located at the intersection of the receptive fields. With a brief exposure, only a few neural units may be activated, leaving some spatial ambiguity. Furthermore, spatial ambiguity should increase with peripheral presentation and diverted attention because receptive fields are larger in the periphery and because attention can affect receptive field size in several ways (Colby, 1991). For example, receptive fields may shrink around an attended stimulus (Moran & Desimone, 1985). Thus, from the perspective of visual physiology, neither the occurrence of illusory conjunctions nor the effects of eccentricity, attention, or exposure duration are unexpected.

Given that the occurrence of illusory conjunctions is not surprising, the mystery that one must confront is why illusory conjunctions do not occur more often in daily life. Indeed, the anecdote of Treisman and Schmidt (1982) described in the introduction is startling because it is so unexpected. The paradox is that illusory conjunctions are easy to obtain in the laboratory. To understand how the visual system normally combines features, one needs to understand the constraints that the visual system uses to avoid making illusory conjunctions in everyday life. A number of constraints have been uncovered. The most obvious is that the visual system does not combine features that are far apart (e.g., Chastain, 1982; Cohen & Ivry, 1989; Ivry & Prinzmetal, 1991; Keele et al., 1988; Prinzmetal &

Keysar, 1989; Prinzmetal & Mills-Wright, 1984; Prinzmetal, Treiman, & Rho, 1986; Wolford & Shum, 1980).[4] The robustness of this effect is what led us to postulate that the perceived location of features is important for feature integration. Furthermore, the visual system is more likely to incorrectly combine features that are similar to each other than features that are dissimilar. For example, Ivry and Prinzmetal (1991) found that illusory conjunctions occurred more often between letters that were similar in color than between letters that were dissimilar.

The constraints of interitem distance and similarity may be manifestations of a more basic constraint. Prinzmetal and others have found that illusory conjunctions are more likely to occur between items that form a perceptual group than between items that belong to different perceptual groups (Gallant & Garner, 1988; Prinzmetal, 1981; Prinzmetal et al., 1991; Prinzmetal & Keysar, 1989; Prinzmetal, Treiman, & Rho, 1986). The mechanisms used by the visual system to create objects are the same mechanisms that may be responsible for perceptual grouping. The presumption is that features that belong to one object should not migrate to another object. The effects of distance and similarity may be reflections of this general principle, because proximity and similarity are powerful determinants of perceptual grouping. Perceptual organization is not necessarily an alternative to the location theory, because items within a perceptual group are perceived as closer together than items in different perceptual groups (Coren & Girgus, 1980).

In addition to location and perceptual grouping, attentional mechanisms may also help explain why illusory conjunctions do not seem to occur readily outside the laboratory. Attention could constrain feature binding in two ways. First, location information may be more accurate for attended items than for unattended items, as previously discussed. Second, attention may influence feature integration by affecting perceptual organization (e.g., Gogel & Sharkey, 1989; Hochberg & Peterson, 1987; Tsal & Kolbet, 1985; Wong & Weisstein, 1982). For example, Prinzmetal and Keysar (1989) presented participants with an evenly spaced matrix of items. The perceptual organization of the matrix into rows or columns was determined by whether participants were attending to digits that were horizontally or vertically aligned with respect to the matrix. The resulting perceptual organization affected the pattern of illusory conjunctions obtained. Hence, attention may operate in several ways to affect feature binding and help prevent the occurrence of illusory conjunctions. Nevertheless, the present research demonstrates that diverting attention is not necessary to obtain such conjunctions.

In summary, we have shown that feature integration errors can be obtained without using a brief exposure or diverting attention. Formal modeling of our data confirms that participants were reporting features in incorrect combinations more often than expected by chance. Illusory conjunctions are not unexpected from our knowledge of the physiology of the visual system. However, a rich set of constraints ordinarily prevents the incorrect combining of features. Our goal is to develop a general theory of feature integration rather than one that applies only to a few limited conditions. Our present techniques of obtaining illusory conjunctions without a brief exposure open up a variety of research possibilities for developing such a theory.

[4] Treisman and Schmidt (1982) reported that features from items that were close together were as likely to be incorrectly joined as features from items that were far apart. However, their experiments were confounded in two ways. First, the letters that were far apart were flanked by digits that were to be reported as the participants' primary task, which confounded attention with the distance between items. Second, the distance between items was confounded with horizontal versus vertical alignment of the items. Illusory conjunctions have been found to occur more readily between horizontally aligned rather than vertically aligned items (e.g., Prinzmetal & Keysar, 1989).

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