9.

AT THE CORE OF FEATURE INTEGRATION THEORY: ON TREISMAN AND SCHMIDT (1982)

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Groundbreaking theories, like feature integration theory (FIT), are multilayered. Like an onion, layers can be peeled away. At the core is a critical observation that exemplifies the theory. Treisman and Schmidt (1982) directly tested the core observation of FIT: for veridical perception, the visual system must correctly combine features. For us to correctly perceive an apple as red, our brains must combine the appropriate features of shape and color. Evidence of this fundamental fact was the occasional incorrect combination of features in perception. The result of the incorrect combination of features was termed illusory conjunctions. I believe that the notion of feature integration as an indispensable mental process for veridical perception is at the core of the theory. Almost all other aspects of the theory can be peeled away, but the central insight, that features must be bound together, was one of the most important insights in perception in the twentieth century.

Treisman and Schmidt call the occurrence of feature-integration errors (illusory conjunctions) the core prediction of FIT (p. 108). However, it seemed unlikely that features would incorrectly combine in perception. If a red apple is lying next to a yellow banana, we usually don't experience the apple as yellow. Treisman and Schmidt's first four experiments were aimed at establishing the phenomenon of illusory conjunctions.

The first experiment was a very simple whole-report task. Subjects were briefly presented stimuli like the one shown in figure 9.1, followed by an achromatic mask. The task was to first report the two black letters, and then as many of the letters and colors as possible, indicating their positions. An incorrect response to the stimulus in figure 9.1 might be "3,7 left; green T, middle; N, right brown." There were five possible colors and five possible letters. A report of a letter and color in an incorrect combination ("green T") was termed a conjunction error. The report of a color or letter not present ("brown") was termed a feature error. Thirty-nine percent of the reported colors and shapes were incorrectly combined features ("green T") compared to 15 percent erroneous feature reports. Apparently, observers were quite willing to report colors and letters in incorrect combinations.

Treisman and Schmidt were aware that observer's responses were contaminated with memory. The second experiment eloquently addressed this concern with a detection task. They used the same stimuli, but observers were given a probe before each trial ("green T"). They simply had to respond whether the probe was in the display, minimizing memory requirements. There were three kinds of probes: identical probes containing one of the stimulus letters (e.g., red T), conjunction probes containing a combination of features that were part of the display (green T), and feature probes containing a single feature that was part of the display (brown T). Observers made significantly more false alarms to conjunction probes (18 percent) than to feature probes (11.5 percent) suggesting that colors and shapes did incorrectly combine in perception and could not be attributed solely to memory.

However, the results of the second experiment could be accounted for by a feature-counting strategy. If observers detected two features that matched the target (i.e., a color and a shape), they might be more likely to respond target present than if they only detected one feature. To overcome this problem, they performed a clever matching experiment, illustrated in figure 9.2. Observer's had to indicate whether there were any exact matches in the display (e.g., 2 red H's). Figures 9.2a and 9.2b are target-absent stimuli; they contain no exact matches. In figure 9.2a, there are two ways the features could completely switch to form an illusory match. The color red could switch with the blue O. The red of the H could switch with the blue of the O. In figure 9.2b, there are four ways of creating an illusory match. Specifically, the red from the X or H could switch with the O. Similarly, the red from the H or O could switch with the blue O.[1] Thus stimuli like 9.2b should generate more false matches than stimuli like 9.2a. There were significantly more false matches with stimuli like figure 9.2b (40 percent) than like figure 9.2a (25 percent). In Experiment 2, subject could have simply counted the number of features of the probe (green + X) that they found in the briefly presented stimulus. In this experiment, there is no probe so there are no specific features for subject to count.

The results of the second experiment clearly cannot be accounted for by conjunctions in memory because there is little to remember. The third experiment illustrated that the errors were not the result of simply counting target features in the display because there was no target per se.

Subsequent to Treisman and Schmidt, we have looked at a number of guessing biases that might account for feature integration errors (Prinzmetal, Ivry, Beck, & Shimizu, 2002). For example, consider a task in which subjects have to indicate whether the target letter is an X or a T, and what

Figure 9.1 Sample stimulus used by Treisman and Schmidt, experiment 1. (See color Figure 9.1.)

the color of this letter is (red, blue, or green). One might suppose that if a subject perceived an X in one position, and something green in another position, they might guess "green X," giving the impression of an illusory conjunction. However, such a scenario would not represent a real perceptual combination of features. Using a multinomial model, we were able to demonstrate that this was not the case. Illusory conjunctions in many cases cannot be attributed to guessing strategies (also see Prinzmetal, Diedrichsen, & Ivry, 2001). This task also addresses the memory issues because subjects only have to retain one letter and one color (e.g., respond "green X"). Prinzmetal, Henderson, and Ivry (1995) found evidence for conjunction errors with this task and exposure durations of two seconds, provided attention was overloaded or the stimuli were sufficiently far in the periphery.[2]

In the real world, illusory conjunctions seem rare. We are rarely surprised to think we spot our friend's green Honda only to discover that the Honda is blue, but the Ford next to it is green. The reasons that illusory conjunctions are so rare in the real world are discussed later. However, in the laboratory, where the natural constraints on illusory conjunctions can be eliminated, they are not rare. In a target detection task, like that illustrated in figure 9.1, we have observed as high as 40 percent illusory conjunction false alarms and as few as 7 percent feature false alarms (Prinzmetal, Presti, & Posner, 1986). In an experiment with words as stimuli, Prinzmetal, Hoffman, and Vest (1991) found up to 25 percent conjunction errors, whereas only 0.8 percent color feature errors (report of a color not in the display) and 1.7 percent letter feature errors occurred (report of letters not present in the display). In the years since Treisman and Schmidt, we have learned how to dramatically increase feature integration errors by removing

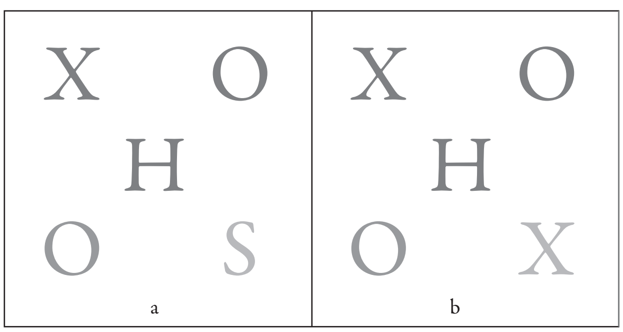

Figure 9.2 Sample stimulus used by Treisman and Schmidt, experiment 3. (See color Figure 3.1.)

some of the constraints, discussed below, that the visual system uses to correctly integrate features.

As the evidence discussed so far shows, under controlled conditions, illusory conjunctions can be quite frequent, cannot be accounted for by guessing biases or memory limitations, and appear to be genuine perceptual phenomena. Despite the objective results, I still get asked whether illusory conjunctions are "real"; does one really experience them? The question seems to challenge logical positivism and asks for anecdotes. There is plenty of anecdotal evidence. For example, about half of Triesman and Schmidt's subjects spontaneously asked about colored numbers (the numbers were always black, see, e.g., Triesman & Schmidt, p. 121; also Prinzmetal, 1981, p. 334). The existential reality of the phenomena was apparent to me when I took the experiment from the tachistoscope to a computer. I was writing a computer program that would replicate Prinzmetal and Millis-Wright (1984). The program was to briefly present a trigram of colored letters with one constraint: all three letters could not be the same color. I finished the program late one Friday night and came to the lab Saturday morning to test it. I quickly noticed a bug: occasionally, all three letters were the same color. I worked on finding the bug in my program all weekend. Finally, at about 4:00 on Sunday, I came to the conclusion that the bug was in my head. I could clearly see the letters and colors, but the colors occasionally spread across all three letters.[3]

The problem of feature integration, exemplified by illusory conjunctions, has also been called the binding problem (Koch & Crick, 1991). It may seem strange that such a fundamental problem in perception was not discovered earlier. However, many of the most intriguing problems in perception were not appreciated for a considerable period of time. For example, even though artists had been struggling with realistic depictions of nature for perhaps 30,000 years, linear perspective was not appreciated until the Renaissance. When the visual system performs computations easily and nearly flawlessly, such as with depth perception or color constancy, the computations tend to be overlooked. The discovery of the binding problem is all the more remarkable because the discovery was theory driven. Treisman and Schmidt predicted that illusory conjunctions would occur, but they asserted that the idea was "implausible and counterintuitive" (p. 108). Most illusions are discovered by chance. Certainly Müller-Lyer didn't predict his illusion on the basis of a theory, but rather discovered the illusion and then tried to explain it (Day & Knuth, 1981). Nevertheless, there were some precedents for binding errors. Snyder (1972) found that subjects reported colors in adjacent locations, and Wolford and Shum (1980) found line segments could perturbate to adjacent locations. However, the pervasiveness and generality of the problem was not appreciated.

Feature integration errors have been found in many domains besides color and shape. They can occur between features of shape (e.g., Treisman & Paterson, 1984; Prinzmetal, 1981), between syllables of printed words (Treisman & Souther, 1986), between syllables of auditory words (Cutting, 1976), between pitch and timbre (Hall & Pastore, 1993), between pitch and duration (Thompson, Hall, & Pressing, 2001), and between touch and vision (Cinel, Humphreys, & Poli, 2002).

We do not know if all these illusory conjunction phenomena are the result of the same binding process and surely the mental representations that are mistakenly combined are different (e.g., Virzi & Egeth, 1984). No doubt, future research will discover similarities and differences in binding across these domains.

Although various kinds of binding errors can occur, they usually don't occur. The visual system is adept at correctly joining features. That the visual system is proficient at a particular process does not mean that a host of complex processes are involved in the computation. For example, we are able to determine depth relations in three-dimensional visual environments, but depth cues can lead us astray. Treisman and Schmidt speculated that there are three ways in which features can be joined. First, attention may be directed to a specific location that contains information about all the features at that location. Second, we may fit features into "object frames." Finally, features might be randomly joined, leading to errors. It is only the absence of attention and object frames that would lead to feature integration errors.

Treisman and Schmidt do not define the concept of object frame, but I take it to mean that there are a host of configural constraints on feature integration. For example, Treisman and Schmidt observed that illusory conjunctions were more likely between horizontally aligned objects than vertically aligned objects. They are also more likely between items that are close together than far apart (e.g., Ashby, Prinzmetal, Ivry, & Maddox, 1996; Gallant & Garner, 1988; Lasaga & Hecht, 1991). Initially, Treisman and Schmidt did not think that the distance between items affected feature integration. In experiment 1, letters were presented on the corners of an imaginary horizontally oriented rectangle, and they observed that illusory conjunctions between near items (vertically aligned) were no greater than far items (horizontally aligned). Their tentative conclusion was that the distance between items did not matter. However later they realized that this observation was confounded by a greater probability of illusory conjunctions in a horizontal direction. Treisman and Schmidt's conception of "feature maps" suggests that there should be distance effects, as do other accounts of feature integration (e.g., Ashby, et al., 1996; Logan, 1996).

Other configural properties that seem to affect feature integration include physical similarity of features (Prinzmetal, 1981; Ivry & Prinzmetal, 1991), conceptual similarity (Esterman, Prinzmetal, & Robertson, 2004); good continuation (Prinzmetal, 1991), and goodness of form (Gallant & Garner, 1988; Lasaga & Hecht, 1991). The general principle is that features should be less likely to migrate from object to object (or perceptual group to group, see Khurana, 1998). Even syllable-like or morpheme structure in printed words (Prinzmetal, et al., 1991; Seidenberg, 1987) or Chinese characters (Fang & Wu, 1989) can constrain feature integration such that features are more likely to move within a printed syllable or character than between syllables or characters. It makes good computational sense for features, which define surface properties, to be constrained to migrate within objects (Prinzmetal & Keysar, 1989). Given that feature integration is multiply constrained, it is not surprising that the binding problem was overlooked.

Attention has a special place in feature integration theory, and, to pursue this idea, Treisman and Schmidt (1982) compared a situation where attention was overloaded (experiment 4) with one in which attention was not overloaded (experiment 5). In experiment 4, subjects were presented four colored shapes, flanked by two digits. The stimulus display was followed by a bar marker that indicated which object subjects should report. In experiment 5, there were no digits to report, and the bar marker appeared before the colored shapes. Subjects made more illusory conjunctions when attention was taxed than when it was not (i.e., experiment 4 versus 5). Obviously there were several different factors that may have contributed to the difference such as having the bar marker appear before or after the display and whether there were digits to report or not. Treisman (1985) later provided a cleaner demonstration of the effect of attention on feature integration. She used the spatial cueing task of Posner, Snyder, and Davidson (1980). The stimuli were colored shapes on the circumference of an imaginary circle centered at fixation. Subjects had to indicate the presence of a target shape as in Treisman and Schmidt's experiment 2 (described earlier). The stimulus display was preceded by a bar marker that indicated the location of the target on 75 percent of the trials (valid trials), and a nontarget location on 25 percent of the trials (invalid trials). Subjects made more illusory conjunctions on invalid trials than on valid trials, not because the attention manipulation also affected feature errors, but because they did not affect them to the same extent as illusory conjunctions.

There are at least three ways in which attention might be involved in feature integration that are consistent with the preceding results. First, Treisman and Schmidt used the metaphor of attention as a spotlight. They hypothesized that the metaphorical spotlight of attention forms a kind of barrier so that features within the spotlight can incorrectly combine, features outside the spotlight can incorrectly combine, but features will not jump the spotlight boundary. If attention has time to focus to a single item, feature-integration errors will be prevented. The best evidence for this role of attention comes from Cohen and Ivry (1989, experiment 3). The stimuli consisted of colored letters presented in a line, with two digits to report within the string (see figure 9.3). There were two conditions. In the large spotlight condition, the digits were at the location of the circles in figure 9.3 (between the A–B and E–F). In the small spotlight condition, the digits were at the location of the triangles in figure 9.3 (between the B–C and D–E). The critical finding involves illusory conjunctions between B–C and between D–E in the large spotlight condition compared to the small spotlight condition. In the large spotlight condition, letters in these positions are within the spotlight. In the small spotlight condition, they span the spotlight boundary. Cohen and Ivry found more than twice as many illusory conjunctions in the large spotlight condition than the small spotlight condition. Thus, features are unlikely to jump the spotlight boundary. In a sense, these results parallel the effects of perceptual organization: features are unlikely to jump from object to object, observing object boundaries. Attention plays a similar role in that features are unlikely to jump the boundary of the attention spotlight. Disentangling

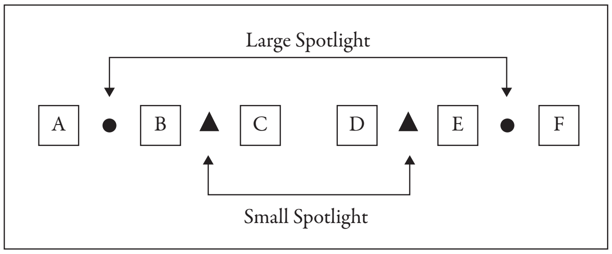

Figure 9.3 Design of stimuli used by Cohen and Ivry.

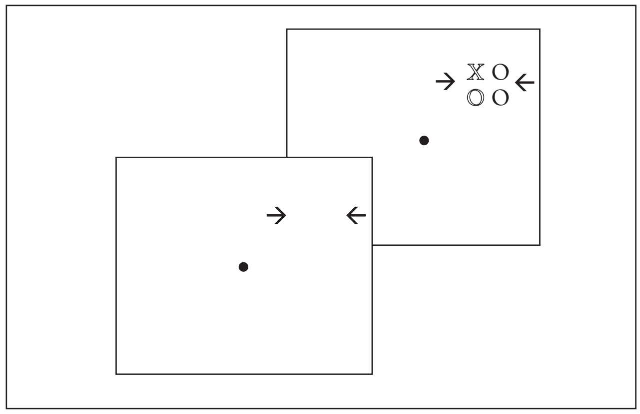

Figure 9.4 Cue and targets used by Prinzmetal, Presti, and Posner. Outlined letter represent one color, solid letters represent another color. Task is to determine color of the X.

the effects of attention and perceptual organization on feature integration will be difficult because attention affects perceptual organization (e.g., Prinzmetal & Keysar, 1989) and perceptual organization affects attention (e.g., Egly, Driver, & Rafal, 1994).

A second way in which attention can affect feature integration involves the fact that there are fewer illusory conjunctions where one *is* attending compared to where one *is not* attending, even if all of the stimulus items are within the spotlight of attention. For example, Prinzmetal, Presti, and Posner (1986) used the spatial cueing paradigm to manipulate attention. On 75 percent of the trials, the target letters appeared in the location indicated by the arrow, and in 25 percent of the trials, the target appeared in an uncued location (see figure 9.4). The targets were 4 colored letters in close proximity. When the letters appeared in the expected location, there were fewer illusory conjunctions than when the appeared in an unexpected location. The arrow cues did not isolate any one of the 4 target locations, thus attention was to all of the letters. The probable mechanism for this effect is that there is more precise location information where one is attending than where one is not attending (Prinzmetal, 2005; Prinzmetal, Amiri, Allen, & Edwards, 1998; Tsal, Meiran, & Lamy, 1995). Features are more likely to be correctly conjoined if there is precise location information. Prinzmetal et al. (1995) found a similar effect with a load manipulation of attention.

The final way in which attention affects feature integration is on the perception of features. Features cannot be correctly or incorrectly combined unless they are correctly perceived. Treisman (1985) and Prinzmetal et al. (1986) both found that attention affected not only feature integration, but also the probability of correctly registering features. Because attention is likely to affect both feature errors and feature-integration errors, it is useful to have an explicit model to correct for feature errors when manipulating attention (e.g., Prinzmetal et al., 2002).

Despite the fact that the best evidence for the core of feature integration was presented in 1982, the evidence most often cited in favor of feature integration involves the display-size effect measured with reaction time in visual search (Treisman & Gelade, 1980). Reaction time increases with the number of display items when the search involves a conjunction of features, but reaction time increases less when the search involves a simple feature. This sort of evidence was used to claim that conjunction search was conducted serially, whereas feature search was conducted in parallel. Identifying serial and parallel search on the basis of reaction time has always been difficult (e.g., Thornton, & Gilden, 2007; Townsend, 1971), but I contend that making the distinction is not necessary for the core of the theory. It might be that in a reaction-time task, where subjects are trying to be accurate, if there is a possibility of incorrectly combining features, subjects will be motivated to "take their time." Processing could be parallel, but in order to avoid conjunction errors, subjects raise their threshold and take longer to respond (Dosher, Han, & Lu, 2004). This idea, although it involves parallel search, is still consistent with the core of the theory: feature integration is a problem that must be solved by the visual system. Feature integration is not the only difficult problem in vision that might lead to a display-size effect. Making feature search more difficult by changing the similarity of the target to distractor should also lead to substantial display-size effects (Duncan & Humphreys, 1989). Again, this does not violate the central core of the theory. Between serial and parallel search, there are a host of hybrid possibilities. For example, Treisman (1982) found that under some circumstances, conjunction search was best described as serial between groups of items but parallel within groups of homogeneous items. The idea of hybrid serial-parallel processes is quite old (e.g., Eriksen, & Schultz, 1979; Harris, Shaw, & Bates, 1979; McClelland, 1979).

Difficulties in identifying serial and parallel search have led some investigators to distinguish "efficient" and "inefficient" search (e.g., Wolfe, Cave, & Franzel, 1989). This change in terminology does not solve the identifiability problem. There is no theory to describe how steep search slopes must be to be classified as "inefficient" search. Indeed, in almost every published experiment, even in feature search, reaction-time display-size functions are almost always positive and there is no bimodal distribution of search slopes (Wolfe, 1998). Thus, with search-reaction time, there is no principled way to determine if there is a feature-integration problem. This situation is in contrast with the experiments that observe illusory conjunctions in which there are models and statistical tests for feature-integration errors (e.g., Ashby et al., 1996; Prinzmetal et al., 2002). These theoretical-based tests are elaborations of Treisman and Schmidt.

In sum, at the core of FIT is a perceptual problem: the visual system (and other perceptual systems) must correctly combine information for veridical perception. The clearest manifestation of this problem is the phenomenon of illusory conjunctions, first described by Treisman and Schmidt in the accompanying article.

NOTES

1. The way that Treisman and Schmidt counted color switch did not allow for colors to spread over letter, but only allowed for color (or shapes) to switch. However, even if only allows for colors to spread from letter to letter (leaving a ghost behind), the prediction remains the same.
2. Prinzmetal, Henderson, and Ivry terminated the displays after two seconds, but this should have been sufficient time to encode one letter and one color into memory.
3. Treisman and Schmidt didn't find that colors spread across letters, but did spread to the flanking digits. It is unclear when colors will spread across locations or simply switch positions.

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