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JOURNAL: Vision Research
ARTICLE: Simultaneous orientation contrast for lines in the human fovea.
AUTHOR: Westheimer, G
YEAR: 1990
MONTH:
DAY:
QUARTER:
SEASON:
VOLUME: 30
ISSUE: 11
NUMBER:
PAGES: 1913-21
PAGED LOCATIONS: >>za006<<, 9unl0, 9cubp
Staff Note:

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HOLDINGS: v.1 (1961)-v.42 (2002)

Vision Res. Vol. 30, No. 11, pp. 1913–1921, 1990
Printed in Great Britain.

0042-6989/90 $3.00 + 0.00

SIMULTANEOUS ORIENTATION CONTRAST FOR LINES IN THE HUMAN FOVEA

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(*Received* 10 *August* 1989; *in revised form* 23 *December* 1989)

Abstract—When it is surrounded by lines of a differing orientation, a test line changes its apparent orientation in a direction away from that of the surround lines. Using a nulling technique to arrive at numerical values, the properties of this simultaneous orientation contrast have been analyzed: it diminishes with distance of the surround lines; rises and then falls off as a function of surround line orientation; decreases with exposure duration; is sharply tuned (±100 msec) for synchrony of test and surround line presentation; is robust to differences between test and surround line disparity but not intensity; and is reduced with dichoptic presentation of test and surround lines. Orientation contrast can be induced in a variety of oriented features, including illusory contours, an ellipse, a moving dot and a row of dots or lines, but two dots alone don't suffice. The results are taken as evidence that orientation is a domain *sui generis*, in which simultaneous contrast is exhibited in the same manner as in the domains of color, brightness and disparity.

Tilt illusion   Line orientation   Simultaneous orientation contrast   Illusory contour

INTRODUCTION

The human observer is extremely effective in sensing the orientation of lines: precision of less than a degree were reported quite early in the history of psychophysics (Jastrow, 1893). Even in the absence of an immediate comparison, a single line spanning the human fovea, i.e. 30 min arc in length, can have its orientation identified to better than half a degree (Westheimer, Shimamura & McKee, 1976). Ever since Hubel and Wiesel (1959) drew attention to the existence in the primary visual cortex of neural units with oriented receptive fields in the cat and later in the monkey (Hubel & Wiesel, 1968), orientation sensitivity has been a favorite topic in visual physiology. The tuning width for orientation of these units is, however, quite broad so that they cannot be postulated as the immediate neural substrate for the whole animal's orientation sensitivity. The situation is analogous to that for the eye's position sense: the spacing and receptive field sizes of neural units are too coarse to account for hyperacuity directly. Rather, a complex neural circuit must be involved that processes the signals from a set of coarse-grain units and derives a measure of feature position that is finer than the mosaic of retinal receptors by up to an order of magnitude. Concepts such as simple differencing (opponency) or ratio mechanisms between units with overlapping receptive fields have been proposed, but as yet nothing is known about the details of this processing.

By the same token, the mechanism by which the value of the orientation attribute of a line is elaborated is not clear. From what is known about the tuning width and the shift of mean orientation from cell to cell in neurons of the primate striate visual cortex, it is safe to say that more than a single cell is involved. Simple concepts of lateral inhibition in the orientation domain (Blakemore, Carpenter & Georgeson, 1970) won't do either because such mechanisms may sharpen the tuning but cannot give values of the attribute finer than the spacing of the members of the ensemble. Lateral connections between orientation-selective cells in the visual cortex have been shown to exist by anatomical and functional tests (Gilbert & Wiesel, 1983). Since there is a large repertoire of psychophysical findings relating to the effect on perceived orientation of lines and gratings of neighboring (in time or space) oriented stimuli, the attempt to appose psychophysical and electrophysiological data in this area seems timely.

The literature in this area is voluminous and it has been reviewed recently (Howard, 1986). Because of the wide diversity of stimuli used in the many previous investigations on the tilt illusion and tilt aftereffect, as these phenomena have been called, the subject is here approached by a consolidated series of experiments. The stimuli have been selected to highlight specific characteristics of the interaction of the orientation parameter of foveal line stimuli.

If the interest is in the interaction of ensembles of orientation-tuned cortical cells, and if one wishes to seek the closest possible psychophysical correlates, the stimuli must be chosen accordingly. Some of the criteria are that the stimuli be simple and unambiguous, and that they be directly locatable in space and time in much the same way as stimuli that are presented to the animal's eye to map a neuron's receptive field and the interaction between neurons. Receptive fields of neurons serving the primate fovea are small, almost always have only a single peak position and the time course of response and interaction between responses is a fraction of a second. Moreover, to study interaction it is wise to use stimuli that do not physically overlap, so that one can separately vary the parameters of the stimuli probing the test region and the region sending interacting signals. Neurophysiological experiments in this vein are beginning to be reported. The psychophysical literature, to which one might turn for results in the human that ought to be more or less correlatable with primate cortical neurons, contains data which almost without exception does not meet these criteria. For example, gratings are used extensively but they unfortunately do not confine stimuli to the receptive fields of a limited set of neurons. There is a lot of information on the tilt aftereffect, but the long time course of events in this phenomenon, a matter of many minutes or even days (Wolfe & O'Connell, 1986), makes its relevance to the questions posed here a matter of some doubt.

The approach followed here places the phenomena in the wider context of interaction between simultaneously presented stimuli in adjoining regions of the visual field. In the domain of color, this is known as simultaneous color contrast, as when a white patch next to a red one assumes a greenish hue. In the domain of brightness, there is simultaneous brightness contrast, clearly exhibited by Hering's well-known figure in which a gray patch on a black surround appears lighter than on a white surround. Accordingly, and following the lead of the pioneer in this research (Gibson & Radner, 1937), the phenomenon subjected to examination in this study is called *simultaneous orientation contrast*. Here follows a series of experiments that highlight the spatial and temporal factors governing these interactions.

METHOD

Normal human observers were shown simple stimuli, mostly lines, on oscilloscope screens at a distance of 3 m in an otherwise dark room and were required to make binary judgments about their orientation. The test line most usually employed was 12 min arc long; it appeared every 3 sec in the middle of a fixation area that was delineated by a set of four brackets outlining a square 45 min arc on a side. The fixation pattern was usually extinguished 250 msec before the appearance of the test pattern and did not light up until 250 msec after its offset. Except as specifically described for each experiment, there were no immediate companion stimuli in the visual field. For the record it can be stated that the results are hardly affected if the room lights were on and the usual contours of a small laboratory were visible.

To obtain a measure of the observer's orientation sensitivity, the test line was shown, say, 300 times in succession, once every 3 sec, on each occasion in one of seven orientations: randomly vertical or n, $2n$ and $3n$ deg away from the vertical in either the clockwise or the counterclockwise direction, where n depended on the situation and was in the range of 0.6–2.2 deg. Each time the observer had to signal, if necessary by guessing, whether the line appeared tilted right or left at the top. Fitting a cumulative normal curve to the data yielded a measure of the orientation at which the observer reported verticality (the mean of the curve) and also of the orientation sensitivity. The threshold, i.e. half the difference between the line orientation for which the observer reported "right" on 25% and 75% of occasions, gives the sensitivity of judgments for orientation differences. In a practiced observer, a comparison is not needed. An internal reference for the mean of the ensemble of test stimuli is quickly established, and this applies even for stimuli that are not vertical. Although only fragmentary data are available, there is no reason to believe that the findings, which in this study were restricted to vertical test lines, would not apply to other orientations.

Patterns were created under computer control on HP1345 vector scopes equipped with a fast white phosphor (P4). Line intensity was of the order of 0.5 cd/m. In the dichoptic experiments a beam-splitter/polaroid arrangement allowed the presentation of patterns to each eye separately. Observation was binocular except where indicated, with normal pupils and with refractive correction where needed. Data were accumulated in runs of 300. All points shown in graphs or tables represented at least 600 responses, often many more, obtained on at least 2 days. Because the concept of a veridical perception was not employed here, there never were any error signals when the observer called a line "clockwise" when in fact it was shown "counterclockwise."

RESULTS

When a single line, 12 min arc long, is shown in the center of the fovea for 200 msec, the orientation sensitivity obtained by the method described above is about 0.5 deg arc. The observer may exhibit a small bias, i.e. he may call a line "vertical" when it is slightly tilted to one side or the other, but the bias is seldom more that a degree with our method of presenting stimuli. More important, with a sufficiently large set of responses (300 or more) the standard error of the mean is usually less than 0.1 deg, so that context-induced changes in the apparent vertical can be estimated quite accurately.

The following experiment illustrates the basic phenomenon of simultaneous orientation contrast and the nulling method adopted to quantify it. The center, 12-min arc line, identified as the test line, is now surrounded by six similar lines, 20 min arc away, arranged hexagonally as shown in the inset of Fig. 1. When these surround lines are tilted, say 20 deg, clockwise, a vertical test line appears tilted counterclockwise. Rather than merely reporting this fact, or have the observer make a judgment of the amount of apparent tilt, a nulling method was employed to measure the induced tilt in the test line: when the psychophysical procedure described in the above paragraph is used with a configuration consisting of the test lines surrounded by inducing lines rather than the test line alone, the psychometric curve is now shifted and its mean, representing the test line orientation at which it appears vertical, expresses numerically the magnitude of the simultaneous orientation contrast. There remains the problem of a possible observer bias, which was overcome by running presentations with equal and opposite surround line tilts in an interdigitated fashion and using half the differences between the mean values of the two curves as the measure of the orientation contrast for this particular surround line tilt. This is what is plotted along the axis of ordinates of most figures in this study.

Figure 1 shows the orientation contrast for a hexagonal configuration of surround lines as a function of their tilt. The peaking at values of 15–30 deg is in accord with previous studies of the tilt illusion with other patterns. The fundamental finding is that the effect is one of repulsion, except for a small reversal towards attraction as the inducing lines approach orthogonality. The test line appears tilted in a direction opposite to that of the inducing lines; in order to null out this orientation shift, i.e. make the test line appear vertical in the presence of the inducing lines, the test line has to be presented with a tilt that is in the same direction as the inducing lines. The large interobserver variability is a significant feature of this research. As expected, there is no orientation contrast when the inducing lines are exactly parallel or exactly orthogonal.

Orientation contrast, measured at the observers' optimum inducing orientation (i.e. the peak of the curves in Fig. 1) diminishes with distance between test and inducing lines (Fig. 2). These data are in broad agreement with the findings of Virsu and Taskinen (1975) and of Wenderoth and Johnstone (1988a). It will be demonstrated later that the curve does not turn down with decreasing separation and that, rather, the inter-

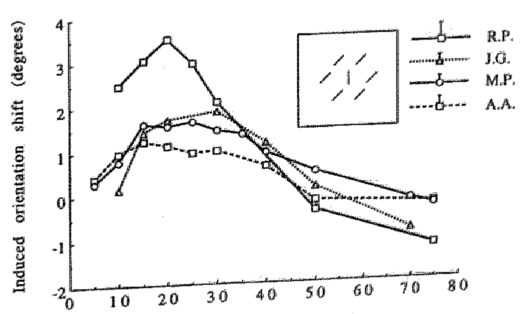


Fig. 1. Induced orientation shift for a 12 min arc foveal line surrounded by a hexagonal array of inducing lines (see inset) as a function of orientation of inducing lines. Exposure duration 20 msec, separation between test and inducing lines 20 min arc. Except for orientations that are almost orthogonal to the test line, inducing lines generate a repulsion effect in the domain of orientation. Symbols and average standard errors of the data points for the four observers are shown to one side. Each data point in this figure is based on at least 600 responses.

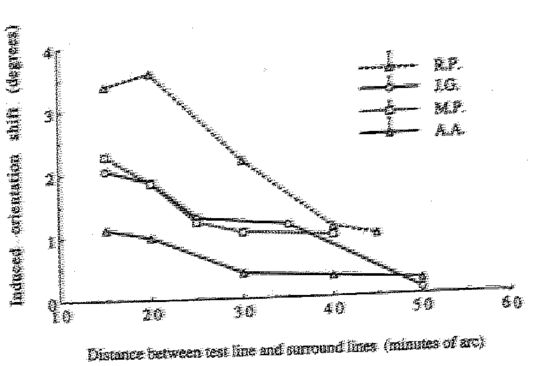


Fig. 2. Induced orientation shift for a 12 min arc foveal test line, surrounded by a hexagonal array of inducing lines (see inset of Fig. 1) as a function of separation between test and inducing lines. Exposure duration 20 msec. Inducing lines were at the most effective angle for each observer (see Fig. 1). Symbols and average errors of the data points are shown to one side. Each data point in this figure is based on at least 600 responses. Because six superimposed inducing lines would drown out the test line, data were not obtained for zero separation. Evidence presented in Fig. 13 suggests that the curves rise further as they approach the y-axis.

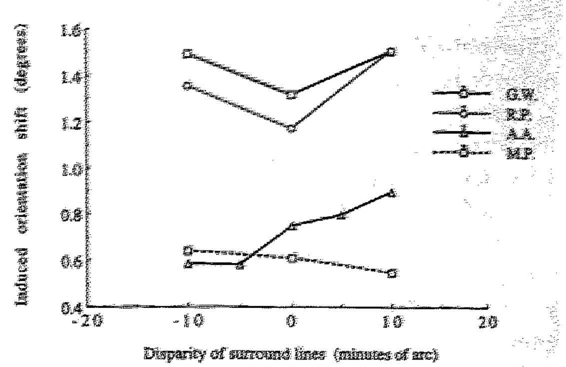


Fig. 4. Induced orientation shift for 12 min arc foveal test line surrounded by a hexagonal array of inducing lines (see inset of Fig. 1) as a function of the disparity of the inducing lines (negative values represent uncrossed disparity). The test line remained in the fixation plane throughout. Placement and orientation of inducing lines were optimal for each observer. Exposure duration 550 msec.

action characterized by this experiment extends right through the center.

The pattern of inducing lines was chosen to surround the test line uniformly. The question arises whether, since we are dealing with oriented stimuli, there is an anisotropy in the effect with respect to the meridian along which the inducing lines are placed, favoring a direction at right angles to the direction of the test line. The data in Fig. 3 seem to suggest that indeed this is the case, although in one observer the effect is not pronounced.

In view of the indications found by Nakayama, Shimojo and Silverman (1990) that perceptual effects change when interacting stimuli are given a different disparity, an experiment was performed in which the test line remained in the fixation plane, but inducing lines were either also in the fixation plane or were shown with various crossed or uncrossed disparities. Figure 4 shows that there is almost no disparity effect; if anything, simultaneous orientation contrast is stronger when the test and inducing lines do not share the same depth plane.

On the other hand, when there is a difference in intensity between the test and inducing lines, either way, the simultaneous orientation contrast is diminished (Fig. 5).

For a study of interocular transfer of simultaneous orientation contrast, the stimulus pattern shown in Fig. 6 was used. A row of obliquely oriented lines was displayed monocularly above and below the test line, which was also viewed monocularly. The orientation change of the test line was determined when the

Meridional Placement (degrees)	Induced Orientation Shift (degrees) R.P.	J.G.	A.A.
0°	3.61 ±.47	2.07 ±.04	0.99 ±.09
45°		1.35 ±.11	0.71 ±.06
90°	1.61 ±.22	1.02 ±.11	0.79 ±.06

Fig. 3. Induced orientation shift for a 12 min arc test line as a function of placement of two sets of two inducing lines, which were at optimal orientations and separation. Exposure duration 20 msec.

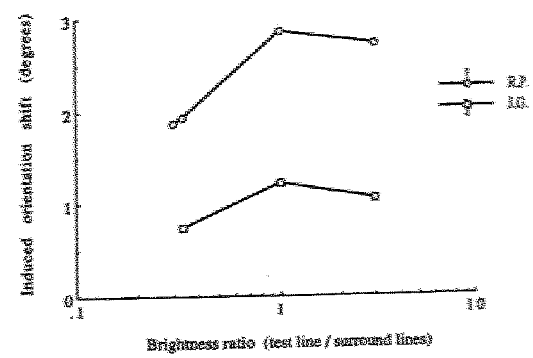
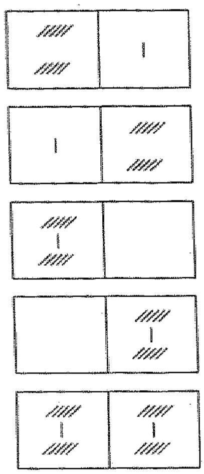


Fig. 5. Induced orientation shift for a 12 min arc foveal test line surrounded by a hexagonal array of optimally placed and oriented inducing lines as a function of the brightness ratio of the test and inducing lines. Exposure duration 30 msec.



Induced Orientation Shift (degrees)

	A.A.	G.W.
a.	3.13 ±0.45	1.81 ±0.64
b.	2.90 ±0.58	0.88 ±0.39
c.	3.84 ±0.51	3.37 ±0.57
d.	4.45 ±0.71	1.55 ±0.53
e.	2.89 ±0.26	2.03 ±0.28

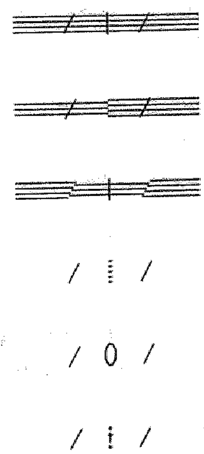
Fig. 6. Interocular transfer of orientation contrast. Inducing pattern consisted of five oriented lines, 12 min arc long, their ends separated by 4 min from the end of the test line. Test and inducing lines were either monocular, dichoptic or binocular as shown in figure. Induced orientation shift is reduced to about 2/3 on the average when test line is in one eye and inducing pattern in other. Exposure duration 30 msec for observer GW and 20 msec for A.A.

test and inducing lines were in the same eye and when they were in different eyes (monocular and dichoptic effects). This kind of pattern has the advantage of allowing some instability in the horizontal eye vergence position without causing the test line to overlap the inducing lines during dichoptic viewing. As is seen in the figure, the transfer from one eye to the other is about 2/3. This is about the same value as was found by Virsu and Taskinen (1975) for the tilt illusion and by Mitchell and Ware (1974) for the tilt aftereffect in normal observers. There is some binocular summation but it is not immediately clear how this observation relates to the hierarchical model on binocular summation put forward by Frisen and Lindblom (1988).

The above experiments have demonstrated salient aspects of the interaction that takes place in the realm of orientation using lines as stimuli. Now the question is asked: what oriented features other than lines can participate in orientation contrast?

Illusory contours

A virtual boundary was created by a series of three parallel horizontal lines, 3 min arc apart, coming in from the far left edge of the oscilloscopic field and terminating in the center along a boundary which could be given a slope just as would a real line. At the same time a series of four horizontal lines, also 3 min arc apart and offset by 1.5 min arc from the other set, came in from the far right edge of the oscilloscopic field and terminated in the same boundary, which now became a prominent illusory contour. At the outset it was determined that the basic phenomenon of simultaneous orientation contrast is not affected by the presence of a set of intersecting horizontal lines (Fig. 7, condition a). Now the center, test line was replaced by the illusory contour described above. The simultaneous orientations contrast is now very prominent (Fig. 7, condition b). Illusory contours can also induce orientation contrast in a real line (Fig. 7, condition c). In some observers, including the author, it requires some manipulation to arrive at the optimum stimulus; a gap is needed between the termination of the two



Induced Orientation Shift (degrees)

	A.A.	G.W.	M.P.
a.	0.67 ±.04	1.77 ±.11	0.65 ±.05
b.	0.68 ±.09	2.08 ±.17	0.71 ±.07
c.	0.40 ±.04	0.71 ±.08	0.79 ±.05
d.	0.51 ±.05	1.78 ±.08	0.61 ±.05
e.	1.07 ±.09	3.00 ±.16	1.16 ±.10
f.	3.38 ±1.05	3.77 ±.68	1.04 ±.17

Fig. 7. Induced orientation shift for a variety of patterns. Inducing pattern is always 20 min arc from center and at the observer's optimum induction angle, which remained the same for each observer for all conditions. Exposure duration 550 msec for conditions (a)–(e); 70 msec for condition (f). (a) Test and inducing lines 12 min arc, superimposed on a set of four horizontal lines, 3 min arc apart. This gives normal values for the orientation contrast and indicates that the four-line background neither aids nor interferes with induction; (b) normal orientation contrast is exhibited when an illusory border is created by offsetting lines by half their standard separation; (c) illusory contours can also induce orientation contrast in a line, but are not as effective as lines; (d) a stack of five short horizontal lines, 2 min arc long, exhibits orientation contrast; (e) an elliptical contour, long axis 12 min arc and short axis 6 min arc is as good a target as a single line for purposes of orientation contrast; (f) a point of light, moving through 12 min in 70 msec, exhibits a strong orientation contrast.

sets of lines, but this has its origin probably in the optical factors needed in a particular eye to delineate a recognizable contour.

Simultaneous orientation contrast could also be induced in a column of five stacked short (3 min arc) horizontal lines (Fig. 7, condition d) but, as will be seen below, two dots are not enough.

Ellipses, long axis 12 min arc and short axis 6 min arc, were created by placing 30 dots on the screen in appropriate positions, and they could be presented with their long axis oriented either vertical or at designated orientations. These stimuli have only a small proportion of their contours parallel to the principal direction of the whole feature, yet there is a much stronger orientation contrast than for a single test line (Fig. 7, condition e).

Finally, a moving dot, traveling in a straight line through 12 min arc in 70 msec has its apparent orientation, i.e. apparent direction of motion, changed by flanking tilted lines in the same manner as a solid line but with a greater magnitude (Fig. 7, condition f). Illusions in the apparent direction of motion have been reported before (Marshak & Sekular, 1979) but in the present context the finding highlights the kind of feature (illusory contour, ellipse, stack of short lines or dots, moving spot) in which orientations contrast can be induced.

To distinguish further the range of features that can participate in simultaneous orientation contrast, a sequence of test patterns was created extending from a solid line, through five and three dots, to just two dots marking the end of the lines. In all cases, the outside dimension of the pattern was 12 min arc and the refresh rate was adjusted so that in each condition the retinal light flux from the whole configuration was the same. The induced tilt was always measured the same way, i.e. by the angle from the vertical of the line joining the two termination points. The results, Fig. 8, show a gradual decrease from the full-blown contrast when the line is solid to an essential absence when a 12 min line is represented by only its end points. Three points 6 min apart and five points 2.4 min apart give intermediate values. It is interesting that even the latter condition, when the points are only a couple of point-spread functions apart, does not fully address the line-orientation processing potential, at least as far as it is revealed in the orientation domain giving orientation contrast. In observer J.G., who has superior resolution and detection thresholds, a full set of results was obtained with lines only 6 min long with very similar results (not shown). Here again, five points (now only 1.2 min apart) did not accept the same contrast that is shown for a solid line.

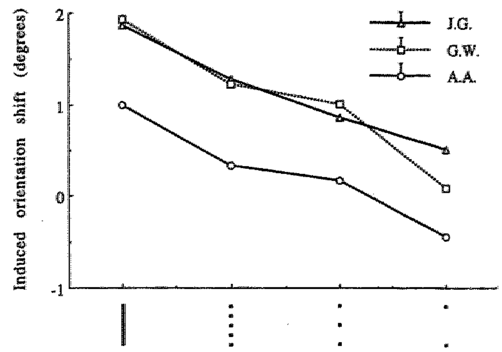


Fig. 8. Orientation shift induced by a hexagonal array of tilted lines, as a function of dot density making up the test target, from two dots marking out the ends of a line (right) to a full line, 12 min arc long. Exposure duration 500 msec.

There is disagreement in the literature (O'Toole, 1979; Wolfe, 1984; Wenderoth & Johnstone, 1988b) about the effect of exposure duration on this kind of task. The simultaneous orientation contrast was therefore measured as a function of exposure duration using the hexagonal inducing pattern. Test and inducing lines were presented simultaneously for different fixed durations. When the duration is short, intensity factors enter due to the operation of the Bunsen–Roscoe–Bloch reciprocity law. Therefore, constancy of total flux was assured by suitable changes in the refresh rate in the three shortest exposures used here. Figure 9 illustrates, in agreement with Wolfe and with Wenderoth and Johnstone, that in general the magnitude of the contrast effect diminishes with increase in duration. The observers executed

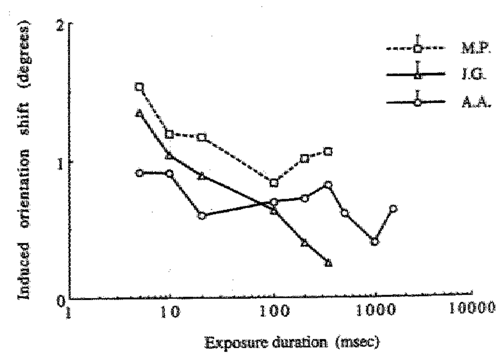


Fig. 9. Orientation shift induced in a 12 min arc foveal test line by a hexagonal pattern of inducing lines at the optimum orientation for the observer, as a function of exposure duration of the whole pattern. Durations shorter than 100 msec had compensating increases in line intensity to provide for constancy of total flux.

normal eye movements, so that there is reason to believe that during exposures longer than, say, 300 msec, there would be at least one saccade. This resetting should produce the effect of the beginning of a new presentation. Yet in one observer there is a further decrement with increasing duration up to the longest one used here, 1 sec.

To examine the fine time course of the orientation contrast phenomena, the orientation shift of a briefly flashed test stimulus was measured when a brief flash containing the inducing surround lines was delivered with various asynchronies, ranging from +300 msec, i.e. the surround lines preceding the test line, through strict synchrony to −300 msec, i.e. the surround lines trailing the test line. The results for four observers are shown in Fig. 10. Most observers have the most pronounced orientation shift with a −50 msec asynchrony, i.e. the test line leading the inducing surround lines by 50 msec.

Interobserver differences, a prominent feature of this kind of research, show up well in Fig. 10. The four observers differ by a factor of about eight in the maximum effect; of the dozen or so participants in these experiments, G.W.'s large values were matched by one other observer and B.C. had by far the smallest values. In fact, it required the sharpest optimum stimulation conditions—a brief flash, 50 msec asynchrony, full hexagonal array of surround lines at the best angle and distance, to yield a measurable orientation shift in this observer.

DISCUSSION

Simultaneous contrast is a phenomenon widely manifest in a variety of visual qualities such as brightness, color and position. Its demonstration for line orientation opens up the question whether line orientation is an attribute *sui generis* or whether it surfaces here merely as a secondary phenomenon.

The contrast effect is in the direction of repulsion: the apparent orientation of a line is changed to increase its difference (in the orientation domain) from the inducing line. Repulsion effects have been described for positions of features in the visual field (Badcock & Westheimer, 1985); for example a pair of vertically aligned vernier lines is shifted out of alignment by the introduction of another line flanking one of the original ones. Position repulsion begins at separations about 3 min arc, is maximal at about 6 min arc and then monotonically decreases with increasing distance. This effect cannot, however, be the origin of the repulsion in the orientation domain, which is the subject of this study, because it is in the wrong direction. This can be seen by looking at Fig. 11. A vertical line T appears tilted in a counterclockwise direction when flanked by the two tilted surround lines S_R and S_L. It is as if the top of line S_R pushed the top of line T towards the top of line S_L. But the top of S_R is farther from the top of T than the top of S_R and hence its position repulsion is less. Thus if position repulsion caused the orientation contrast, the latter would be in the direction of attraction, i.e. the surround lines would assimilate the orientation of the test line. An excellent illustration of the difference between position repulsion, or as it may be called, simultaneous position contrast, and simultaneous orientation contrast, is given in Fig. 12. The orientation shift of a line and of a pair of dots marking just the end of a line are shown as a function of separation from a set of surrounding tilted lines.

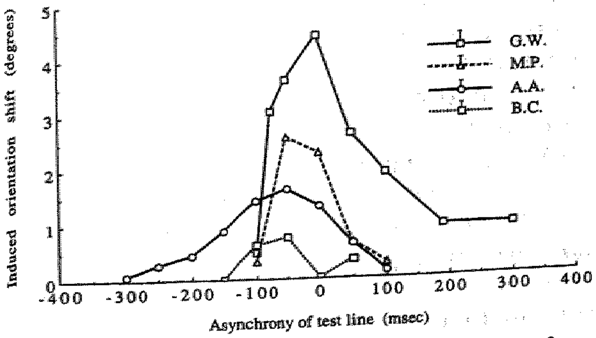


Fig. 10. Orientation shift induced in a 12 min arc foveal line stimulus by a hexagonal pattern of inducing lines, as a function of asynchrony of test and inducing lines, each of which always had a duration of 20 msec. Negative asynchrony denotes condition in which the test line preceded the inducing lines.

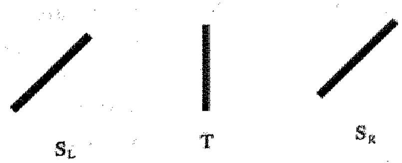


Fig. 11. Illustration to show that orientation contrast is not attributable to the position repulsion effect described by Badcock and Westheimer (1985). The top end of the inducing line S_L is closer to the top of the test line than the top of the other inducing line. If position repulsion were the only effect, the top of the test line would appear to have moved away from S_L and towards S_L. The observed orientation contrast is in the opposite direction and this is interpreted as an indication that line orientation is a separate domain exhibiting simultaneous contrast.

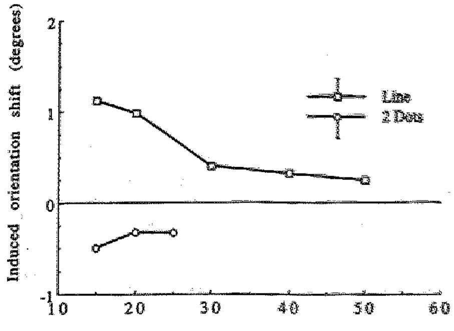


Fig. 12. Shift in orientation of a 12 min arc line, and shift in relative position of two dots separated by 12 min arc, as a function of separation of the inducing pattern, both plotted in comparable units. Exposure duration 20 msec, observer A.A., hexagonal inducing pattern. The dots show a position repulsion effect approximately inversely proportional to the pattern separation, as would be expected from the Badcock and Westheimer (1985) data. For line features, on the other hand, the repulsion is in the domain of orientation and hence in a direction opposite to that for the dots.

The effect is in the opposite direction for these two classes of test features, emphasizing the point that these psychophysical experiments confirm the notion that line orientation is a separate perceptual domain.

When two features are very close together, either in lateral position or in disparity, they tend to share their local position (Badcock & Westheimer, 1985) or depth (Westheimer, 1986) signals, i.e. there is an attractive interaction. As the separation increases, the interaction changes to repulsion. In the human fovea this critical distance is about 3 min arc. The domain under discussion in this study is line orientation and the equivalent question is: do features just a few degrees apart in their orientation begin to share their orientation signals rather than having the difference enhanced? This was tested in one observer (G.W.), who showed a repulsion, albeit small, with a 2 deg orientation difference. The reversal of sign of the orientation contrast values for orientation differences nearing 90 deg, of which there is some indication in Fig. 1, does not really bear much resemblance to the attractive interaction seen in the position and disparity domains.

This author does not wish to dwell on conjectures concerning the neural mechanisms underlying the phenomena described in this study. The analogy with center/surround apparatus and lateral inhibition (Blakemore et al., 1970) is obvious. One can only speculate as to the site of the interaction. Orientation is a prominent characteristic of the receptive field of units in the primate striate cortex, and there is now good evidence for neural connections between adjoining regions of cortex (Gilbert & Wiesel, 1983). The results of the present study suggest inhibitory signals within the domain of orientation and the data of Figs 7 and 8 in particular highlight the range of visual stimulus patterns that can address the concerned mechanisms; the range is wider than usually described within the context of adequate stimuli for units in the striate cortex, but it presumably still awaits confirmation whether in the striate cortex there are units the intensity of whose response to visual stimuli is approximately the same as the capability of these stimuli to participate in psychophysically-based orientation contrast.

The time factors, Fig. 10, point to early neural processing, where synaptic interaction would be expected to occur within the time span of at most 200 msec and according to our data perhaps even less than 50 msec. Thus the term simultaneous orientation contrast is apt.

While the experiments in this paper give coherent characterization of the simultaneous orientation contrast, a connection needs to be established with the so-called tilt aftereffect whose properties in many ways are similar. The data in this paper with the maximum asynchronies of Fig. 10, show only a minimal after effect, yet many researchers have reported long after effects (e.g. Wolfe & O'Connell, 1986). The prominent difference between their experiments and ours is the stimulus pattern. We have avoided as far as possible the overlapping of the test and inducing stimuli, whereas in other experiments this is almost always allowed.

In this connection, one additional finding is of interest. The data in Fig. 2 show a decrement of orientation contrast with increase in separation of test and inducing stimuli, but it is not clear from this figure whether the interaction also extends to overlapping features. Indirect evidence points to that (Magnussen & Kurtenbach, 1980). The experimental procedure adopted here, viz. the use of discrete, individually localizable features, stressed non-overlapping rather than overlapping contours because there is always some position-sharing in the latter, and we know that this can lead to attractive as well as repulsive interaction in the position domain, whereas the attempt here has been to examine the orientation domain on its own ground as far as possible. The experiment depicted in Fig. 13, leaves no doubt that orientation contrast is

Induced Orientation Shift (degrees)

	A.A.	G.W.
	1.77 ±.21	3.57 ±.24
	1.02 ±.09	3.03 ±.11

Fig. 13. Induced orientation shift for a foveal line 24 min arc long in the presence of a pair of inducing lines which were either superimposed on the test line or laterally separated from it. Parameters: separation G.W. 25 min arc, A.A. 20 min arc; exposure duration: G.W. 200 msec, A.A. 30 msec; inducing angle: G.W. 15 deg, A.A. 30 deg. The data imply that the curves of Fig. 2 would rise further somewhat if extended to reach zero separation.

exhibited also by overlapping features differing in orientation so that the mechanism responsible for it must be present within a single location in the visual field. Neural circuits for this kind of interaction must therefore exist within a single set of orientation representation, and the data of Fig. 2 then would point to the decline of the concerned neural connectivity with distance in the visual field.

Acknowledgements—The author gratefully acknowledges the collaboration of Armand E. Abulencia in many stages of this work, which was supported by the National Eye Institute, U.S. Public Health Service under grant R37EY00220. Jay Gibson helped with the programming and observations.

REFERENCES

Badcock, D. & Westheimer, G. (1985). Spatial location and hyperacuity: The center/surround localization function has two substrates. *Vision Research*, *25*, 1259–1267.

Blakemore, C., Carpenter, R. H. S. & Georgeson, M. A. (1970). Lateral inhibition between orientation detectors in the human visual system. *Nature, London*, *228*, 37–39.

Frisen, L. & Lindblom, B. (1988). Binocular summation in humans: Evidence for a hierarchic model. *Journal of Physiology, London*, *402*, 773–782.

Gibson, J. J. & Radner, M. (1937). Adaptation, after-effect and contrast in the perception of tilted lines. *Journal of Experimental Psychology*, *20*, 453–467.

Gilbert, C. D. & Wiesel, T. N. (1983). Clustered intrinsic connections in cat visual cortex. *Journal of Neuroscience*, *3*, 1116–1133.

Howard, I. P. (1986). The perception of posture, self motion and the visual vertical. In Boff, R. K., Kaufman, L. & Thomas, J. P. (Eds.), *Handbook of perception and human performance* (Chap. 18). New York: Wiley.

Hubel, D. H. & Wiesel, T. N. (1959). Receptive fields of single neurones in the cat's striate cortex. *Journal of Physiology, London*, *148*, 574–591.

Hubel, D. H. & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *Journal of Physiology, London*, *195*, 215–243.

Jastrow, J. (1893). On the judgement of angles and position of lines. *American Journal of Psychology*, *5*, 214–223.

Magnussen, S. & Kurtenbach, W. (1980). Linear summation of tilt illusion and tilt aftereffect. *Vision Research*, *20*, 39–42.

Marshak, W. & Sekuler, R. (1979). Mutual repulsion between moving targets. *Science*, *206*, 1399–1401.

Mitchell, D. E. & Ware, C. (1974). Interocular transfer of a visual after-effect in normal and stereoblind humans. *Journal of Physiology, London*, *236*, 707–721.

Nakayama, K., Shimojo, S. & Silverman, G. H. (1990). Stereoscopic depth: Its relation to image segmentation, grouping, and the recognition of occluded objects. *Perception*, in press.

O'Toole, B. I. (1979). Exposure duration and spatial-frequency effects in the tilt illusion. *Perception*, *8*, 557–564.

Virsu, V. & Taskinen, F. (1975). Central inhibitory interactions in human vision. *Experimental Brain Research*, *23*, 65–74.

Wenderoth, P. & Johnstone, S. (1988a). The different mechanisms of the direct and indirect tilt illusion. *Vision Research*, *28*, 301–312.

Wenderoth, P. & Johnstone, S. (1988b). The differential effects of brief exposures and surrounding contours on direct and indirect tilt illusions. *Perception*, *17*, 165–176.

Westheimer, G. (1986). Spatial interaction in the domain of disparity signals in human stereoscopic vision. *Journal of Physiology, London*, *370*, 619–629.

Westheimer, G., Shimamura, K. & McKee, S. P. (1976). Interference with line-orientation sensitivity. *Journal of the Optical Society of America*, *66*, 332–338.

Wolfe, J. (1984). Short test flashes produce large tilt after-effects. *Vision Research*, *24*, 1959–1964.

Wolfe, J. M. & O'Connell, K. M. (1986). Fatigue and structural change: Two consequences of visual pattern adaptation. *Investigative Ophthalmology and Visual Science*, *27*, 538–543.