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WHITE'S EFFECT: A DUAL MECHANISM

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Abstract—White (1979) has described a phenomenon in which grey bars replacing segments of the white phase of a square-wave grating appear darker than identical grey bars replacing segments of the black phase of the grating. We have investigated the properties of this effect with a view to discovering the underlying mechanisms. Four experiments are reported which reveal the effects of the heights and widths of both the flank and coaxial inducing bars upon the brightness of the grey bars. The results show that two processes, one the local corner effect, and one a spatially extensive process (possibly involving filters with elongated end-zones) operate to produce the effect. The implications of the findings for models of brightness perception are discussed and suggestions are made for further experiments.

Spatial vision Brightness induction Receptive field Neural modelling Computational vision

INTRODUCTION

It has been well known for over a century that the brightness of a surface is determined not merely by its luminance but also by the luminances of its surrounding elements (Helmholtz, 1862; Hering, 1864). Brightness is commonly said to be induced into the stimulus by its surround. The best known example of this is that an illuminated grey surface looks lighter when placed on a black background than when it is placed on a white background, a phenomenon known as "simultaneous contrast". Another, less frequently reported example of brightness induction, known as "assimilation", occurs when backgrounds of various reflectances and hues can be made to appear either lighter when overlayed with white lines or patterns, or darker when overlaid with dark lines or patterns (Bezold, 1876; Helson, 1963; Steger, 1968; Jameson & Hurvich, 1975). The assimilation effect is in the opposite direction to that of simultaneous contrast, and its origin has thus been attributed to a different underlying mechanism. Both classes of phenomena have been studied using relatively simple stimuli. In the case of simultaneous contrast, these have usually been test discs surrounded by homogeneous annuli (Heinemann, 1972; Whittle & Challands, 1969; Yund & Armington, 1975). In the case of assimilation, a typical configuration is that of grey backgrounds overlaid with grids of white or black lines (Helson, 1963).

White (1979) has discovered a particular spatial luminance arrangement of surround that produces an especially vivid and unexpected form of brightness induction, and his figure is reproduced in Fig. 1. In the figure short grey bars have replaced segments of either the white or black phases of a square wave grating. The grey bars are of identical luminance yet appear to be markedly different in brightness, depending on the phase of the grating that they replace. Inspection of the figure will show that the grey bars on the white phase of the grating appear darker than those on the black phase.

What is particularly interesting about White's effect is that it does not readily fall into either the "simultaneous contrast" or the "assimilation" camp. The grey bars on the white phase of the grating are bordered more by black than by white, and on simultaneous contrast grounds might therefore be expected to be lighter than the grey bars on the black phase of the grating, the exact opposite of what is found. On the other hand the assertion that this effect could be merely another example of assimilation, in this instance assimilation between the grey bars and either the black or white bars of the grating that alternate with them, runs counter to all previous findings with simple grating stimuli. An early experiment by Helson and Joy (in Helson, 1963) showed that grey bars alternating with white bars of equal width never appeared lighter than grey bars alternating with black bars of equal width (which is what the assimilation story of Fig. 1 would require), at any of the variety of bar widths they employed. More recently Hamada (1984), using a different technique, has

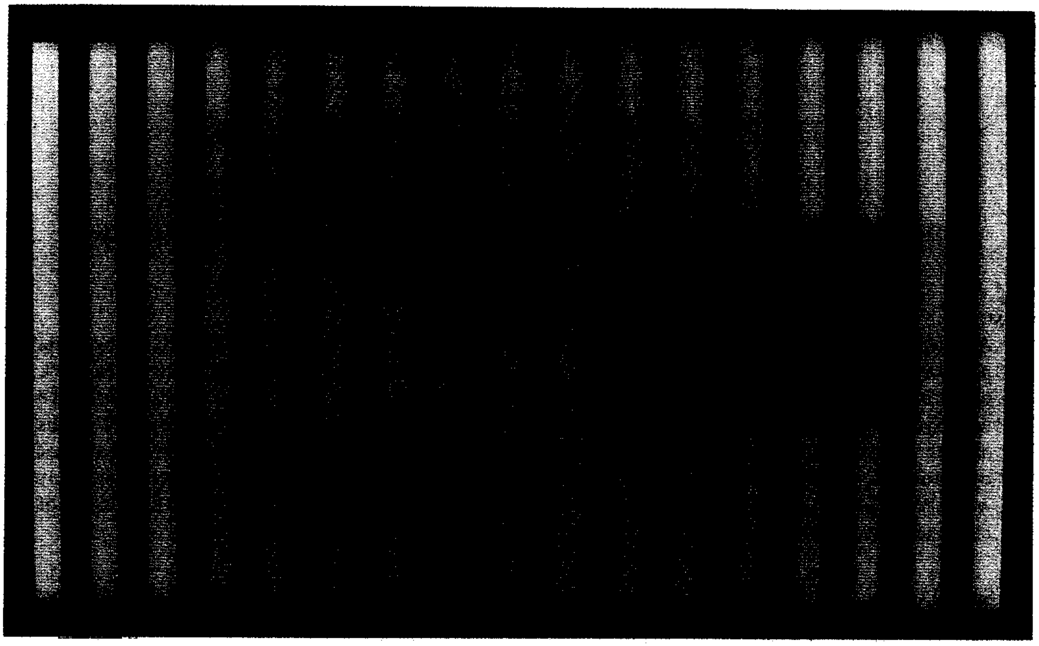

Fig. 1. White's (1979) effect.

confirmed this result for a wide range of grating spatial frequencies and reflectances of the black and white phases. It would seem therefore, that the phenomenon discovered by White occurs because of a specific spatial arrangement of grey, white and black figures, which is contained within, and indeed exemplified, by Fig. 1. One of the principal purposes of this paper will be to clarify the precise nature of the spatial luminance arrangement that provides the necessary and sufficient conditions for the brightness difference that is under investigation.

One particularly fruitful approach to phenomena such as White's effect has been to compute the response of modelled receptive fields to critical stimuli. If the post-convolution output of an array of modelled retinal ganglion cells operating upon the stimulus in question has a distribution of magnitudes that corresponds with perceived brightness, then this offers the beginnings of an explanation in terms of low-level mechanisms, even though it may not be possible at this stage to offer a complete computational theory in the sense of being able to specify exactly how the retinal output is integrated to generate the final percept. This paper is concerned with the attempt to describe the apparent properties of the input mechanisms as a first step towards the construction of an explanatory theory.

Recently Morgan and Ward (personal communication) have advanced an explanation of White's effect in terms of the operation of circularly symmetric filters such as those widely believed to exist in the mammalian retina. The stimulus features in Fig. 1 which Morgan and

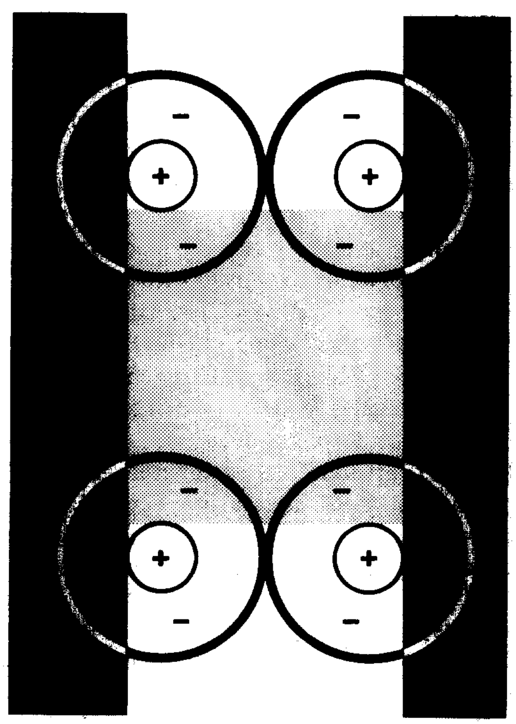

Fig. 2. Circularly symmetric receptive fields stimulated by the corner intersections of a grey square with the black and white phases of a grating. From Morgan and Ward (personal communication).

Ward suggest are particularly significant for such filters are the corners at the intersections of the grey stripe with the coaxial and flanking bars. Where the grey stripe is on the white phase of the grating it is surrounded by four white corners, as illustrated in Fig. 2 (here the grey stripe is square). On the other hand where it is on a black stripe it is surrounded by four black corners. If the receptive field of such a filter is placed so that its centre is inside a white corner the extent of activation depends upon the amount of inhibitory surround that escapes from being also filled by the white area. This is greater in the corner than, for example, when the receptive field lies along a straight border. The sum of the outputs of the filter across the border of the grey stripe with the coaxial bar is greater than the sum of the outputs across the border with the flanking bar, because of the contribution in the former but not the latter of the strong corner signals. Thus the magnitude of the contrast across the coaxial bar—grey stripe border will be greater than that across the flank bar—grey stripe border. If the relative magnitudes of the contrast signal generated at this early stage in processing were to be important in determining the brightness of the grey stripe, this would result in a difference in that brightness that would depend on the luminance polarities of the flanking and coaxial bars, which is what is observed.

The argument can best be illustrated by careful inspection of Figs 3 and 4. The two figures at the top of Fig. 3 show "cruciform" patterns at right angles to each other. Below each cruciform is the same pattern but with the flanking squares extended vertically to the top and bottom of the figure. The bottom two figures of 3a may be thought of as being sections of Fig. 1 with the exception that the grey stripe is now a square. The observer may notice a difference in the brightness of the grey square in the bottom two figures which is absent in the cruciforms. The bottom two figures may be considered as the elemental stimuli of White's effect if the Morgan and Ward story is correct, since their model only requires the presence of the corner around the grey patch to induce the effect. That

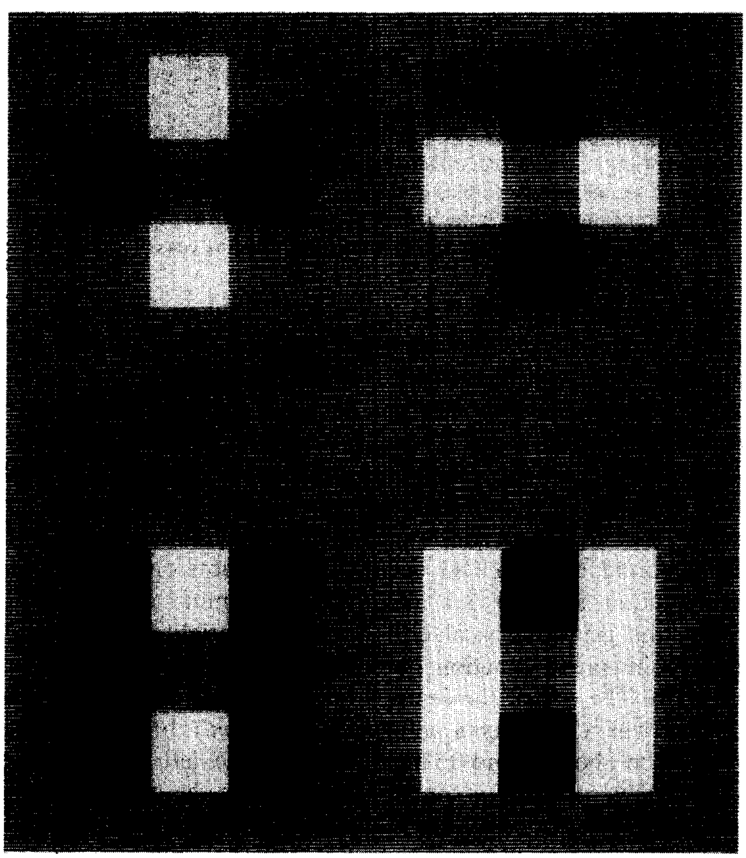

Fig. 3. Top—Cruciform patterns; bottom—sections of Fig. 1 but with grey squares instead of bars. The bottom two figures may be thought of as the cruciforms with vertically extended flanks. If the figure is viewed from a distance, the illusory difference in the brightness of the grey squares is present in the bottom stimulus pair but not in the cruciforms.

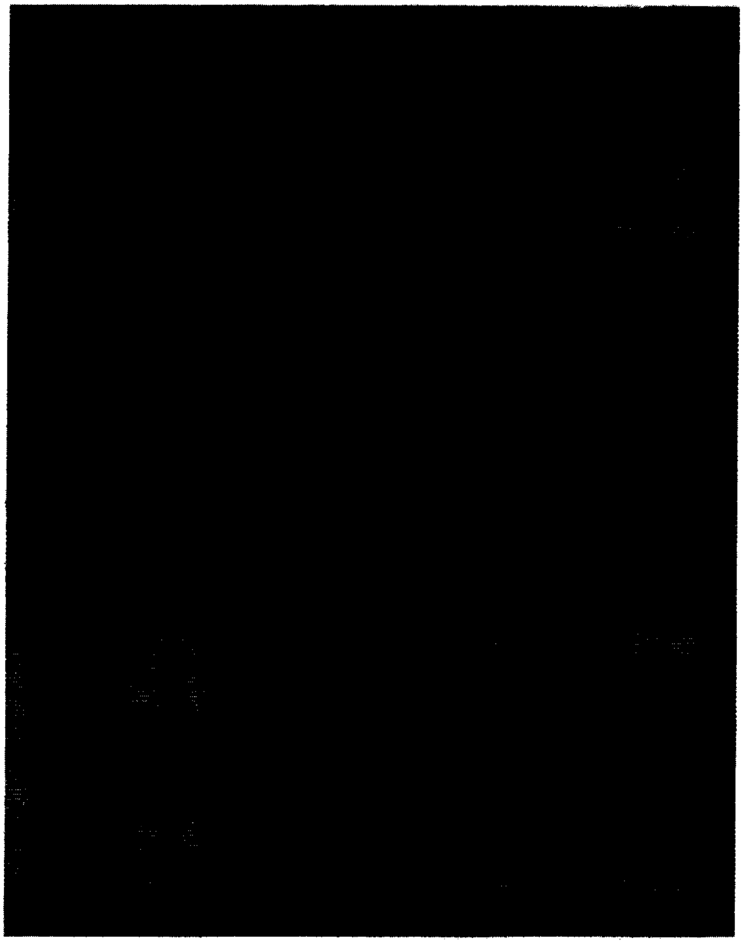

Fig. 4. Convolution of Fig. 4 with a DOG (Difference of Gaussian) approximation of a retinal receptive field. The "hot-spots" on the outside corners of the grey square are present on all four sides of the grey squares in the cruciform patterns, but in the bottom pair of patterns "hot-spots" are present only on the sides of the grey square which interface with the coaxial bars.

the effect is clearly not as strong in Fig. 3 as it is in Fig. 1 should be noted and will be discussed later. Figure 4 illustrates the result of convolving the figures in Fig. 3 with a Difference of Gaussians (DOG) approximation to the receptive field of a ganglion cell. If the grey squares are viewed such as to subtend about half a degree of visual angle, then the space constants of the centre and surround of the DOG employed in the convolution subtend 3.3 and 5.76 min respectively, the psychophysical estimates of the foveal pointspread function obtained by Wilson (1978). The size of the centre and surround of a filter which had such a point spread function would be about 8 and 15 min respectively (see also Kelly, 1977 for a similar estimate). The output of the DOG is encoded as luminance in Fig. 4, bright areas indicating a positive output, dark areas a negative output. If, as is widely believed, the positive response component of the DOG model is carried by "on" centre ganglion cells, the negative by "off" centre cells (Marr, 1982), then the bright parts of Fig. 4 represent the outputs of "on" centre cells, the dark parts those of "off" centre cells.

Consider first the post-convolution image of the upper pair of figures. At the corners of the grey squares are "hot-spots", but in each figure there are the same number of bright as there are dark hot-spots on each side of the edge, and if these determine the direction of contrast, and hence the brightness of the grey squares, then the two grey squares should look similar, all else being equal. In the bottom two figures however, there are *only* bright hotspots on the outside edge of the left hand square and *only* dark hotspots on the outside edge of the right hand square. If it is these hotspots which are the principal determinants of contrast, and hence brightness, then the grey squares will look different in brightness, as indeed they do.

What evidence is there in support of this explanation? Using stimuli similar to that shown in Fig. 6 and a technique that will be described below, Morgan and Ward (personal communication) have recently investigated the effect of inducing bar height on the size of the effect. Their data show that the magnitude of the effect was critically dependent on the presence of between 0.1 and 0.2 deg (6–12 min) height of the flanking and coaxial bars above and below the grey patch. Below that value the brightness difference was reversed, that is, the grey with a black flank appeared lighter than the one with a white flank. Above that value the size of the effect increased rapidly to an asymptote roughly between 0.3 and 0.8 deg (24–48 min). The foveal point spread function has a centre and surround of roughly 8 and 15 min. One would expect, according to the corner story, that the flanking bar height below which the effect would disappear would be about that corresponding to the centre size of this function, and the flanking bar height at which the effect asymptotes to be its surround size. The results were therefore reasonably consistent with both these predictions.

The corner model also offers an explanation of the SF dependency on the size of the effect. If one considers just the filters whose receptive fields lie along the edge of the grey square with the coaxial inducing bars, then the proportion of their total output contributed by the filters stimulated by the corners will increase as the coaxial bar decreases in width. If all else remains equal, this result in an increase in the size of the effect as bar width decreases, which is what is claimed to occur (White, 1979).

The purpose of this paper is to look for evidence that is consistent with the operation of this putative "corner effect" and to discover whether this mechanism alone might provide the basis of an explanation for White's effect or whether additional mechanisms must be taken into account.

GENERAL METHOD

Stimulus generation

All stimuli were generated by an 8-bit PLUTO II graphics display system interfaced to a CORVUS CONCEPT host computer. The stimuli were displayed on a BARCO INDUSTRIES type 2 TVMR monochrome TV monitor. The programs were written in PASCAL using ASM68K assembly language subroutines to interface the host and graphics computers. The 256 grey levels available on the Pluto were calibrated using a purpose-built photodiode and amplifier system with a photometric filter. The pixels on the screen were 0.68 mm in height by 0.33 mm in width subtending 2.03 by 0.98 arc minutes respectively at the viewing distance of 114 cm used throughout the experiments described.

Subjects

The two authors acted as subjects in all the experiments described. Both were experienced psychophysical observers. FK had normal, BM corrected, vision.

Stimuli

Spatial characteristics. While Fig. 1 shows a grating as the inducing stimulus for a row of grey patches, we have chosen to use just three inducing bars and one grey patch for each member of the pair of stimuli which reveal the effect. For the first experiment the stimulus arrangement is shown in Fig. 6, while for the remaining experiments Fig. 7 illustrates the typical arrangement. The two stimuli containing the test grey patches will be referred to as BWB and WBW patterns (W = white, B = black), thus describing the luminance arrangement of the three inducing bars in each pattern. The principal difference between the two arrangements in Figs 6 and 7 is that in the former the pair of

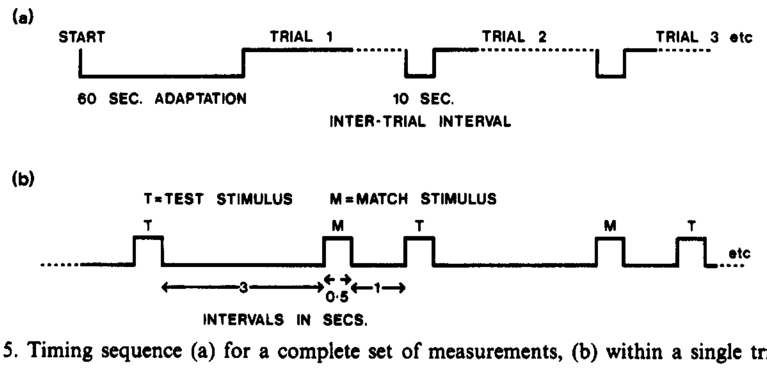

Fig. 5. Timing sequence (a) for a complete set of measurements, (b) within a single trial.

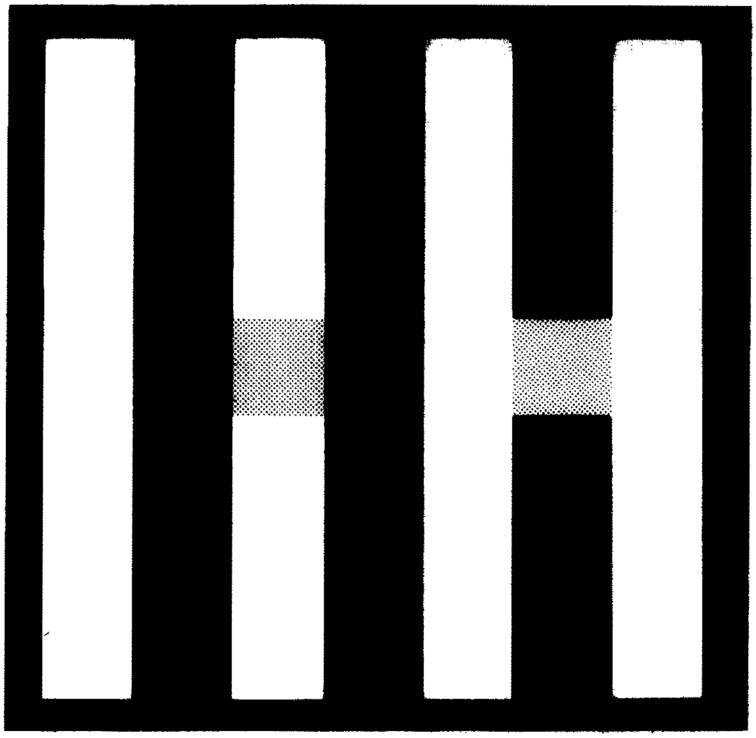

Fig. 6. Stimulus arrangement for expt 1. The left grey patch forms part of the BWB (black-white-black) condition, while the right grey patch forms part of the WBW (white-black-white) condition. In the experiment the luminance of one of the grey patches was adjusted until it was matched in brightness to the other grey patch.

stimuli are displayed against a black background while in the latter, the stimuli are displayed against a grey background. The central grey test patch was, unless otherwise stated, of square aspect ratio subtending 24.5 min arc in width and height. Bordering the horizontal edges of the test patch were vertical "coaxial" bars, while bordering the vertical edges were vertical "flanking" bars; these were of the same width as the test patch unless otherwise stated. Except in expt 1, in which the two stimuli were displayed together on each trial, each member of a pair was displayed on its own alternating in time with a match stimulus. The match stimulus was a square patch with the same spatial dimensions as the test patch, but was presented against a homogeneous grey background.

Luminance characteristics. The luminance of the background in expt 1 was approx 0.1 cd m^{-2}, while for the remaining experiments it was 20.0 cd m^{-2}. The white and black inducing bars in all the experiments described were 40.0 and approx. 0.1 cd m^{-2} respectively. The luminances of the test grey patches were varied from experiment to experiment and details will be given with the description of each experiment.

Procedure

Experiment 1. All the experiments described employed a matching method. In this experiment the match was made between the two grey patches in the BWB and WBW stimuli illustrated in Fig. 6. The two stimuli were presented simultaneously and the subject adjusted the luminance of the test grey patch in one of the stimuli until it appeared equal in brightness to the test patch in the other stimulus. There was no time limit and when the subject was satisfied with the match, he pressed a button and the match luminance was recorded. Data were collected both for the situation in which the WBW pattern was to the left of the BWB pattern, and for the reverse configuration. Similarly, data were collected with the adjustable stimulus either on the left or on the right. At the start of each experimental session the subject was pre-adapted to a blank, black, screen for 60 sec.

Experiments 2–4. For the remaining experiments, each member of the stimulus pair was presented on its own on a given trial and alternated in time with a match stimulus, which was a 24.5 arc min square presented on a homogeneous grey background of 20.0 cd m^{-2}. The

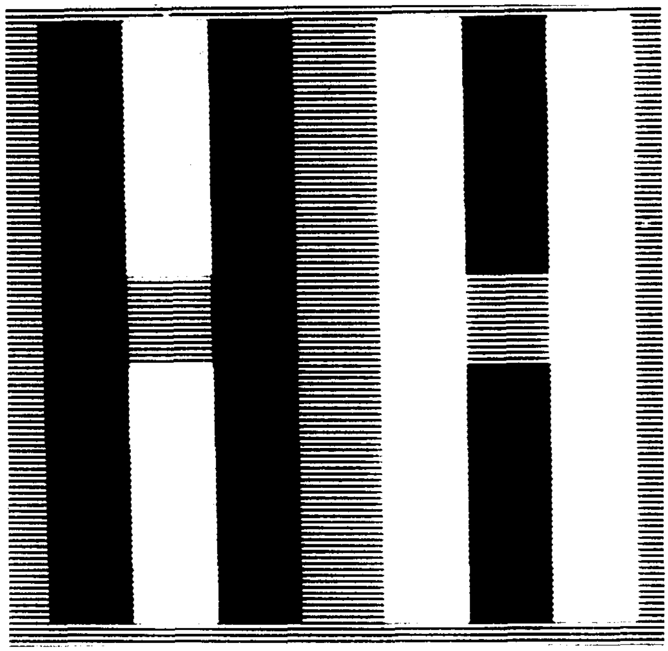

Fig. 7. Typical stimulus arrangement for expts 2–5. The left hand stimulus is the BWB condition, the right hand stimulus the WBW condition. The brightness of the test grey patch in each condition was separately measured by adjusting the luminance of a grey patch which temporally alternated with the test condition.

task of the subject was to adjust the brightness of the match stimulus until it was equal in brightness to the test grey patch. He was permitted as many alternations of the test-match sequence as was necessary to make a satisfactory match. The timing sequence is illustrated in Fig. 5. The purpose of the 1.5 sec interval between the test and match stimuli was to ensure there was no build up of afterimages.

EXPERIMENT 1

Replication of Morgan and Ward: effect of inducing bar height

Introduction. It was established in the introduction that a critical test for the hypothesis that White's effect results from a local processes at the corners of the test grey patches with the inducing bars involves measuring the size of the effect as a function of the height of the inducing bars. The model predicts that as the height of the inducing bars above the test patch is increased from zero, the occurrence of the effect will depend upon the inducing bar height exceeding that of the test patch by some fixed, small extent, corresponding to the dimensions of the receptive fields involved. Beyond about half a degree there should be no further increase in the size of the effect.

Morgan and Ward's data were consistent with this hypothesis and the purpose of this experiment was to confirm their finding. The experiment is essentially the same as the one they conducted except that we have additionally measured the brightnesses of the two grey patches when the flanking bars were *shorter* than the grey patch. The procedure for this experiment has already been described.

Stimuli. 12 heights of inducing bars were tested. They were 0.0, 0.1, 0.2, 0.3, 0.4, 0.54, 0.61, 0.68, 0.8, 1.6, 3.3 and 6.5 deg arc.

It is necessary from the outset to understand exactly what a change in "inducing bar height" implies for the stimuli illustrated in Fig. 6. For the right hand, WBW, stimulus in Fig. 6, reducing "inducing bar" height actually means reducing *only* the height of the *flanking* bars, since the coaxial bar, which in this instance is black, remains the same as "part of" the background. On the other hand reducing the "inducing bar" height in the left hand, BWB, stimulus means reducing *only* the height of the *coaxial* bar, since in this instance the flanking bars are part of the black background, and remain invariant. Furthermore, when the "inducing bar" height is *less* than that of the test grey the left hand, BWB, stimulus is just the same grey patch against a black surround, since the coaxial bar cannot be made less than the height of the test grey. On the other hand, in the right hand, WBW, stimulus the flanking bars are still visible. The significance of these points will become clear in the discussion of the results of this experiment below.

Results. For each value of inducing height, the mean percentage difference in the matched luminances of the grey patches was calculated. A positive difference implies that the grey patch in the WBW condition was set to be higher in luminance than the grey patch in the BWB condition. A negative difference implies the reverse. In terms of the perceived brightness difference between the two grey patches when identical in luminance, a negative percentage implies that the brightness difference was in the direction of that of Fig. 1, that is in the direction of the effect under investigation, while a positive percentage indicated that the brightness difference was in the opposite direction to that of Fig. 1.

The results for the two subjects are shown in Fig. 8. The standard error bar gives two standard errors for the data point which had the largest between trial variation. The pattern of results may be described as follows. When the inducing bars have zero height (that is the comparison is just between two grey patches on a black background), there is, as one would expect, no significant brightness difference. As the height of "inducing bar" is increased from zero, the BWB condition remains as simply a grey patch against a black background, while the flanks in the WBW condition increase in height. Up to the point where the flanks are equal in height to the grey patch, the patch with the WBW stimulus appears progressively darker, as revealed by the rise in the curve in Fig. 8. Once the flanks become taller than the patch, the white coaxial bar "appears" in the BWB stimulus, and there is a dramatic reversal in the relative brightnesses of the two patches, with the two patches appearing once again equal in brightness when the inducing bars are approximately within the range 0.6–0.7 deg in height. As the inducing bars increase further in height the brightness difference, now in the reverse, negative, direction increases to an asymptote approximately in the range 0.8–1.6 deg. The brightness difference at this point is about 15% and constitutes the maximum size of the effect obtainable with the particular stimuli employed in this experiment.

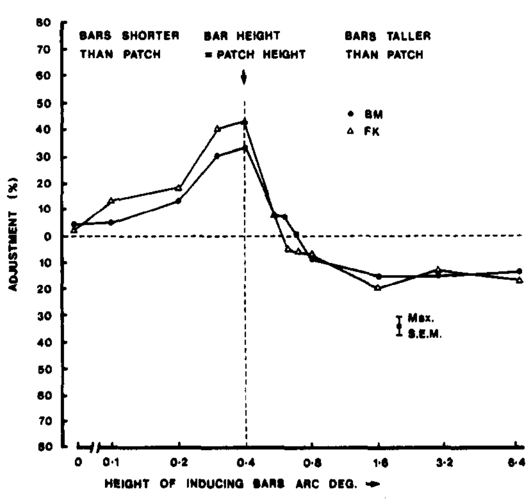

Fig. 8. Results from expt 1. The ordinate represents the percentage difference in the brightnesses of the two grey patches in Fig. 6. Values above zero imply that the left grey patch in Fig. 6 (BWB condition) appeared lighter than the right grey patch (WBW condition). Values below zero implied the reverse situation, indicating that the direction of the brightness difference was the same as in Fig. 1.

Discussion. When the heights of the white flanking bars were less than that of the test patch height, the results are entirely what one would expect on grounds of simultaneous contrast. The presence of the short white flanks made the test grey patch appear darker than it would do on a plain grey background, to an extent dependent on the amount by which those flanks bordered the patch.

When the flanking bars were greater than that of the test patch, (the conditions common to both this experiment and Morgan and Ward's) the results of this experiment are very similar to those of Morgan and Ward. If one measures flank height not as total flank height but as the *height of the flank above the test patch*, we can compare our results directly with Morgan and Ward. Their boundary conditions for the effect were 0.1–0.2 deg for the minimum and approx. 0.3–0.8 deg for the maximum, which compare very closely with our figures of 0.1–0.15 deg (minimum) and approx. 0.2–0.6 deg (maximum). The remarkable and robust finding that the brightness of the grey patch is dramatically changed as soon as the height of the flanking bars exceeds that of the grey patch by some critical amount lends powerful support to the idea that brightness is at least in part determined by some local process occurring at an early stage in processing.

The method and the stimuli used in this kind of experiment have two main limitations. The first is that the type of matching technique employed, while giving a direct measure of the relative brightness between the two patches, does not allow the investigator to measure the brightness levels of the two patches separately against a common standard. Knowledge of the individual brightnesses of the patches in the BWB and WBW conditions is potentially very informative. We would like to know whether it is in fact the case that the grey bars in the left half of Fig. 1 appear lighter, and in the right half darker, than a homogeneous background of the same luminance as the grey patch, which is intuitively what one might believe to occur. It is, on the other hand, perfectly possible that both grey patches are lighter, or both grey patches darker, than such a background, but to a different degree.

The second limitation is that with this stimulus the effect on the size of the effect of the heights and widths of each of the flanking and coaxial bars cannot be separately investigated, and this information is crucial to an understanding of the properties of the underlying mechanisms.

The following experiments were designed to overcome these limitations.

EXPERIMENT 2

Effect of flank height with constant coaxial height

Method. The procedure for this experiment has been described under General Methods. The tallest flank height condition is illustrated in Fig. 7. Only flank heights greater than that of the test patch height were used, and flank height is given from now on as height *above* test patch. The flank heights used were 0.0, 0.1, 0.2, 0.3, 0.4, 0.8 and 1.6 deg. Coaxial height was held constant at 1.6 deg above and below the test patch. Five test patch luminances were employed within each condition, and were presented in random order, as were also all other conditions. We used more than one test patch luminance in order to reduce the likelihood of any bias in the settings. The five test patch luminances were 16.0, 18.0, 20.0, 22.0 and 24.0 cd m^{-2}.

Results. The raw match luminance values were converted into percentage differences between the match and test grey patches. Since there were no appreciable differences in the percentages as a function of test grey luminance the results were pooled. Fig. 9 displays the results separately for each subject. On each figure are three curves. The continuous lines represent the individual results for the two types of stimulus pattern, while the dashed lines represent the net difference between the continuous lines for each flank height.

First, notice that the test greys were in every case matched by greys that were of *lower* luminance. In other words, *both* stimulus patterns made the test grey patches appear darker than they would be against a background of 20.0 cd m^{-2}. Second, examination of the dashed lines, which indicate the *difference* in the brightness matches of the test greys in the two test patterns, shows slightly different patterns for the two subjects. With BM, when the flank height did not exceed that of the test patch, the brightness difference, if any, was in the opposite direction to that of White's effect. On the other hand FK showed a difference of about 6% and in the direction of White's effect, at this point. As flank height increased from zero, both subjects showed a rapid, downward, trend to an asymptote of about 12% brightness difference at a flank height of between 0.1 and 0.2 deg.

Discussion. The main finding is that, as in the previous experiment, only a relatively small extent of flank bar (0.1–0.2 deg) above and below the test patches is needed to elicit the effect, giving further support to a local process model. There are, however, some notable differences between the results of this and the previous experiment. It would appear that the height at which the asymptote is reached in this experiment, 0.1–0.2 deg, is shorter than that found in expt 1, where it was found to be approximately between 0.2 and 0.6 deg. One possible explanation for this follows from an important difference in the stimuli used in the two experiments. Whereas in expt 1 coaxial height 'grew alongside' flank height in the different conditions, in this experiment it was fixed at a large height of 1.6 deg above and below the test patches. If the long coaxial bar in this experiment were to contribute to the determination of the test patch brightnesses over and above its contribution to any local effect at the test patch borders, one would expect the asymptote to be reached earlier than if it "grew alongside" the flanks. This is so since any contribution to the effect of a long coaxial bar would be manifest in every condition in this experiment. In expt 1 on the other hand, the asymptote would be reached only when *both* the local (short flank and coaxial required) and the secondary (longer coaxial required) effects

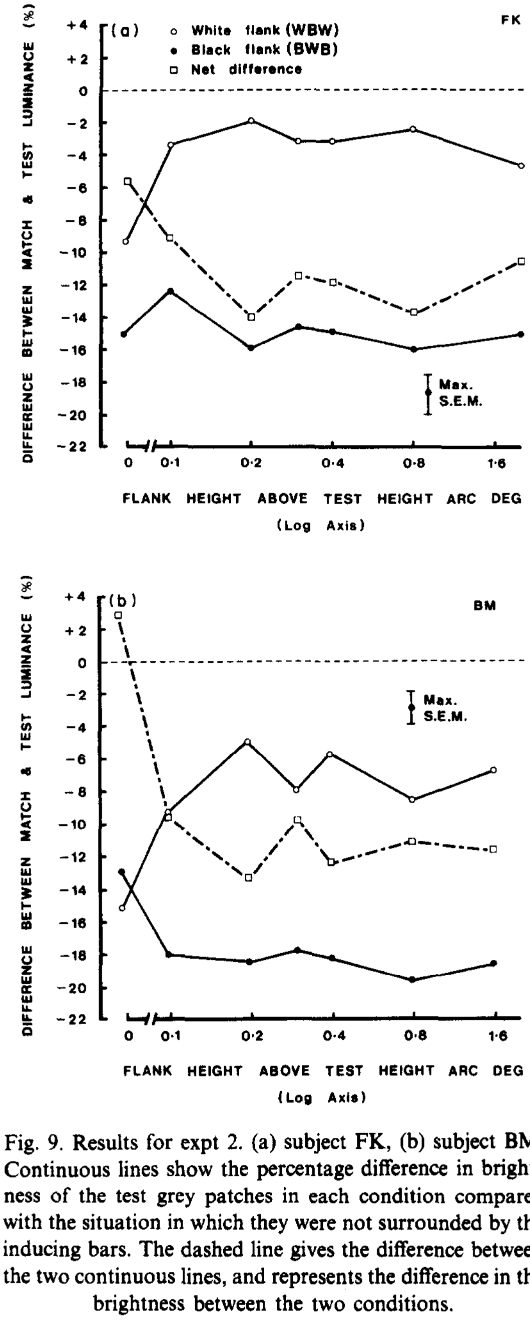

Fig. 9. Results for expt 2. (a) subject FK, (b) subject BM. Continuous lines show the percentage difference in brightness of the test grey patches in each condition compared with the situation in which they were not surrounded by the inducing bars. The dashed line gives the difference between the two continuous lines, and represents the difference in the brightness between the two conditions.

had reached their maximum levels. There is some support for this interpretation in the data of FK, in which there was an initial, approx. 6%, brightness difference when the flank was no higher than the test patch, though not in BM's data, which showed if anything a reversed brightness difference at this point. We will shortly be describing an experiment on the effect of coaxial height with constant flank height which will throw further light on this issue, and we will take up this discussion again after reporting the results.

The finding that the test greys were always matched by greys of lower luminance is an important and unexpected finding, and one that the nulling technique could never have revealed. The results of the nulling experiments (both our own and that of Morgan and Ward) would by default have been taken to suggest that one configuration produces a brightness effect in one direction (say brightening) while the other configuration produces a brightness effect in the other (say darkening). The results of this experiment show that this inference would be wrong: both configurations produce an apparent darkening of the test patch. The two configurations produce different brightnesses only because they produce different degrees of darkening.

The main conclusion that has been reached, namely that a small amount of flank above and below the test patch is necessary to elicit the brightness difference, is, however, potentially confounded by the possibility that instead of that amount being a constant, it might in fact be a *proportion* of the height of the test patch. In other words, the critical size of the flank increment may either be dependent on or independent of test patch height. The experiment that will now be described is designed to test between these alternative possibilities.

EXPERIMENT 3

Effect of flank height for three test patch heights for WBW condition only

Introduction. In this experiment we investigated the effect of flank height for three different values of test bar height, in order to see whether the asymptote in the induced brightness difference was reached for a constant or proportional increment in flank height above and below the test patch. We carried out the experiment only with the WBW condition, on the grounds that the additional information that might be given by the BWB condition was not necessary to resolve the issue.

Stimuli. In this experiment the flank heights used were 0.0, 0.1, 0.2, 0.3, 0.4 and 1.6 deg arc, where flank height was measured in height above the test bar. The three test bar heights used were 0.2, 0.4 and 0.8 deg arc. Thus for each test bar height, a different range of absolute flank heights was used.

Results. The results for the two subjects are shown in Fig. 10. The data clearly show that the asymptote is reached at approximately the same point *irrespective of the test bar height*, and the

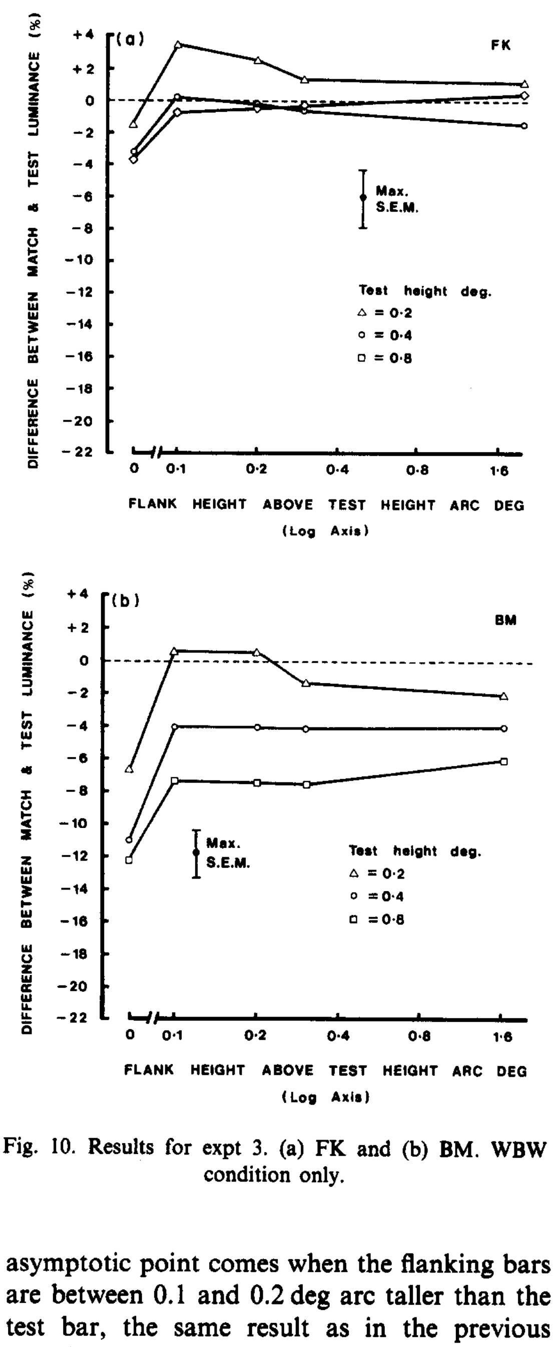

Fig. 10. Results for expt 3. (a) FK and (b) BM. WBW condition only.

asymptotic point comes when the flanking bars are between 0.1 and 0.2 deg arc taller than the test bar, the same result as in the previous experiment. There is a hint that there may even be a slight decline after the asymptote is reached in the case of the smallest test height.

Discussion. This experiment greatly strengthens the idea that the brightness of the grey bars in Fig. 1 is determined by an essentially local process in the immediate neighbourhood of the junction between them the flank and coaxial bars. The "corner effect" explanation is therefore supported by this experiment. The slight decline of test patch brightness with flank height after the asymptote was reached, observed in both subjects in the smallest test patch condition, might conceivably implicate filters whose centres fell within the test patch, but whose surrounds extended a considerable way into the outlying regions where the flanks extended vertically. The tall white flanks, stimulating the inhibitory surrounds of such filters would act to reduce their output.

EXPERIMENT 4

Effect of coaxial bar height with flank height held constant

Introduction. The "corner effect" explanation predicts that as the height of the coaxial bar is increased from zero, the brightness of the grey patch should first be affected in one direction as the coaxial bar fills the centre of the receptive field, but should reverse in direction once the bar encroaches on the receptive field surround. On the other hand we have seen hints in the data of expts 1 and 2 that there might be a process operating beyond the immediate border vicinity of the grey patches that is due to the presence of the long coaxial bars. If so, one would expect that increasing coaxial bar height should have a unidirectional and more spatially extensive effect. The purpose of the next experiment was to test between these two predictions.

Stimuli. In this experiment, flank height was held constant at 1.6 deg above and below the test patch, while coaxial height was varied. The coaxial heights used were 0.07, 0.14, 0.2, 0.4, 0.8 and 1.6 deg above and below the test patch.

Results. The results are shown in Fig. 11. Solid symbols show the effect of black coaxial bars on brightness, and open symbols show the effect of white coaxial bars. The dashed lines represent the size of the difference in matched brightness between the test patches in the two cases, and as can be seen there is only a suggestion of an asymptote for one subject (BM), between 0.4 and 1.6 deg, while for FK the brightness difference is still increasing at 1.6 deg. As can also be seen the black coaxial bars have no consistent effect on the brightness of the test patch: all the illusory difference is due to the effect of the white bars.

Discussion. These data show that white coaxial bars exert an influence on the brightness of the test patches over a greater spatial extent than do the flanking bars, whose effect was demonstrated in the previous experiments. This implies the operation of an additional mechanism besides the corner effect, one with a significantly larger receptive field summation

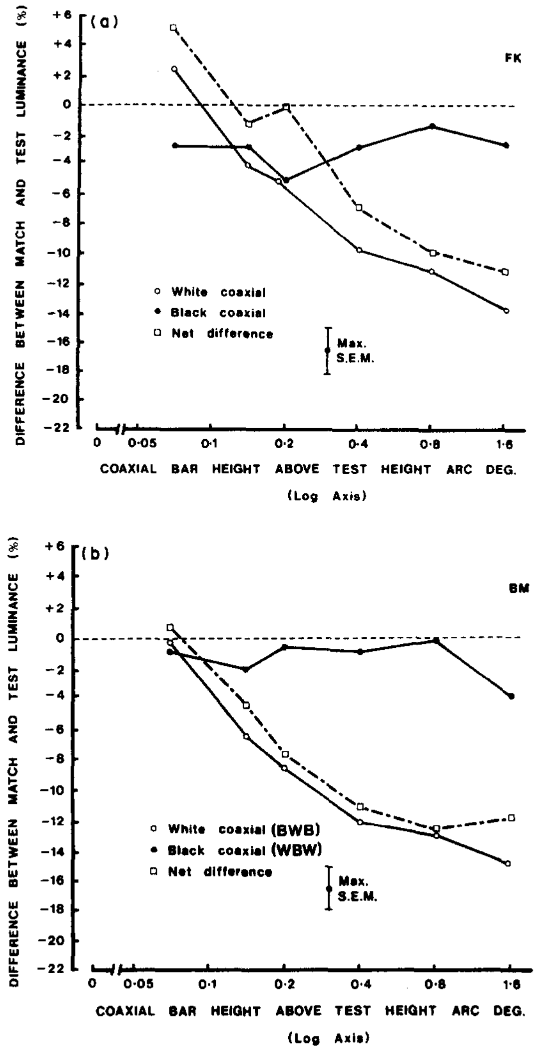

Fig. 11. Results for expt 4. (a) FK and (b) BM.

area that operates on the extended coaxial bar, and in part determines the brightness of the grey patches. In the experiment reported here the asymptote for this secondary effect was reached when the coaxial bars were at least 0.4–1.6 deg height above the test patch. This is greater than the 0.2–1.6 deg asymptote found in expt 1 where coaxial bar height was a covariate (at least in one of the stimuli). We currently have no ready explanation for this difference. The crucial point however is that we have demonstrated the operation of the secondary mechanism, even though we are unable at this stage to provide a precise estimation of its spatial summation area.

GENERAL DISCUSSION

To summarise, we have isolated two factors affecting the size of White's effect, measured here as the *difference* in the match brightnesses of the test patches between the WBW and BWB stimuli.

(1) The effect is critically dependent on the presence of between 0.1 and 0.2 deg of flank and coaxial height above and below the test patch (expts 2, 3 and 4).

(2) The size of the effect increases with coaxial bar height up to an as yet unspecified height.

The most parsimonious explanation of these findings involves the operation of two distinct processes involving different classes of filter.

First, we suggest that the effect is principally due to local processes operating in the immediate vicinity (less than half a degree) of the border of the test grey patch with the coaxial and flank bars. This local process most likely involves an array of elongated cortical filters with centre-surround profiles lying along the perimeter of the patch, with their long axes parallel with the border. The sum or weighted sum of the outputs of these filters in part determines the brightness of the test patch. Such filters receive as their input the outputs of circularly symmetric filters on the retina. Of this latter array of filters, the ones in the corners of the interface between the coaxial bar and test patch give a disproportionately large response compared with the others along the border, and so therefore also will the cortical filters that lie along this interface compared with those that lies along the interface between the flanking bar and test patch. The evidence for such a corner effect is given by our data showing the effect of flank height on the size of the effect which shows a rapid asymptote in the size of the effect when there is between 0.1 and 0.2 deg of flank bar above and below the test patch.

Secondly, there is a process which operates beyond the immediate vicinity of the border, as evidenced from the data on the effect of coaxial height, in which the brightness of the test patches was found to be affected by stimulation from as far away as 1.6 deg arc. The suggestion is that this secondary mechanism involves filters with relatively large spatial summation areas compared with the ones involved in the local process just described. The most intuitively appealing structure of these filters is that they have elongated end-zones with relatively small receptive field centres.

Alternative models of White's effect have been put forward. White (1981, p. 218) has suggested that the effect is mainly a consequence of a process he refers to as "pattern specific inhibition" (PSI). PSI is the process whereby cortical filters tuned to similar spatial frequencies and orientations, and which serve adjacent or overlapping areas of the visual field, are held to mutually inhibit each other. The effect of such mutual inhibition is to reduce the output of the filters and consequently, if the stimulus is a grating, to reduce its apparent contrast compared with the situation in which PSI were not in operation. The grey bars simply "carry" this reduced apparent contrast: when the grey bars are on the white phase of the grating their contrast with the adjacent black phase is reduced by PSI, resulting in their appearing darker than they otherwise would. By a similar argument, the grey bars on the black phase appear lighter than they otherwise would. Our data are not consistent with this model, since one would predict according to the PSI story that the flanking bars would continue to exert an influence on the brightness of the grey patch beyond the asymptotic height of approx. 6–12 min arc found in expts 2 and 3. Moreover, the evidence put forward by White in support of the PSI hypothesis is entirely consistent with the dual mechanism hypothesis offered here. For example, White showed that if the surround and test grating (the test grating is the area of the grating containing the grey bars) were similarly oriented, the effect was greater than if they were oriented differently. While the corner effect might still be in operation with the latter configuration, our secondary, spatially extended process, would certainly be reduced, and with it the size of the effect.

Foley and McCourt (1985) have suggested that White's effect is caused by the same mechanism as that underlying their grating induction effect (GIE) (McCourt, 1982), in which an illusory grating is induced into a grey stripe running at right angles through a sine-wave grating. They suggest that both effects implicate the existence of cortical filters such as the ones illustrated in Fig. 12. The key property of these filters is their elongated surrounds, and it is possible that such filters may be identified with the additional spatially extensive mechanism required to account for the results of expt 4. However, there is now strong evidence for a highly localised border mechanism (the corner effect) in addition to such a secondary process, and therefore Foley and McCourt's model must be at best an incomplete description of White's effect. On the other hand, the fact that White's phenomenon clearly involves the operation of a corner effect, while Foley and McCourts' GIE is most marked for low-frequency sinusoidal gratings (in which corner effects either would not occur, or would be weak and spatially infrequent), suggests that it would be wrong to think of the two as being essentially identical effects as has been previously suggested (Foley & McCourt, 1985; White & White, 1985). Indeed the fact that GIE decreases with spatial frequency, while White's effect is said to increase is alone good grounds for believing that the two effects are mediated by different mechanisms.

One of the main theoretical conclusions that can be drawn from our investigations is that a complete model of brightness perception will involve the combined output of not simply the same class of operator at different spatial scales, as in a large number of models of low-level vision (Coltheart, 1971; Watt & Morgan, 1985; Morrone & Burr, 1987; Graham, Robson & Nachmias, 1978; Swanson, Wilson & Giese, 1984), but the combined output of different classes of operator.

It is also of theoretical interest that the effect of the inducing bars was always to make the test grey patch appear darker than when it was placed against a background whose luminance was the average of the inducing bar luminances. This finding implicates an anisotropy in the

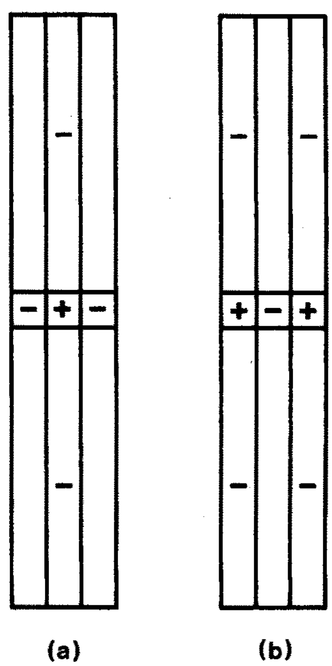

Fig. 12. Receptive field profiles of cortical filters held to be responsible for the grating induction effect (GIE). From Foley and McCourt (1985).

relative effect of black vs white inducing surrounds: white appears to darken more than black lightens. Anisotropies in the brightness and saliency of stimuli depending on whether the test stimulus is greater or lesser in luminance than its surround have been frequently reported in a number of studies of brightness phenomena: Heinemann (1972) with simultaneous contrast; Jory and Day (1979) with Kanizsa's triangle; Hamada (1984) with apparent grating contrast; Spillman and Levine (1971) with the Hermann grid illusion; Magnusson and Glad (1975) with apparent flicker contrast; Spillman, Fuld and Neumeyer (1984) with the Ehrenstein illusion; Legge and Kersten (1983) with contrast discrimination; Kingdom and Moulden (1986) for detection of line signals in visual noise. The anisotropy has been attributed to a non-linear transform of input intensity at an early stage in visual processing, which, if taken into account, gives symmetry to the results of much of the data obtained with increments and decrements, for example contrast matching between increments and decrements (Burkhardt, Gottesman, Kersten & Legge, 1984) and contrast discrimination for incremental and decremental stimuli (Legge & Kersten, 1983; Whittle, 1986). Essentially, the difference in the log transformed luminance between the signal and its background (the suggested correlate of perceived contrast) will have a larger absolute value in the case of a decrement than for an equal sized increment. However, such an explanation wrongly predicts the relative effect of white and black surrounds on grey test patches. With such stimuli the apparent contrast, as just defined, would be greater for the *increment* (grey patch on black background) than the decrement (grey patch on white background), yet it is the latter arrangement that produces the greater effect on the brightness of the grey test stimulus. For this type of phenomenon, of which our data provides an example, there must be a different sort of explanation. The segregation of "on" and "off" centre units in the retina and LGN (Waessle, Peichl & Boycott, 1983) provides a possible physiological basis for a separation of the mechanisms that encode increments and decrements. There is some general psychophysical evidence for such a separation (see for example Krauskopf, 1980), as well as some more specific evidence suggesting that the two mechanisms differ both in terms of their spatial weighting functions and gain (du Buf & Roufs, 1987). These latter differences may well turn out to be responsible for the anisotropy found in this study and elsewhere.

There are a number of remaining questions associated with White's effect that still need to be answered. Firstly, although it is said that the effect increases with spatial frequency (White, 1979) there is at present no quantitative data with which to assess this claim. Secondly, casual inspection suggests that the effect is stronger in its repeated grey bar version (Fig. 1) than in the single grey patch version (Fig. 7). We believe that this is principally due to the difference in spatial scale between the two figures, but may also result from some of the grey bars in Fig. 1 being scanned by more peripheral visual areas where receptive fields are known to be larger. Such peripheral stimulation would be equivalent to reducing the spatial scale of the figures with foveal fixation. The existence of the corner mechanism raises the question of the size of its effect relative to the border mechanisms operating along the rest of the contour. A possible way to investigate this would be to artificially introduce opposite (physical) hot spots to remove the corner effect. We are currently investigating a number of these possibilities and will report the results of our investigations in due course.

Finally it should be emphasised that the analysis presented here in terms of low-level input mechanisms is only a prelude to the generation of a computational model that will describe the integration of these inputs to give a final percept.

CONCLUSION

White's effect involves the operation of two mechanisms, one local, the other spatially extensive. The former operates principally at the corner intersections of the grey bars with the white and black phases of the inducing grating, whilst the latter operates principally along the long axis of the phase of the grating that is coaxial with the grey bar. Computational models of brightness perception must therefore be prepared to integrate the outputs of more than one class of spatial filter.

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Note added in proof—Zaidi (1989) has recently shown that grating induction effects similar to those reported by Foley and McCourt (1985) can be produced by inducing stripes set at an oblique angle to the inducing region. On these and other grounds he rejects Foley and McCourt's explanation in terms of elongated filters with narrow centres. Zaidi himself offers no formal model for his findings, but they could clearly be explained quite simply in terms of the operation of our local "corner effect". This suggests that both of our proposed mechanisms are in operation in the original Foley and McCourt demonstration.

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