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# The combination of filters in early spatial vision: a retrospective analysis of the MIRAGE model

**Michael J Morgan**
Institute of Ophthalmology, University College London, Bath Street, EC1V 9EL, UK;
e-mail: m.j.morgan@ucl.ac.uk
**Roger J Watt**
Department of Psychology, University of Stirling, Stirling FK9 4LA, UK
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**Abstract.** Since the discovery of spatial-frequency-tuned channels in the visual system, most theories attempting to account for pattern encoding have assumed that the filters can be independently accessed and flexibly combined. We review here an alternative model, 'MIRAGE', in which the filters are inflexibly combined before pattern analysis. In the MIRAGE model the half-wave rectified outputs of all spatial-frequency channels are combined before locating spatial zero-bounded regions in the neural image, which serve as the spatial primitives for pattern analysis. We describe the evidence that led to this model, and review recent evidence on the rules of filter combination.

## 1 Introduction

Psychophysical and physiological evidence tells us that there are mechanisms in the visual system tuned to specific bands of spatial frequency (Campbell and Robson 1964; De Valois et al 1982). These mechanisms have since formed the central theme of most models of the early stages of human vision. We adopt the normal terminology of describing each spatial-frequency-selective mechanism as a filter. Each of the different filter mechanisms could produce a potential response at every point in visual space, subject to its coverage of the retina. Any difference between two images will result in differences in the response values of the outputs of various filters at various places in visual space. There is thus a massive set of data available to the visual system with which to analyse any given image or to distinguish differences between two images. Subject only to certain boundary conditions of spatial and luminance/contrast resolution, there are no image differences that would not be represented as filter output differences. This massive set of data should be regarded as nothing more than a registration of the stimulating image. There are several general approaches to the issue that follows of how the data can be used for the performance of visual tasks.

This paper revisits a specific proposal that we made concerning this question. The MIRAGE model (Watt and Morgan 1985) is rather different from others that have been proposed since, and we wish to start by explaining the key conceptual differences.

### 1.1 *Approach 1: Random access in spatial frequency and space*

The simplest approach to conceive is one in which the output of any filter at any point in space can be taken, and if need be combined with any others, to produce a measurement that leads to a response. Thus, for example, the model of Wilson and Gelb (1984) for the discrimination of spatial separation (for small separations) is able to demonstrate that the limits on performance found psychophysically are close to what would be expected from known limits of differential responsiveness of the individual filters. The model shows that just discriminable stimuli cause just detectable variations in filter outputs. An identical approach is used by Wilson and Richards (1989) to account for aspects of line curvature discrimination. The measurement applied to the bank of filter outputs is different, but the limitations on performance are found to be similar: just discriminable stimuli cause just detectable variations in filter outputs.

There are two very significant assumptions of this class of model.

The first is that the bank of filter outputs, sampled in visual space, is the appropriate database for use. In essence what is assumed is that each filter output at each point in space is independently accessible.

The second assumption is that there is a high, perhaps unlimited, degree of flexibility in how the task can become compiled into a measurement on that database.

### 1.2 *Approach 2: Random access in spatial frequency, constrained access in space*

An alternative had previously been proposed that sought to explain the appearance of stimuli and to relate these early stages to visual computations more generally. The computational approach of Marr and Hildreth (1980) led to the proposition that only certain types of spatial configuration of filter response (zero-crossings) would be represented and therefore used at later stages of the visual system. The configurations were seen as edges and could be used, it was argued, as a sufficiently powerful representation of the grey-level image for most purposes.

Although this aspect was not well-developed in the theory, it seems clear that Marr and Hildreth envisaged unconstrained access to different spatial-frequency outputs. These could be used for mutual confirmation (zero-crossing alignment constraint), but for this to be possible they had to exist independently. Independent access to different spatial scales was also a feature of the second Marr–Poggio theory of stereocorrespondence (Marr and Poggio 1979) in which matches at a coarse scale guided matches at fine scales.

There have been at least two more recent variants on the same lines. The MIDAAS model of Kingdom and Moulden (1992) [recently extended to two dimensions by Moulden and MacArthur (in preparation)] is similar to Marr and Hildreth's model in that it starts by locating features in each spatial-frequency band. The key difference from MIRAGE is that the interpretation rules are applied to each channel before combination, and the results of the symbolic analysis are combined. In other words, if each channel finds an edge, in different places, there will be two edges in the final combination.

The local-energy model (Morrone and Burr 1990; Burr and Morrone 1994) employs a multi-scale analysis, and each scale separately convolves the image with matched pairs of odd- and even-symmetric filters. The output of these pairs is combined by Pythagorean sum, and peaks in the output are used to locate edges and bars, depending on the relative strengths of the odd- and even-symmetric filters.

### 1.3 *Approach 3: Constrained approach in spatial frequency and space*

A different approach to the issue of how the filter outputs are used by the visual system was proposed by us (Watt and Morgan 1985). It was already known that there were defects in the view that the different spatial frequencies might be detected independently (Henning et al 1975). We accumulated a range of data indicating that, in other respects, pattern at some spatial frequencies could not be processed independently of irrelevant pattern at other spatial frequencies (Morgan and Watt 1982; Watt and Morgan 1983, 1984, 1985).

To account for these data and others we constructed a model in which the outputs of different spatial-frequency filters were combined before they could be accessed for performing tasks. As will be described below, a key feature of the combination was an essential nonlinearity that was needed to preserve high spatial resolution.

A second distinguishing aspect of the MIRAGE model is the proposition we made that only certain spatial configurations were available for later stages of visual processing. In the same spirit as (and inspired by) the Marr-and-Hildreth approach, we proposed that zero-bounded regions of response were to be treated as indivisible spatial primitives. Thus, performance of visual tasks had to be based on certain specified simple descriptors of zero-bounded regions.

## 2 The specific details of the MIRAGE model

The logic of the MIRAGE model is based on the two propositions that spatial-frequency filter outputs are combined (specifically summed) at every point in space and that zero-bounded regions of the resultant response are the basic spatial primitive. Evidence for each proposition had been obtained, but the two at first glance contradict each other. If we take two gratings of different spatial frequency (say separated by two octaves) and process them in this fashion, then the only primitives that will result will correspond to the spatial structure of the lowest spatial frequency. We characterised this as being a problem of resolution and recognised that the solution to the problem lay in introducing a stage of segregating responses according to sign (ie half-wave rectification in on-centre and off-centre filters). Resolution is preserved, provided the summation across spatial frequency applied only to the responses of like sign. Thus all positive responses across spatial frequency are summed, and separately all negative responses are summed. This results not in one response per point in visual space, but two. In any one filter the positive responses and negative responses are mutually exclusive, but they are not across different spatial frequencies. Thus the combination of two gratings considered above now results in two types of primitive: large, coarse scale ones, and small, fine scale ones. Watt (1988) showed that the effect of this was to preserve the spatial pattern at the two extreme spatial scales in any signal.

The main stages in the model are as follows. We flag with (*x) an assertion that will be assessed in the later discussion.

(1) The primitive spatial code involves both a range of spatial filters and positional signals (*a).

(2) The image is initially filtered by a bank of difference-of-Gaussian (DoG) filters (*b) (or similar) of different centre spatial frequency. The result of this is a set of filtered images. The filters span a range of space constants (SDs) from 0.35 to 2.8 min arc, and all have the same unadapted amplitude impulse function (*d) and equal noise amplitude. These filters have a linear bandwidth that is proportional to centre frequency (ie their bandwidth expressed as a proportion of their centre frequency is constant) (*c).

(3) The filters have independently adjustable gain (*g).

(4) Each filtered image is half-wave rectified. Luminance increments are encoded in the response of on-centre filters and decrements by off-centre filters. On-centre and off-centre filters correspond to on-centre and off-centre retinal ganglion cells, and these two streams of processing are kept separate until a stage after cross-scale filter combination (*e).

(5) Before any further analysis, the half-wave rectified outputs from all the filters in the on-stream are summed into a single on-signal. The outputs of the off-stream are similarly but independently summed. Thus, for each point in space there are two signals: the summed response of all on-filters centred at that point in space; and the summed off-response (*h).

(6) The spatially distributed pattern of activity of the summed filter responses is analysed by isolating zero-bounded regions of response and measuring the location, spread, and mass of each. The pattern of zero-bounded regions is then interpreted according to a set of rules that determines whether each region belongs to an edge or bar, or belongs to an ***n*** area with no activity. For example, the code for an edge is a region of on-activity bounded on one side by a zero region and on the other by a region of off-activity.

An example of the MIRAGE transform for bars and edges is illustrated in figure 1.

### 2.1 *Recent relevant evidence on the details of MIRAGE*

We now consider each of the points flagged in the above list in the light of more recent evidence:

(*a) *Positional coding.* At the time MIRAGE was developed, the success of Fourier analysis in describing adaptation and masking phenomena had led to a widespread

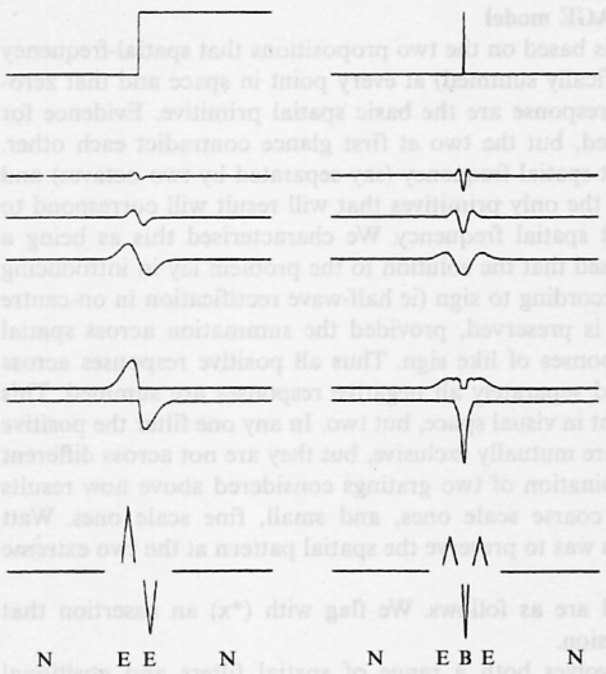

**Figure 1.** MIRAGE rules for interpreting the sequence of primitive elements. In the top row are shown the two basic stimuli: a step edge and a point. Beneath this are shown the responses of a range of filters to the stimuli. In the third row the signals resulting from half-wave rectification and addition cross filters are plotted, and beneath these the list of primitives. A [RESP] is shown by a chevron, of an amplitude proportional to its mass and a base width proportional to its SD, and located with its apex at the locus of the centroid. A [ZVSP] is shown by a horizontal bar. These are marked by the letters N, E, and B to state which interpretative rule is used. Reproduced with permission from Watt and Morgan (1985, figure 5).

hope that most if not all the phenomena of spatial vision could be explained without recourse to a positional code. This hope has not been realised. It is now generally accepted that there is at least some role for positional information. For example, the accuracy of encoding the distance between two spatially separated targets is not reduced by placing spatially jittered distractors between them (Morgan et al 1990). Similarly, the distance between two lines can be encoded independently of two spatially jittered flanks (Morgan and Ward 1985). The distance between two lines can be encoded when they have opposite contrast polarity (Morgan and Regan 1987). In all these cases, it is impossible for the separation to be encoded by the distribution of activity over linear filters of different scale.

The fact that positional encoding is needed in some cases does not mean that it is necessary in all. Texture analysis is a clear counterexample, in which it is unlikely that recognition of a texture depends on the spatial position of its elements. A hybrid model gaining acceptance is that early vision involves both positional coding for well-separated features, and nonpositional filter encoding for nearby filters that fall within the span of a local filter ensemble [see Levi and Waugh (1996) for a recent review of the evidence]. Evidence includes the fact that Vernier acuity for opposite-polarity bars is reduced if they are sufficiently close together (Morgan 1990).

(*b) *Filters.* We were originally noncommittal on the question of physiological locus for the various proposed stages of MIRAGE. This remains our position in some regards, although evidence concerning aspects of the neurophysiology of the cortex has accumulated to the point where some speculation is sensible. The filters that we used were broadly conceived of as being balanced centre–surround operators with a spatial-frequency bandwidth of around 1.5 octaves. The question of whether the filters needed to be circularly symmetric or oriented was not addressed since the data and phenomena we were concerned with could all be expressed in one dimension of space.

It is unlikely that the filters are to be found before the visual cortex. The DoG model of the retinal ganglion cell was originally proposed by Rodieck (1965) and has not been contradicted by subsequent evidence (eg Kaplan et al 1990; Croner and Kaplan 1995). Indeed, the standard way of deriving the impulse response function of retinal ganglion cells is to determine the Fourier transform of their contrast sensitivity functions in response to drifting sinusoidal gratings, fitted by a DoG model. A caution for modelers is that real cells have a strong DC component. For example, Croner and Kaplan (1995) found that the average ratio of surround/centre gain is 0.55. This differs from Marr's idealised retinal ganglion cell, which was given a perfectly balanced surround/centre gain, in order to make it approximate most closely to the Laplacian of a Gaussian, which would be preferred on theoretical grounds (Marr and Hildreth 1980). Even so, the retinal filters could suffice for the MIRAGE scheme, if there was a spread of spatial frequencies available at each point in visual space. There is some scatter in receptive field size at each retinal eccentricity, of which much, but not all, is attributable to the larger size of parasol (P-beta) cells relative to midget (P-alpha) cells. Receptive field size of both ganglion cell classes increases with eccentricity, and that of parasol cells increases relatively more rapidly (Croner and Kaplan 1995, figure 13). The relative proportion of parasol cells increases with eccentricity (Dacey 1994). Taken overall, however, the evidence on this last point seems to point away from multi-scale analysis and this would mean that the retina could not be the site of MIRAGE.

Cortical simple cells in primates are also well-modelled by DoG functions, although a parametric spatial phase offset between centre and surround is required to produce the best possible fits between models and data (Hawken and Parker 1987). Neurons in V1 have significantly narrower bandwidths than LGN neurons (eg De Valois et al 1982), which is further evidence that the retina is not the site of the MIRAGE first-stage filters. Psychophysical masking data (Wilson et al 1983) reveal spatial-frequency bandwidths at intermediate and high spatial frequencies that are much narrower than those ever reported for retinal ganglion cells, but are in excellent agreement with De Valois et al (1982).

Spatial-frequency bandwidths of neurons in V2 and V4 are slightly greater than those in V1 (Desimone and Schein 1987; Levitt et al 1994) but not so large as those predicted by the MIRAGE addition across all frequencies. If this is indeed the case, it follows that the MIRAGE transformation occurs later than V2 and V4 and that neurons in these areas are not directly accessible for shape encoding, any more than those in V1 are (He et al 1995, 1996).

In summary, the DoG model of spatial filters remains useful, but we do not know where the filters postulated by MIRAGE and other models should precisely be located. Multiple-tuned mechanisms could arise from any of the following, singly or in combination: (1) different sizes of each class of retinal ganglion cell at each eccentricity; (2) different classes of retinal ganglion cells (parasol vs midget) at each retinal locus; (3) changes in receptive field size with eccentricity; (4) second-stage cortical filtering.

(*c) and (*d) *Bandwidth and amplitude of early filters.* There is recent evidence that cortical simple cells (V1) have constant log bandwidth and equal peak sensitivity (see Brady and Field 1995 for review; also Brady 1997). Bex et al (1995) point out that flat spectrum noise would provide an abnormally high relative input to high-spatial-frequency channels, since natural images have a $1/f$ rather than flat spectral structure. They suggest that certain phenomena indicating high-spatial-frequency masking of low frequencies may depend upon the use of flat masking spectra.

(*e) *Half-wave rectification.* There were two reasons for incorporating half-wave rectification of the signal in MIRAGE. One was physiological: the separation of retinal ganglion cells into on-centre and off-centre classes, and the subsequent separate projection of these streams in the inner or outer portion of the inner plexiform layer of the retina, and subsequently in alternating layers of the LGN. The other arose from the modelling itself. We wished to combine additively across spatial scale, but it is evident that to do this linearly would compromise the resolution potentially available in highest-spatial-frequency channels. It is true that high-spatial-frequency channels will still produce

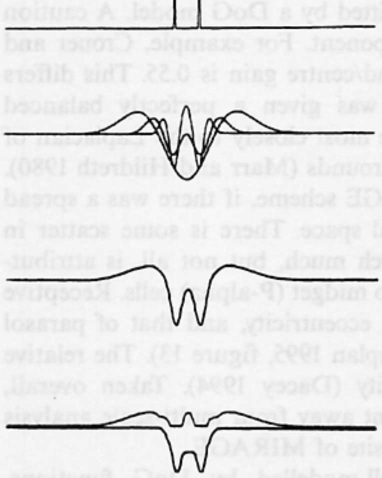

**Figure 2.** The MIRAGE mechanism for visual resolution. At the top is a stimulus comprising two bars separated by the minimum angle of resolution. In the second row the responses of a range of filters are shown superimposed. Note that only the smallest produces a central positive region of response and thereby resolves the double. In the third row the sum of the filter responses is drawn. Although there is some effect of the central positive region in the averaged response, it does not cross zero and would be difficult to detect in the presence of noise. In the bottom row the sum of the positive portions of the filter responses is shown, as is the sum of the negative portions. The resolution of the smallest filter is preserved.

features (local peaks and troughs) in the summed channel signal, but they would not produce zero-bounded regions, or any other easily identifiable feature. We found that resolution of the highest-spatial-frequency channel would be maintained if channel combination occurred only within half-wave rectified channels (figure 2).

*Physiology:* The distinction between on-centre and off-centre channels in the retina, and their continued separation up to LGN has not been questioned (see Dacey 1994). The metabotroic glutamate antagonist APB (2-amino-4-phosphonobutyrate) has been used to selectively block ON bipolar cells and thus putatively the ON-pathway (reviews by Schiller et al 1990; Schiller 1992) and this procedure has the expected effect of reducing sensitivity to incremental but not decremental contrast signals. There is thus a good reason for supposing that an approximate half-wave rectification is an important feature of early visual processing, and that it is sufficiently important for the two halves of the signal to be kept distinct, at least up to the level of primary visual cortex (V1). This is supported by the finding of Harris and Parker (1995) that there is independent stereoscopic analysis of luminance increments and decrements.

What happens in cortex remains more controversial. A common objection to MIRAGE has been to claim that linearity is recovered in cortical simple cells by recombining the ON and OFF pathways [see Shapley (1994) for a recent review]. This is at odds with the original Hubel and Wiesel (1959) model which derived the receptive field of simple cells from aligning geniculate afferents of the same class (ie all on-centre or all off-centre). Discussion of the Hubel-and-Wiesel models has centred on the question of orientational selectivity; rather less attention has been paid to the implication of their model that simple cells should inherit the approximate half-wave rectifying properties of their retino-geniculate ancestors (Morgan 1992a, 1994). Tolhurst and Dean (1990) argued that the rectifying response of LGN neurons should lead to nonlinear distortion in cortical neurons, such as frequency doubling and response to contrast reversal of gratings, if the simple additive model is correct. But observations in cat (Movshon et al 1978) and monkey (Shapley 1994) simple cells indicate linear summation without distortion.

On the other hand, some recent evidence has supported the Hubel-and-Wiesel model. APB does not affect orientational tuning of on-centre simple cells (Schiller 1992). Intracellular recording shows simple cell summation of geniculate afferents (Ferster et al 1996). The ferret is an interesting case because on-centre and off-centre afferents project to different patches of cortex, and these cells are still orientationally selective (Chapman et al 1991). The ferret is at least an existence proof that simple cells can be designed from half-wave rectified afferents. If ferret simple cells showed the quasi-linear behaviour of some cat and monkey simple cells this would be evidence that push – pull inhibition is not required for quasi-linearity.

We are unable to reconcile the conflicting physiological evidence about the role of rectification in cortex. A crucial test is whether the quasi-linear behaviour of some simple cells would survive reduction of the on-centre input by APB.

*Psychophysics:* Since the original MIRAGE proposal of half-wave rectification, a number of schemes have appeared in which full-wave or half-wave rectification is used to explain diverse 'non-Fourier' phenomena [for a review see chapters in Bock and Goode (1994)]. However, these have usually been proposed as higher-order adjuncts to a fully linear system of analysis. The MIRAGE proposal that half-wave rectification of the signal is an essential part of early spatial analysis has had little impact. This is in part because of the widespread conviction that the physiology supports linear cortical processing, whatever the uncertainties surrounding the nature of the afferent to simple cells might be (see above). However, we feel that another reason may be that there have been few attempts to explore the extent to which the predictions of a linear model are also predictions of MIRAGE.

In the case of texture analysis most models have employed full-wave rectification. The standard model is to filter linearly, rectify, and then apply a second-stage filter to find boundaries (Malik and Peroma 1990; Bergen and Landy 1991; Wilson and Richards 1992; Graham 1994). Rectification has the possible sensitivity advantage of using the information from both ON and OFF channels, but the second-stage filters could operate equally well on the output of ON or OFF channels alone. We know of no critical demonstration that full-wave rectification is required. One test would be to look at the efficiency of texture detection in constant-polarity versus mixed-polarity textures. In the case of stereo segmentation, Harris and Parker (1995) have found inefficient use of mixed-polarity dots, consistent with half-wave rectification. Morgan, Wilkinson, and Baker (in preparation) found that the just-noticeable-difference in dot density was somewhat lower in mixed-polarity than in constant-polarity patterns; and also that the density of dots of one kind of polarity could be judged accurately, independently of the presence of dots of the opposite polarity. They concluded that observers have access to both the half-wave and full-wave signal.

(*g) *The filters have independently adjustable gain.* An obvious objection (H S Smallman, personal communication) to the MIRAGE contention that there is obligatory pooling across spatial frequency before spatial analysis is that psychophysical studies indicate independently adaptable mechanisms (Blakemore and Campbell 1969). But in MIRAGE there is a stage of individual channel gain-control prior to channel combination. Logically, channels can be independently adaptable, but not individually accessible at a higher level. This truism is supported by at least two recent demonstrations that channels can be specifically adapted by stimuli that are indistinguishable to the observers from stimuli that do not cause adaptation (He et al 1996; Smallman et al 1996).

Since contrast adaptation is orientationally specific, its presumed locus is cortical. In retinal ganglion cells, as noted above, peak sensitivity is inversely proportional to receptive field area. Enroth-Cugell and Shapley (1973) attributed this to light adaptation to the integrated light flux within the receptive field centre. This is gain control, but it is local and individual to each receptive field rather than a class of cells having the same receptive field size.

(*h) *Obligatory combination of filter outputs.* There have been further reports of situations where the visual system apparently lacks the ability to independently access individual filters. For example, the body of work by Olzak, Thomas, and Wickens (Olzak and Thomas 1991, 1992; Thomas and Olzak 1996; Olzak and Wickens 1997) has led them to a broad conclusion that filter outputs are combined before further processing. One second-order mechanism mediates spatial-frequency discrimination and sums signals across orientations; another mediates orientation discriminations and sums across spatial-frequency bands. Georgeson (1992) (see also Georgeson 1994) has also proposed that different orientationally tuned channels are combined before any analysis for spatial features. This explains well the appearance of plaids composed of several oriented components, and shares with MIRAGE the key idea of an obligatory cross-channel combination. Georgeson (1994, page 163) proposes that an important advantage of combining narrow-band filters to synthesise broad ones is to suppress noise.

This concludes the review of recent evidence relevant to the main assertions of MIRAGE. We turn now to the experimental evidence originally put forward for MIRAGE and to possible alternative interpretations of that evidence.

### 2.2 *Evidence for MIRAGE*

2.2.1 *Appearance of luminance waveforms.* MIRAGE predicts the appearance of Mach bands and other illusory bar and edge phenomena such as the Chevreul illusion. However, since MIRAGE, several alternative multi-scale models have been put forward for explaining classical edge and bar illusions such as Mach bands. These include the local energy model (Morrone and Burr 1990), the MIDAAS model (Kingdom and Moulden 1992), and the model of Georgeson (1994). The different models of Mach bands have been reviewed recently by Pessoa (1996). There have been very few attempts to decide between the models experimentally. An exception is the analysis of Mach band data by Ross et al (1989) which they claim to be inconsistent with MIRAGE. The key issue is that Mach bands are not seen with sharp edges, but require a certain length of linear luminance ramp. Ross et al state (page 712) that MIRAGE predicts disappearance of bands when the ramp is smaller than 25 min arc, some 6 times larger than the value they observed. We are puzzled by this objection, because in our 1985 paper we specifically say that the critical width is predicted to be 5 min arc, which indeed we compared with data previously reported by Ross et al (1981). This value is determined by the space constant of the largest filter in MIRAGE, which is a Laplacian of a Gaussian with $\sigma = 2.8$ min arc.

Ross et al (1989) also state that MIRAGE fails to explain the dependence of Mach bands on spatial frequency and contrast. If we assume that the zero-bounded masses constituting the MIRAGE bar primitives must reach a threshold mass to be seen, it is evident that the threshold rises with spatial frequency, since the magnitude of the second derivative of the blurred profile rises similarly. This is what actually happens (Ross et al 1981, figure 5). It is unclear to us, therefore, why Ross et al say: "[MIRAGE] *wrongly* (our italics) predicts that sensitivity to Mach bands should become greater with increasing spatial frequency (due to the increased high frequency components) up to a critical frequency, whereupon the bands become edges".

2.2.2 *Blur discrimination.* If the observer has the task of saying which of two edges is more blurred, discrimination thresholds generally decrease as the reference blur decreases. But there is an anomaly. Below a certain criterion blur, thresholds rise again (Watt and Morgan 1983). In other words, there is an optimum pedestal blur, just as there is an optimum pedestal contrast for contrast discrimination (Nachmias and Sansbury 1974). If account is taken of retinal image blur through a 2 mm artificial pupil, and blur extent is expressed as the distance between the peak and the trough in the second derivative of the image of the blurred edge, we find that the optimum is at a peak-to-trough separation of 2–5 min arc (Watt and Morgan 1983, figure 5).

These data are not predictable from the performance of the highest-spatial-frequency channel, either in MIRAGE, or in Wilson's model, or in Marr et al's (1980) theoretically highest-spatial-frequency channel. The problem is that the highest-spatial-frequency channel carries information that would be well able to discriminate finer changes in edge blur below 5 min arc than human subjects can. In the MIRAGE model the half-wave rectified outputs of each filter are added to produce positive and negative zero-bounded masses, and blur is computed from the separation of the positive and negative masses, with a Weber's law dependence for just-detectable separation as function of reference separation. Informally, blur is computed from the separation of on-centre responses from off-centre responses, after pooling across spatial scale. The spatial separation of the peak and trough in the combined response for nearly sharp edges will tend to be greater than the edge blur itself, hence the raised thresholds at low blurs.

An alternative model for edge blur has been put forward by Georgeson (1994), involving comparison of the first and third spatial derivatives of the luminance profile. This explains invariance of edge blur with contrast (as does MIRAGE) and the matching of edge blur with sine waves. The latter data are held by Georgeson to be better predicted by his ratio rule than by the half-separation between peak and trough, but as he notes (page 160) this is not the MIRAGE model directly. A critical test of Georgeson's model against MIRAGE is needed.

Another model of blur discrimination has been proposed by Tolhurst and Tadmor (1997), mainly to explain discrimination between patterns of different fractal dimension, *f*. Their model is simply that the observer compares contrast energy of the two patterns through a filter with a peak frequency near to the peak of the contrast sensitivity function. The dipper function for blur can then be explained by the dipper function in contrast sensitivity (Nachmias and Sansbury 1974). The implication of their model is that blur discrimination thresholds would be raised by random contrast jitter between the two patterns, by an amount predictable from the variance of the contrast jitter. To the best of our knowledge this test has not been performed, but, as noted above, Georgeson has shown that blur discrimination is not affected by a *constant* difference in contrast between the reference and test stimuli.

Mather (1997) has modelled blur discrimination on the basis of the idea that the task is performed by discriminating just-noticeable-differences in the highest spatial frequency in blurred patterns. The dipper function arises, as in the MIRAGE model from intrinsic blur. As in the case of the Tolhurst-and-Tadmor model, the challenge will be to explain how blur comparison can be made between images with randomly differing contrasts.

2.2.3 *Spatially sampled stimuli.* One of the strongest objections to an independent-access model is the Harmon-and-Julesz (1973) 'Abraham Lincoln' effect, in which a block-sampled image of a face is unrecognisable, despite the presence in it of low-frequency components which would, in isolation, be sufficient for its recognition (compare the $D_{\max}$ limit for motion, below). This could be considered to be the result of masking, with intrusion into the low-frequency channel of spurious components introduced by sampling. However, Morrone et al (1983) showed that adding high-frequency noise, or randomising the phase relationships of the high-frequency components, could restore the visibility of a block-sampled Mona Lisa, which is incompatible with the masking interpretation [see also Morgan and Watt (1984) for a demonstration of phase randomisation].

The local-energy model explains sampling failure by the peaks in local energy introduced by block sampling, which distort visibility of peaks in lower-frequency channels after the channels have been combined (Burr and Morrone 1994; Morrone and Burr 1997). This account is similar to MIRAGE, in which there is no independent access to low-frequency channels. A different case in which high-frequency noise can distort the identification of a blurred edge in a phase-dependent manner is given in Watt and Morgan (1984).

One problem with the block-sampling effect is that it is difficult to quantify. We therefore attempted (Morgan and Watt 1982) to measure the effects of discrete sampling upon Vernier and stereoscopic acuity for gratings. The stimulus we used and the results we obtained are shown in figure 3. The stimuli consisted of 1-D Gabor functions in which approximately 2 cycles of a sinusoid were visible through a Gaussian window.

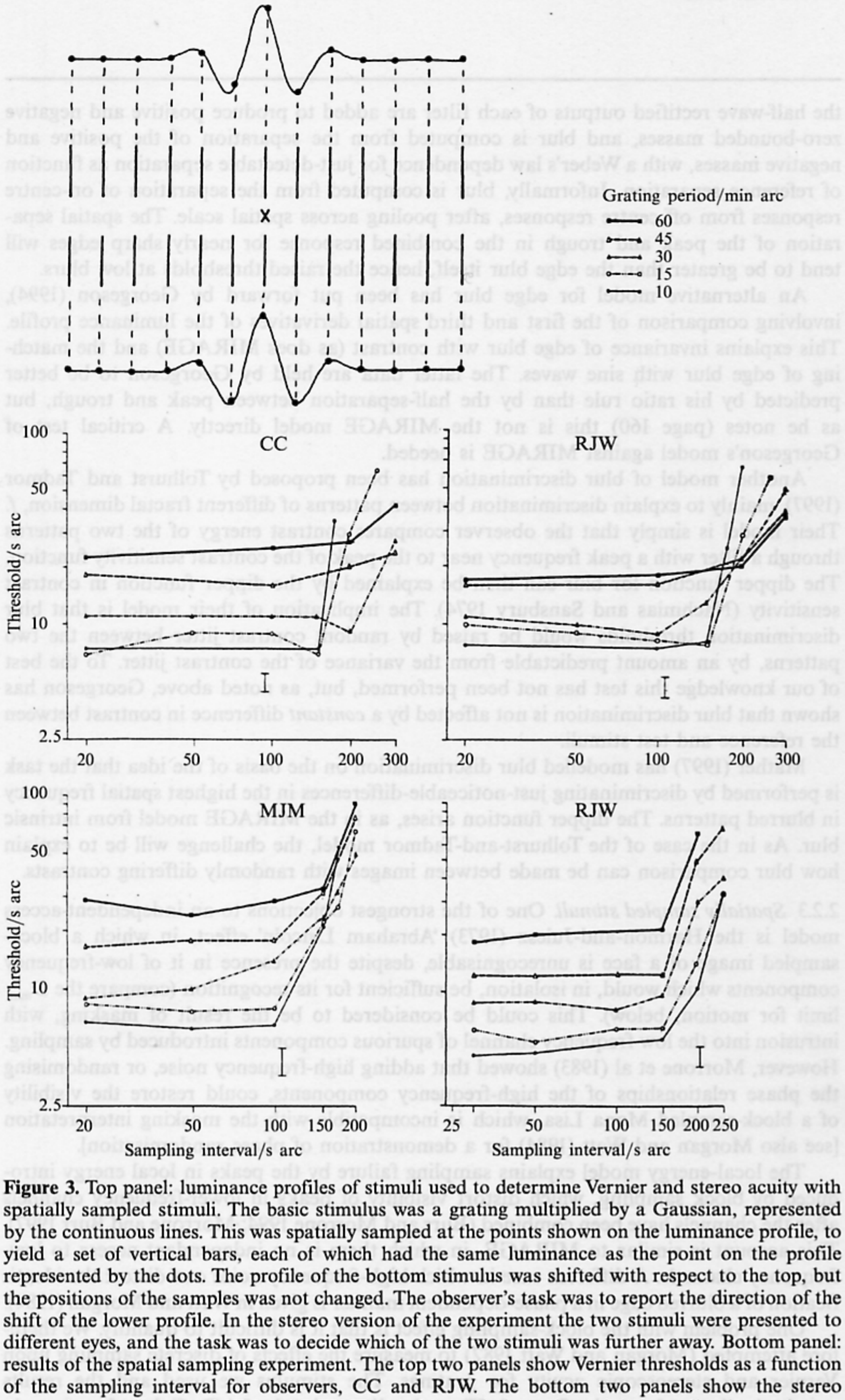

**Figure 3.** Top panel: luminance profiles of stimuli used to determine Vernier and stereo acuity with spatially sampled stimuli. The basic stimulus was a grating multiplied by a Gaussian, represented by the continuous lines. This was spatially sampled at the points shown on the luminance profile, to yield a set of vertical bars, each of which had the same luminance as the point on the profile represented by the dots. The profile of the bottom stimulus was shifted with respect to the top, but the positions of the samples was not changed. The observer's task was to report the direction of the shift of the lower profile. In the stereo version of the experiment the two stimuli were presented to different eyes, and the task was to decide which of the two stimuli was further away. Bottom panel: results of the spatial sampling experiment. The top two panels show Vernier thresholds as a function of the sampling interval for observers, CC and RJW. The bottom two panels show the stereo thresholds for observers MJM and RJW. Thresholds are independent of the sampling interval up to about 180 s arc (3 min arc) and then rise abruptly. The different curves are for different periods of grating. Vertical bars denote ±1 SE. [Reproduced with permission from Morgan and Watt (1982).]

The stimulus was then discretely sampled, effectively by multiplying it with a comb function. The energy of the fundamental sinusoid was kept constant by changing the refresh rate, which meant that the individual samples increased in intensity as the interval between them was decreased. Vernier or stereo thresholds were measured either with the samples in alignment, or with the sampling phase between the two stimuli randomised. In either case, the observer's task was to detect shifts in the underlying luminance profiles, independently of sampling phase. The result (see figure 3) was that thresholds were unaffected by discrete sampling frequencies of about 20 cycles $\text{deg}^{-1}$ or higher, but were increased by lower sampling frequencies. Note that at 20 cycles $\text{deg}^{-1}$ the samples were clearly resolved [this was formally demonstrated by Morgan and Watt (1984)] but hyperacuities in the 5 s arc region were still obtained. The sampling frequency at which interpolation broke down depended little on the spatial frequency of the sinusoid, and was much higher than the Nyquist limit for all the gratings.

The completely accurate interpolation implied by 5 s arc Vernier acuity with 150 s arc spacing between samples demonstrates that some degree of low-pass or bandpass spatial filtering is occurring. But if we were able to rely exclusively on the lowest frequency filter available ($\sigma = 2.8$ min arc in MIRAGE) we should be able to interpolate down to sampling frequencies of 5 cycles $\text{deg}^{-1}$. In MIRAGE, sampling failure results when the highest-spatial-frequency channels resolve the samples and distort the representation of the waveform in the combined channel output [see Watt and Morgan (1985) for the relevant analysis].

A challenge to our interpretation of these findings is that the detectability of gratings is also reduced by discrete sampling (Burr et al 1985). This would not be predicted from MIRAGE, or from other models employing linear filters. The explanation, as proposed by Burr et al could be that an early compressive nonlinearity reduces the effective amplitude of the sampled grating when more and more energy is poured into each individual sample as the sampling frequency decreases. From Burr et al's figure 4 we see that visibility for a $\sim 5$ cycles $\text{deg}^{-1}$ grating was the same at all sampling frequencies greater than $\sim 10$ cycles $\text{deg}^{-1}$, but that it declined at $\sim 20$ cycles $\text{deg}^{-1}$. This is quite close to the limit for sampling failure found in our experiments.

Since both Vernier and stereo acuity decrease with the square root of contrast, our effects could have been due to a reduction in effective contrast. The experiment should be repeated with all the sampled gratings at the same multiple of their contrast detection threshold. However, by comparing the visibility data of Burr et al with our own data we can predict that not all of the sampling failure will be accounted for by contrast reduction. The decline in visibility with increased sampling interval followed a power law with an exponent of $\sim -1.6$, whereas for stereo and Vernier acuity in our data the exponent was $\sim -2.9$, indicating a much more rapid deterioration. The contrast of our stimuli was 0.6 (60%) and the amplitude of the fundamental was kept constant by increasing the refresh rate of the display to compensate for the increased sampling interval.

In summary, spatial interpolation failure is not explained completely by an early compressive nonlinearity, and it is evidence against the independent accessibility of low-frequency filters.

2.2.4 *Contrast dependence of spatial hyperacuity.* Bowne (1990) has pointed to a difficult problem faced by models of spatial pattern acuity such as that of Wilson (1986), which attempt to explain discriminations in terms of the distribution of activity over different channels. This class of model implies that all discriminations are limited by contrast discrimination thresholds in the early channels. It is known that for contrasts above $\sim 3 \times$ detection threshold the contrast discrimination threshold $\Delta C$ rises with approximately the 0.6 power of contrast. The prediction is therefore that orientation and spatial-frequency discriminations should rise as a function of contrast with the same exponent as contrast discrimination. On the contrary, Bowne found that, in this range, spatial-frequency and orientation thresholds are nearly independent of contrast.

The findings concerning the effects of contrast on spatial discriminations are basically as follows. The following discriminations are largely independent of contrast: orientation, spatial frequency, and line separation. The following discriminations are dependent on contrast: Vernier offset, edge blur, Gaussian width, and detection of spatial discontinuities in edges (Morgan 1986). Bowne concludes that spatial-frequency and orientation discrimination thresholds are limited not by noise in early channels but by contrast-independent central noise, which he relates to the 'Weber's law for mass' in the MIRAGE model. It is true that MIRAGE incorporates a form of central noise which is involved whenever the metrical relationship between two or more primitives has to be decided. However, MIRAGE also incorporates propagating noise from early channels, which is assumed to be responsible for the dependence of Vernier acuity on contrast (Watt and Morgan 1984). MIRAGE therefore has the same difficulty as line-element models in explaining the contrast-independence of spatial-frequency discriminations.

In an answer to Bowne's objection to the line-element class of model, Wilson (1991) has suggested a hybrid model of spatial discriminations, in which some discriminations, like Vernier acuity for abutting bars, are performed by local filter comparisons, without a positional code; while others are limited by the accuracy of positional information, as in MIRAGE. Spatial-frequency discriminations fall into the latter category, and are limited by positional noise, which may arise from cumulative cone-position uncertainty. The advantage of postulating a limit depending on cone-position uncertainty is that it explains contrast independence, and also the rapid decline of hyperacuity in peripheral retina (Westheimer 1982; Levi et al 1985).

A remaining problem is that Vernier acuity, but not orientation acuity, is contrast-dependent. The most-widely accepted model of Vernier acuity is that it depends on the differential output of orientationally tuned channels (Findlay 1973; Sullivan et al 1992; Mussap and Levi 1996). This might seem to support the original MIRAGE contention that Vernier acuity depends on the localisation accuracy for spatial primitives. However, a possible rejoinder is that Vernier stimuli are broad-band in spatial frequency so that increasing their contrast recruits higher-spatial-frequency filters, which have higher orientational acuity (Morgan 1986; Burr and Wijesundra 1991). The idea that spatial pattern acuities are limited by contrast in their high-spatial-frequency components has also been put forward to explain the deleterious effects of motion upon Vernier and stereo acuity (Morgan et al 1983; Morgan and Castet 1995; Levi 1996). The different contrast dependences of Vernier and orientational acuity (with sine-wave stimuli) cannot therefore be regarded as a decisive problem for the Wilson (1986) model of Vernier acuity.

2.2.5 $D_{\max}$ *and motion.* The original MIRAGE model was not specifically designed to account for motion and it is unlikely that the same range of spatial filters is involved. It is also unlikely that movement is analysed by tracking the displacement of spatial features, such as zero-crossings, that can be detected in the time-frozen image. For example, Lu and Sperling (1995) show that the contrast threshold for detecting a moving grating is unaffected by the presence of a stationary pedestal of twice the threshold contrast, despite the fact that the pedestal prevents the zero-crossings of the stimulus from moving in a consistent direction.(1) Nevertheless, the spatiotemporal derivatives upon which motion detection depends will be strongly influenced by the spatial statistics of the image; and therefore the same question arises as for nonmoving stimuli: is there evidence for independent access to different spatial scales for moving stimuli?

(1) A computational analysis is provided on the Perception Electronic Supplement, http://www.pion.co.uk/perception/per0897/morgan.http and on the CD-ROM supplied with issue number 12 of the current volume.

The relevant evidence is as follows: the upper-displacement limit for random noise ($D_{\max}$, Braddick 1974) increases if the display is low-pass filtered (Chang and Julesz 1983) and is approximately inversely proportional to the centre frequency of bandpass filtered patterns (Cleary and Braddick 1990). This evidence is consistent with a bank of motion channels of differing centre frequency, each having its own $D_{\max}$ limit, as would be predicted from the elaborated Reichardt model (van Santen and Sperling 1985).

However, there are problems. First, the displacement limit for broad-band patterns is lower than that for the same patterns when they are low-pass-filtered, indicating that the presence of high spatial frequencies prevents the low-spatial-frequency channels from acting independently. This is the motion analogue of the Harmon–Julesz problem. Second, the displacement limit for broad-band or filtered patterns increases with the spacing between edges in the pattern (Morgan 1992b; Morgan and Fahle 1992). Third, the large displacement limit found with sparse patterns remains very similar if the images are filtered to remove low frequencies (Eagle and Rogers 1996; Morgan et al 1997). All these findings suggest that the true determinant of $D_{\max}$ is the repetition frequency in the pattern after different spatial frequencies have been combined, rather than the properties of a particular spatial-frequency filter. This conclusion is compatible with a MIRAGE-type model.

Caution is needed, however, before concluding that early independent filters are combined prior to motion analysis, because the same data could be compatible with a single, broadly tuned channel (Yang and Blake 1994; Morgan et al 1997). Morgan et al (1997) modelled the $D_{\max}$ data for filtered and unfiltered noise patterns with different noise element sizes by a single, low-pass Gaussian filter with a space constant of 10 min arc. Although very little energy from high spatial frequencies gets into this channel, it is sufficient to account for the high $D_{\max}$ values from sparse patterns. According to this model, the reason why high spatial frequencies in dense patterns reduce $D_{\max}$ is similarly that these frequencies enter the passband of the broadly tuned filter and corrupt low-spatial-frequency information (Morgan and Mather 1994) by moving the zero-bounded regions closer together.

Eagle (1997) has also presented evidence for a predominantly low-frequency channel of broad bandwidth (2.6 octaves) in motion. He, however, claims that higher-frequency channels also exist, but can be ignored when dealing with patterns containing relevant low frequencies. As in the Morgan et al (1997) model the reason why the high frequencies in broad-band patterns decrease $D_{\max}$ is that they enter into the broadly tuned low-frequency channel. It may be thought that motion transparency with gratings of different frequencies moving in opposite directions is an objection to a single broad-band filter. It is not. The half-wave rectification in MIRAGE ensures that the zero-bounded regions corresponding to the low-frequency component move in their correct direction, while those corresponding to the high-frequency component move in theirs.(2)

## 3 Conclusion

The original contention of the MIRAGE model that there is little evidence for independent access to different spatial-frequency channels in spatial discriminations appears largely to stand, and is featured in more recent models (MIDAAS, Local Energy Model, Georgeson 1994). The importance given to half-wave rectification in the model has been echoed in more recent models of 'non-Fourier channels'. We have found little evidence to refute the MIRAGE conjecture that all the early channels are 'non-Fourier'. Finally, the MIRAGE conjecture that positional noise is the limiting factor for many elementary spatial discriminations appears now to be widely accepted.

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(2) Images including this are provided in electronic form. See footnote 1 for the address.

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