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The Fraser illusion: Simple figures

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The Fraser illusion occurs when a line formed from a number of tilted segments itself appears tilted. Two explanations of this illusion were examined: (1) that the illusion results from lateral facilitation between orientation selective cells, and (2) that it is due to orientation being processed only at a local level. In Experiment 1, variations in the strength of the Fraser illusion and a comparable Zöllner illusion, with change in the angle of inducing elements, were examined. There were no differences between the angular functions, but it was shown that in both cases assimilation occurred at angles as great as 18° and that solid figures showed weaker contrast illusions at larger angles. Experiment 2 indicated that this might be due to the different Fourier composition of the solid figures. Experiment 3 measured the local effects of lateral inhibition/facilitation and confirmed that facilitation did not take place. That indicates that the illusion results from the direct contribution of local information provided by the tilted segments to the global perception of the line. Finally, Experiment 4 showed that when the amount of background field used in the Zöllner illusion was increased, it became negative at smaller angles, due to the increased contribution of lateral inhibition.

The Fraser illusion was first described by James Fraser in 1908. A simple version of the illusion is shown in Figure 1a. In this figure, the letters of the word LIFE appear to be tilted with respect to one another. Physical measurement of this figure reveals that the apparent tilt is a powerful visual illusion. The illusion seems to be due to the influence of the tilted elements that make up the lines. The orientation of the elements somehow seems incorporated into the orientation of the letters as a whole. This feature of these tilted elements led Fraser (1908) to call them "directional elements."

The significance of this illusion for theories of visual orientation processing is twofold. First, the direction of the illusion is opposite to that found in such other orientation illusions as the angle expansion illusion (Blakemore, Carpenter, & Georgeson, 1970) and the Zöllner illusion (Oyama, 1975; Wallace & Crampin, 1969; White, 1975). Second, an unexplained process similar to that which occurs in the Fraser illusion has been invoked to explain features of two other major classes of illusion, the Zöllner (Rock, 1975) and Munsterburg (McCourt, 1983) illusions (Figures 1b and 1c). In both of these illusions, local distortions are incorporated somehow into the perceived orientation of longer lines.

In general, attempts to explain the Fraser illusion fall into two broad classes. The first is based on the premise that the illusion is due to lateral interactions between orientation detectors, and that these become *facilitatory* at small angles, producing a reverse illusion (Lennie, 1972; O'Toole & Wenderoth, 1977). There have been reports of such reversals at small angles in other orientation illusions (Adam, 1964; Imai, 1962; Lennie, 1972; Oyama, 1975; Wallace & Crampin, 1969). However, it is by no means clear that these reversals reflect facilitation between orientation detectors. Wallace and Crampin (1969) considered their result to be artifactual, in the sense that it was due to limitations in visual acuity for intersecting lines. This explanation is equally applicable to the results of Adam (1964) and Lennie (1972). In any case, these reversals only occurred at small angles, whereas the angle of the directional elements in the Fraser illusion is 8°. The only two studies that have reported reverse illusions at angles greater than 5° (Imai, 1962; Oyama, 1975) used Zöllner illusions with very short inducing lines, producing configurations very similar to the Fraser illusion itself.

Tyler and Nakayama (1984) reported that an illusion very similar to the Fraser illusion, made of short tilted lines, remains assimilative when the short line segments are tilted up to 15°. (Their figure was very similar to those in Figure 3c, but subtended 10° of arc and had only six elements.) This is an angle close to that at which maximum orientation *contrast* effects occur in other orientation illusions (Robinson, 1972). The lateral inhibition theory, therefore, clearly must be modified in order to explain both classes of illusion. Tyler and Nakayama (1984) have suggested that the critical difference between these illusions is that the lateral interactions in the Fraser illusion take place between detectors with different receptive-field sizes. They suggest that facilitation takes place between such receptors at much greater angles than it does when the receptive field sizes are comparable.

There are a number of possible objections to this class of theories. The first is that there is no neurophysiological evidence that facilitation occurs at small angles. In fact, Blakemore and Tobin (1972) found that inhibition was greatest when a surround stimulus was at the *same* orientation as a test grating. A slightly different concept of

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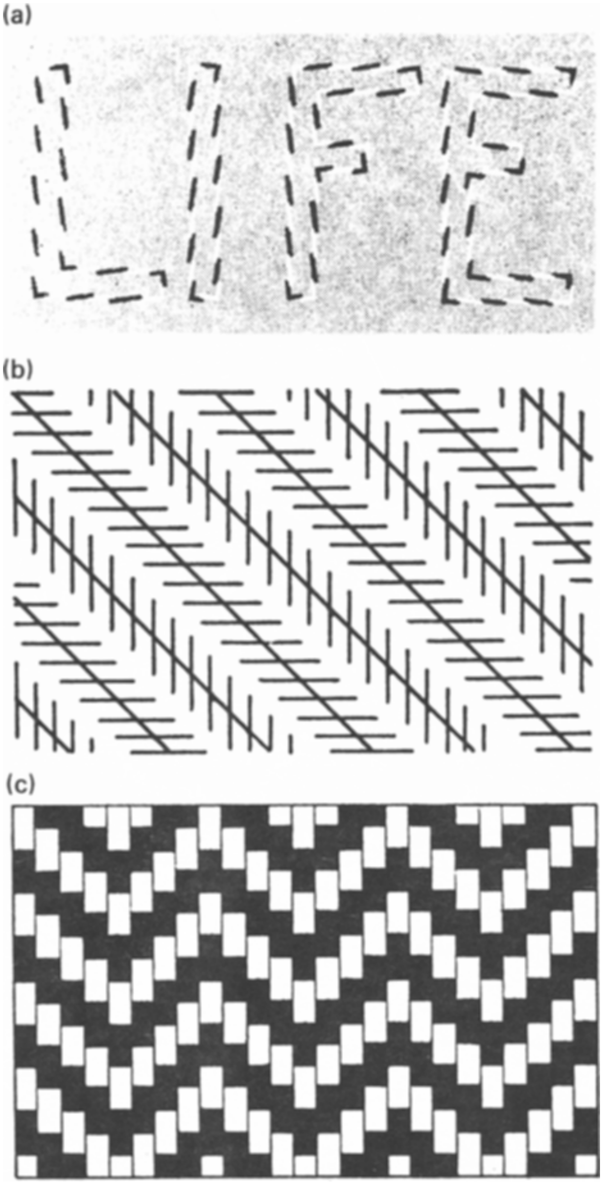

Figure 1. Versions of the (a) Fraser, (b) Zöllner, and (c) Munsterberg illusions.

facilitation has arisen from the original model of Blakemore, Carpenter, and Georgeson (1970). They held that the population response to a pair of lines was the sum of the population responses to individual lines. Others, such as Lennie (1972) and O'Toole and Wenderoth (1977), extended this reasoning to lines intersecting at smaller angles, and concluded that facilitation might occur at these angles.

The main difficulty with this theory is that it implies that the response of an orientation selective cell to a pair of lines can be derived by simple summation of the responses to the lines presented singly. This may be valid for larger angles in which the major source of mutual inhibition arises from beyond the classical receptive field (Nelson & Frost, 1978). In this situation, direct excitation of a cell is tempered by inhibition from cells tuned to quite different orientations. Since there is no summation of excitation, the model works well. However, in this model, facilitation requires that excitatory influences be added to each other. At very small angles, this implies that the response of a cell to two intersecting lines should be almost twice that produced by a single line. Clearly, the second line would fall partly in the inhibitory receptive field of a cell tuned to the first line, *reducing* its response. Careful consideration reveals that the maximum excitation in this situation should occur when one of the lines lies precisely in the excitatory zone of the receptive field. Any mutual inhibition will then push the peaks of the population response apart, as it does at larger angles. This explains why such attraction effects are not generally obtained at the angles predicted by a model that is based on simple summation of population responses.

An alternative theory, which has been given only brief consideration by Howard (1982), is that during early visual processing, orientation is coded only on a local basis. This may be regarded as a modern form of Fraser's (1908) concept of directional elements that influence the orientation of the longer lines that they compose. The influence of the directional elements on judgments of orientation is mediated by the presence of other cues, both orientational and spatial, present in the stimulus. Only when other cues are removed will assimilation be complete. Near-complete assimilation has been reported for more complex versions of the illusion (Cowan, 1973; Fraser, 1908), which we will examine further in a companion paper.

There is now some indirect evidence, both neurophysiological and psychophysical, that supports this alternative theory. First, let us consider the characteristics of visual cortical cells described by Hubel and Weisel (1962, 1968). The two most important characteristics of these cells are: (1) Simple and complex cells do not show "end-stop" inhibition. This means that the cells are not responsive to the length of a line in the visual field. As long as a line or a segment of a line fills their receptive field, they will respond maximally. Only hypercomplex cells seem tuned to detect the ends of lines. (2) These cells have an upper limit to their receptive field size. Poggio (1972) reported that, for the monkey, the long axes of foveal receptive fields of cells in the primary visual cortex varied from 6′ to 30′ of arc. This estimate has been confirmed by Dow, Snyder, Vautin, and Bauer (1981). If this was also a characteristic of human receptors, a line longer than 6′ to 30′ of arc could not have its orientation coded by a single receptor. Rather, the orientation of a line would have to be coded by the response of several receptors arranged along its length. This mechanism would be perfectly adequate for coding the orientation or curvature of long lines and edges. However, it would be very susceptible to the manipulations made in the Fraser illusions, in which the parts of the line have a different orientation to the whole.

It is difficult to find a psychophysical task that reflects the activity of orientation-selective cells at their upper size limit. Such tasks as acuity for parallelness or vernier acuity probably involve spatial cues. The best line of evidence comes from spatial summation studies. It has been known for some time that the shape, as well as the area, of a stimulus affects its luminance threshold. Lamar, Hecht, Shlaer, and Hendley (1947) found that only for stimuli below 100′ square was a square target optimal; for larger targets, those with a more elongated shape had lower luminance thresholds. Kulikowski (1969) obtained consistent findings, also showing that complete summation occurred only for small targets. For line stimuli, sensitivity increased as the square root of line length from 6′ to 60′ of arc, beyond which there was no further improvement. These findings were taken to reflect integration of output from lower level cells with small roughly symmetric receptive fields into orientation detectors up to 60′ in length. These results have been confirmed and extended by Vassilev and Penchev (1976), Bacon and King-Smith (1977), and Thomas (1978).

Since all these studies used free viewing, implying the use of foveal vision, it can be concluded that there is rough agreement between psychophysical estimates of the maximum size of orientation-selective cells in humans and neurophysiological measurement of foveal receptive fields in the monkey. The aim of the present series of experiments was to determine whether the Fraser illusion in its simple form was due to such a limitation in the coding of orientation or whether it could be explained on the basis of a more general theory of lateral interactions between orientation selective cells.

GENERAL METHOD

Psychophysical Method

Because of apparent ceiling effects associated with the parallel matching method of measuring apparent line tilt (e.g., Carpenter & Blakemore, 1973), we devised a new method—right-angle, or *orthogonal*, matching. If an adjustable line is made to form an exact right angle with a stimulus line, then perhaps the problems associated with parallel matching can be avoided, with the advantage that the whole display still remains mainly in foveal vision. The main advantage of this method is that it does not appear to be so obvious that the illusion influences the placement of the adjustable line, because any additional sources of orientation information are not as salient as the distances between apparently parallel lines, particularly at their endpoints.

This new method resulted in stronger illusions than those obtained by the parallel matching method. However, this increase was not confined to more powerful illusions. This indicates that the extra cues in the parallel matching display, being veridical cues, have a general dampening effect on illusions that are measured by this method. Consequently, the general pattern of results obtained with the parallel matching method seems reliable, and only the overall magnitude seems questionable.

Nonetheless, all results reported here were obtained using the orthogonal matching procedure. The display as seen by the subjects is represented in Figure 2. The adjustable line in this figure is precisely at right angles to the Fraser illusion stimulus. In the actual display, the adjustable line was 4 cm long, and one end was at the center of the display, 3 cm from the middle of the 8-cm-long illusion stimulus.

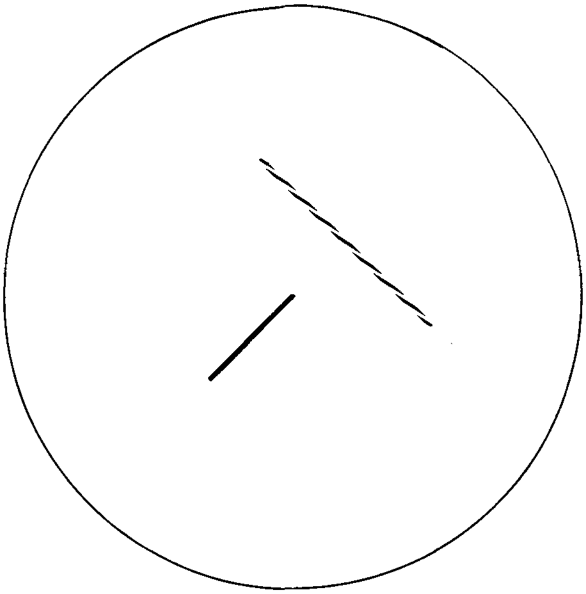

Figure 2. Schematic representation of the experimental display.

All stimulus lines in the experiments were mounted at an angle of 45° counterclockwise because it was felt that one angle of presentation should be used throughout the experimental series to avoid duplicating each experiment at several angles. Since most orientation illusions are stronger in the oblique axes (Oyama, 1975; Wallace, 1964; White, 1975), we decided to use one of these orientations. Rochlin (1955) has shown that parallel lines do not appear parallel at all orientations, a finding confirmed by Carpenter and Blakemore (1973) and White (1975). Even more surprisingly, Rochlin reported that parallel lines are distorted away from parallel when tilted clockwise from vertical, but not when they are tilted counterclockwise from vertical. Taking all these factors into consideration, we decided to use the counterclockwise oblique orientation.

Subjects

All subjects were paid volunteers between the ages of 17 and 30 years. Most were undergraduates. They were screened for visual acuity using the Bosch and Lomb Ortho-rater, and were required to have at least 20/20 binocular visual acuity on the test for near vision.

Apparatus

The same basic apparatus was used in three of the four experiments. Its purpose was to measure the apparent orientation of simple line versions of the Fraser illusion by means of an orthogonal matching line. This could not be done using a computer-generated display because of the complexity of the Fraser illusion. Consequently, the figures were drawn at four times their desired size of 8 cm and then reduced photographically. These photographs were then mounted on cardboard disks 21.3 cm in diameter. The matching line was a black adhesive strip that was stuck to the bottom of a clear Perspex disk of the same diameter. When this disk was placed on top of the photographs, the matching line and the Fraser figures appeared in the same plane, and their relative orientations could be changed by rotating the clear Perspex disk.

Both the photograph and the clear Perspex disk were held in place by an annulus of 3-mm-thick white Perspex, mounted on the top of a table. At its right side, a 35° section was removed, allowing the subject to rotate the clear Perspex disk by means of a wire fixed into its edge. The position of the clear disk, and therefore that of the matching line, was measured by the displacement between fine lines scored on the outer edge of the clear disk and the inner edge of the annulus. These lines were obscured by a second, removable, annulus that had an inner diameter of 19.3 cm and fitted into raised notches. A chinrest fixed above the apparatus controlled viewing distance at about 64 cm. This meant that the 8-cm lines subtended a visual angle of 7.2°. A light illuminated the apparatus at 700 lx.

Procedure

After being screened for visual acuity, a subject was shown the apparatus. A stimulus line was selected at random and placed in the apparatus. The task was then explained to the subject, with the experimenter demonstrating what was required. It was emphasized that the head should not be tilted to compensate for the orientation of the display, and that normal binocular viewing should be employed. The stimuli were then presented to the subject according to the design of individual experiments. The degree and direction of the illusion was measured by the displacement of the lines on the outer edge of the clear disk and the inner edge of the white annulus, which were collinear when the lines were exactly orthogonal. This displacement was measured to the nearest 0.2 mm with vernier calipers, and recorded for later analysis.

Statistical Analysis

Because repeated measures designs were used, and there was a strong possibility of violation of the assumption of homogeneity of variance, three robust alternatives to the conventional univariate analysis of variance (ANOVA) were carried out when appropriate. These were the multivariate analogue a to repeated measures ANOVA and two *df*-corrected F tests, the Greenhouse-Geisser and Huyn-Feldt F tests (Rogan, Keselman, & Mendoza, 1979). Fortunately, the results of all three were always in agreement. For ease of reporting, we use only the F statistic associated with the multivariate analogue, since it does not require fractional degrees of freedom. The subscript M is used to identify these F statistics.

EXPERIMENT 1

Experiment 1 was designed to test a number of hypotheses simultaneously. A working hypothesis was that both the Fraser and Zöllner illusions might be influenced by both lateral inhibitory distortions and direct integration of local orientation cues, with the latter perhaps playing a greater role in the Fraser illusion. If this were true, then it might be expected that the Fraser illusion would display a stronger assimilative illusion at small tilts of the inducing elements, and that this would persist at larger angles than in the Zöllner illusion (henceforth, a Fraser illusion is defined as a line made up of tilted elements, whereas a Zöllner illusion is a continuous line set against a background of tilted elements). Furthermore, if contrast effects in either illusion result from lateral inhibition, then it might be expected that assimilative effects will predominate when the illusions are defined entirely by oblique elements (as in the usual Fraser figures) as opposed to when vertical (with respect to the longer line) line segments or edges are present, as in most versions of the Zöllner illusion.

Two less critical hypotheses were also tested. It has been suggested that the Fourier components of checkerboard inducing fields may play a role in orientation illusion (Anstis & Tyler, 1980). The role of these components was examined by using solid and outline versions of the illusions. If the solid figures behave differently from the outline figures, this hypothesis would be confirmed. Specifically, since the low-frequency components of solid elements are tilted at a smaller angle, assimilation should occur at greater angles (when this is defined by the edges or high-frequency components). If the solid and outline figures behave similarly, but differently from illusions composed only of oblique elements, this would show that it is the shape, and hence the implicit tilt, of the entire element, not its Fourier components, that is critical (see Hartley, 1982).

Method

Subjects. Eighty-four subjects—49 females and 35 males—participated.

Apparatus. The apparatus was the same as that described in General Methods.

Materials. The stimulus lines used in Experiment 1 were designed to test the hypotheses set out above. Seven angles were used with a greater concentration at the smaller angles: 4°, 8°, 12°, 18°, 25°, 35°, and 45°. The number of elements in the lines was held constant, and so, with increasing angle, the thickness of the elements increased. Both Zöllner and Fraser illusions were used at each of these angles. The full set of stimulus lines is shown in Figures 3a, 3b, and 3c. At each of the seven angles, three different versions of the Zöllner and Fraser illusions were constructed: (1) the solid versions of the illusions, (2) outline versions of the illusions, and (3) versions with only the oblique line segments of the illusions present.

Design. A three-way factorial design was employed. The angle of inducing segments (hereafter referred to as *angle*) was a nonrepeated measures factor, and the other factors, *type* of illusion (Zöllner or Fraser) and *form* of illusion (solid, outline, or obliques-only), were repeated measures factors. Twelve subjects were used for each of the seven angles, accounting for all 84 subjects.

Procedure. The stimulus lines were presented in random order. Two measurements were made of each line, and ascending and descending runs were strictly alternated.

Results and Discussion

The results of Experiment 1 are shown in Figure 4. The analysis was carried out in stages. The positive (in the same direction as the Fraser illusion, i.e., assimilative) and negative (i.e., contrast) illusions were analyzed separately, because overall main effects and interactions were difficult to interpret due to the complexity of the results. At 12°, a two-way ANOVA showed that there was no significant difference in the strengths of the two types of illusion [$F(1,11) = 0.28$, n.s.], the three forms of illusion [$F(2,10) = 0.08$, n.s.], or any interaction between these two factors [$F(2,22) = 1.12$, n.s.]. We therefore analyzed the results from 4° to 12° and from 12° to 45° separately.

The solid figures, both Fraser and Zöllner, seemed to show a considerably weaker *negative* illusion than did the outline and obliques-only figures. A two-way ANOVA was carried out to compare the average scores of these two groups of curves. In the 12° to 45° range, the solid figures showed a less negative overall illusion [$F(1,55) = 61.19, p < .0001$], and there was a significant inter-

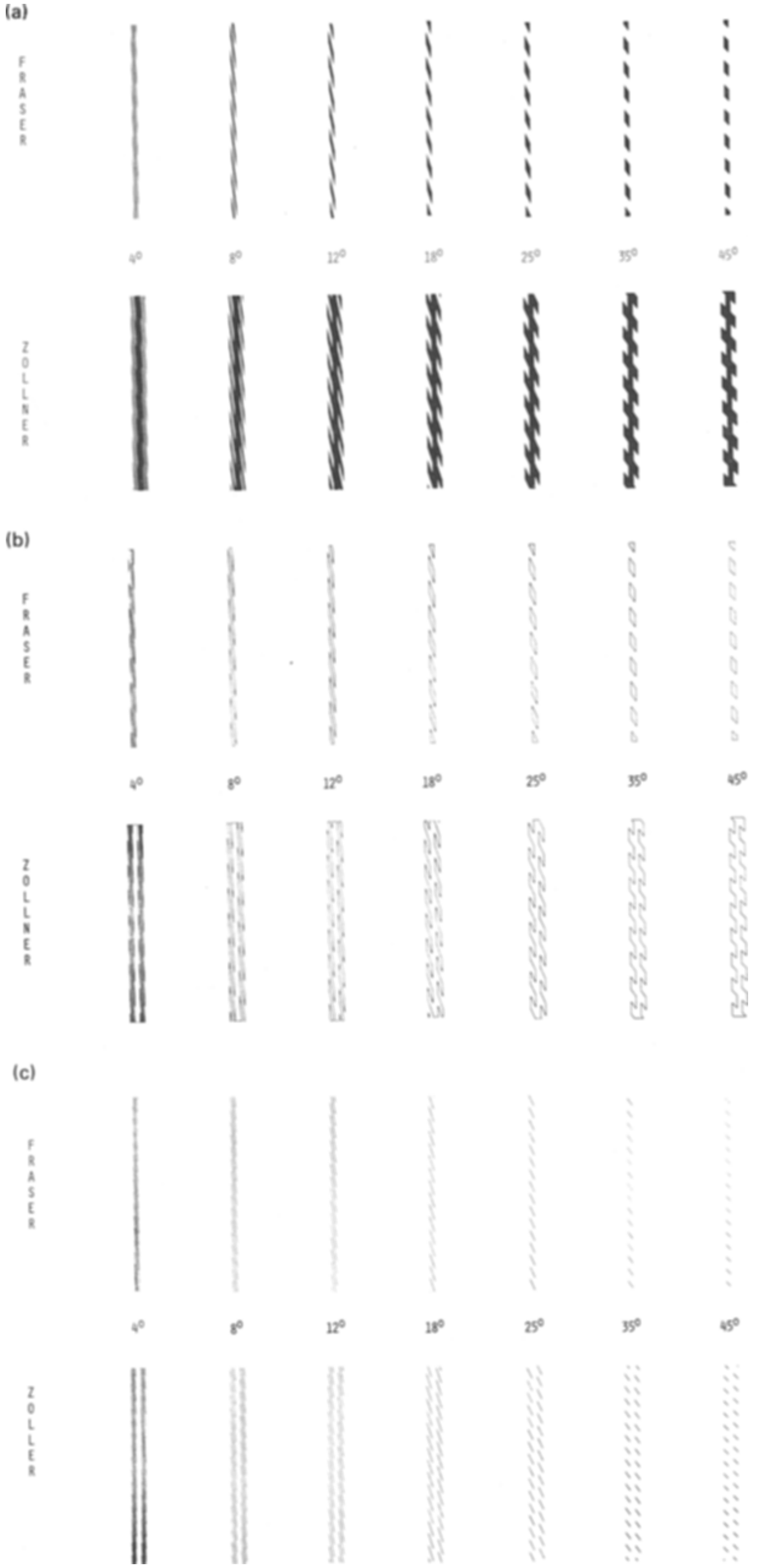

Figure 3. Stimulus figures used in Experiment 1: (a) solid, (b) outline, and (c) obliques only.

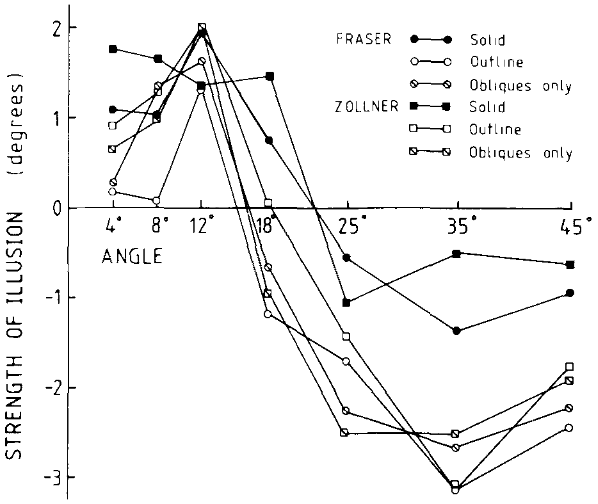

Figure 4. Results of Experiment 1.

action with the angle of the elements [$F(4,55) = 5.14$, $p < .01$}. This indicates that the Fourier fundamentals in the directional elements of these figures may play a role in determining the overall perceived orientation. It must also be assumed that the positive component is active to some extent at the range of angles used, since the solid illusions are less negative at all angles tested.

There is one possible exception to these generalizations. At 12°, the solid illusions are no stronger than the others, and yet it has been argued that, at both lesser and greater angles, the solid figures contain directional information that leads to more positive illusion in them than in the outline figures. The only solution to this problem is to abandon the notion that these components are strictly additive: They may add to a weak positive illusion, or counteract a negative illusion, but may have little additional effect on an already strongly positive illusion. There may be ceiling effects due to other sources of information in the display, particularly the vertical edges of the directional elements.

Up to this point, it has been assumed that the solid forms of the illusion exhibit one angular function and the other forms, a different function. However, it could be argued that there is a range of functions present, and so this dichotomy is artificial. One way to justify this procedure is to show that, at some angle, there is a definite break in the range of illusory distortions (i.e., the strongest illusion in the solid-forms subset is less than the weakest illusion in the other-forms subset). When this comparison was carried out at 35°, the difference did not reach statistical significance [$t(11) = 1.851$], although it bordered on it. Note, however, that at every angle between 12° and 45° the solid figures were always less negative than the others. At different angles, members of the hypothesized subgroups changed in the rank order of their strengths, but at no angle did the subgroups overlap.

The next major observation is that in the range of 12° to 45°, there was little difference between the outline and obliques-only figures. This was confirmed by a three-way ANOVA that yielded no significant main effects or interactions. This is another finding that cannot be accounted for by conventional lateral inhibition theory, which holds that lateral inhibition takes place between units sensitive to line stimuli. If the negative effect is indirectly produced by lateral inhibition, then the theory must be extended to allow point orientation markers or subjective contours to be influenced by these processes. Another implication is that it is the lower frequency components, not the shape and implied tilt of the inducing elements, that are critical.

In the range of angles between 4° and 12°, the results were not quite so clear-cut. An overall analysis using a three-way ANOVA indicated that there were significant main effects of both form of illusion [$F_{\mathrm{M}}(2,32) = 5.20$, $p < .05$] and type of illusion [$F(1,33) = 7.25, p < .05$]. No other components of the variance were significant. These differences apparently were due to a combination of two effects: The outline and solid Zöllner illusions showed a more positive illusion than did the outline and solid Fraser illusions, and the outline illusions were weaker than the solid illusions. The latter finding can be explained in the same manner as before: The outline figures lacked the positive Fourier components of the solid figures. The stronger positive illusions in the solid and outline Zöllner figures was probably due to a confusion between the edges of the line and the oblique segments; at very large oblique angles, it was difficult to tell where one started and the other finished. This was not the case for the obliques-only figures, which behave very similarly at all angles, nor did it appear to be a problem in the Fraser illusions.

Some questions were still left unanswered by Experiment 1. No great difference was obtained between the angular functions of the Fraser and Zöllner illusions, implying that the same processes might be at work in both illusions. However, this result sheds no light on the question of whether the assimilative illusions observed at small angles are due to facilitatory interactions between orientation-selective cells. The solid figures produced generally more positive illusions than did the other figures, but it is not clear that this was due to the influence of the fundamentals. The lateral inhibitory interactions produced by solid figures could be quite different from those produced by outline figures. Lastly, the Zöllner illusions that have been used so far have not been true Zöllner illusions in that they could be regarded as black lines sandwiched between two Fraser illusions. It would be interesting to see what happens to these Zöllner figures when the amount of background is extended. These questions were examined further in Experiments 2, 3, and 4.

EXPERIMENT 2

The aim of Experiment 2 was to examine further the possible role of Fourier components in the Fraser illusion. We have suggested that because the Fourier fundamental components of the solid figures are at a smaller

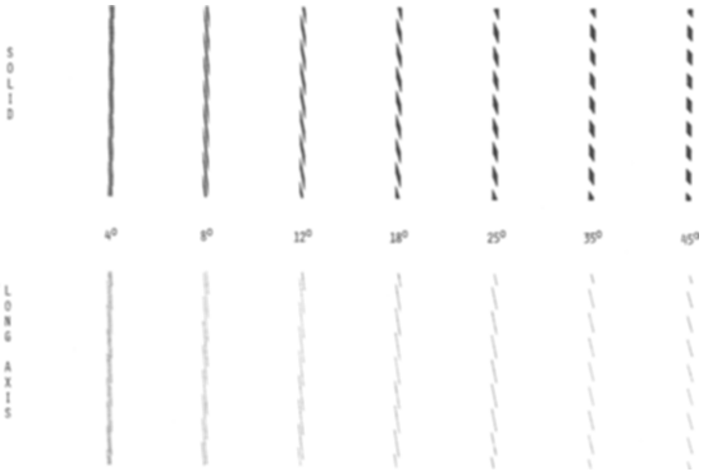

Figure 5. Stimulus figures used in Experiment 2.

angle than the edges of the elements, more positive illusions result (except where there may be ceiling effects). It was not technically possible to test this hypothesis directly by filtering out all but the fundamental components from the solid figures. As an alternative, we used elements with the same length and orientation as the Fourier fundamentals (i.e., the same length and orientation as the long axes of the directional elements). We looked at this issue only in Fraser illusions, as the Fourier composition of the Zöllner illusions would have been much more complex.

Method

Subjects. Twenty subjects—11 males and 9 females—participated.

Apparatus. The apparatus was the same in all respects as that described in General Methods.

Materials. The stimulus patterns used were made up of lines of the same length and orientation as the long axes of the directional elements in the solid versions of the Fraser illusion. They are shown in Figure 5, along with the corresponding Fraser illusions.

Design. A two-way repeated measures design was used, the two factors being angle of illusion and type of illusion (solid or fundamentals-only). The stimuli were presented in random order.

Procedure. Two measurements, one ascending and one descending, were made of the apparent orientation of each line, in a strictly alternating sequence. The rest of the procedure was exactly the same as that used in Experiment 1.

Results and Discussion

The solid symbols shown in Figure 6 represent the results of Experiment 2. The figures that were composed only of the fundamental components showed a strong positive illusion across the range of angles studied, whereas the solid Fraser illusions showed a function that was similar to that obtained in Experiment 1. These findings were confirmed by a two-way ANOVA, which showed significant main effects of both angle [$F_M(6,14) = 4.26$, $p < .05$] and illusion type [$F(1,19) = 63.82$, $p < .0001$], and a highly significant interaction [$F_M(6,114) = 21.30$, $p < .0001$]. The negative illusion component, while present, was somewhat weakened. This might represent a range effect, since the majority of illusions in Experiment 2 were assimilative.

Nevertheless, the fundamental components would provide a positive illusion in the solid Fraser illusions that is of sufficient range to explain the difference between them and the outline illusions. For comparison, this difference is illustrated in Figure 6 by the open triangle symbols. Given that these results were derived from different experimental groups, and that one set consists of difference scores, the functions suggest that the hypothesized components may be real. At the very least, the positive influence of the fundamental components can be said to persist over a wide enough range of angles to explain why the solid figures showed a reduction in negative illusion at all angles tested rather than a shift in the point of maximum negative illusion.

The strength of the fundamentals component is slightly larger than that of the difference scores. However, it must

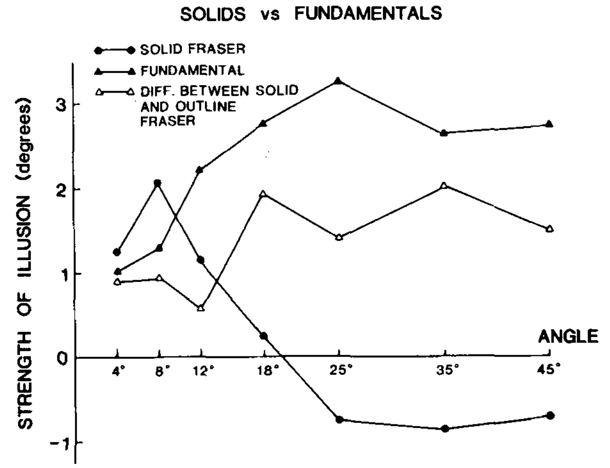

Figure 6. Results of Experiment 2. Fundamentals are plotted as the angle of the edge of the solid element from which they are derived.

be kept in mind that the elements were not truly Fourier fundamentals and that there were other components in the solid figures.

As a footnote to this experiment, the use of illusions with eight fine-line elements enabled us to compare the behavior of these illusions with similar illusions that had 16 elements, the obliques-only Fraser illusions of Experiment 1. These results are shown in Figure 7. The data from the fundamental components has been replotted according to the actual tilt of the components. The figures with the smaller number of elements gave rise to stronger illusions—a result that was also obtained by Tyler and Nakayama (1984). They did not attempt to explain this finding in terms of lateral facilitation between orientation detectors with different receptive field sizes. However, Wallace and Crampin (1969) and Oyama (1975) found that the strength of the Zöllner illusion increased with the number of background elements. If a dual-process explanation is appropriate, the negative component of these illusions would be increased by the addition of extra directional elements. Consequently, this finding is not really a critical test of the two theories. Experiment 3 was an attempt to provide such a critical test.

EXPERIMENT 3

In Experiment 1, no differences were found between the Fraser and Zöllner illusions on any of the dimensions that were varied. This means that lateral facilitatory processes may play a part in the positive illusion components. In the introduction, direct, positive effects of the type suggested by Fraser and others were contrasted with lateral inhibitory processes that act indirectly by tilting sections of lines, which are then integrated into the orientation of the line as a whole.

Thus *positive* tilts of the line segments produced by lateral *facilitation* still might be integrated into the overall line orientation. If this were true, both hypotheses would be correct, but the direct integration effect would be operating at much smaller angles than expected under the assumption that all positive illusions are due to direct effects. The only way to resolve this issue is to measure the orientation of the line segments independently of the overall line orientation. If the orientation of the segments corresponded closely to the orientation of the line as a whole, this would indicate that indirect effects were important in both positive and negative illusions; if positive illusions of overall orientation occurred when the segments were still tilted negatively, this would indicate the extent of the direct contribution of directional elements.

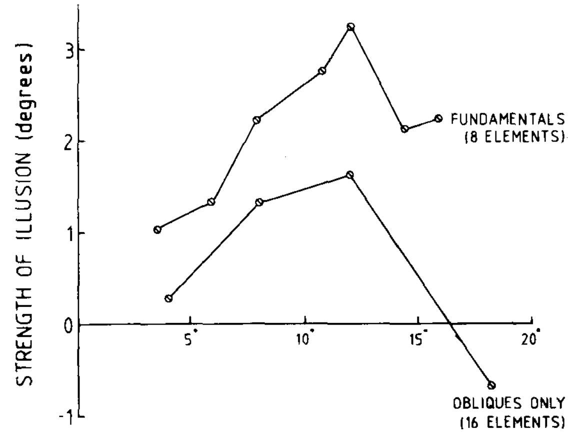

Figure 7. Angular functions for obliques-only figures of Experiment 1, and fundamental components of Experiment 2. Note that the actual tilt of both sets of elements is plotted.

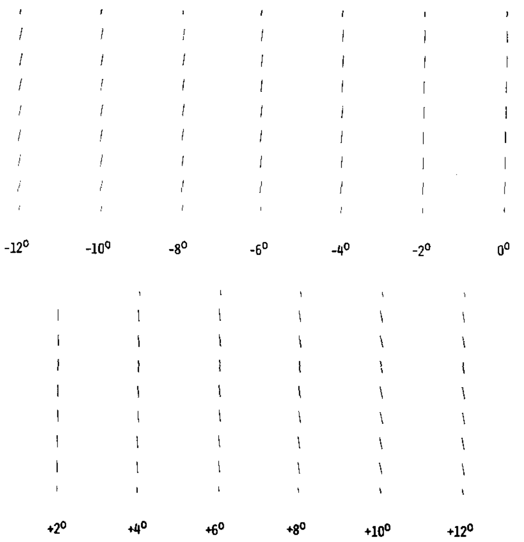

Figure 8. Comparison figures used in Experiment 3.

Although this is a good idea in principle, no conventional psychophysical method, including orthogonal matching, seemed to be suitable to measure this component of the illusion. We therefore used a new matching method designed to measure the apparent tilt of the edges of the directional elements relative to the hypothetical "true" alignment. In the latter, these edges would be perfectly lined up along the edge of the illusory line.

Accordingly, we prepared a series of comparison lines, each with eight elements to represent the vertical edges of the directional elements in the Fraser illusion or the visible edges of the induced line in the Zöllner illusion. These comparison lines are shown in Figure 8. In Experiment 3, these comparison lines were used to measure the extent to which indirect components contribute to the illusion at various angles.

Method

Subjects. Twenty subjects—12 females and 8 males—participated.

Apparatus. A different apparatus was used in Experiment 3. It was constructed entirely of white cardboard. At the top was a

26×20 cm pocket, with a 20-cm-diam circular hole in the front for displaying the stimulus lines. These were presented at an angle of 45° counterclockwise, as in all the previous experiments. Underneath this was a slot, 64 cm long and 12 cm high, designed so that a piece of cardboard the same length could be moved to either side. Upon this the comparison lines were mounted in an ascending series and 4.5 cm apart horizontally; they were also tilted 45° counterclockwise. The experimenter could move this card under the subject's instructions so that the comparison line that most closely matched the stimulus line was directly underneath it. Marks on the back of this card indicated its position and hence which comparison line was underneath the stimulus line. The whole apparatus was set up vertically at a distance of 64 cm from the subject, so that the lines again subtended an angle of 7.2°. The lighting conditions were exactly the same as in previous experiments. A chinrest was used to maintain the viewing distance and to keep the subject's eyes at a height approximately midway between the stimulus and comparison lines.

Materials. The stimulus lines were identical to those used in Experiment 1, with the obvious exception of the obliques-only figures; that is, solid and outline Fraser and Zöllner illusions were used at all seven angles employed previously. There were 13 comparison lines (see Figure 8), one representing no illusion, six a positive illusion, and six a negative illusion. The elements were tilted progressively in the appropriate direction in 2° steps.

Procedure. After the subjects were screened for visual acuity, they were instructed on how to carry out the matching task. An example of a line illusion with a noticeable induced tilt of the vertical edges was placed in the top part of the apparatus, and the subject's attention was drawn to the fact that these did not appear to be perfectly lined up. The subjects were shown the comparison stimuli and asked to select the one whose tilt most closely resembled that of the vertical segments of the illusory stimuli by instructing the experimenter to place it exactly under the experimental stimulus.

Each of the stimulus lines was placed in the apparatus and two matches were made, starting from either end of the scale. The stimuli were presented in a strictly random order, and the runs were alternated. The experimenter recorded the matches for later analysis.

Results and Discussion

The results of Experiment 3 were quite clear. They are shown in Figure 9. There was no indication of a positive tilt of the edges of the lines except at the very smallest angles used. No illusion was significantly different from zero in the positive direction. This finding is consistent with previous studies of positive illusions in simple angular figures and in Zöllner illusions. It also represents firm evidence that the positive illusions of orientation in the lines as a whole must be due to direct contributions from the oblique edges or from Fourier components. The other trends in the data were analyzed using a three-way ANOVA. As expected, there was a main effect of angle of illusion $[F_M(6,14) = 5.47, p < .001]$. The maximum negative illusion occurred at an angle of 18°, which is in line with previous studies. This finding is strong evidence for the existence of a positive illusion component in the Fraser and Zöllner illusions used in these experiments. There was no main effect of form of illusion (outline vs. solid). The interaction between angle and form failed to reach significance. $[F_M(6,14) = 2.15$, n.s.].

The most surprising finding was that much stronger negative tilts of edges were apparent in the Zöllner illusions $[F(1,19) = 23.12, p < .0001]$. It is strange that this result is not reflected in the strength of the overall illusion. It is possible that the limited extent of the background in the Zöllner illusions leads them to be treated as a black line sandwiched between two Fraser illusions. If Zöllner illusions with more extensive backgrounds were used in an experiment, this issue could be resolved. A related issue is that of whether in this situation the angular functions would shift so that negative illusions would occur at much smaller angles, as has been observed previously for the Zöllner illusion.

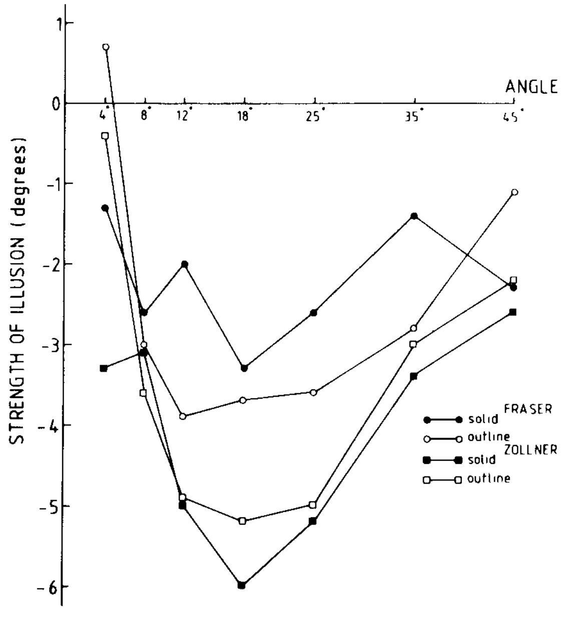

Figure 9. Results of Experiment 3.

EXPERIMENT 4

The purpose of Experiment 4 was to establish how the Zöllner illusion would behave relative to the Fraser illusion when a more extensive background inducing field was used. Two hypotheses were investigated in this regard: (1) that increasing the amount of background field would increase the negative component of the illusion, at all angles, up to the limits of around 1° of visual angle described by Wallace (1969), and (2) that a fuller background might mask the line-like character of the inducing field in the Zöllner illusions that we have used so far, again making the negative component more predominant.

Method

Subjects. Twenty subjects—13 females and 7 males—took part in Experiment 4.

Apparatus. The apparatus was the same as that used in Experiments 1 and 2.

Materials. Four illusions were used at each of three angles. The rationale was as follows: Since the aim was to see if negative illusions could be produced at smaller angles, we decided to use only three angles so that a fully repeated measures design could be employed. These were 12° as the strongest positive illusion in Experiment 1; 18° as the closest to the crossover point in Experiment 1, but where strong negative illusions have been reported in the case of the Zöllner and angle expansion illusions; and 25° as a strong negative illusion, to see if it would increase in strength.

At each of these angles, the original Fraser and Zöllner illusions were used; two more Zöllner illusions were created by adding first one and then two line widths of extra background to either side of the induced line. The resulting set of stimuli is shown in Figure 10. To reduce any possible effects due to the subject's using the edge of the background as an alignment reference, the instructions stressed that the subject attend only to the induced line during matching.

Design. A three-way repeated measures design was used. The stimuli were presented in random order.

Procedure. The procedure used in Experiment 4 was identical to that used in Experiments 1 and 2.

Results and Discussion

The results of Experiment 4 are shown in Figure 11. They show quite clearly that the contribution of the negative component of the illusion increases when the amount of background increases. This was confirmed by the results of a two-way ANOVA that indicated significant main effects of both angle [$F_M(2,18) = 56.19$, $p < .0001$] and amount of background [$F_M(3,17) = 10.37$, $p < .001$].

Although it is interesting to note that the Fraser illusion was considerably weaker than the Zöllner illusion at the 25° angle, there was no significant interaction component. Thus, the Zöllner illusion might behave more like might be expected when other, more powerful Zöllner illusions are present. When only the reduced form and the Fraser illusion are used, it tends to be processed as a "double" Fraser illusion.

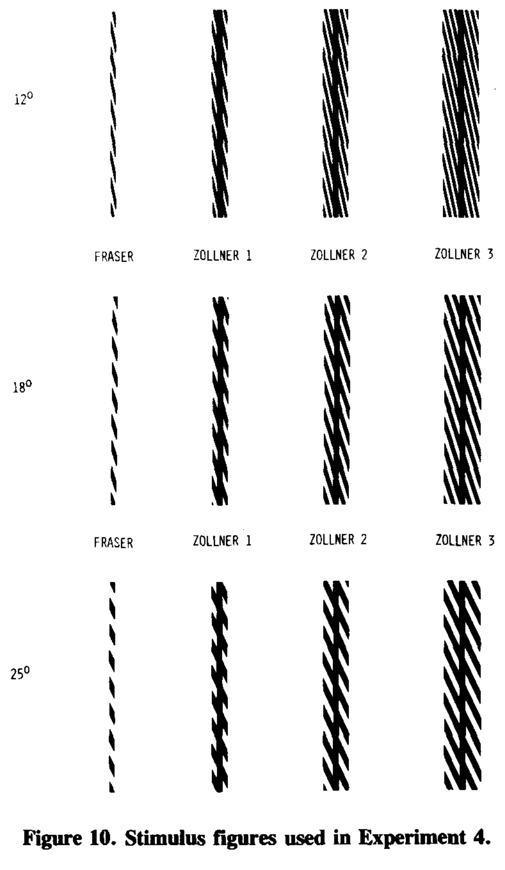

Figure 10. Stimulus figures used in Experiment 4.

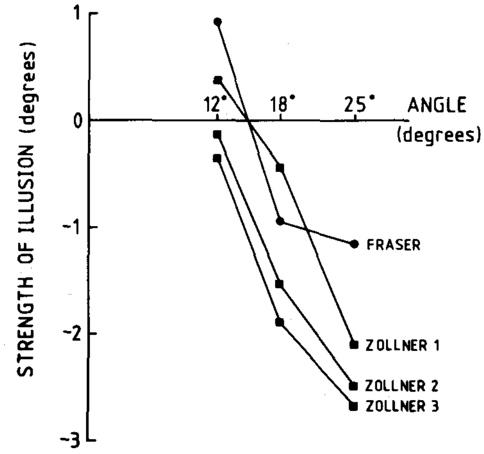

Figure 11. Results of Experiment 4.

GENERAL DISCUSSION

In general, the experimental findings strongly support the occurrence of a direct "orientation integration" effect of the type postulated by Fraser (1908). Some type of lateral inhibition seems to be the primary influence on negative, or contrast, illusions, but local distortions are probably transferred to longer lines through orientation integration effects. There is no convincing evidence that lateral interactions between orientation-selective cells can produce assimilative illusions, even at very small angles. In fact, no functional role has been suggested for such a process. On the other hand, both processing speed and efficiency of visual analysis could be enhanced by parallel processing based on units with a limited range of receptive field sizes.

This dual-process theory of orientation illusions is supported by a number of lines of evidence. In Experiment 3, it was shown that the indirect component of even the strongly positive illusory lines, as represented by the tilt of the edges, is negative. The positive illusions present in these lines must therefore result from the *direct* contribution of the orientation information present in the directional elements.

In the Fraser and Zöllner illusions, both processes seem important, and the direction of the illusion appears to be dependent on their relative contributions. The results of Experiment 1 show that positive and negative forms of both illusions occurred at the same angles when the size of the Zöllner illusion's background field was restricted. When the amount of this background was increased, as in Experiment 4, negative illusions became more predominant. This is in agreement with previous research, which has shown that strong positive illusions occur in the Zöllner figures only when the amount of background is restricted (Imai, 1962; Oyama, 1975).

There are two possible reasons for this. First, both Wallace (1969) and Oyama (1975) have shown that up to a limit of about 1° of visual angle, increasing the amount of inducing field increases the contrast illusion. A stronger negative component means that positive illusions are less likely to be observed at small angles. Second, increasing the amount of background may destroy the line-like character of the more reduced versions of both illusions. There is some evidence that this might be the case in Experiment 4, where the Zöllner illusion in its most reduced form was more negative than the Fraser illusion. This might have been because there was a greater tendency to see it as a line on a background field than as a line sandwiched between two Fraser illusions. However, since this result was not significant, this must remain merely conjecture.

These findings may also explain why positive illusions at small angles are so weak or absent in the angle expansion and tilt illusions; the form of these illusions is such that it is unlikely that orientation integration processes play a role. The slight positive illusions in these figures, as well as in Zöllner illusions with extensive backgrounds, are probably due to spatial interactions or acuity effects as suggested by Wallace and Crampin (1969).

Several other interesting results have been obtained, although these do not bear on the main theoretical issue of whether there is an orientation integration process. When solid elements were used, the fundamental components of these seemed to contribute to the illusion, and since these fundamental components fall at a smaller angle than the oblique edges of the elements, a more positive illusion results. It was shown that it is these components, rather than the long axes of the elements, which produce this effect, since the outline elements did not show the same angular function.

Another interesting finding is that even when there were no vertical lines and edges in the Fraser stimuli, as in the obliques-only figures, lateral inhibition took place. This supports the view of Smith and Over (1977) that subjective contours are processed in the same way as those defined by luminance boundaries. Von der Heydt, Peterhans, and Baumgartner (1984) have recently established that there are cells in the visual system of the monkey that respond to subjective contours. It only remains to be established that these cells interact in a similar way to those that respond to real contours for Smith and Over's (1977) view to be confirmed completely.

Although the results of these experiments using simple figures have supported the existence of a direct orientation integration effect, it is not inconceivable that the proponents of lateral facilitation could modify the theory to account for the present findings. However, it seems that this theory would run into difficulties in explaining the interactions present in the more complex figures originally described by Fraser (1908). These figures are also of interest because the illusions seem to be much stronger, implying that integration effects may be playing a much greater role. The results of a series of experiments using more complex figures will be reported in a companion paper. As well as establishing the properties of the complex forms of the Fraser illusion, this series of experiments will provide some further tests of the two alternate theories of the illusion.

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