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An orientation anisotropy in induced brightness

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Abstract. It is shown that an orientation anisotropy exists for the magnitude of induced brightness in a cruciform stimulus consisting of a grey test patch positioned at the intersection of two inducing bars, one black and one white, oriented at right angles to each other. When the cruciform was oriented such that the white bar was horizontal, the grey patch appeared darker than when the same cruciform was oriented such that the white bar was vertical. The contribution of the black and white inducing bars towards the brightness of the test patch was investigated. A simple mathematical function, which took into account both the contribution of the two component inducing bars and the orientation anisotropy, was fitted to the data. No consistent orientation anisotropy was found with inducing stimuli at oblique orientations.

1 Introduction

It has been well known for more than a century that the brightness of a surface depends not only upon its luminance but also upon the luminances of its surrounding elements. The best-known example of this is that a grey patch surrounded by black appears lighter than the same grey patch surrounded by white, a phenomenon known as simultaneous contrast. In such cases brightness is often said to be 'induced' in the test patch by the surround. Here we describe a case in which the magnitude of brightness induction is dependent on the orientation of the inducing stimulus. The orientation anisotropy was an unexpected finding which emerged during an investigation into the way the brightness of a grey patch is affected by the simultaneous presence of two inducing surrounds of equal spatial extent but markedly different luminance. The question was, is the brightness of the test patch in the presence of the two inducing surrounds some simple function of the combined effects of the two surrounds when measured alone? The basic stimulus we used to address the issue was a cruciform pattern, varieties of which are illustrated in figure 1. In addition to describing the orientation anisotropy we also present our findings on the way different luminance surrounds combine to determine the brightness of the test patch in the cruciform stimulus.

2 Method

2.1 *Subjects*

The two authors acted as subjects in all the experiments described. Both were experienced psychophysical observers. FK and BM have normal and corrected vision respectively. In the population study there were eight subjects, five males and three females. All had normal or corrected vision. They were naive as to the purpose of the experiment.

2.2 *Stimulus generation*

All stimuli were generated by an 8-bit PLUTO II graphics display system interfaced to a CORVUS CONCEPT host computer. The programs were written in PASCAL with ASM68K assembly language subroutines to interface the host and graphics computers.

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All luminance calibrations were performed with a purpose built photodiode and amplifier system with a photometric filter. The aperture of the photodiode was positioned in front of the glass surface of the monitor and the photodiode was focussed onto a small patch of pixels, whose grey level or RGB value had been preset. The stimuli were displayed on a BARCO INDUSTRIES type 2 TVMR monochrome TV monitor. The pixels on the screen were 0.68 mm in height and 0.33 mm in width, subtending 2.03 min and 0.98 min respectively at the viewing distance of 114 cm used throughout the experiments described. The luminances of the 256 grey levels were calibrated as described above.

2.3 *Stimuli*

The basic cruciform stimulus used in all the experiments is illustrated in figure 1A. It was a matrix of five square patches, consisting of a central grey test patch whose brightness was the dependent variable bordered by four 'arms' whose effect on the brightness of the test patch was under investigation. Each patch was a square, 24.5 min on a side. The test stimuli used in the first three experiments described are illustrated in figures 1 and 5. The different orientation configurations of the various cruciform patterns are referred to as white horizontal (WH) and white vertical (WV). In experiment 2, a subset of the cruciforms had one or both sets of arms 98 min in length, as shown in figures 1B, 1C, and 1D. Finally, in experiment 3, 'monoaxial' (M) stimuli were used along with cruciforms; these are illustrated in figures 5B, 5C, 5E, and 5F. They can be considered as component parts of the cruciform; eg a WH cruciform is made up from a WH monoaxial and a BV (black vertical) monoaxial. Figures 5D, 5E, and 5F illustrate the cruciform and monoaxial stimuli which were oriented at $+45°$ or $-45°$ to produce right oblique (RO) and left oblique (LO) stimuli respectively. Oblique stimuli were produced by generating the stimuli as in experiments 1 and 2, and then tilting the TV monitor $+45°$ or $-45°$ as appropriate. There was thus no confounding of stimulus orientation and raster direction.

The match stimulus in all experiments consisted of a square patch of side 24.5 min, which was always oriented in the same manner as the grey test patch.

The test and match patterns in all experiments were displayed on a homogeneous background of luminance 20.0 cd m^{-2}. The luminances of the grey test patches in the

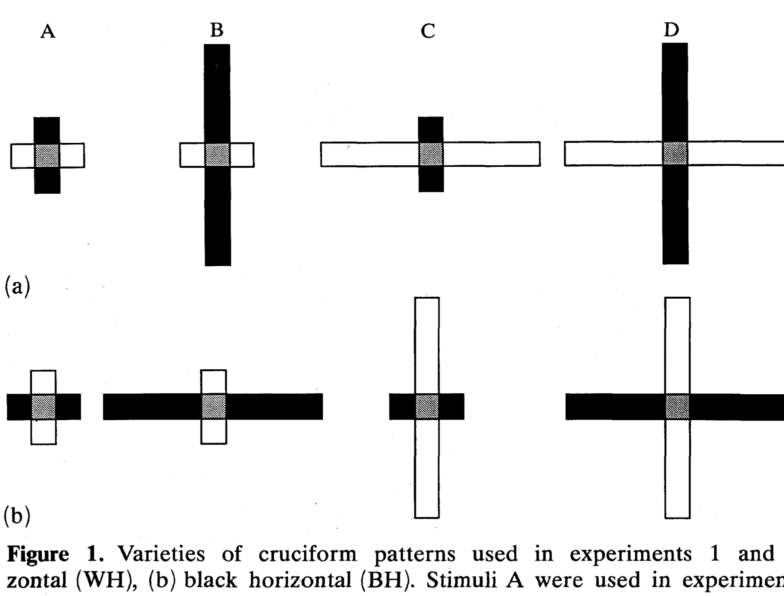

Figure 1. Varieties of cruciform patterns used in experiments 1 and 2. (a) White horizontal (WH), (b) black horizontal (BH). Stimuli A were used in experiment 1, stimuli A–D in experiment 2.

cruciform stimuli in experiments 1 and 2 were 18.0, 20.0, and 22.0 cd m^{-2}, whereas in experiment 3 they were 12.0 and 16.0 cd m^{-2}. The luminance of the arms of the test stimuli was either 40.0 cd m^{-2} ('white') or approximately 0.01 cd m^{-2} ('black'). The luminance of the match patch was adjustable.

2.4 *Procedure*

In all the experiments described, viewing was binocular with natural pupils. Because the test patch was small no fixation point was necessary. The method of adjustment was used to find the luminance of the matching stimulus which matched the grey test patch for brightness. In order to prevent the buildup of afterimages and long-term adaptation the test and match stimuli were alternated in temporal sequence with an intervening interval in which a homogeneous background of luminance 20.0 cd m^{-2} was presented. The temporal sequence between and within each trial is illustrated in figures 2a and 2b respectively. Each trial consisted of a different condition (test patch luminance, orientation and type of test pattern) which was randomly drawn from the set for each experiment. The reason for having more than one luminance of test patch was to reduce the likelihood of bias in the settings by making it more difficult for the subject to generate a single internal match value for each condition. The luminance of the match patch at the start of each measurement was also randomised. During a trial the subject pressed one of two buttons to increase or decrease the luminance of the match patch. When the subject was satisfied that the brightnesses of the test and match patches were equal, he or she pressed a third button which ended the trial, at which point the match luminance was recorded.

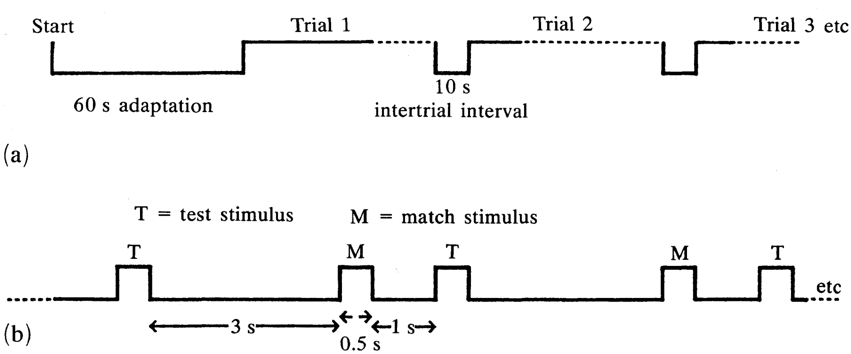

Figure 2. Temporal parameters (a) across trials, (b) within a trial.

2.5 *Analysis of results*

For each condition in each experiment five measurements were made per subject. These were converted to percentage differences in luminance between the test and match patches ($L_t - L_m$). The percentages were subjected to separate analyses of variance for each subject, with the error term provided by the between-trial variation.

We now describe the results and analysis of each of the three experiments separately.

3 Results

3.1 *Experiment 1*

In the first experiment we measured the brightness of the cruciform stimulus in two orientations, WH (white horizontal) and WV (white vertical). As a check that any orientation difference was not due to monitor effects the experiment was repeated with the monitor rotated 90°. Since there were no significant differences in the percentage difference between test and match patches at the PSE (point of subjective equality) as a function of test luminance, the percentage values were averaged across test luminances and the results are displayed in figure 3. The values on the ordinate show the degree of darkening of the test patch. It can be seen that for both subjects and in both monitor orientations the WH cruciform darkened the grey patch more than did the WV cruciform. This orientation difference was found to be significant for both subjects (BM: $F_{1,24} = 44$, $p < 0.01$; FK: $F_{1,24} = 4.5$, $p < 0.05$).

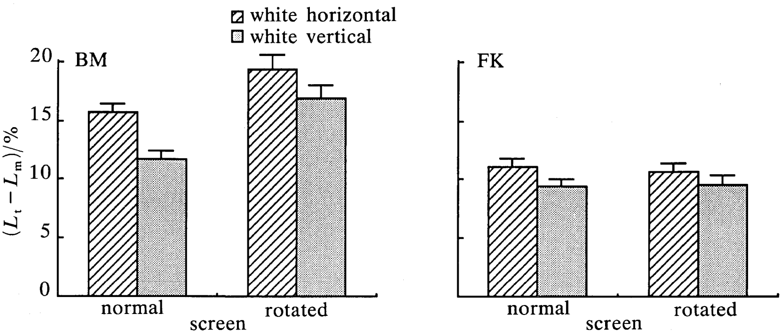

Figure 3. Results of experiment 1 for cruciform type A in figure 1 for two subjects. The ordinate represents the average percentage difference between the luminance of the test patch in the cruciform (L_t) and that of a match patch on a homogeneous background (L_m), when the two patches were set to be equal in brightness. The positive values on the ordinate imply that the grey test patch was darkened by the presence of the inducing arms of the cruciform.

In order to check that this result was not due to any context-dependent screen effects, we performed three tests. First, as mentioned above, we repeated the experiment with the screen rotated on to its side, and the results are shown in figure 3. If the effect was a screen artifact then it should reverse in the screen-rotated condition. Inspection of figure 3 shows that the effect still occurs. Second, we made a number of measurements in which we masked off the inducing bars of monoaxial stimuli (see figure 5) with black card fixed to the monitor surface. The brightness of two test patch luminances, with and without inducing bars, was measured. The (invisible) inducing bars were either black or white and each was presented in both horizontal and vertical orientation. Owing to the occlusion of the inducing bars, the subject (FK) who performed the experiment was unable to tell which condition was being presented on a given trial. In none of the conditions was there any significant difference between the luminances of the match and test stimuli when matched for brightness. Finally, we took a number of physical measurements of luminance with a photodiode whose aperture was positioned on the screen surface over the central portion of the grey test patch. Again there was no difference in luminance with type of surround. We conclude that the orientation anisotropy was a perceptual rather than a physical effect.

It is possible that these effects might be caused by a predominance of horizontal, as opposed to vertical, saccadic eye movements. Since local border mechanisms are an important factor in determining brightness (Shapley 1986; Kingdom and Moulden 1989), a predominance of horizontal scanning might stimulate neurons sensitive to the vertical rather than the horizontal borders of the stimulus. Given the greater brightness inducing effect of the white as opposed to the black surround components, this could be the cause of the greater overall darkening effect of the cruciform with the white horizontal bar. Although both subjects did attempt to maintain central fixation during presentation of the cruciform stimuli, it cannot be assumed that no eye movements occurred. However, if the cruciform stimuli were exposed for just 200 ms, the likelihood of such eye movements would be substantially reduced, given that it takes something approaching this length of time to initiate a saccade. We therefore repeated our observations with such an exposure duration. The results again showed that the test patch in the WH cruciform appeared darker than in the WV cruciform for both subjects. The average difference in percentage darkening between the two conditions was 7.2% for subject FK and 12.0% for BM [notably greater than the 2.5% (FK) and 5.0% (BM) found in the initial study]. Both results were significant (FK: $F_{1,38} = 10.9$, $p < 0.01$; BM: $F_{1,38} = 56.5$, $p < 0.01$).

Having established the existence of the anisotropy for two subjects, we wished to confirm that the effect was general rather than specific to the authors. We therefore repeated the initial experiment on eight naive subjects, and the results are shown in table 1. All eight subjects showed the same direction of anisotropy, and the effects were significant when tested by the Wilcoxon matched pairs signed rank test ($T = 0$, $p < 0.01$). The average difference in percentage darkening between the cruciforms with white horizontal and white vertical bars was 6.2%. Once again the effect was small, but consistent and significant.

These investigations show, therefore, that, at least with cruciform stimuli, there exists an orientation anisotropy in induced brightness. It is as if the horizontal arms of the cruciform have a greater brightness inducing effect than do the vertical arms. Whether this is due to (a) the greater darkening effect of a horizontal white bar compared with a vertical white bar or (b) the greater lightening effect of a horizontal black bar compared with a vertical black bar or (c) the combination of both effects remains to be resolved. The third experiment which we report here is an attempt to do this.

The next experiment was designed to investigate the effect of bar length on the size of the orientation anisotropy.

Table 1. Percent darkening of the test patch in cruciform type A of figure 1, in eight naive subjects (experiment 1). (WH = white horizontal cruciform, WV = white vertical cruciform.)

Stimulus	Subject							
	DS	CY	RS	JC	SC	MS	JP	DJ
WH	8.9	18.5	13.8	11.6	4.2	5.0	16.9	2.4
WV	3.6	11.0	4.6	3.4	−3.5	3.4	10.3	−0.7
WH-WV	5.3	7.5	9.2	8.2	7.7	1.6	6.6	3.1

3.2 *Experiment 2*

The stimulus set we used in this experiment is illustrated in figure 1, and the results are shown in figure 4. As can be seen from figure 4 the orientation anisotropy appeared in

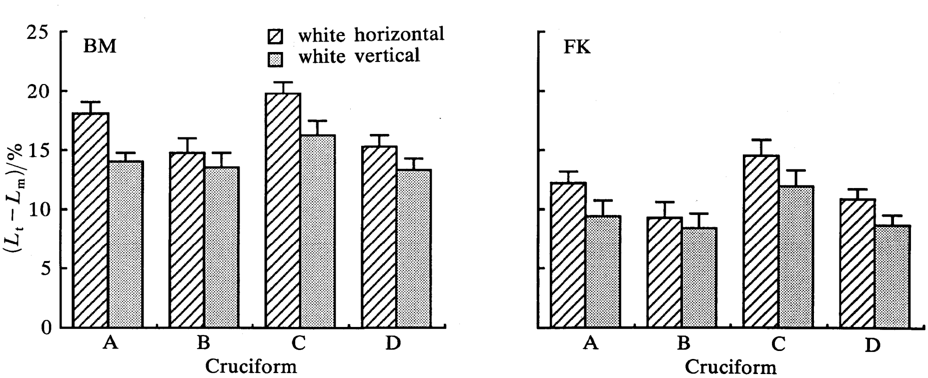

Figure 4. Results for experiment 2 for cruciform types A–D in figure 1 for two subjects. The ordinate represents the average percentage difference between the luminance of the test patch in the cruciform (L_t) and that of a match patch on a homogeneous background (L_m), when the two patches were set to be equal in brightness. The positive values on the ordinate imply that the grey test patch was darkened by the presence of the inducing arms of the cruciform.

all conditions for both subjects and was highly significant (BM: $F_{1,96} = 1.93$, $p < 0.0001$; FK: $F_{1,96} = 9.55$, $p < 0.0001$). Although there is a suggestion in the data that the size of the orientation anisotropy was reduced by the presence of the elongated compared with the short arms, the effect was not significant for either subject. The overall extent of darkening of the grey test patch was, however, significantly affected by the type of stimulus in both subjects (BM: $F_{3,96} = 12.1$, $p < 0.0001$; FK: $F_{3,96} = 14.9$, $p < 0.0001$). The stimulus which produced the greatest darkening effect was stimulus C, the cruciform with elongated white arms and short black arms.

The results of this experiment confirm the presence of an orientation anisotropy in induced brightness in a variety of cruciform patterns. Although the length of the inducing arms appears to affect the magnitude of induced brightness, it does not appear to affect the magnitude of the orientation anisotropy.

The third experiment was designed to investigate the relative contribution of the two polarities of luminance (black versus white arms) in the cruciform to the orientation anisotropy, as well as to test whether a similar effect occurs with obliquely oriented cruciform stimuli.

3.3 *Experiment 3*

The stimulus set for this experiment is illustrated in figure 5. The basic cruciform stimulus from both previous experiments was used again (figure 5A) and presented in addition at oblique orientations (figure 5D). The arms of the cruciform were presented separately as monoaxial patterns in both horizontal, vertical, right-oblique, and left-oblique orientations. An important difference between the conditions of this experiment and the previous ones was that a different set of test patch luminances was used, namely 12.0 and 16.0 cd m^{-2} (as opposed to 18.0, 20.0, and 22.0 cd m^{-2}). We felt it necessary to make the test patches markedly different in luminance from the background since with the monoaxial stimuli part of the test patch bordered the background directly. Moreover, we wanted to know whether there was some simple function which could account for the pattern of induced brightness when one of the independent variables was test patch luminance.

The results are shown in figure 6. As in the previous two experiments, the results for the different test luminance conditions have been averaged for the purposes of graphical display. Note first the reversal of sign on the ordinate compared with previous figures: in figure 6 the negative values, which indicate the test patch was darkened by the inducing pattern, are given below the abscissa. Positive values above the abscissa indicate that the test patch was lightened. As can be seen from the figures the white monoaxial stimuli invariably darkened the test patch whereas the black monoaxial stimuli invariably lightened it. The cruciform stimuli darkened the test patch for all orientations for subject FK, as was found in the previous experiments, but for subject BM this only occurred significantly for the WH (white horizontal) cruciform.

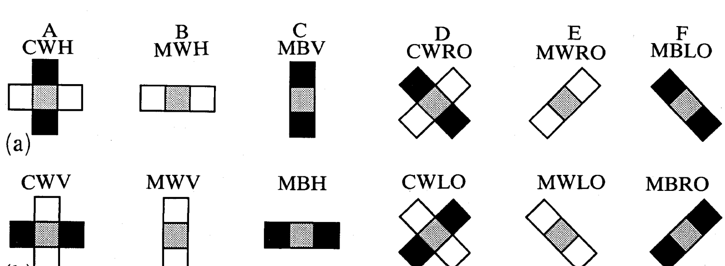

Figure 5. Stimuli used in experiment 3. Key to the labels: C = cruciform; M = monoaxial; W = white; B = black; H = horizontal; V = vertical, RO = right oblique; LO = left oblique. Thus MWLO = monoaxial, white, left oblique. The letters A to F label each orientation pair.

The horizontal/vertical orientation anisotropy appears once again in the cruciform stimuli, but also in both the white and the black monoaxial stimuli. In both subjects the monoaxial stimulus with white horizontal arms darkened the test patch to a greater degree than did its vertical counterpart, whereas the monoaxial stimulus with black horizontal arms lightened the test patch to a greater degree than did its vertical counterpart. It should be noted, however, that for subject FK the size of the orientation difference with white monoaxial stimuli was almost negligible.

For the obliquely oriented stimuli we expected that there would be no orientation differences in any of the conditions. The data do not unambiguously confirm this expectation. Examination of figure 6b reveals there are some orientation differences but it is also apparent that there is no systematic pattern of differences either within or between subjects.

The next stage in the analysis of the data was to attempt to derive a simple description for the inducing effects observed. Of principal interest here was not so much the orientation effects we had observed but the pattern of brightness induction as a function of the surround luminance characteristics.

It should be clear from the figures that the combined effects of two different inducing luminances cannot be predicted from the sum of their individual effects measured alone. Notice that although the lightening effect of the black monoaxials is greater than the darkening effect of the white monoaxials, the combined effect of both in the cruciform produces in most instances a darkening effect. Closer analysis of the data shows that in this experiment the cruciform darkened the test patch in thirteen out of sixteen instances. Clearly a nonlinear expression is required. We began by supposing

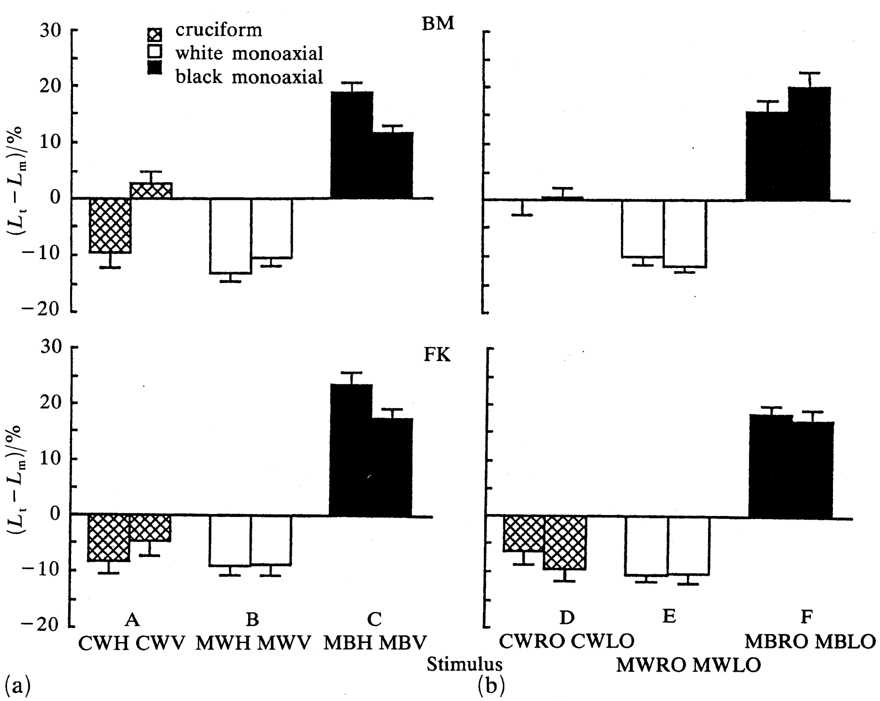

Figure 6. Results of experiment 3 for stimuli A–F in figure 5 for two subjects. (a) Horizontal/vertical orientations, (b) oblique orientations. The ordinate represents the average percentage difference between the luminance of the test patch (L_t) and that of a match patch (L_m), when the two patches were set to be equal in brightness. Note that for this figure the ordinate must be reversed in sign compared with previous figures. A negative value here implies that the grey test patch was darkened by the inducing surround, whereas a positive value implies that it was lightened.

that in general the brightness of a test patch, B_t, as a function of its luminance, L_t, and the luminance of its surround, L_s, can be given by

$$B_t = \frac{L_t}{1+KL_s}, \tag{1}$$

where K is a weighting constant which depends on the orientation of the inducing surround. This expression is limited by virtue of the fact that it does not take into consideration either the area of the test patch or the area of the inducing stimulus, factors which are known to be important (Yund and Armington 1975; Shapley and Reid 1985). The constant 1 in the denominator of the expression places an upper limit on B as L_s reduces to zero. We further suppose that the brightness of a test patch surrounded by two luminances which bound an equal length of the border of the test patch is given by

$$B_t = \frac{L_t}{1+K_v L_{s.v} + K_h L_{s.h}}, \tag{2}$$

where the subscripts v and h refer to the orientation of the inducing luminance, in this example vertical and horizontal respectively. The brightness of the match patch, B_m, is given by a similar expression, with L_m its luminance and L_b its background luminance (in our experiment 20.0 cd m^{-2}). At the PSE, B_t and B_m must be equal so their equations may be combined and solved for L_m thus:

$$L_m = \frac{L_t(1+K_v L_b + K_h L_b)}{1+K_v L_{s.v} + K_h L_{s.h}}. \tag{3}$$

We have derived values for K_v and K_h for the horizontal/vertical stimuli and for K_{ro} and K_{lo} for the oblique stimuli which best fit the data using an iterative search method. The criterion for the best fit was the minimum mean squared deviation of the predicted values of L_m from the empirically determined values. The values are given in table 2, along with values of R^2, the coefficient of determination of the linear fit of empirical to predicted L_m values. As can be seen from the table, K_h is greater than K_v in both subjects, though the difference is very small for FK. This difference represents the

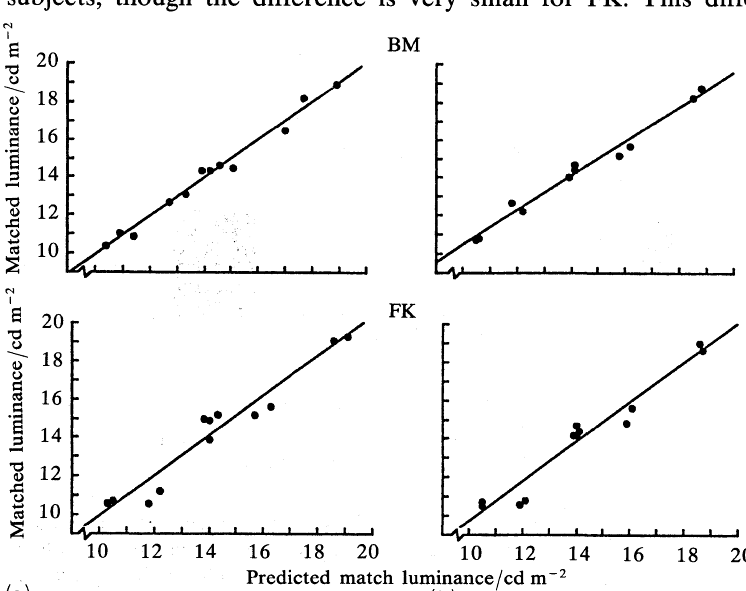

Figure 7. Comparison of measured match luminances from experiment 3 with values predicted from equation (3) for two subjects. (a) Horizontal/vertical, (b) oblique orientations. The parameters which result in the fit shown are given in table 1.

greater weighting required for horizontal inducers in order to fit the data. The values of K_{ro} and K_{lo} are virtually identical, implying no net orientation difference for oblique orientations. In figure 7 the predicted versus actual L_m values are plotted for both horizontal/vertical and oblique orientations for both subjects. Each graph has twelve points representing three stimulus classes (cruciform, white monoaxial, and black monoaxial), two orientations, and two values of L_t (12.0 and 16.0 cd m^{-2}).

Table 2. Weighting constants K for horizontal (h), vertical (v), and oblique (right, ro, and left, lo) stimuli. R^2 is the coefficient of determination of the linear fit of empirical to predicted L_m (luminance of the match patch) values.

Subject	Horizontal/vertical			Oblique		
	K_h	K_v	$R^2/\%$	K_{ro}	K_{lo}	$R^2/\%$
BM	0.010	0.006	98.5	0.009	0.010	98.1
FK	0.012	0.010	93.6	0.010	0.010	94.5

4 Discussion

We have shown that there is a small but consistent orientation anisotropy in induced brightness in stimuli consisting of a central grey patch bordered by elongated arms. It appears that horizontally oriented inducing bars have a greater effect on the magnitude of induced brightness compared with vertical bars. On the other hand, stimuli with inducing bars in oblique orientations do not produce a systematic orientation anisotropy.

We found that a horizontally oriented white bar darkened a test patch more than did a vertically oriented bar, and that a horizontally oriented black bar lightened a test patch more than did a vertically oriented test bar. The cruciform stimulus appears to combine both orientation effects: the combination of white horizontal (strong darkening) with dark vertical (weak lightening) in the WH cruciform results in its test patch appearing darker than in the cruciform consisting of a black horizontal (strong lightening) and white vertical (weak darkening). This description of the results is, however, merely a useful mnemonic and does not constitute an explanation for either the orientation effect or the overall pattern of brightness induction we observed. Since we have shown that equation (3) gives a reasonably good description of the data, let us reexamine the phenomenon with this expression in mind.

Conventionally, a dark surround is said to lighten a grey patch and a light surround darken it, implying two opposite effects. This implication is of course misleading; the two effects are identical, differing only in degree. A grey patch looks brightest on a black background and looks darker as the surround luminance increases: as surround luminance increases from zero the brightness of a test bar is reduced from its starting value. Consequently, the equation we have used attributes *only* a darkening effect to inducing surround luminance (see Creutzfeldt et al, 1987, for a similar argument). The function is not linear, but accelerates until a point is reached where brightness is inversely proportional to surround luminance. The orientation anisotropy is thus viewed simply as an orientation anisotropy in the rate of growth of brightness induction as a function of surround luminance.

Recently, Creutzfeldt et al (1987) have investigated the effect of multiple-element surrounds on test patch brightness with stimuli similar to our own, and concluded that a simple equation suffices to account for their data:

$$P_T = L_T - CL_S,$$

where P_T is the perceived brightness of the test field, L_T its luminance, L_S the average luminance of the surrounding elements, and C a constant. This equation is linear and assumes a subtractive effect of surround luminance on test patch brightness. Our equation, on the other hand, is nonlinear. The average luminance of the surround has a proportional effect on the brightness of the test patch.

The nature of the function (ie whether it is linear or nonlinear) is important, because it has implications for the inferred site of the mechanisms producing the effect. Creutzfeldt et al (1987, page 280) have put the argument very succinctly:

> "A linear subtraction of luminance ... implies that the mechanism of darkness induction should be located at a level before the brightness signals are compressed to the narrow range of brightness discrimination at a given adaptation level. As this compression takes place between the receptors, which have a dynamic range of only about 3 - 4 log units, and the retinal ganglion cells, which have a dynamic range of only about 1.0 - 1.5 log units ... darkness induction must be a retinal process ... and it should be ... located peripherally from the ganglion cells."

However, our finding of a nonlinear function is not in direct conflict with the conclusion reached by Creutzfeldt et al, because there were a number of important differences in the experimental conditions. For example, their stimuli consisted of nine by nine arrays of grey patches, each of which was a 4.75 deg square; the overall size of the array was thus 42.75 deg by 42.75 deg. The maximum luminance of their stimuli was 215 cd m^{-2}. Our display elements were 24.5 min squares, the maximum overall size of the display was 1.6 deg × 1.6 deg (the cruciforms with elongated arms in experiment 2), and the maximum luminance was 40 cd m^{-2}. The effects we measured were therefore much more local, both in terms of space and in terms of luminance, than theirs, and thus the visual function is described at different scales in the two experiments. It seems likely that no simple formulation will be capable of describing the visual function at all scales.

Returning to the main subject of this paper, namely the orientational anisotropies in brightness induction, we note that there are very many other examples of spatial anisotropy (see Appelle, 1972, for a review). Perhaps the best known of these is the greater acuity for vertical and horizontal than for oblique gratings (eg Campbell et al 1966; Freeman et al 1972). (We wondered, since the effects described here could be interpreted as a greater apparent contrast across vertical than across horizontal edges, whether those findings might be reflected in some slight advantage in the detection of vertical as opposed to horizontal gratings, but there is no sign of this in the available data.)

Many different kinds of explanation have been offered for these effects, and we can only speculate about the origin of our brightness anisotropy. It is possible that retinal ganglion cells may be horizontally elliptical rather than symmetrically circular, that the weighting functions of opponent surrounds may be orientationally anisotropic, or that there is an inbalance in the distribution of orientationally-tuned cortical cells. What is clear is that the existence of these anisotropies should be taken into account in any experiments involving brightness induction and similar phenomena, and of course in any attempt to model the data they generate.

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