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Does Attention Affect Visual Feature Integration?

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Two questions are investigated in this work: first, whether the integration of color and shape information is affected by attending to the stimulus location, and second, whether attending to a stimulus location enhances the perceptual representation of the stimulus or merely affects decision processes. In three experiments, subjects were briefly presented with colored letters. On most trials, subjects were precued to the stimulus location (valid cue); on some trials, a nonstimulus location was cued (invalid cue). Subjects were less likely to incorrectly combine colors and letter shapes following a valid cue. The attentional facilitation afforded by the cue was not limited to feature integration but also affected the registration of features. However, when the amount of feature information was strictly controlled, attention still affected feature integration. The results indicate that orienting attention to the location of the cue affects the quality of the perceptual representation for features and their integration.

The present study involves two areas of research in visual perception. The first concerns how the visual system combines information about independent stimulus features, such as color and shape. If different features or attributes of an image are processed independently, then these features must somehow be combined to yield a veridical view of the world. The second area concerns what it means to attend to a particular area in visual space. The specific questions that we attempt to answer are, first, does attention affect visual feature integration, and if so, how? Second, does attending to a particular object or location affect the quality of the perceptual representation?

Attention in psychology has several different operational and theoretical definitions (Hirst, in press; Keele & Neill, 1978). In the experiments described in this article, attention is operationally defined as the benefit in recognition or detection performance that occurs when subjects are cued in advance to the location of a relevant stimulus event (Posner, Nissen, & Ogden, 1978). This facilitation has been called *covert orienting* by Posner (1978) because it can occur independently of eye movements. Several investigators have demonstrated this type of facilitation (e.g., Bashinski & Bacharach, 1980; Jonides, 1980, 1981; Posner, 1980; Posner, Snyder, & Davidson, 1980). An experiment reported by Jonides (1976) exemplifies this effect. On each trial, subjects were briefly presented an array of four letters and they had to decide as quickly as possible whether the display contained the letter *L* or the letter *R*. On *valid* trials the stimulus display was preceded by a cue that indicated the position where the target letter would appear. On *invalid* trials the cue indicated a nontarget position. Subjects were both faster and more accurate in target identification on valid trials than on invalid trials, even when there was not enough time to complete an eye movement before the end of a trial. These results and others seem to correspond to the phenomenal impression that it is possible to fixate one's eyes on one location and at the same time attend elsewhere (Helmholtz, 1925).

There are at least two ways of describing the benefits of a cue. The first type of theory proposes that attention facilitates performance by improving the pick-up of information in the cued position (Jonides, 1980; Posner et al., 1978). Thus attention affects the quality of the perceptual representation. More information about the presence of features, and perhaps about the combinations of these features, exists in the cued location than in the uncued locations. The second type of theory accounts for the facilitation in performance in terms of decision processes (Kinchla, 1980; Shaw, 1984). According to these decision theories, the pick-up of information is not affected by the cue. To understand how the cue affects performance in a task such as the experiment by Jonides, described above, consider what could happen if there was no cue. On each trial, there is some probability that one of the nontarget items will be incorrectly identified as a target item, and this may lead to an error. The probability of incorrectly identifying a noise item as the target item increases as the number of noise items increases (Gardner, 1973). With a valid cue, subjects may be able to disregard the possibly misleading information from the noise items when they decide which target was present. A valid cue, in a sense, reduces the effective display size from four items to one item. However, the quality of the representation in the cued and noncued locations is assumed to be the same. The question of whether attention affects the quality of the representation or merely a decisional process is a central interest of the present study.

The second area addressed by this study concerns the integration or combination of features in vision. There exists considerable evidence that different stimulus attributes, such as color and shape, are at some level(s) of analysis processed separately (see Prinzmetal & Millis-Wright, 1984, for a review). If they are,

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then part of the job of visual analysis is not just to correctly register features, but to correctly combine this information. In this study, we will be concerned with features of shape (i.e., letter identity) and color, although feature integration is a logical problem in vision regardless of whether features are letters and colors, parts of letters, or even spatial frequencies (Wolford & Shum, 1980). If the visual system correctly registers features of color and shape but does not correctly combine this information, then subjects should occasionally perceive colors and shapes in incorrect combinations. Treisman and Schmidt (1982) found in whole-report, partial-report, search, and *same–different* tasks that with briefly presented colored letters, subjects reported colors and letters in incorrect combinations more often than expected by chance. For example, if subjects were presented with a red *X*, a blue *T*, and a brown *N*, they may have perceived and reported the *X* as blue. Treisman and Schmidt called this type of error a *conjunction error*, or an illusory conjunction. Errors that resulted from not perceiving either the color or shape were referred to as *feature errors*.

Treisman and her associates (Treisman & Gelade, 1980; Treisman & Schmidt, 1982) proposed that features are registered automatically without attention and that focal attention subsequently acts to "glue" features together into conscious percepts. However, the fact that the visual system must somehow combine feature or attribute information is logically distinct from the proposals that attention is not required to detect features and that focal attention uniquely mediates feature integration. There are theories of feature integration that can account for effects of attention but that do not assume that features are registered automatically nor require attention for feature integration (e.g., Prinzmetal, 1981; Wolford, 1975). These theories are considered in the General Discussion.

Two lines of evidence have been used to support the notions that features are registered without attention and that attention mediates feature integration. Both of these deserve scrutiny. The first comes from a series of studies conducted by Treisman and her colleagues (Treisman, 1982, Experiments 1 and 3; Treisman & Gelade, 1980, Experiments 1 and 4; Treisman & Paterson, 1984, Experiment 2; Treisman, Sykes, & Gelade, 1977, Experiment 1) that examine search reaction time as a function of display size. In these experiments, subjects were asked to search for targets that were defined by single features (e.g., the letter *X* or any blue letter) or to search for a target that was defined by a conjunction of two features (e.g., a blue *X*). In conjunction search, subjects presumably attend serially to each item in the display to avoid making a conjunction error. When subjects searched for conjunctively defined targets, reaction time increased linearly with display size. In feature search, serial attention to each item is not necessary.

Note that because these studies did not manipulate focal attention, the inferences about attention are indirect. There are serious problems in interpreting reaction time data. First, it is difficult to identify serial and parallel processes only on the basis of mean reaction times (Townsend, 1971; also see Egeth, Virzi, & Garbart, 1984, for a hybrid model). Second, in each experiment, reaction time did increase with feature search so that even feature search does not appear to be conducted automatically with unlimited capacity (Treisman & Gelade, 1980, p. 118). Third, increases in reaction time with display size might be the result of decisional processes and not attentional limitations (see, e.g., Gardner, 1973). Finally, conjunction search might be limited by attention, but it might not operate in a strictly serial manner (e.g., Treisman, 1982). The results certainly do not show that feature detection is without attentional limitations, and they do not unambiguously show that attention is involved in feature integration.

The second source of evidence for the role of attention in feature integration comes from a comparison of a pair of partial-report experiments by Treisman and Schmidt (1982, Experiments 4 & 5). In these experiments, subjects were presented four colored shapes and were instructed to report all they could about the one item indicated by a bar marker. In one experiment, an attempt was made to prevent attention from being allocated to the target item (Experiment 4), whereas in the other experiment, attention to the target item was not prevented (Experiment 5). In Experiment 4, the partial-report marker appeared after the stimulus, subjects had a dual task, and the exposure durations were relatively long (averaged 199 ms). In Experiment 5, the bar marker appeared before the stimulus, there was no dual task, and exposure durations were shorter than in Experiment 4 (averaged 89 ms) so that the total number of errors was equated across experiments. Treisman and Schmidt's measure of conjunction errors was the proportion of responses for which subjects reported a feature of a stimulus item that was not indicated by the bar marker. Their measure of feature errors was the proportion of responses in which subjects reported a feature that was not present in the stimulus display at all. (Note that our measures, described below, make slightly different and less restrictive assumptions.)

Treisman and Schmidt (1982) found that when attention to the cued item was prevented (Experiment 4), subjects made more conjunction errors than feature errors, whereas when attention was not prevented (Experiment 5), there were nearly equal numbers of conjunction and feature errors. However, it is difficult to see how this result could not have been obtained. Because the total number of errors in the two experiments was equated, the number of feature and conjunction errors are not independent, but they must covary. The proportion of feature errors would be expected to be greater in Experiment 5 because, with shorter exposure durations, the probability of registering features would be less. If feature errors increase, conjunction errors must decrease because there is only one degree of freedom in this comparison. The problem could have been avoided by equating feature errors in the two experiments and letting conjunction errors (and total errors) vary freely. In summary, there has not been adequate investigation of (a) the claim that features are encoded automatically or (b) the role of attention in feature integration.

Experiment 1

In our study we sought to examine the role of attention on feature integration by precuing the target location. We wished to determine whether spatial attention affects conjunction errors alone or whether it also affects feature errors. Furthermore, we wanted a procedure where valid cues did not indicate which item was the target, but rather would indicate where all of the stimuli were located. Hence, any effect of cuing would not be

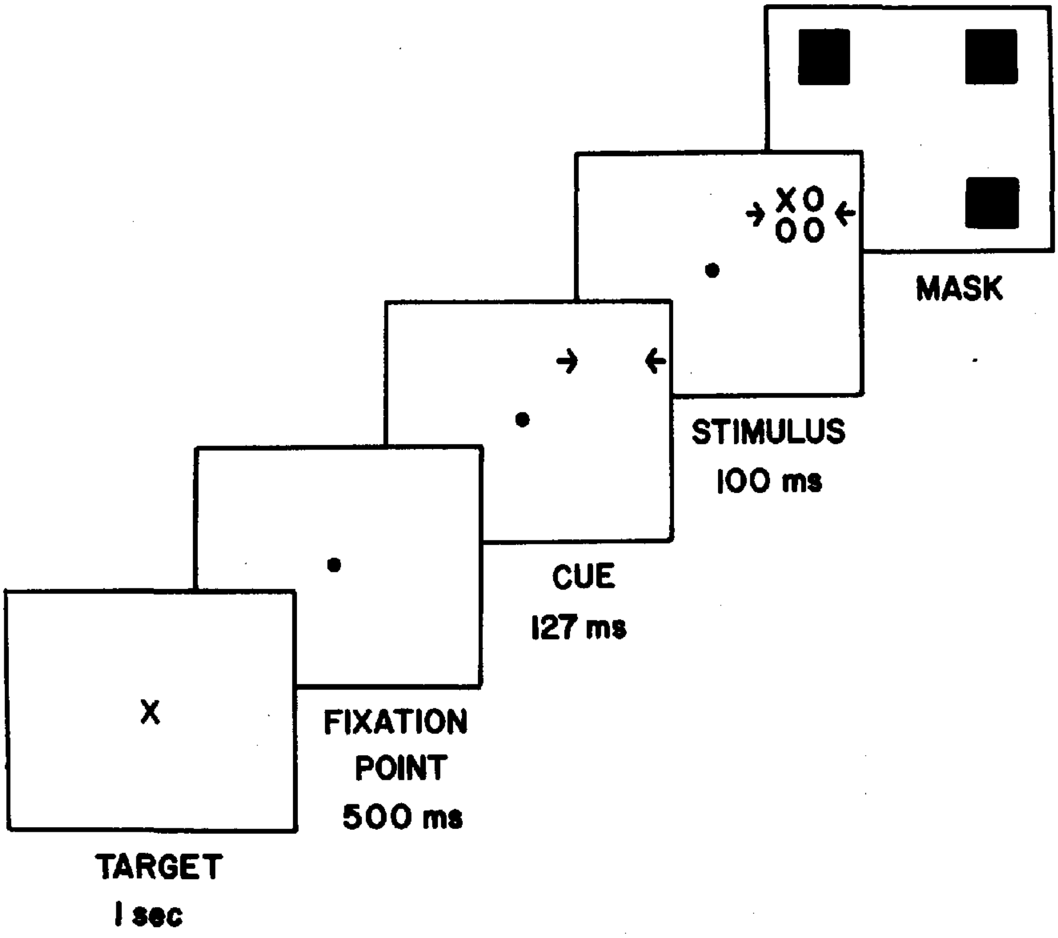

Figure 1. An example of a valid trial.

the result of differentially weighting information from the target item in a decision stage, but would reflect a difference in encoding the stimulus and, therefore, affect the quality of perceptual representation. If cue validity has an effect, it would indicate that more information about features or about their correct integration is available in the attended location. The paradigm for our first two experiments is illustrated in Figure 1.

On each trial, subjects were first shown a colored target letter, such as a pink *X*. This letter was replaced first by a fixation point and then by a pair of arrows that pointed to one of four locations in the field. The arrow cues were followed by the stimulus. The stimulus consisted of four colored letters. Finally, the stimulus was replaced by a mask. The subject was to respond whether the colored target appeared in the field. For example, if the target was a pink *X*, subjects were to give a positive response if and only if they saw a pink *X*. On valid trials, the cue indicated the quadrant that contained the stimulus array (see Figure 1). On invalid trials, the cue indicated a location that did not contain the target and noise items.

Feature errors and conjunction errors were measured by examining the false-alarm rates with two kinds of stimuli (see Treisman & Schmidt, 1982, Experiment 2). A feature stimulus matched the target in either color or shape, but not both. For example, if the target were a pink *X*, the stimulus might contain a blue *X* and no pink letters, or pink letters and no *X*. False alarms with these stimuli are a measure of only feature errors. A conjunction stimulus contained the target letter and color, but in incorrect combination. For example, if the target were a pink *X*, the stimulus might consist of a pink *O* and a blue *X*. A false alarm to this stimulus may indicate a conjunction error, because a subject could have combined the pink of the *O* with the *X*. However, in this paradigm a false alarm with a conjunction stimulus might also indicate a feature error. For example, subjects might make a false alarm if they do not accurately perceive the color. In summary, false alarms to feature stimuli measure feature errors, whereas false alarms to conjunction stimuli may indicate both feature and conjunction errors. Finally, we will assume only a monotonic relation between our false-alarm rates and the occurrence of feature and conjunction errors.

Method

Procedure. The sequence of visual events during a trial is outlined in Figure 1. At the beginning of a trial, a letter *X* appeared in the center of the monitor. The color of this letter was chosen from the set (pink, yellow, green, blue) and remained the same for all trials within a block. After 1 s the target was replaced by a small fixation point. Subjects were instructed to keep their eyes fixed on this point for the remainder of the trial. After the fixation point had been displayed for 500 ms, two white arrows (the cue) appeared in one of four locations near the four corners of the monitor screen. Subjects were told that the arrows correctly indicated, on most of the trials, the location where the subsequent stimulus would appear. After the cue had been displayed for 127 ms, the stimulus appeared either in the gap between the two arrows (valid trial) or in the corresponding location in one of the other three corners of the monitor (invalid trial). The stimulus was displayed for 100 ms and consisted of four colored letters (three *O*s and one *X*, or four *O*s).[1] The fixation point and the cue remained present during the display of the stimulus. Following the stimulus presentation, the stimulus and the three other corner locations on the screen where stimuli could occur were masked with solid white rectangles. The location of the stimulus was chosen randomly, and on invalid trials the location of the cue was chosen at random from among the three possible nonstimulus locations. Two thirds of the trials in a block were validly cued and one third were invalidly cued. The order of presentation of stimuli within a block was random.

Following three 20-trial blocks for practice, subjects were given eight blocks of 72 trials each. There were two blocks for each of the four possible target colors (presented in random order). On one third of the trials (i.e., one third of the valid trials and one third of the invalid trials), the target letter–color combination was present in the stimulus (target-present stimulus). On one third of the trials, the target letter (*X*) and the target color were both present, but not in combination (conjunction stimulus). That is, the target color belonged to two of the *O*s, and the remaining *O* and the *X* were of another (nontarget) color. On one sixth of the trials, the target letter (*X*) was present and the target color was not present (letter-present stimulus). Finally, on one sixth of the trials, the target color was present and the target letter was not present (color-present stimulus). In the color-present stimuli, all of the items were the letter *O*. These various trial types were randomly interspersed within a block.

We wished to minimize the number of misses (response of *no* on target-present trials) inasmuch as it is not possible to determine whether a miss is due to a conjunction error or to a feature error. Thus subjects were informed when they made miss errors by the occurrence of a brief tone from the computer. Subjects were not informed when they made errors other than misses.

Stimuli. The stimuli were presented on a Heath-Zenith 13-in. color monitor (Model 13-PF-5) controlled by an Apple 2e computer. Ambient lighting was from fluorescent ceiling lights. Subjects viewed the display from a distance of 210 cm. The fixation point subtended a visual angle of 0.05°. The length of each arrow and the width of each arrowhead subtended 0.41° and 0.46° of visual angle, respectively. The arrows were oriented horizontally, with the two heads pointing toward each other. The tips of the two arrowheads were separated by a gap subtending 0.95° of visual angle. The visual angle separating the center of the arrow pair from the center of the monitor screen (fixation point) was 1.25°. The stimulus consisted of a rectangular cluster of four letters: either one *X* and three *O*s, or four *O*s. Two colors were present in any given stimulus cluster: two letters of one color and two letters of another color. The colors, the positions of the two colors within the letter cluster, and the location of the *X* within the letter cluster were randomly determined. The colors matched Munsell values 5RP 7/10 (pink), 10YR 8/14 (yellow), 2.5BG 8/6 (green), and 5PB 6/10 (blue). An individual letter subtended 0.31° of visual angle in height and 0.27° in width. The distance between letters was equal to the width of a character stroke (approximately 0.03°). Each white rectangle in the mask subtended 0.71° × 0.79°.

Subjects. Sixteen subjects, recruited from the subject pool at the University of Oregon, were paid for their participation in the 1-hr session. They ranged in age from 16 to 38 years; 11 subjects were women and 5 were men. All of them had normal or corrected-to-normal visual acuity and no known deficiencies in color vision.

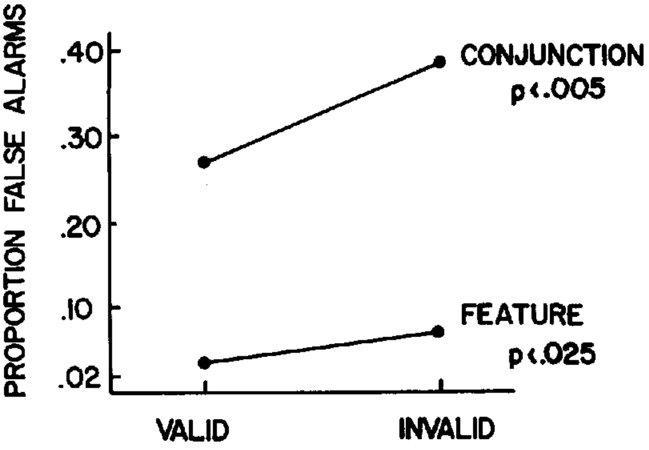

Figure 2. Proportion conjunction and feature false alarms in Experiment 1.

Results

The critical results in this experiment, the false alarms with the target-absent stimuli, are shown in Figure 2. Subjects made significantly more false alarms when the stimulus contained the target color and letter (conjunction stimuli) than when the stimulus contained either the target letter or the target color, but not both (feature stimuli), $F(1, 15) = 59.35$, $p < .01$. The mean false-alarm rates for conjunction and feature stimuli were .32 and .05, respectively. Subjects were also more likely to make false alarms on invalid trials than on valid trials, .22 versus .15, $F(1, 15) = 12.52$. The interaction of cue validity and feature versus conjunction stimulus was significant, $F(1, 15) = 8.61$, $p < .05$. When considered separately, the cue-validity effect was significant for both conjunction stimuli and feature stimuli, $t(15) = 3.52$ and 2.44, $p < .05$, respectively. Considering only the two types of feature trials, there was a cue-validity effect for false alarms when the target color was present, .057 versus .113, $t(15) = 2.54$, $p < .025$. When the target letter was present, the validity effect was in the same direction, but not significant, .014 versus .022, $t(15) = 1.07$. The failure to obtain a validity effect with the letter-present feature trials is probably due to a ceiling on performance. Finally, there was no significant difference in the miss rates for valid and invalid trials, .15 versus .19, $t(15) = 1.34$.

Discussion

Although the results on this experiment were simple, the interpretation is relatively complex. The difference between valid

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[1] As the total presentation time for cue and stimulus (227 ms in Experiment 1, 200 ms in Experiments 2 & 3) was less than the time required to complete a saccade, eye movements were not monitored in our experiments. Subjects reported that they had no trouble maintaining eye fixation. Moreover, on practice trials in which they attempted to move their eyes to the cue or the stimulus, subjects found that they did not see the stimulus as clearly, and were thus further motivated to hold their eyes fixed on the center of the monitor screen throughout a trial.

and invalid cues was greater for the conjunction stimuli than for the feature stimuli. One might be tempted to assert from these data that cue validity is more important for feature integration than for initial feature encoding. This conclusion would be unwarranted. Notice that we do not know the exact number of conjunction and feature errors, but we have only an indirect measure of them with false-alarm rates. The function that relates false alarms to feature and conjunction errors is unknown, and many reasonable monotonic transformations of the number of feature and conjunction errors could give a spurious interaction in the false-alarm rates (Loftus, 1978). If it is inappropriate to claim that the cue is more important to the process of feature integration than to initial feature encoding, perhaps it can be concluded that attention affects both. The problem here is that although false alarms with feature trials are a measure of only feature errors, false alarms with conjunction stimuli represent an unknown mix of feature and conjunction errors. The only defensible conclusion that can be made from this experiment is that attention affects feature errors. This conclusion is justified because false alarms with feature stimuli can arise only from feature errors. Contrary to Treisman and Gelade (1980), features are not registered without attention.

Given that cue validity affects feature errors and given the analytical constraints already discussed, the problem is how to test whether attention affects feature integration in a manner that is independent of feature encoding. One possibility is that if the proportion of feature errors could be equated on valid and invalid trials, then a direct comparison of conjunction errors would be possible. We attempted to equate feature errors in Experiments 2 and 3. It is important to note that we are not claiming that attention does not affect feature registration. Experiment 1 clearly shows that feature encoding benefits from attention. The question is, if we could equate the amount of feature information in valid and invalid trials, would attention affect the proportion of conjunction errors?

Experiment 2

In Experiment 2, an attempt was made to equate valid and invalid feature errors by reducing the amount of feature information available on valid trials. This experiment was exactly like Experiment 1 but for two modifications. The first and the most important difference was that the exposure duration of the valid trials was adjusted following each block so that the proportion of feature errors was approximately the same for valid and invalid trials. The exposure duration for valid trials was initially set at 100 ms. If a subject made more feature false alarms on invalid than on valid trials, the exposure duration on all valid trials was reduced on the next block of trials by one refresh cycle of the monitor (16.67 ms). Therefore, the exposure duration of the valid trials was always equal to or less than the exposure duration of the invalid trials. The exposure duration for valid trials ranged from 50 ms to 100 ms and averaged 85.25 ms. The exposure duration of the invalid trials was always 100 ms. The idea was to reduce the amount of feature information in the valid trials to the amount in invalid trials.

The second modification was to reduce the time that the cue was presented to 100 ms, so that the total time from the onset of the cue to the offset of the stimulus was 200 ms. We did this to further guard against eye movements. Sixteen subjects (7 women) were recruited as before. Four of the subjects had participated in Experiment 1.

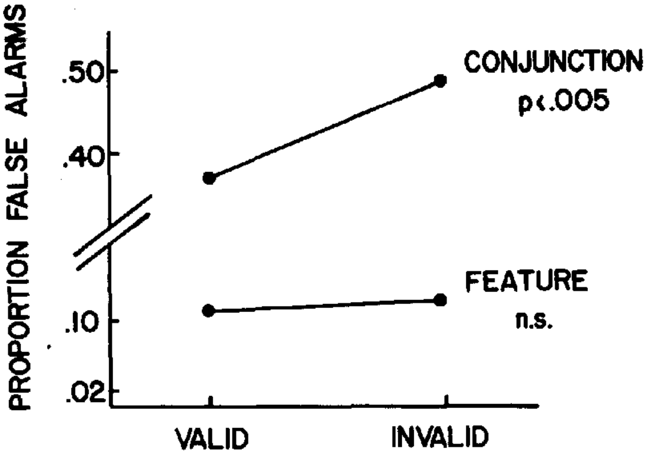

Figure 3. Proportion conjunction and feature false alarms in Experiment 2.

Results

The false-alarm rates for this experiment are shown in Figure 3. As in Experiment 1, subjects made significantly more false alarms with conjunction stimuli than with feature stimuli, .43 versus .12, $F(1, 15) = 58.86, p < .01$. The interaction of the type of stimulus with cue validity was significant, $F(1, 15) = 18.08$, $p < .01$. As in the first experiment, the cue had a significant effect in reducing false alarms with conjunction stimuli, .377 versus .482, $t(15) = 3.47, p < .01$. Unlike the previous experiment, cue validity had no effect with the feature stimuli. Overall, the false-alarm rate for valid and invalid feature stimuli was .115 versus .124, respectively, $t(15) = .48$ (*SE* of difference = .01824). Of the 16 subjects, only 7 had fewer false alarms with valid cues than with invalid cues. When the feature trials are further broken down into those with the target color present and those with the target letter present, neither shows an effect of cue validity. For color-present feature stimuli, the false-alarm rates were .185 versus .207, $t(15) = .635$, for valid and invalid cues, respectively. For the letter-present feature stimuli, the false-alarm rates were .045 versus .041, $t(15) = .38$, respectively. Finally, the miss rates for valid and invalid cues did not differ significantly, .258 versus .247, $t(15) = .35$.

Discussion

From the results of this experiment, it can be concluded that attention can affect feature integration, independent of the effect of attention on feature encoding. Formally, the only assumptions that need be made in this experiment are that feature errors are monotonically related to the number of feature false alarms and that conjunction errors are monotonically related to the number of conjunction false alarms. Because false alarms on feature trials represent only feature errors, and these do not vary with the type of cue, the true proportion of feature errors was the same with valid and invalid cues. Hence, the difference in false-alarm rates with valid and invalid conjunction stimuli can represent only a difference in conjunction errors.

A comment on the method of equating feature errors is in order. We are not implying that manipulating exposure duration uniquely affects feature errors and not conjunction errors. With unlimited exposure to our stimuli, subjects would make neither feature errors nor conjunction errors. As exposure duration is decreased, subjects would begin to make both feature errors and conjunction errors. These two types of errors may grow at different rates as exposure duration is decreased. Our manipulation of exposure duration for valid trials was successful because it was in a range where a change in duration happened to affect feature errors more than conjunction errors. The logic of our conclusions rests on the empirical equating of feature errors and not on any a priori assumptions about feature integration and exposure duration.[2] In the final experiment, we attempted to equate feature errors on valid and invalid trials with a method that did not require a physical difference in valid and invalid trials.

Experiment 3

The final experiment had two goals. First, we wanted to equate feature errors without using different display parameters for valid and invalid trials. Second, our results would have greater generality if we measured conjunction and feature errors in a different manner. In this experiment, the stimulus displays were similar to those in the previous experiments, except that each of the stimuli contained either the letter *X* or the letter *F*. The subjects' task was to respond whether the stimulus contained an *X* or an *F* and to report the target's color. For example, a typical response would be "pink *X*." Letter-feature errors were measured with the proportion of trials in which the subjects responded with an incorrect letter. Color-feature errors were measured with the proportion of trials in which subjects responded with a color that was not part of the stimulus array. Conjunction errors were measured with the proportion of trials in which subjects responded with the correct letter but combined with a color of a nontarget item.

We tried to equate feature errors on valid and invalid trials by attempting to have subjects make no feature errors. One might object that this creates a ceiling effect that might disguise an effect on feature errors. We know from Experiment 1 that features are not encoded automatically. The question is, if feature errors are equated across attention conditions, will the cue affect feature integration? To reduce the proportion of feature errors, the task was made easier by using slightly more saturated colors and spacing the letters in the stimulus array a little further apart.

Method

Procedure. The beginning of a trial was signaled by a tone from the computer. Following the tone, a small fixation cross (subtending 0.14° of visual angle) appeared in the center of the television screen. After the fixation cross was displayed for 1 s, the cue (two horizontal white arrows pointing toward each other) appeared in a direction toward one of the four corners of the television screen. The cue was displayed for 100 ms prior to the appearance of the stimulus. The stimulus contained three *O*s and either an *X* or an *F*. The stimulus colors and arrangements were chosen as in the previous experiments. Eighty percent of the trials in a block were validly cued and 20% were invalidly cued. The two types of trials were randomly interspersed. The subjects' task was to report verbally whether the display contained an *X* or an *F* and to report the target's color. For example, typical responses would be "pink *X*" or "blue *F*." Responses were recorded by the experimenter. Following three 20-trial blocks for practice, subjects were given five 100-trial blocks.

Stimuli. Subjects viewed a 13-in. Zenith color television monitor from a distance of 210 cm. The colors, which were chosen to be more discriminable than in the first two experiments, matched the following Munsell values: 3.75RP 6/12 (pink), 2.5YR 7/10 (yellow), 10GY 8/8 (green), and 10B 6/10 (blue). In the first two experiments, the letters seemed difficult to discriminate because they were crowded together (the interitem distance was about 0.03° of visual angle). In this experiment, the interitem distance was increased to about 0.20°. Thus the rectangular cluster of items was slightly larger, subtending a visual angle of 1° × 0.78°. Corresponding to this slightly larger stimulus display, the tips of the two arrowheads were separated by a gap subtending 1.19° of visual angle and each of the masking rectangles subtended 1.09° × 1.01° of visual angle. The visual angle separating the center of the four stimulus items and the fixation point was 1.36°. Otherwise, the spatial layout of the cues, the stimuli, and the masks were as in the previous experiments. Sixteen subjects (10 women, 6 men) were recruited as before to participate in a 1-hr session. Five of the subjects had participated in Experiment 1 or 2.

Results and Discussion

The results of this experiment were quite remarkable. Subjects erred in identifying the target letter (*X* or *F*) on less than 2% of the trials. Furthermore, subjects reported a color that was not present in the stimulus array on less than 1% of the trials. Although this is not perfect performance, it is fair to say that the subjects had little trouble seeing the target letters and the stimulus colors. Nevertheless, subjects reported the target in a color of one of the noise items on 14.7% of the trials. An intuitive definition of conjunction errors involves situations where subjects clearly perceive the colors and letters in the display, but incorrectly combine this information. The present results, to us, satisfy this intuitive definition. The data are broken down by category in Table 1.

Conjunction errors were measured with the proportion of trials in which subjects reported the correct target letter, but combinted with the nontarget color present in the stimulus. Subjects made significantly more of these errors on invalid trials than on valid trials, .174 versus .119, $t(15) = 4.26, p < .01$.

A variety of different types of errors measure feature errors (see Table 1, Types B to E). For example, subjects could err in reporting the target letter. Alternatively, they could report the letter correclty, but report a color that was not part of the stimu-

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[2] By the logic of this argument, if we had selected a different range of exposure durations and performance levels, it is possible that one could obtain a difference in feature false alarms on valid and invalid trials, but not a difference in conjunction false alarms. Such an outcome, together with the present results, would be strong evidence that feature registration and integration were indeed different processes and also that the effect of attention was not limited to feature integration.

Table 1
Error Proportions in Experiment 3

Type of error	Valid	Invalid
A. Conjunction (letter correct, color on)	.1190	.1740
B. Color error (letter correct, color off)	.0034	.0094
C. Letter error (letter wrong, color correct)	.0084	.0094
D. Letter error (letter wrong, color on)	.0084	.0069
E. Letter and color error (letter wrong, color off)	.0005	.0006
All feature errors (B + C + D + E)	.0207	.0263

lus display (*off* error). None of these error types by themselves exceeded 1%, and so analysis is probably inappropriate. When all of these measures of feature errors are summed, the difference between valid and invalid trials is not significant, .0207 versus .0263, $t(15) = 1.43$. Of the 16 subjects, only 9 had fewer total feature errors on valid than on invalid trials. For each of the Error Types B to E, taken individually, never more than one half of the subjects had fewer erors on valid than on invalid trials.

The purpose of this experiment was to equate feature errors in valid and invalid trials by creating a situation where subjects would make virtually no feature errors. This, of course, does not show that attention affects only feature integration, but rather that a difference in feature errors cannot explain the effect of attention on conjunction errors. To underscore this point, we divided our subjects into those who did and those who did not have fewer total feature errors with valid than with invalid trials. The 7 subjects who did not have fewer feature errors with valid cues nevertheless showed a significant effect of cue validity on the measure of conjunction errors, $t(6) = 2.50$, $p < .05$.

Finally, one might question whether equating feature errors at nearly perfect performance is sufficient. It could be true that although feature errors reached an asymptote at nearly perfect performance, there is nevertheless more feature information with a valid rather than with an invalid cue. Fortunately, it is difficult to apply this argument to both Experiments 2 and 3 at the same time. Taken together, we have equated feature errors at two different levels of performance and have found that conjunction errors varied with cue validity.

General Discussion

Experiment 1 demonstrated that attention affects the encoding of feature information. Attention also was shown to affect feature integration in a manner that cannot be accounted for by an artifact of measuring conjunction errors. Feature errors were held constant using two different methods and cue validity still affected feature integration (Experiments 2 & 3). To use a metaphor, it seems that the spotlight of attention both illuminates and helps to integrate features. The effect of attention is not unique to feature integration. In light of the present results, three issues should be addressed. First, this research bears on the nature of the facilitation that occurs when subjects are cued to attend to a particular item or location. Second, several different perspectives on theories of feature integration need to be examined. Finally, this research has methodological implications for a number of questions that might be asked about feature integration.

The present study addresses a fundamental issue in the nature of attention. Recall that one set of theories postulates that *attention affects the amount of information encoded from the* stimulus. Other theories postulate that the effect of the cue is not in the encoding stage, but on the weight assigned to each stimulus item after an internal representation has been formed. More weight is assigned to the cued item than to noncued items. Our studies provide prima facie evidence that the encoding stage of processing is affected by the cue. In the present experiments, the cue indicates where the four stimulus letters will appear, but it does not indicate which of the stimulus items is the target. Hence the cue does not allow a subject to ignore the noise items in making a decision.

There is particularly virulent form of the decision theory that is more difficult to deal with. The idea is that all tasks can be considered as search tasks. Consider an experiment by Posner et al. (1978) that measured simple reaction time to the onset of one of two lights in an empty field. Simple reaction time was found to be faster when the light was preceded by a valid rather than an invalid cue. In this case, there does not seem to be competing noise-item information to affect response selection. However, Duncan (1984) argued that information in the nontarget location could be considered as noise and that the subject must discriminate this noise from an actual light (signal). A valid cue would decrease the probability that the noise from an empty location would be considered a signal. In the present experiments, one might consider the task as discriminating the target item from three real noise items and from 12 empty locations in the other three quadrants. A valid cue would reduce the display size from 16 to the actual 4 items. This explanation can be rejected on the basis of the present results. Consider the last experiment and what would happen if the empty locations did contain randomly generated noise. This phantom noise would increase the number of feature errors because it would induce subjects to respond randomly with colors and letters that were not necessarily part of the stimulus. A valid cue would reduce these phantom feature errors. However, in the last experiment, subjects were very unlikely to report colors and letters that were not present. More important, in both Experiments 2 and 3, the cue did not affect any of our measures of feature errors. The only effect of the cue was on the measure of conjunction errors, and this effect is not predicted by postulating phantom noise in the empty locations. Thus, we have evidence that more information about the combination of features is encoded in the attended location.

Our results are only in partial accord with Treisman's feature integration theory (Treisman & Gelade, 1980; Treisman & Schmidt, 1982). The theory specifies that features are encoded without attentional limitations, but we found that this is not the case. There is a further problem with the theory in accounting for our results. According to the theory, features within the spotlight of attention are prevented from combining with features from outside the spotlight. Conjunction errors will be prevented if the spotlight focuses on a single item. The theory cannot account for our results. This is so because the positional cues in our experiments do not indicate which single stimulus item should be focused on. All of the items initially would be in the spotlight on valid trials, and all of the items would be outside the spotlight on invalid trials. Hence, conjunction errors would not be prevented in either the valid or invalid trials. An ad hoc assumption that could be used is that refocusing attention takes time in proportion to the distance that attention must travel. On valid trials the spotlight needs only to narrow its focus to a single item, whereas on invalid trials it needs to move across the field before focusing on a single item. The probability of completing the focusing to a single item would be greater on valid trials than invalid trials.

Given the problems with Treisman's approach, two other theories will be considered. These theories can account for attentional effects, but they do not postulate that attention uniquely affects feature integration nor do they require focal attention to isolate a single item for correct feature integration. According to Wolford's feature perturbation theory, features are encoded with location information (Wolford, 1975). The spaces between letters are encoded like any other feature and serve to segregate feature bundles. With time, positional information decays and features perturbate to neighboring positions, leading to recognition errors. Within this framework, there are two ways to explain our results. First, the additional processing time that is required following an invalid cue could allow positional information to decay. The notion that conjunction errors are caused by a decay of positional information is similar to several accounts of performance in partial-report experiments dealing with iconic memory (Coltheart, 1980).[3] Alternatively, it could be that in the initial feature-encoding stage, the probability of picking up information about spaces is greater in the attended location than in the unattended location. Hence there would be more information about the correct combination of features following a valid cue than an invalid cue.

Prinzmetal's perceptual grouping hypothesis could account for the results by also appealing to the idea that more information is available in the attended location. Prinzmetal (1981; Prinzmetal & Millis-Wright, 1984) proposed that the visual system parses stimuli by rules analogous to Gestalt principles. The parsing can be hierarchical so that individual letters are units within larger units consisting of several letters. Features from different perceptual units are prevented from combining. To explain the present findings, one needs to assume that more detailed information about the organization of the stimulus display is available from attended locations. This would include information about the spaces between letters, but it would not be limited to that information. Attention could also indirectly influence performance by affecting perceptual organization. Tsal and Kolbet (1985) have shown that the organization of an ambiguous figure (e.g., the duck–rabbit figure) is affected by spatial attention. Thus, attention may influence perceptual organization, but it is perceptual organization that determines feature integration.

The present study makes explicit a methodological constraint in studying feature integration. Specifically, the problem is measuring conjunction errors in a manner that is independent of feature errors. Tests of a number of very interesting hypotheses hinge on a solution to this problem. Consider Wolford's (1975; Wolford & Shum, 1980) hypothesis that features from the periphery are more likely to perturbate than features from items located in the center of the visual field. It is undoubtably true that it is more difficult to register features in the periphery. Hence a test of this hypothesis depends on equating the amount of feature information either empirically (as was done in the present experiment) or theoretically. A theoretical solution would separate feature errors from conjunction errors in a manner analogous to the way signal detection theory separates signal detectability from the observer's criterion.[4] Presently, such a theoretical solution does not exist, and we have relied on the empirical solution. The situation is similar to the problem of the speed–accuracy trade-off. When comparing reaction times, many investigators attempt to equate accuracy across conditions by having uniformly low error rates. If a generally applicable and accepted speed–accuracy model were available, it would not be necessary to equate error rates.

Attention can be studied in many ways. On one level, attention may involve modality-specific operations, but it may also involve more general systems. It is important to know the level of attention involved in feature registration and integration. If the attention involved in these operations is specific to vision, perhaps only a visual secondary task will influence feature and/or conjunction errors. If the attention involved is more general, perhaps a nonvisual task, such as remembering the names of letters, would also interfere. Because we do not yet know the level of attention involved when a cue directs a subject's attention to a specific location, these speculations remain matters for further research.

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[3] We are grateful to an anonymous reviewer for this suggestion.

[4] It is probably inappropriate to use signal detection theory in the present situation. Shaw (1982) has shown that in many instances where there are multiple sources of information in a search task, signal detection is not appropriate because subjects often make independent decisions on the basis of each source of information and then pool their decisions. In any experiment where the display size is greater than one, there is more than one source of information. The present two search experiments present an even more complex situation (Experiments 1 & 2). In order to make a presence/absence decision, subjects must combine information not only over different spatial positions, but also over the dimensions of color and shape.

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