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Pattern discrimination with increment and decrement Craik–Cornsweet–O'Brien stimuli

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Abstract—Previous studies have reported that the magnitude of induced brightness in Craik–Cornsweet–O'Brien (CCOB) figures is greater for decrement compared with increment figures. Moulden and Kingdom (*Spatial Vision*, 1990, **5**, 101–121) suggested this was due to larger Off-centre compared with On-centre receptive fields. Such an explanation would also predict an increment-decrement difference in the contrast threshold for discriminating a CCOB stimulus from its step-edge equivalent. To test this prediction contrast thresholds were measured for discriminating 'cusp' from 'square-bar' stimuli, for both increment and decrement forms. Contrary to prediction however, no difference was found between increment and decrement discrimination thresholds. These findings suggest that On- versus Off-centre receptive field size differences are unlikely to underlie the polarity-based asymmetry in induced brightness in CCOB figures. More generally they demonstrate that the magnitude of induced brightness in CCOB figures does not have a direct parallel in the ability of observers to discriminate those stimuli from their step-edge equivalents. The significance of these findings for models of brightness coding is discussed.

1. INTRODUCTION

The well known Craik–Cornsweet–O'Brien (CCOB) illusion (O'Brien, 1958; Craik, 1966; Cornsweet, 1970) describes the situation in which a difference in brightness is observed between two equal-in-luminance regions separated by a luminance-defined edge consisting of both a sharp and gradual discontinuity (Fig. 1). The illusion has prompted a good deal of investigation over the years, and is a test bed for models of brightness coding (for a review see Kingdom and Moulden, 1988; see also Todorovic, 1987; Burr, 1987; Kingdom and Moulden, 1992; Pessoa *et al.*, 1995). There are many varieties of the basic CCOB figure and one commonly employed is the 'cusp' stimulus, illustrated in Fig. 1. Although the centre of the cusp is the same luminance as the background, it appears brighter when an increment, and darker when a decrement.

Measures of induced brightness in cusp stimuli have found its magnitude to be significantly greater for decrements compared to increments (Davidson and Whiteside, 1971; Hamada, 1985; Todorovic, 1987; Moulden and Kingdom, 1990; Cole *et al.*, 1992). Moulden and Kingdom (1990) advanced the hypothesis that such a polarity-based asymmetry was due to larger Off-centre compared with On-centre receptive

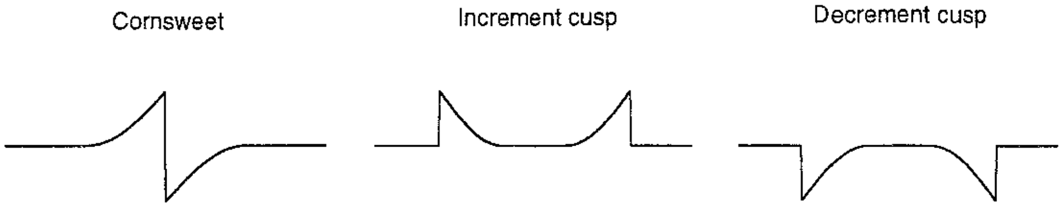

Figure 1. Luminance profiles of a Cornsweet, increment cusp and decrement cusp stimulus.

field filters. This explanation was put forward on the basis of an analysis of the convolution outputs of model centre-surround receptive fields of different sizes in response to the cusp stimuli, as part of a multi-scale model of brightness coding. Figure 2 demonstrates the model as applied to just one half of the cusp stimulus, which produces an illusory step in brightness at low contrasts. Only the responses of one On–Off filter pair are shown for simplicity, even though in the model the responses of many filter-pairs of different sizes were involved. The filters in Figs 2(a), (b) have a second-difference-of-a-Gaussian weighting function, with a space constant (of the underlying Gaussian) 1.5 times greater for the Off-centre compared to the On-centre filter (for details see Moulden and Kingdom, 1990). The responses of the two filters are shown in Fig. 2(d). Each filter's response is half-wave rectified, but for illustrative purposes is shown as positive activity for the On- and negative activity for the Off-centre filter, around a zero-response level represented by the continuous horizontal lines. As can be seen in Fig. 2(d), the sloping parts of the half-cusp luminance profiles are registered by a relatively low amplitude response lobe on the right side of each half-wave rectified response. In the case of the increment half-cusp, this response lobe is in the Off-centre's response, whereas for the decrement half-cusp, it is in the On-centre's response. The dotted lines in Fig. 2(d) represent arbitrary thresholds, and one can see that this particular response lobe is above threshold for the increment half-cusp but below threshold for the decrement half-cusp. Moulden and Kingdom (1990) assumed that when this response lobe was below threshold, the visual system interpreted the combined filter-pair response profile as signalling an 'edge', but when above threshold a 'bar' (Fig. 2(e)). When an edge was signalled, an illusory brightness step would be seen. If the receptive field sizes of On-centre filters were on average smaller than Off-centre filters, more from the full range of sizes of filter-pairs would produce an edge signal in response to a decrement compared to increment half-cusp. Thus the magnitude of the illusory brightness step would be greater for the decrement case, assuming some degree of additivity between the individual-sized filter-pair generated brightness signals.

The presence of larger Off-centre compared with On-centre receptive fields would also predict a polarity-based asymmetry in terms of the contrast threshold for discriminating the cusp stimulus from its square-bar equivalent. This prediction follows directly from the analysis presented in Fig. 2. As the contrast of the half-cusp stimulus is increased from zero, a point is reached when the critical response lobe becomes suprathreshold for a given sized filter-pair. At this point the cusp will become distinguishable from a square-bar, since the latter produces no such response activity. For the decrement cusp, this will occur at a higher contrast than for an increment cusp

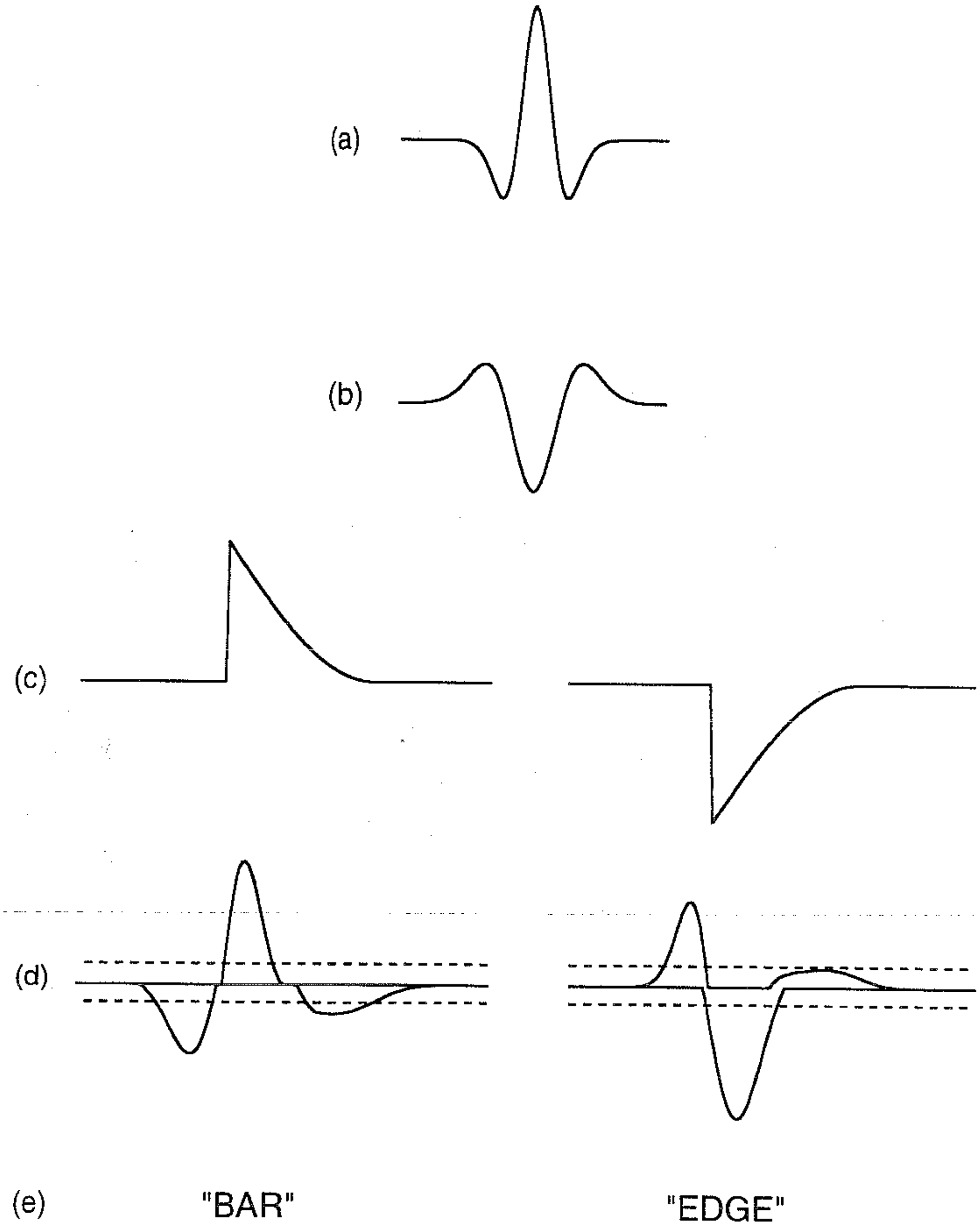

Figure 2. Application of Moulden and Kingdom's (1990) model to increment and decrement half-cusp stimuli. In the original model a range of filter sizes are involved, but only the operation of one On–Off filter-pair is shown here to demonstrate the principle of the model. (a) On-centre 2DG (second-difference-of-Gaussian) filter. (b) Off-centre 2DG filter with Gaussian space constant 1.5 times that of the On-centre filter. (c) Increment and decrement half-cusps. (d) Convolution of both On- and Off-centre filters with stimuli. The response of each filter is half-wave rectified, but for ease of exposition the half-wave rectified response of the Off-centre filter is shown as below-zero response activity. Dashed lines represent arbitrary thresholds. (e) The interpretation of the combined-filter response. See text for details.

according to the model, at least relative to detection threshold. The main purpose of this study was to test this prediction.

The measurement of the CCOB illusion in terms of the contrast threshold for discriminating the stimulus from its step-edge equivalent is best associated with the studies of the 'missing fundamental' carried out by Campbell *et al.* (1971, 1978). The missing fundamental stimulus is a square-wave with its fundamental harmonic removed. At spatial frequencies below some critical value the missing fundamental stimulus appears indistinguishable from a square-wave over a range of contrasts above detection threshold. The stimuli used in this study are essentially single-cycle versions of the stimuli employed by Campbell *et al.* (1971, 1978). They were obtained by multiplying periodic waveforms by a Gaussian envelope with a suitable space constant, and increment and decrement versions were obtained by centering the waveforms at phases 0 and 180 deg respectively.

To summarise: the main prediction of the study is that the contrast threshold for detecting the cusp stimulus and for discriminating the cusp stimulus from an equal amplitude square-bar, will be greater for decrement compared to increment versions of the stimuli.

2. METHOD

2.1. Apparatus

The stimuli were generated using the VSG2/1 Digital Signal Generator (DSP) hosted by a DELL 386 computer and displayed on a BARCO CDCT 6551 RGB monitor. The VSG2/1 DSP generates stimuli using 12 bits-per-channel (4096 levels) look-up-tables, whose values are selected from 14 bits-per-channel DACs (digital-to-analog converters). For this study all three RGB channels were set to the same DAC values, thus producing an achromatic display. The monitor was gamma-corrected by employing a look-up-table which had been Z-linearised after calibration with a UDT photometer. The photometer was centered on the middle bar of a one cycle-per-screen square-bar similar to that used in the actual experiments. The square-bar was generated with an approximately linearised look-up-table, and measurements were made at a range of contrasts. These measurements were then used to generate an accurately linearised look-up-table.

2.2. Stimuli

The luminance profiles of the stimuli are shown in Fig. 3. They were generated by multiplying sine-wave, square-wave and missing fundamental waveforms by a Gaussian envelope to produce respectively 'round-bar', 'square-bar', and 'cusp' patterns. The round-bar luminance profile was defined as:

$$L(x) = M + A\cos(2\pi f x + \rho)\exp(-x^2/2\sigma^2), \tag{1}$$

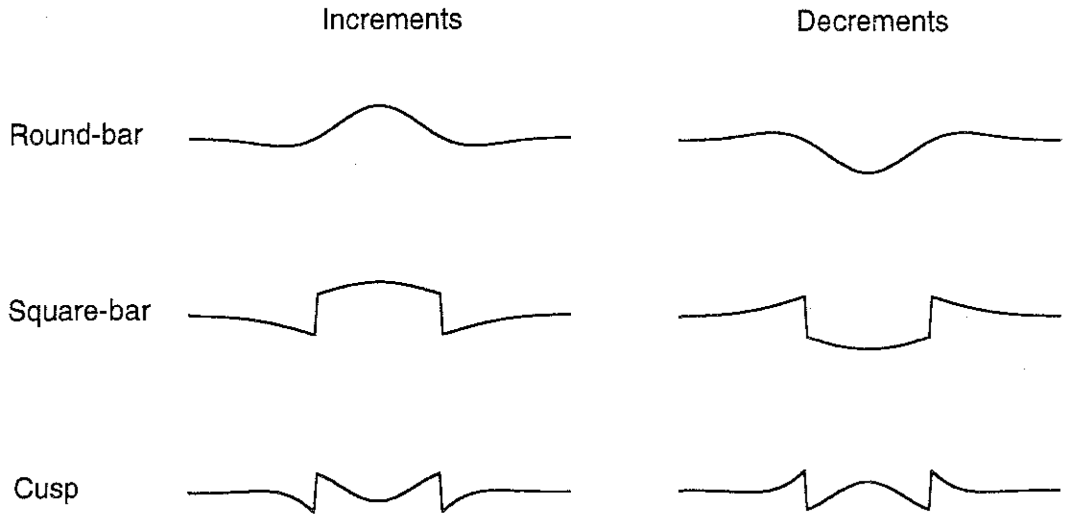

Figure 3. Luminance profiles of the stimuli used in this study.

where M is mean luminance, at 32 cd m^{-2}, A amplitude, f spatial frequency, ρ phase and σ the space constant of the Gaussian envelope. σ was always set to a quarter of a cycle, or $1/4f$ deg. ρ was set to 0 radians to produce an increment round-bar, or π radians to produce a decrement round-bar. The square-bar stimulus was a similarly Gaussian enveloped square-wave. The cusp stimulus was obtained by subtracting a sine-wave of amplitude $4/\pi$ (relative to the square-wave) from the square-wave, and then multiplying the stimulus by the Gaussian envelope. The amplitude A of both the square-bar and cusp stimuli were defined as the amplitude of the square-wave from which they were derived. Thus the cusp stimulus was the difference between a square-bar and a round-bar of amplitude $4/\pi$. Stimulus contrast was defined in terms of dB of attenuation, in which $\text{dB} = 20\log(1/C)$, where C, Michelson contrast, was defined as A/M.

Eight spatial frequencies of the underlying waveforms were altogether employed, from 0.03125 to 4 cyc deg^{-1} in octave steps, though not all spatial frequencies were represented in each subject's data. Viewing distance was 73.5 cm except for the 0.03125 cyc deg^{-1} condition where it was set to 36.5 cm, i.e. half the value. This was necessary to ensure that for this condition a full cycle of the waveform was present.

2.3. Subjects

Two subjects were employed, FK and KH. Both had normal, uncorrected, vision and were experienced psychophysical observers. FK was the author of the study, while KH was an undergraduate volunteer who was naive as to the purpose of the experiment.

2.4. Procedure

A 2IFC (two interval forced choice) procedure was employed for all experiments. In the detection task, the subject was required to indicate on each trial in which interval the stimulus was present, by means of a button press. In the discrimination task, which established the contrast threshold for discriminating a square-bar from an equal-in-contrast cusp stimulus, the subject was required to indicate in which interval the square-bar was present. Contrast thresholds were obtained using a standard two-up, one-down staircase procedure (Levitt, 1971), which establishes the contrast threshold at the 70.7% correct level. The session was terminated after ten reversals of the staircase, and the threshold calculated as the mean dB value over the last eight reversals. Three thresholds for each condition were obtained in this way, and the mean and standard error of the three thresholds define the data points displayed in each figure.

2.5. *Experiment 1. Detection and discrimination thresholds for round-bar, square-bar and cusp stimuli*

The first experiment measured contrast thresholds for detecting round-bars, square-bars and cusps, and contrast thresholds for discriminating cusps from square-bars. The results are shown in Fig. 4. Note that because contrast thresholds are given in dB, the ordinates of Fig. 4, as well as subsequent figures, may be considered as representing contrast sensitivity. In examining Fig. 4 it is useful to consider the range of spatial frequencies below and above 0.25 cyc $\deg^{-1}$ separately. Below 0.25 cyc $\deg^{-1}$, cusp and square-bar detection thresholds are very similar and show a more-or-less flat dependence on spatial frequency. Round-bar detection thresholds, and square-bar versus cusp discrimination thresholds are also very similar, and both show a marked decline at low spatial frequencies. Above 0.25 cyc $\deg^{-1}$, square-bar and round-bar detection thresholds, and square-bar versus cusp discrimination thresholds are all very similar, with cusp detection thresholds alone showing a marked decline at high spatial frequencies.

This pattern of results is very similar to that found by Campbell *et al.* (1978), whose measurements were made on periodic versions of the stimuli. Campbell *et al.* argued that such a pattern of results would be expected on the basis of independent, linear, narrowband-in-spatial-frequency detectors subserving threshold luminance vision. Applying Campbell *et al.*'s reasoning to our stimuli, one supposes that below 0.25 cyc $\deg^{-1}$ the square-bar and cusp stimuli are both detected by mechanisms predominantly sensitive to the 3rd harmonic in the stimuli (which is the lowest harmonic in the cusp stimulus). This is so since the fundamental harmonic in the square-bar will be below its own detection threshold, as evidenced by the round-bar threshold data. As Campbell *et al.* also found with their periodic stimuli, one finds here that the contrast at which the cusp and square-bar become discriminable is close to the contrast at which the round-bar reaches its own independent detection threshold (the exact prediction for this result is described below). Above 0.25 cyc $\deg^{-1}$, the pattern of results is different because the square-bar detection thresholds are now determined by sensitivity to the fundamental, whereas the cusp detection thresholds continue to be determined by sensitivity to the 3rd harmonic. Thus cusp versus square-bar discrimination thresholds are now similar to square-bar detection thresholds, since subjects could identify the square-bar stimulus in the square-bar versus cusp discrimination task simply as the stimulus which was most visible in the forced-choice pair.

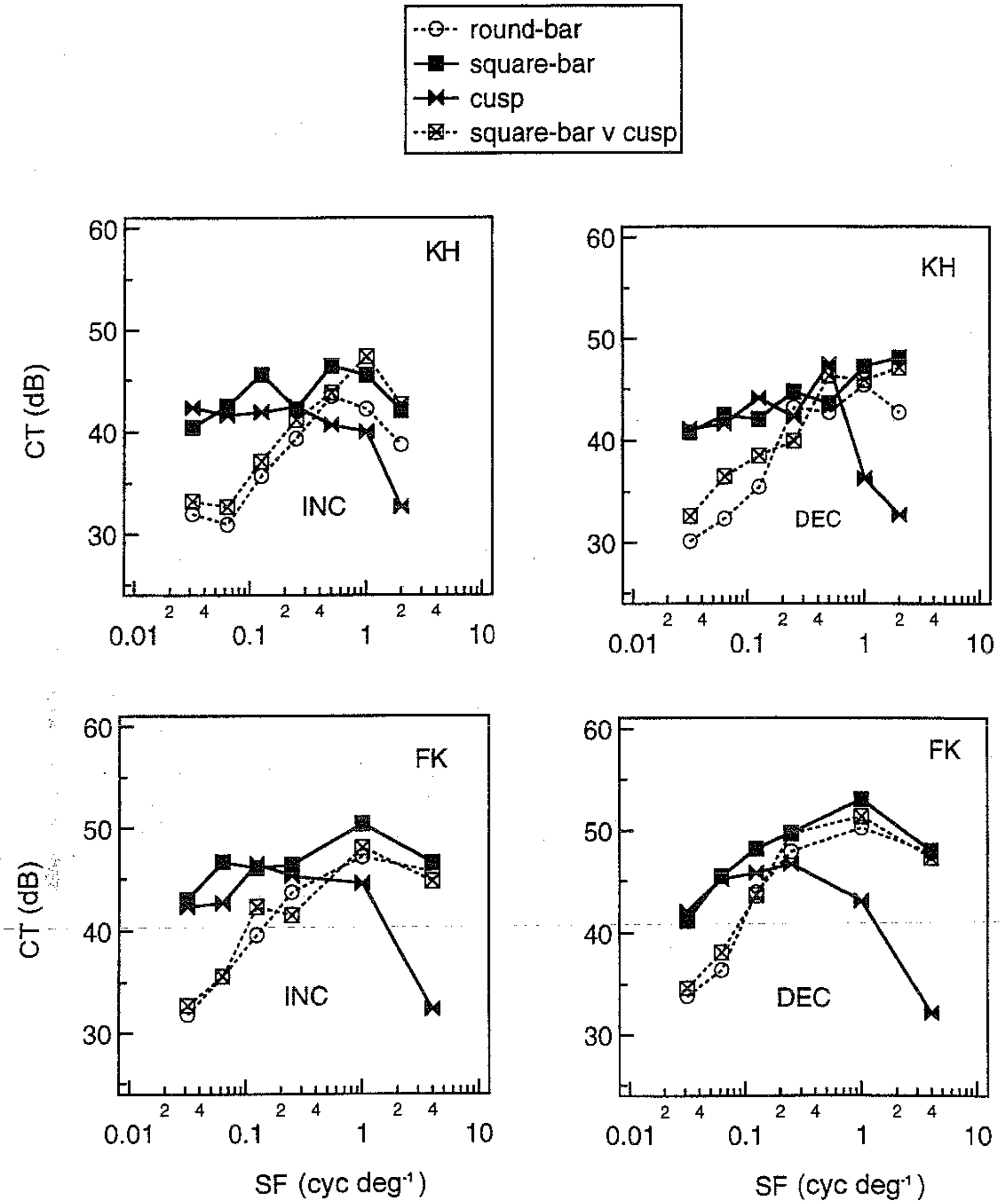

Figure 4. Results of Experiment 1. Plotted are contrast detection thresholds for round-bar, square-bar and cusp stimuli, and contrast discrimination thresholds for square-bar versus cusp stimuli, as a function of spatial frequency. The ordinate gives contrast thresholds in dB, which can be regarded as a measure of contrast sensitivity. Left-hand graphs are for increments, right-hand graphs are for decrements.

To test directly the prediction based on Campbell *et al.* that cusp versus square-bar discrimination thresholds are determined by sensitivity to the round-bar, one needs to add 2.097 dB (the equivalent in dB of $4/\pi$) to the round-bar threshold data for the purpose of comparison. Figure 5 shows the *difference* between the prediction (round-bar threshold $+$ 2.097) and the actual cusp versus square-bar thresholds. As

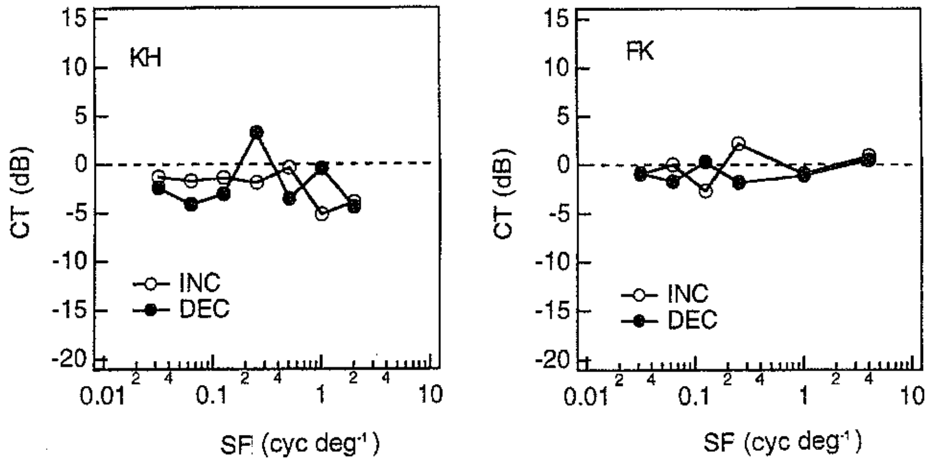

Figure 5. The difference between the predicted and actual cusp versus square-bar discrimination thresholds, with both increment and decrement data shown on the same graph for direct comparison. The predicted discrimination thresholds are given by adding 2.097 dB to the round-bar detection thresholds. See text for further details.

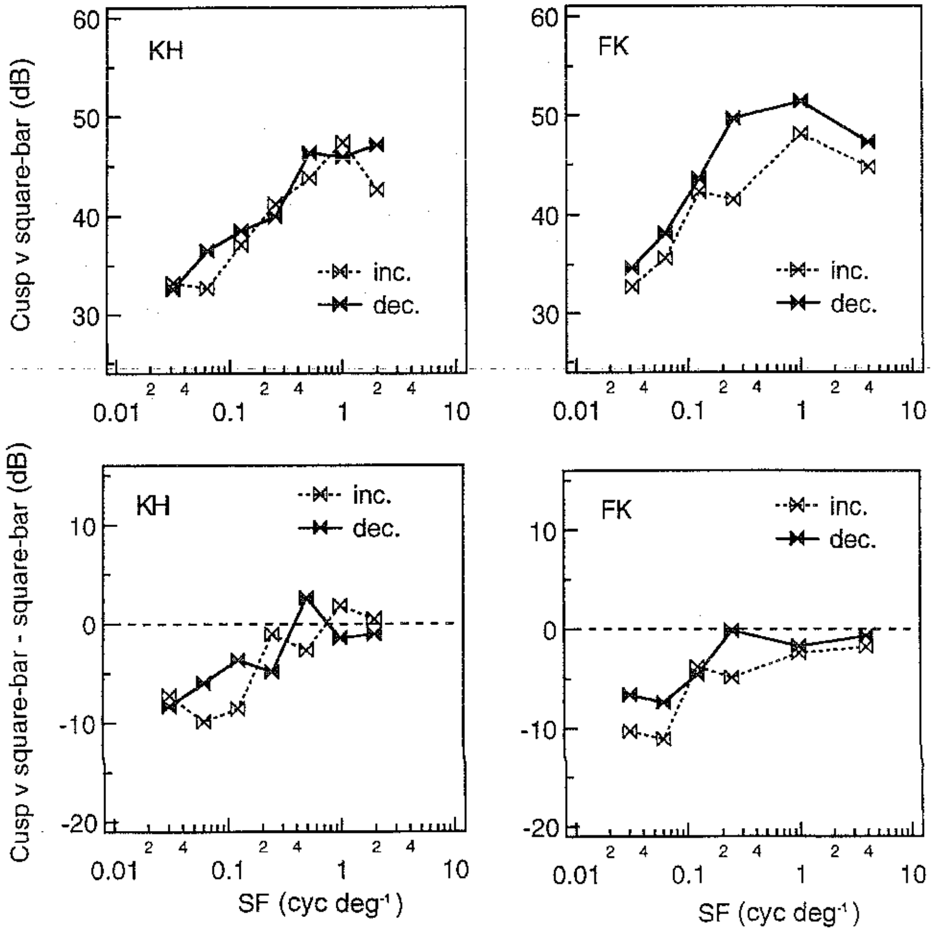

Figure 6. The two top graphs plot cusp versus square-bar discrimination thresholds, with each graph showing both increment and decrement data. The two bottom graphs plot the same data when normalised to square-bar detection threshold.

the figure shows the values are all close to zero, though for KH they generally fall just below the zero lines by an average of about 2 dB. The linear systems prediction is thus reasonably well supported by the data.

The main purpose of this study was to compare cusp versus square-bar discrimination thresholds for increments and decrements, the prediction being that discrimination thresholds would be higher for decrements. The data can be presented in one of two ways: either in terms of the absolute threshold for cusp versus square-bar discrimination, or in terms of the difference in thresholds between cusp versus square-bar discrimination, and square-bar detection. Although the latter method is arguably superior since the data are normalised to detection threshold, Fig. 6 plots the results under both criteria. Since thresholds are in dB, the prediction is that the decrement data should fall below that of the increment data. However, it is clear from the figure that this prediction is not upheld. If anything there is a hint, particularly in FK's data, that the decrement data falls above the increment data.

2.6. *Experiment 2. The amount of fundamental needed to restore a cusp stimulus to its square-bar appearance*

A second way of testing for a polarity-based asymmetry in cusp stimuli is to measure the amplitude of a round-bar needed to make the cusp appear indistinguishable from a square-bar, at contrasts where the cusp would normally appear 'scalloped'. This method therefore tests for a polarity-based asymmetry in cusp versus square-bar discrimination at contrasts higher than those employed in the previous experiment. At contrasts below the threshold for discriminating a cusp from a square-bar, no amount of round-bar need be added to make the cusp indistinguishable from a square-bar, by definition. On the other hand at contrasts above the threshold for discriminating a cusp from a square-bar, one in theory requires up to $4/\pi$ round-bar amplitude to make the cusp stimulus indistinguishable from the square-bar. On the basis of

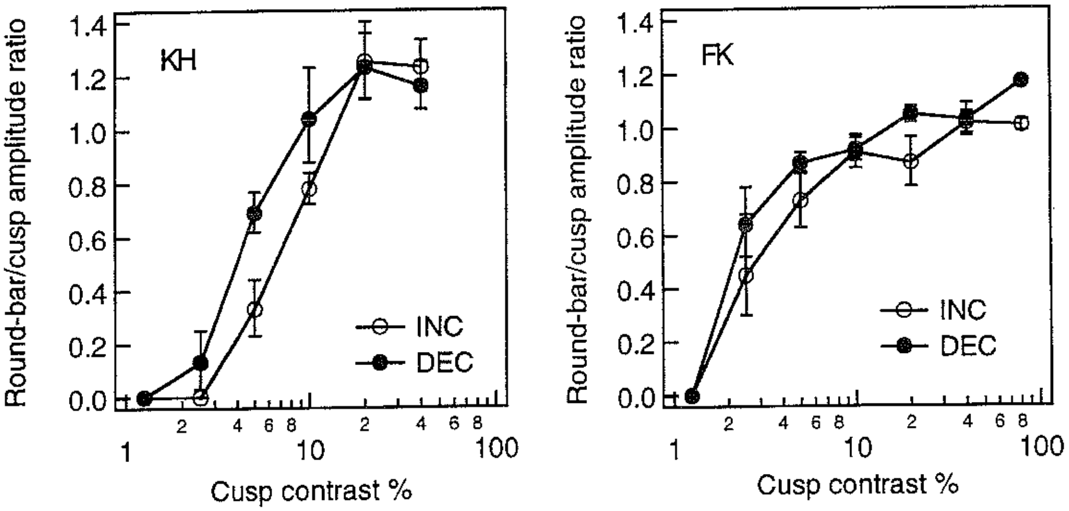

Figure 7. The figure plots the relative amplitude of a round-bar needed to make a cusp indistinguishable from the square-bar, as a function of the contrast of the cusp in percent C. Relative round-bar amplitude is defined as the ratio of the amplitude of the round-bar to that of the cusp.

the main hypothesis of this study, the prediction is that less round-bar amplitude will be needed to make a decrement cusp appear indistinguishable from a square-bar compared to an increment cusp. This was tested using 0.0625 cyc deg^{-1} cusp and square-bar stimuli at a range of contrasts. For each cusp/square-bar contrast, the amplitude of a round-bar necessary to make the cusp indistinguishable from the square-bar was measured. The results are shown in Fig. 7. The ordinate is the ratio of the round-bar amplitude threshold to the amplitude of the cusp, and the abscissa the contrast of the cusp in per cent C (rather than dB). According to prediction, the decrement functions should fall below those of the increments. This is clearly not the case for either subject: there is instead a small superiority for the increments. As with the first experiment therefore, the predicted increment-decrement difference in cusp versus square-bar discriminability has not been borne out by the data.

3. DISCUSSION

The main purpose of the experiments described here was to test the prediction that the contrast threshold for discriminating a cusp from an equal contrast square-bar would be greater for decrement than increment versions of the stimuli. This prediction followed from Moulden and Kingdom's (1990) explanation for the increment-decrement difference in the magnitude of illusory brightness found with cusp figures, which was that it was due to larger Off-centre compared to On-centre receptive fields. However, no evidence was found to support this prediction. Neither the absolute thresholds for cusp versus square-bar discrimination, nor the detection-threshold-normalised discrimination thresholds were found to be greater for decrements than increments. Moreover, the amplitude of an added round-bar needed to make a cusp appear indistinguishable from a square-bar was found to be no less for a decrement than an increment, over a range of contrasts. These results suggest that the explanation for the polarity-based asymmetry found in the magnitude of induced brightness in CCOB figures is unlikely to be due to different sized On- and Off-centre receptive fields. Although these results are negative with respect to the initial hypothesis they are interesting because they reinforce the idea that the mechanisms which are responsible for the illusory brightness in CCOB figures are not wholly commensurate with the mechanisms which enable those figures to be discriminable from their step-edge equivalents (and see Burr, 1987, for a similar conclusion).

It is tempting to seek an alternative explanation for the polarity-based asymmetry in induced brightness found with CCOB figures in terms of the early luminance-based nonlinearity believed to underlie the slightly better detection of decrements compared with equal amplitude increments (Legge and Kersten, 1983). Indeed, in this study both subjects' data in the first experiment showed slightly better decrement than increment detection, by 2.0, 0.9 and 0.4 dB respectively for the round-bar, square-bar and cusp stimuli when averaged across spatial frequency and subject. This asymmetry in simple detection thresholds is readily explained as a consequence of the divisive gain factor due to light adaptation. On the assumption that luminance gain is determined either by the mean luminance of the stimulus (Legge and Kersten, 1983), which in this study is not the same as background luminance and hence different for increments and decrements, or its minimum luminance (Whittle, 1986; Kingdom and Whittle, 1995), the divisive gain factor must be smaller for the decrements than the increments[1]. However, it is not clear why this should result in the larger magnitude of induced brightness for decrement compared with increment CCOB figures found in previous studies. Since the polarity-based asymmetry has been revealed through measurements made by matching the brightness of the region of interest to that of a bar of variable amplitude and polarity, the matching stimulus would be subject to the same nonlinearity as the test stimulus, and thus would not be expected to reveal any asymmetry (Moulden and Kingdom, 1990). It must be concluded therefore that an early luminance-based nonlinearity is also not the explanation for the polarity-based asymmetry in CCOB figures. It seems most likely that the true explanation lies in the rules which combine brightness information across different spatial scales, and further experiments will be needed to determine the exact cause.

This study also generalised the original findings by Campbell *et al.* (1971, 1978) obtained with periodic waveforms to single-cycle versions of the stimuli. Contrast thresholds for discriminating cusp from equal-in-contrast square-bar stimuli were predicted from round-bar thresholds with reasonable accuracy. Such findings provide an interesting test for current models of brightness coding, because they combine an exact prediction from linear systems analysis with a powerful brightness illusion. Indeed, it might seem curious that a cusp stimulus changes its appearance from a square-bar to a cusp only when the round-bar component missing from the cusp becomes independently detectable. Why should we notice a change in the appearance of a stimulus once a component that is not actually present in it becomes visible in its own right? There is no difficulty with this notion however once one accepts the distinction between the rules which govern the appearance of a stimulus and the rules which govern its discriminability from others. In the Introduction we described how Moulden and Kingdom's (1990) model had employed a *symbolic* interpretation of the neural image to account for the appearance of the stimulus, the neural image of the low contrast cusp being interpreted as an alternating sequence of edges with uniform regions in between. This is an old idea, perhaps first stated explicitly by Ratliff (1972), but used more recently in a number of models of early visual processing (e.g. Watt and Morgan, 1985; Kingdom and Moulden, 1992). Whether models which incorporate such symbolic stages for generating representations of surface brightness are also able to account quantitatively for the detection and discrimination threshold results described here remains to be determined.

In conclusion, the asymmetry in induced brightness between increment and decrement CCOB figures found in previous studies does not appear to have a parallel in the measured thresholds for discriminating cusps from square-bars. It is unlikely therefore that the asymmetry reflects a difference in the relative size of receptive fields sensitive to increments and decrements. Future experiments will be needed to determine its exact cause.

Acknowledgement

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NOTE

1. A feature of the results relevant to this point is the ordering of the magnitude of the superiority of decrement over increment detection: round-bar > square-bar > cusp. This is precisely what would be expected on the divisive gain argument. Because contrast was defined *prior* to the stimuli being Gaussian enveloped, the effect of the enveloping was to make an otherwise equal-in-contrast decrement greater in contrast than an increment. If contrast is defined as $C = (L_{\max} - L_{\min})/(L_{\max} + L_{\min})$, the ratio of decrement to increment contrast after enveloping is equal to $(2L_b + D_a)/(2L_b - D_a)$, where L_b is background luminance and D_a the absolute difference between the peak and trough amplitudes of either stimulus. The bigger the value of D_a the bigger the difference in increment-decrement contrast. The relative values of D_a calculated at threshold were found to be round-bar = 1.0, square-bar = 0.5 and cusp = 0.0 when normalised to the rould-bar stimulus, and this accords well with the ordering of the differences in decrement-increment sensitivities.

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