Pergamon

PII: S0042-6989(97)00070-9

Vision Res., Vol. 37, No. 23, pp. 3237–3254, 1997

Printed in Great Britain
0042-6989/97 $17.00 + 0.00

The Mechanisms for Detecting Compressively Sampled Gratings

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Received 16 July 1996; in revised form 21 February 1997

Contrast thresholds for sine-wave gratings are raised when the gratings are compressively sampled into a set of narrow bright bars on a dark background, even though this method of sampling preserves the mean luminance and contrast of the grating. Burr *et al.* [(1985). *Vision Research, 25,* 717–727] suggested threshold elevation was due to localized luminance adaptation to the sample bars, whose average peak luminance necessarily increased when fewer bars per cycle were present. Previously, we reported results using decrement-bar compressively sampled gratings (CSGs), which consist of dark sample bars on a bright background, which favoured the local luminance adaptation hypothesis (Kingdom & Rainville, 1995). Here we report experiments that suggest that this hypothesis is untenable. Using increment-bar CSGs (bright sample bars on a dark background) we found that raising background luminance while holding sample bar luminance constant reduced thresholds by as much as a factor of ten. This suggests that it is the *contrast* of the bars, rather than their *luminance*, which determines thresholds. Further experiments showed that CSG detection was facilitated by unsampled grating pedestals, and thresholds were elevated when the fundamental was physically cancelled. This implied that CSGs were detected by the same mechanisms as the unsampled gratings from which they are derived. Finally, we provide evidence for the involvement of a dynamic gain control component for increment-bar CSG detection. © 1997 Elsevier Science Ltd

Sampling Contrast sensitivity Gain control

INTRODUCTION

A contemporary issue in biological vision is the extent to which adaptation to the ambient light level is a localized process, that is, operating separately within small groups of retinal neurons, or "adaptation pools" (Rushton, 1965). Evidence for localized photopic light adaptation comes from both neurophysiological (Shapley & Enroth-Cugell, 1984; Cleland & Freeman, 1988), and psychophysical (Williams & MacLeod, 1979; Cicerone *et al.*, 1990; MacLeod *et al.*, 1992) studies. In general, the psychophysical evidence for localized light adaptation has emerged from measures of the appearance of stimuli following bleaching adaptation. However, the spatial properties of bleaching adaptation may be different from those of photopic light adaptation under ordinary illumination conditions, and therefore estimates of adaptation pooling size from bleaching studies may not necessarily apply to the latter.

One technique that arguably avoids this problem was introduced by Burr *et al.* (1985). Burr *et al.* measured contrast thresholds for sine-wave gratings that had been compressively sampled. Compressive sampling, unlike ordinary sampling, preserves the mean luminance and contrast of the fundamental harmonic—the nominal spatial frequency of the grating. Figure 1(a) shows an example of a sine-wave grating compressively sampled to an increasing degree, and Fig. 1(b) shows luminance profiles. As the signal is compressed into fewer and fewer sample bars, the luminance and degree of modulation of the bars must necessarily be increased to preserve the mean luminance and amplitude of the fundamental. Throughout the paper, we adopt the convention that increasing the degree of compressive sampling implies concentrating overall luminance into a small set of sample bars. The reader should, therefore, avoid confusing an increase in the "degree of compressive sampling" with the more conventional increase in "sampling rate", where the sample density is increased without affecting the luminance of each sample.

Burr *et al.* measured contrast thresholds for compressively sampled gratings (CSGs) similar to those shown in Fig. 1. They found that thresholds increased proportionately with the degree of compressive sampling. They suggested that this occurred because the luminance gain of the visual system, that is its state of light adaptation, was set by the luminance of the sample bars, which increased proportionately with the degree of compressive sampling. This implied that luminance gain was localized to within the width of the sample bars, and that the between-sample bar luminance did not contribute to gain.

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(a)

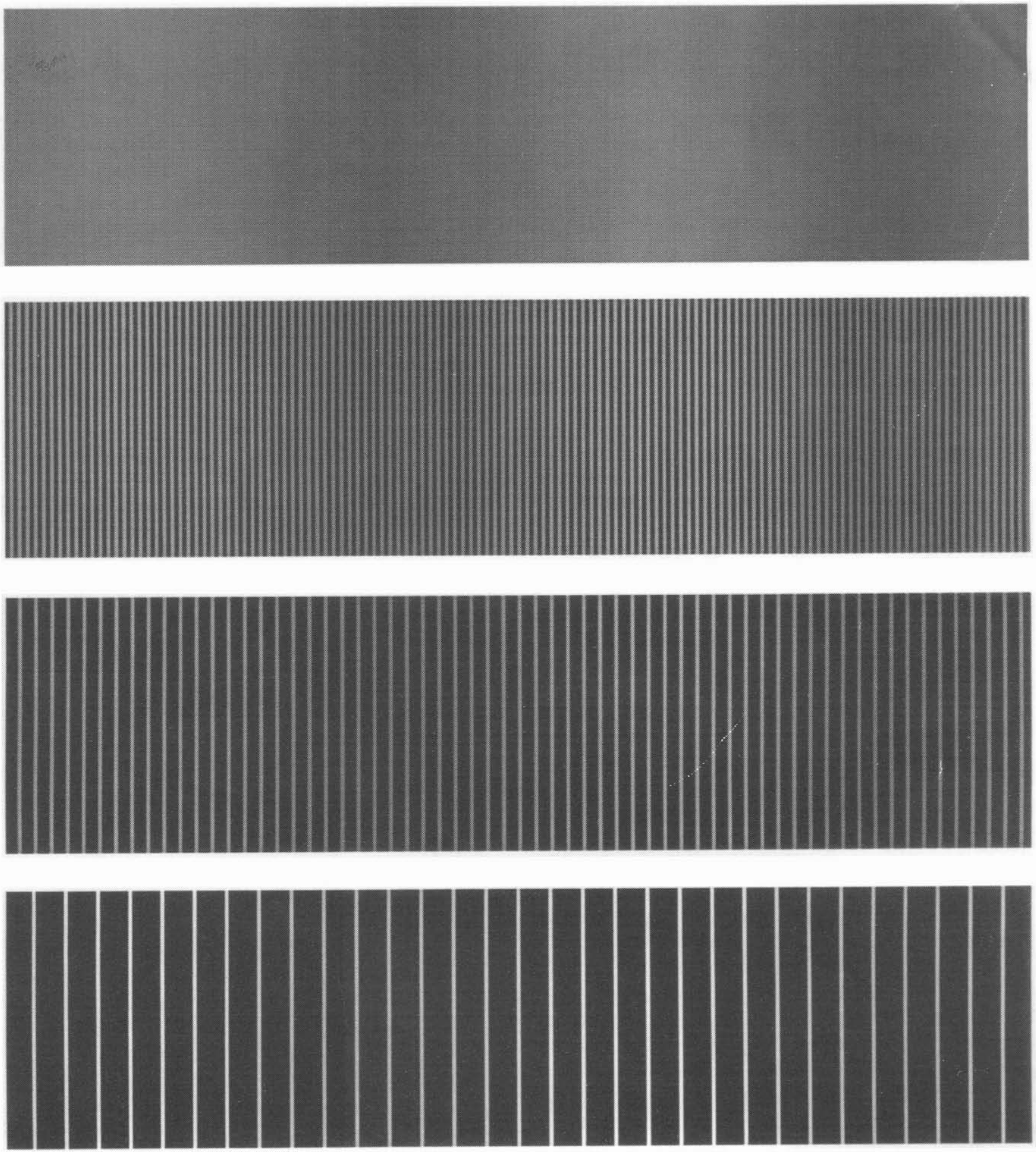

FIGURE 1(a)—*Legend overleaf.*

Given that the adaptational pooling area must nevertheless be finite, it would be expected that at large viewing distances the increase in contrast thresholds with compressive sampling would be less dramatic, and this is indeed what Burr *et al.* found. By measuring CSG thresholds at various viewing distances Burr *et al.* estimated the summation width of luminance gain control to be about 0.5 arcmin.

There are, however, alternative explanations for the elevated thresholds observed with compressive sampling that Burr *et al.* found, which, if correct, would discourage the use of CSGs to estimate the size of light adaptation pools. Firstly, the increase in thresholds might be due to a *contrast*-based rather than *luminance*-based nonlinearity acting on the sample bars, perhaps similar to that believed to underlie the rise in contrast discrimination thresholds with pedestal contrast (Legge & Foley, 1980; Wilson, 1980; Legge *et al.*, 1987; Foley, 1994). Such an

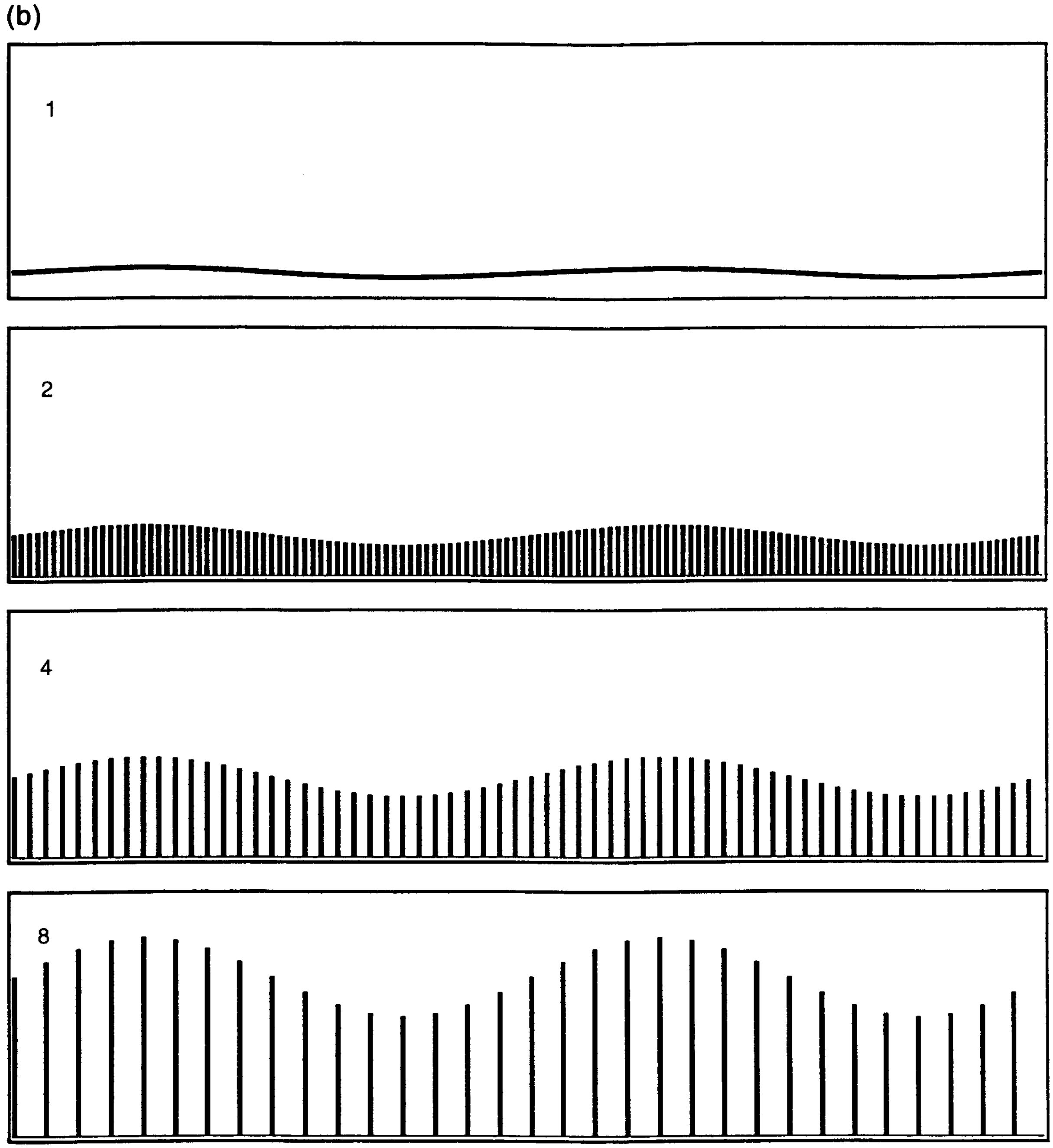

FIGURE 1(b).

FIGURE 1. (a) Constant-bar-width, increment-bar CSGs (compressively sampled gratings); and (b) luminance profiles. The top plots in each figure show an unsampled grating, while the plots below show gratings compressively sampled to an increasing degree. The number in each plot in (b) gives the period-to-bar-width ratio, which is the ratio of the duty cycle of the sample bars to their width. The amplitude and mean luminance of the fundamental harmonic is identical in all four gratings, and has a contrast (amplitude/mean luminance) of 25%. In this type of CSG the bar width is held constant, and thus the number of bars per cycle decreases with an increase in the degree of compressive sampling.

explanation would be consistent with the luminance gain not being set by the luminance of the sample bars, but instead by the luminance of their background. Secondly, the elevated thresholds might be due to difficulties encountered by the visual system in interpolating the sparsely distributed information carried by the sample bars. For instance, Morgan & Watt (1982, 1984) have used sampled gratings similar to those used in this study and have suggested the presence of neural interpolation mechanisms which can perform quite well with stimuli with a fairly sparse sampling grid but ultimately fail when the separation between samples exceeds a distance of 200 sec of arc. Thirdly, the higher harmonics introduced by the compressive sampling could have been masking the fundamental—a process referred to as critical band masking (Harmon & Julesz, 1973). Fourthly, even if a luminance-based nonlinearity was implicated in CSG detection, it might only have reflected the operation of

(a)

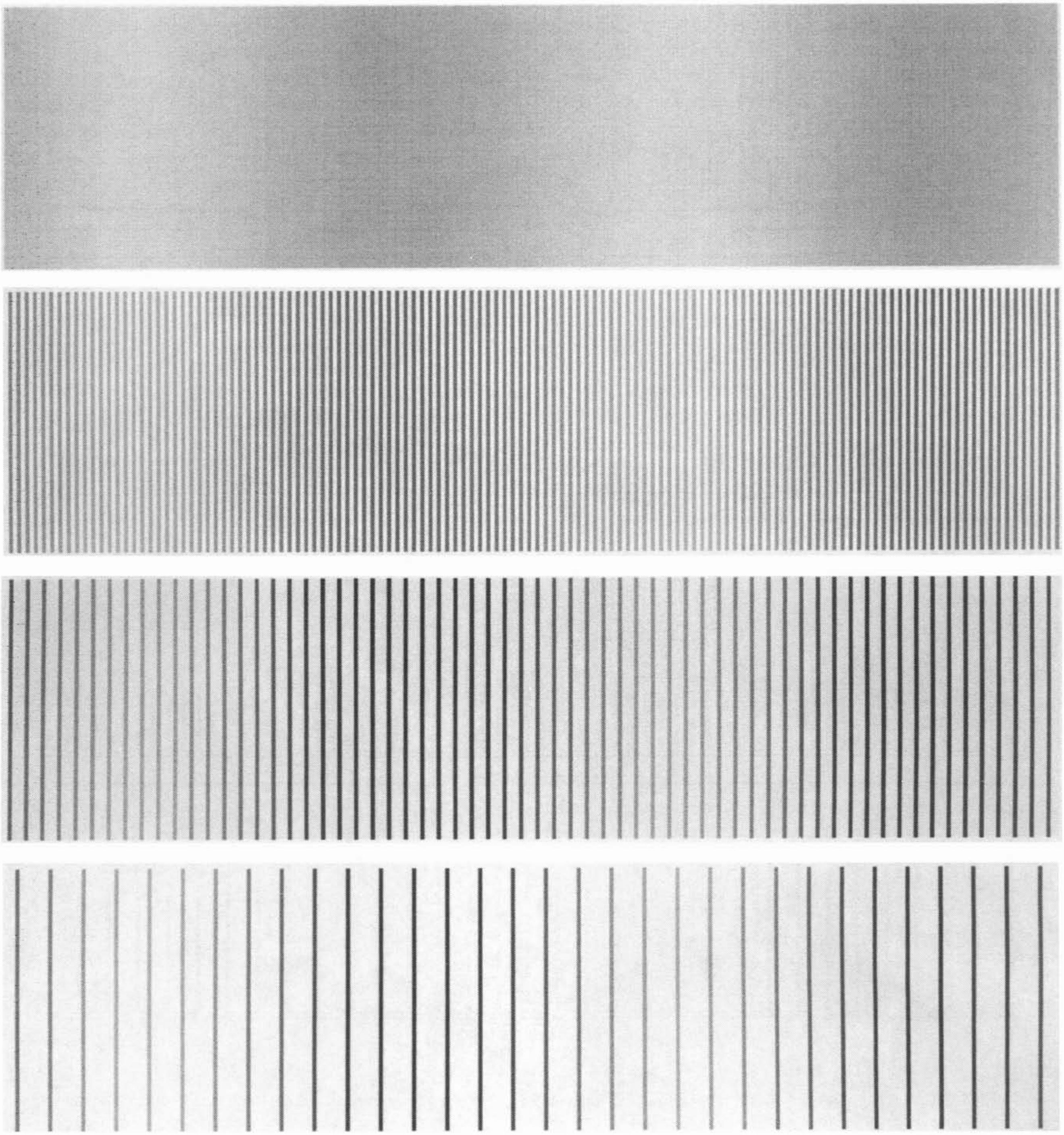

FIGURE 2(a)—*Legend overleaf.*

one component of the light adaptation process, and therefore the estimates of light adaptation provided by Burr *et al.* might not be an adequate representation of the spatial pooling size of light adaptation as a whole. Recent studies on light adaptation suggest that it involves at least two processes, one multiplicative (strictly speaking divisive), the other subtractive (Geisler, 1978; Finkelstein & Hood, 1981; Hayhoe *et al.*, 1987; Hayhoe, 1990; Graham & Hood, 1992). Both processes are believed to be involved in producing the square-root or Weber's law dependence of increment thresholds on background luminance, universally accepted as signatures of light adaptation. While the multiplicative process might be highly localized, the subtractive process appears to be more spatially extensive, and probably mediated by the receptive field surrounds of retinal bipolar and ganglion cells (Hayhoe, 1990; Hayhoe *et al.*, 1992).

One of these possibilities—critical band masking—was considered by Burr *et al.* They found that scrambling the phases of the higher harmonics introduced by

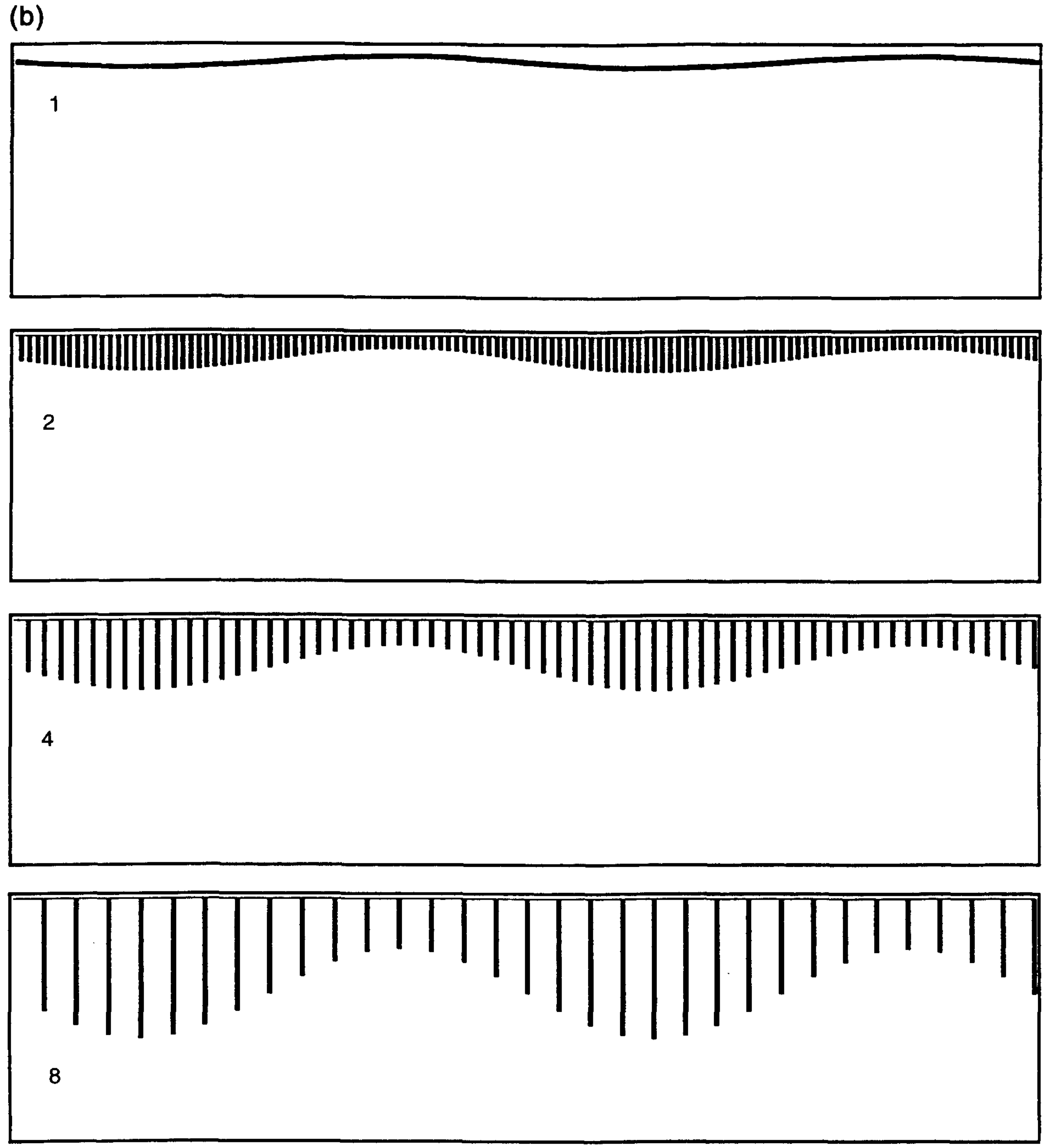

FIGURE 2(b).

FIGURE 2. (a) Constant-bar-width, decrement-bar CSGs; and (b) luminance profiles. As in Fig. 1, the top plots show an unsampled grating, while the plots below show gratings compressively sampled to an increasing degree. Again, the number in each plot gives the period-to-bar-width ratio. The amplitude and mean luminance of the fundamental harmonic is identical in all four gratings, with a contrast (amplitude/mean luminance) of 2.5%.

compressive sampling reduced the magnitude of threshold elevation substantially. This certainly makes critical band masking an unlikely explanation. Of the other alternative explanations raised above, a recent study by Mulligan & MacLeod (1991) is pertinent. They measured detection thresholds for sine-wave gratings discretely sampled in the conventional manner, that is, in which the luminance of each sample patch equalled grating luminance at a given sample position. They found that their results could best be explained by supposing that the sample bars were processed by spatially opponent receptive fields with surrounds of approximately 12 arcmin diameter. This suggests that the elevated thresholds found in Burr and colleagues' study might well be due to a contrast-based rather than luminance-based nonlinearity, since spatially opponent receptive fields are primarily concerned with detecting contrast rather than luminance.

Given the possible alternative explanations to Burr and colleagues' results other than localized luminance gain control, the recent evidence for a spatially extensive

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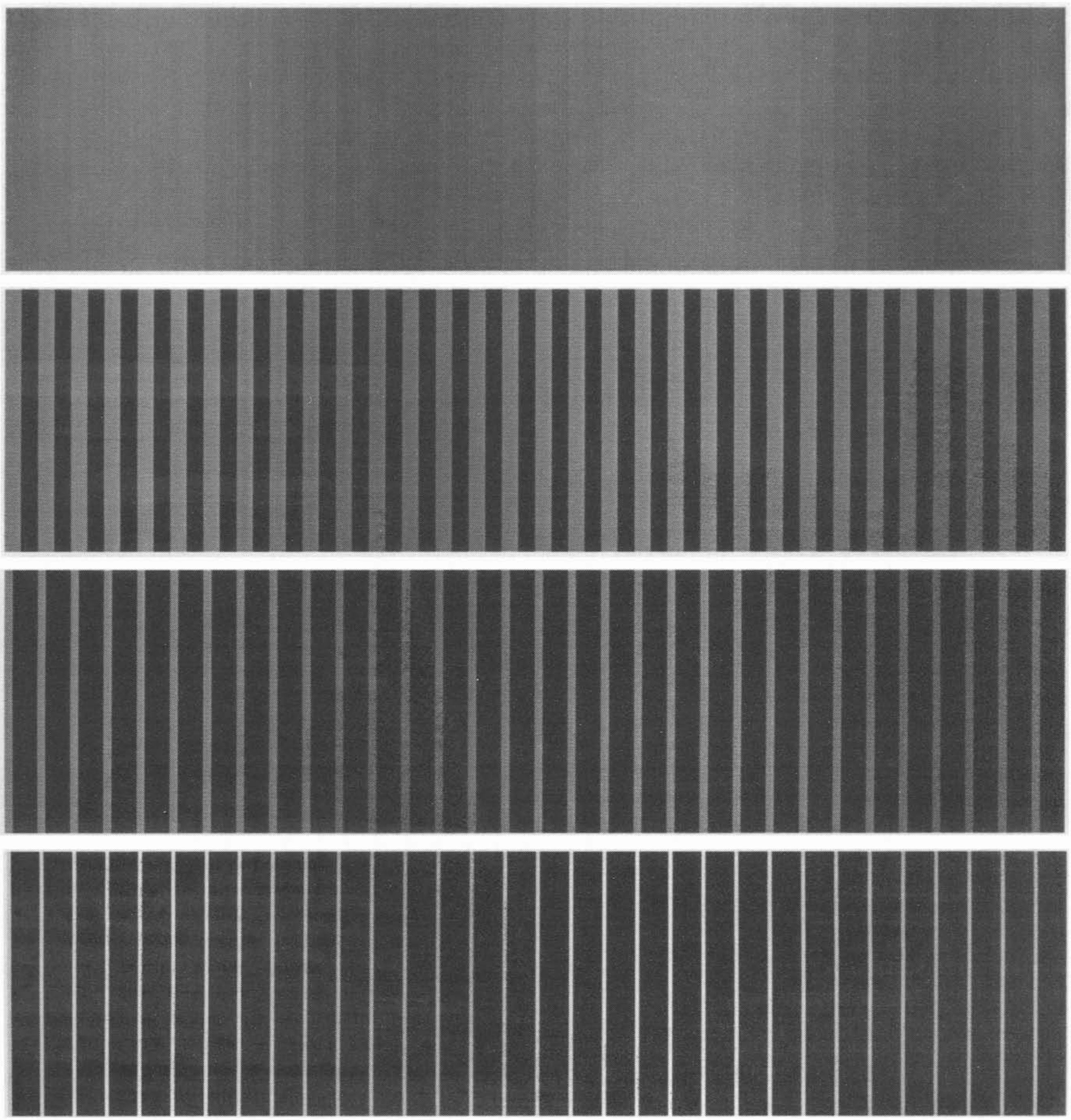

FIGURE 3(a)—*Legend overleaf.*

component of light adaptation (the subtractive), and the results of the study by Mulligan & MacLeod, we decided to take a fresh look at the mechanisms for detecting compressively sampled gratings. The experiments described below were aimed primarily at testing the local luminance gain hypothesis of Burr *et al.*, but like the study of Mulligan & MacLeod (1991) have a wider significance in their aim of understanding the mechanisms involved in processing discretely sampled visual stimuli.

We first describe an experiment which initially led us to support the conclusions of Burr *et al.*, part of which has been briefly reported elsewhere (Kingdom & Rainville, 1995, 1996). This experiment involved measuring detection thresholds for CSGs consisting of dark sample bars on a bright background. We then describe an experiment which led us to reject our initial support of the local luminance gain control hypothesis. Further experiments are then described which aimed to deepen our understanding of the mechanisms for detecting CSGs.

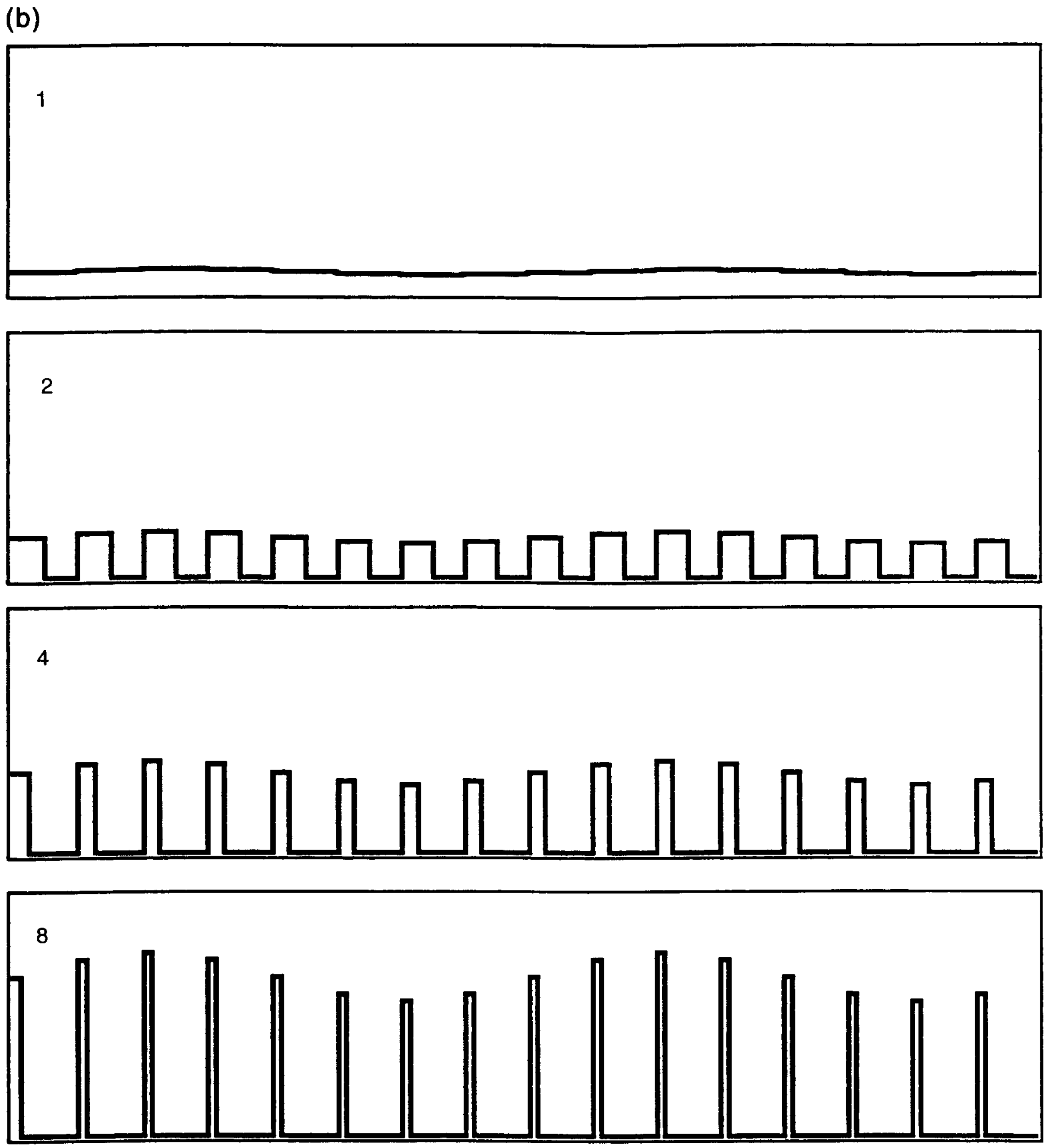

FIGURE 3(b).

FIGURE 3. (a) Constant-period-width, increment-bar CSGs; and (b) luminance profiles. In this type of CSG the number of sample bars is held constant as the degree of compressive sampling is increased. Notice that in the baseline condition (top plot) the grating, although unsampled, is nevertheless coarse quantized to ensure the same number of discrete changes in luminance as in the CSGs beneath.

METHODS

Stimulus generation and calibration

Stimuli were generated using the VSG2/2 Digital Signal Generator (DSP) (Cambridge Research Systems) and displayed on a Barco CCID RGB monitor. The DSP employs 12-bit per gun gamma-corrected LUTs (look-up tables), constructed through suitable selection of 14-bit resolution DAC (digital-to-analogue converters) values. DAC values for all three RGB guns were set equal to give a monochrome display. Photometric calibration was carried out using a Hagner Universal Microphotometer (Opticon). The stimuli were modulated vertically and thus at right angles to the display monitor raster, thus minimizing high spatial frequency contrast loss due to pixel bleeding.

A critical property of CSGs is that their mean luminance remains constant with compressive sampling. We checked this using a photometer, whose distance to the screen was adjusted to ensure that at least five sample

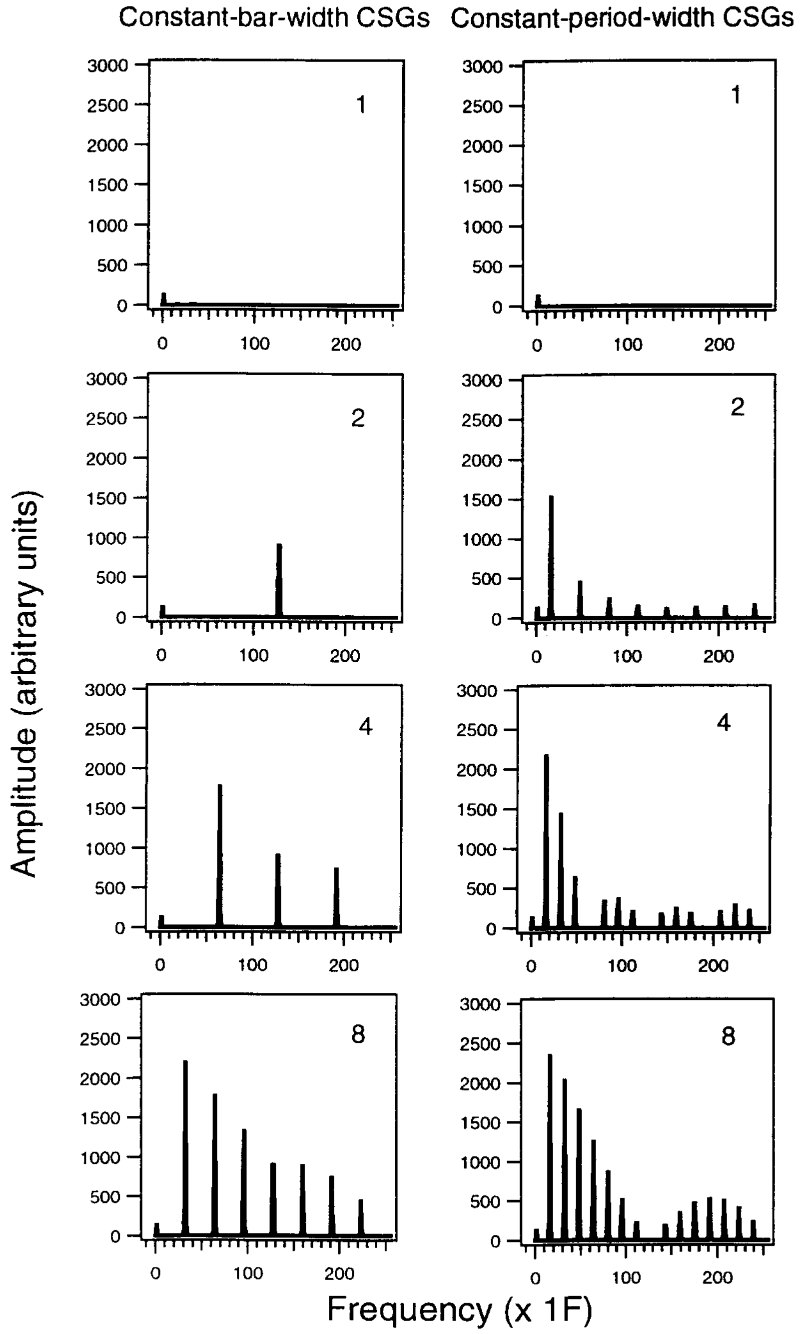

FIGURE 4. Fourier amplitude spectra for the CSGs in Fig. 1 (constant-bar-width) and Fig. 3 (constant-period-width). Discrete Fourier transforms were performed on CSGs with 1 cycle of modulation with 512-point resolution. The width of the sample bars in the constant-bar-width condition was 2, and the width of the sample period in the constant-period-width CSGs was 32. For all degrees of compressive sampling, the contrast of the fundamental was defined to be at 10%. The amplitude spectra are not normalized in any way and direct comparisons between amplitudes of various conditions can therefore be made. The dc level amplitude has been removed from each plot to enable the fundamental to be seen as the short height bar on the abscissa at $x = 1$ (i.e., at near zero). As the plots show, the compressive sampling introduces higher harmonics, and at relatively large amplitudes compared with the fundamental. The pattern of higher harmonics is, however, quite different for the constant-bar-width and constant period-width conditions. Note also that since the spectra are not normalized, the range of amplitudes is considerable and some components with very weak amplitudes may not appear.

bars were always present in the aperture of the photometer. To check further the precision of the calibration, CSGs compressed to various degrees were slowly drifted across the photometer aperture. Measurements confirmed that there were no significant differences in mean luminance for gratings compressively sampled to various degrees.

Stimuli

Example CSGs and their luminance profiles are illustrated in Figs 1–3. The stimulus at the top of each figure is the unsampled grating baseline condition. Figure 1 and Fig. 3 show increment-bar CSGs, Fig. 2 decrement-bar CSGs. All the CSGs within any one figure have a fundamental harmonic identical in mean luminance and amplitude (and hence contrast). Each CSG consists of an array of bars on a constant luminance background. In the case of Figs 1 and 3 the spacing between the sample bars, or the sample bar background, is of near-zero luminance, while in the case of Fig. 2, the sample bar background is the maximum luminance available on the display monitor (see below for details). For the increment-bar CSGs the luminances of the sample bars are greater than the space-average luminance of the CSG, by an amount depending on the degree of compressive sampling. For the decrement-bar CSGs the sample bar luminances are less than the space-average luminance. The degree of compressive sampling is defined here in terms of the ratio of the period, or duty cycle, of the bars to their width, or the period-to-bar-width ratio. This is the number given in each figure.

We have used two forms of compressive sampling for both the increment-bar and decrement-bar CSGs, and these are illustrated just for the increment-bar CSGs in Figs 1 and 3. In Fig. 1, the width of the sample bars is held constant and the spacing between the bars varied to determine the degree of compressive sampling. This results in the number of bars decreasing as the degree of compressive sampling increases. We refer to this as the constant-bar-width condition. In Fig. 3 on the other hand, the number of bars and the spacing between the bars is held constant, while the width of the bar determines the degree of compressive sampling. We refer to this as the constant-period-width condition. The Fourier amplitude spectra of both the constant-bar-width CSGs (Fig. 1) and constant-period-width CSGs (Fig. 3) are shown in Fig. 4. Formal mathematical expressions describing the continuous Fourier spectrum of patterns similar to CSGs can be found in Pelah (1994, 1996).

Our stimuli were viewed at a distance of 73.5 cm, which resulted in one cycle of modulation on the display having a spatial frequency of 0.0625 cpd. At this viewing distance, the display subtended 26 deg of visual angle horizontally and 16 deg vertically. We employed spatial frequencies of 0.0625, 0.125, and 0.25 cpd, which produced respectively 1, 2 and 4 cycles of modulation across the display. In the constant-bar-width condition (Figs 1 and 2) the bars had a width of 1.875 arcmin. In the constant-period-width condition (Fig. 3) the period was set to 0.5 deg, resulting in 16 bars across the whole display. The period-to-bar-width ratios employed in both conditions were 1, 2, 4, 8 and 16, where a value of 1 implied an unsampled grating. In the constant-bar-width condition these period-to-bar-width ratios resulted in respectively 256, 128, 64, 32 and 16 sample bars across the whole display. Since it was necessary to have fairly wide sample periods while ensuring sub-Nyquist sampling of the fundamental modulation, the entire height of the display was used. No special type of windowing was applied and the limits of the screen raster delimited the viewing aperture.

The phase of modulation of the bars was always randomized on each trial, but the position of the bars was fixed. In all except Experiment 5 which dealt with the temporal dynamics of CSG detection, the interval between each stimulus presentation contained an unmodulated CSG. Therefore, when the test stimulus was presented, the bars suddenly appeared modulated in their luminance. For the unsampled grating baseline conditions, the interval between each stimulus presentation was a uniform field of the same mean luminance as the grating.

We define the luminances in our stimuli as % max. for ease of exposition, the percentage of the display monitor's maximum luminance, which was 74 cd/m^2. The lowest luminance achievable on the monitor was approximately 0.75 cd/m^2, and this was the actual value of the increment-bar CSG background referred to in the text as "near-zero" luminance. The contrast of the fundamental in the CSGs was defined conventionally as amplitude divided by mean luminance.

Subjects

The two authors, SR and FK acted as test subjects. FK had normal vision, while SR's vision was corrected-to-normal by spectacles. Both subjects were experienced psychophysical observers.

Procedure

All experiments used a conventional 2IFC (two-interval, forced-choice) procedure, in which the task for the subject was to detect the interval containing the sinusoidal modulation. The subject's response was recorded by button press and feedback in the form of a tone was given for an incorrect decision. A standard two-up, one-down staircase procedure was employed (Levitt, 1971) to obtain thresholds. Contrast was changed adaptively from trial-to-trial in ratios. The sequence of stimulus presentations was terminated after 12 reversals of the staircase, and the threshold was calculated as the geometric mean contrast over the last ten reversals.

THE EXPERIMENTS

Experiment 1. Contrast thresholds for increment-bar and decrement-bar CSGs

Here we report the details of an experiment, part of which has been briefly reported elsewhere (Kingdom & Rainville, 1995, 1996), which initially led us to support the local luminance gain hypothesis proposed by Burr *et al.* (1985). The hypothesis is that the elevation of contrast thresholds with compressive sampling found with increment-bar CSGs is due to localized adaptation to the luminance of the sample bars. We suggested in the Introduction that an alternative explanation was that a contrast-based rather than luminance-based compressive nonlinearity underlay threshold elevation. Kingdom & Rainville (1995) argued that if the compressive non-linearity were luminance-based, one should expect a *decrease* in thresholds with decrement-bar CSGs, since for these stimuli mean bar luminance decreases with increased compressive sampling (see Fig. 2). On the other

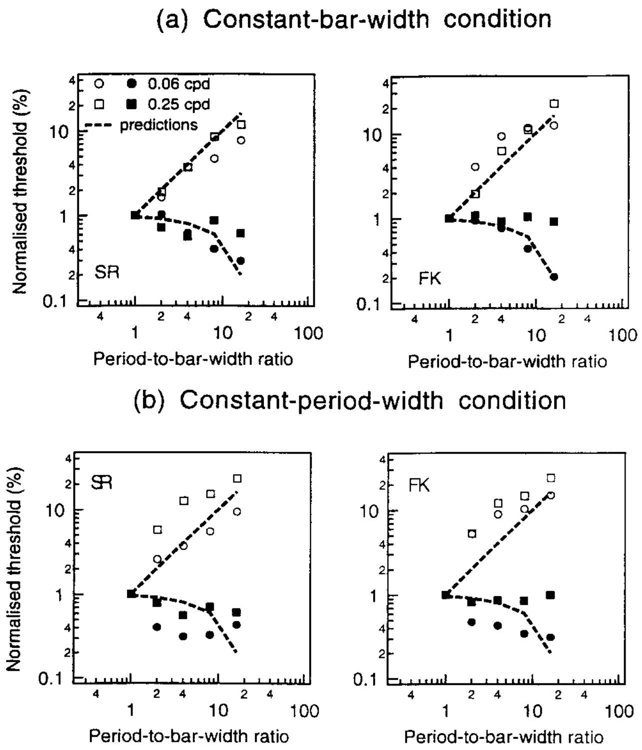

FIGURE 5. Results for Experiment 1. Contrast thresholds for both increment-bar (open symbols) and decrement-bar (closed symbols) CSGs are shown for two spatial frequencies (circles = 0.0625 cpd, squares = 0.25 cpd) of the fundamental harmonic, two subjects, and for two forms of compressive sampling. The degree of compressive sampling is expressed in terms of the period-to-bar-width ratio (see Fig. 1, Fig. 2, Fig. 3). The thresholds have been normalized to that for the unsampled grating whose period-to-bar-width ratio is 1. The dashed lines are the predictions that contrast thresholds are proportional to mean bar luminance.

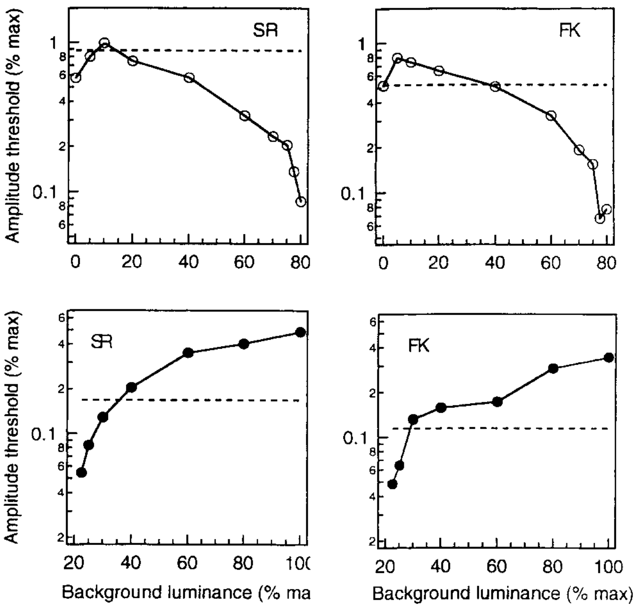

FIGURE 6. Results for Experiment 2. Effect of background luminance on amplitude thresholds for CSGs with constant mean bar luminance and a period-to-bar-width ratio of 8. For the increment-bar CSGs (open symbols), mean bar luminance was 80% max. For the decrement-bar CSGs (filled symbols), mean bar luminance was 20% max. The dashed lines represent amplitude thresholds for unsampled gratings with the same mean luminance as the mean bar luminance of the CSGs.

hand a contrast-based compressive nonlinearity would predict an increase in thresholds for increment-bar *and* decrement-bar CSGs, since the contrast of the individual bars increases with compressive sampling for both classes of stimuli.

Figure 5 plots contrast thresholds for both increment-bar and decrement-bar CSGs as a function of the period-to-bar-width ratio. The top two panels are for the constant-bar-width condition (Figs 1 and 2), the bottom two panels for the constant-period-width condition (Fig. 3). Contrast thresholds for the CSGs have been normalized to the unsampled grating thresholds, which are the most leftward points on each graph (contrast threshold = 1; period-to-bar-width ratio = 1). The dashed lines are the predictions of the local luminance gain hypothesis of Burr *et al.* (1985), that is that thresholds are proportional to the luminance of the sample bars.

Consider first the increment-bar CSG data, given by the open symbols. Thresholds increase with the degree of compressive sampling, and approximately in line with the local luminance gain prediction. This confirms the results of Burr *et al.* (1985) for constant-bar-width CSGs, and extends the basic finding to constant-period-width CSGs. The results for the decrement-bar CSGs, given by the filled symbols, show a very different pattern. There is in most cases a small improvement in thresholds with compressive sampling, less marked for the 0.25 than the 0.0625 cpd condition, and in FKs 0.25 cpd condition absent altogether. Although the prediction from the local luminance gain hypothesis is not particularly good, it appears to account for the main aspects of the data, and in particular the differences between the increment-bar and decrement-bar CSGs. These results, therefore, appeared to us to favour the local luminance gain hypothesis.

The data from Experiment 1 also allow us to consider one other alternative explanation for the Burr *et al.* results mentioned in the Introduction. This is that threshold elevation with increment-bar CSGs results from difficulties encountered by the visual system in interpolating the sparsely distributed sample bar information. We found that both constant-bar-width and constant-period-width CSGs produced a similar pattern of threshold elevation. Given that in the constant-period-width condition the number of sample bars remained constant across all degrees of compressive sampling, the fact that thresholds were nevertheless elevated makes the spatial interpolation explanation highly unlikely. Had interpolation been the critical factor, significant differences in threshold would have been expected between the constant-period-width and constant-bar-width conditions: the number of sample bars remains constant in the former condition while the sample count is inversely proportional to period width in the latter. We now present evidence to counter the local luminance gain hypothesis.

Experiment 2. Effect of background luminance with fixed mean sample bar luminance

If CSG thresholds are determined by the luminance of the sample bars, it follows that they should be unaffected by changes in background luminance, provided bar luminance is held constant. We tested this using 0.0625 cpd increment-bar and decrement-bar CSGs with a fixed period-to-bar-width ratio of 8. For the increment-bar CSGs, mean bar luminance was held constant at 80% max, and thresholds were measured for background luminances ranging from near-zero to 80.0% max. For the decrement-bar CSGs mean bar luminance was held constant at 20%, and thresholds measured for background luminances ranged from 100.0 to 20.0% max.

The results are shown in Fig. 6. Each graph plots amplitude thresholds as a function of background luminance. We plot the data in terms of amplitude, rather than contrast thresholds, because in this experiment the mean luminance of the CSGs changed with background luminance. Thus, under the local luminance gain hypothesis we would expect only amplitude thresholds to remain unchanged with background luminance. The dashed lines in each graph show amplitude thresholds for unsampled gratings whose mean luminance was set to the fixed luminance of the sample bars: 80% max. for the increment-bar, 20% max. for the decrement-bar CSGs. As the figure shows, even though sample bar luminance was constant, changing background luminance altered thresholds dramatically. The pattern of results suggests that bar contrast, rather than bar luminance determined thresholds. To compare our results with those of traditional contrast discrimination experiments, we recast the data from the increment-bar CSGs in terms of the threshold for detecting an "increment" in contrast as a function of "pedestal" contrast, where the increment was the difference in contrast between a sample bar at the peak of the fundamental compared with the mean of the fundamental, and the pedestal was the mean of the fundamental. Bar contrast was defined conventionally using Michelson $C = (L_{max} - L_{min})/(L_{max} + L_{min})$. The data from pedestal contrast $C = 0\%$ to $C = 50\%$ are well fitted by a power law with an exponent of about 0.5 when averaged across the two subjects.* This is very close to that found in classical contrast discrimination experiments using incremental bar stimuli, for example, as in Legge & Kersten's (1983) study in which the exponent was found to be around 0.6. A curious feature of the data is the slight dip-down in amplitude thresholds at very low background luminance in the increment-bar CSG data. This feature may be congruent with a similar dip-down in contrast discrimination thresholds found when the surrounds of high contrast decrements approach zero (Whittle, 1986), or under certain conditions high contrast gratings (Kingdom & Whittle, 1996).

Given this evidence favouring a contrast-based, rather than luminance-based nonlinearity, the issue arises as to how to account for the decrement-bar CSG results from the first experiment, which apparently favoured an explanation in terms of a luminance nonlinearity. The decrement-bar CSG results from Experiments 1 and 2 appear to pose a contradiction. In Experiment 1, in which decrement-bar CSG thresholds were measured as a function of the degree of compressive sampling, an increase in local bar contrast was accompanied by a *decrease* in threshold. On the other hand in Experiment 2, in which decrement-bar CSG thresholds were measured as a function of background luminance for a fixed degree of compressive sampling, an increase in local bar contrast was accompanied by an *increase* in threshold. Note first that the reason for the discrepancy in the results is not because in Experiment 1 *contrast* thresholds were measured whereas in Experiment 2 *amplitude* thresholds were measured. Were we to have plotted the results for Experiment 1 in terms of amplitude thresholds we would have found the same pattern of results. To reconcile these apparently contradictory findings one needs instead to re-examine the results of both experiments in a way other than in terms of the threshold of the *fundamental*. For the stimuli in Experiment 1 an increase in the degree of compressive sampling of a sine-wave of given contrast resulted not only in an increase in the contrast of the sample bars, but also an increase in the amplitude of their modulation, as can easily be seen in Fig. 2. This increase in sample bar modulation is necessary to preserve the amplitude of the fundamental since this amplitude would otherwise become reduced as the sample bars become fewer and further apart. This is so because the fundamental incorporates all the luminance information in the CSG, sample bars and background alike; thus, the sample bar modulation must compensate for the contribution of the background in defining the fundamental. In Experiment 2 on the other hand, there was no such increase in the spacing between the sample bars with bar contrast, as the period-to-bar-width ratio was held constant while background luminance was varied. Suppose now that in both experiments the visual system considered only the contrast information of the sample bars, i.e., did not integrate the background information into a representation of the fundamental harmonic. The consequence of this for the stimuli employed in Experiment 1 would be that even if the individual bars underwent a compressive contrast-based nonlinearity, there would still be a net increase in their post-transduced amplitude of modulation with compressive sampling, perhaps sufficient to produce the observed decrease in thresholds. In Experiment 2 the CSGs were all at one degree of compressive sampling, so the effect of ignoring

*In the case of the increment stimuli, DC begins to diminish at values of pedestal C beyond about 0.5, and diminishes to zero at pedestal $C = 1$. This is an inevitable consequence of casting the metric in terms of Michelson C, which has an upper limit of 1. When an incremental pedestal has a value of $C = 1$, DC must be zero irrespective of the actual size of the just-noticeable difference (jnd) in its amplitude. For this reason we only fitted the power law to the range of pedestal C from 0 to 0.5. The reason for choosing C was to compare our results with those of Legge & Kersten (1983).

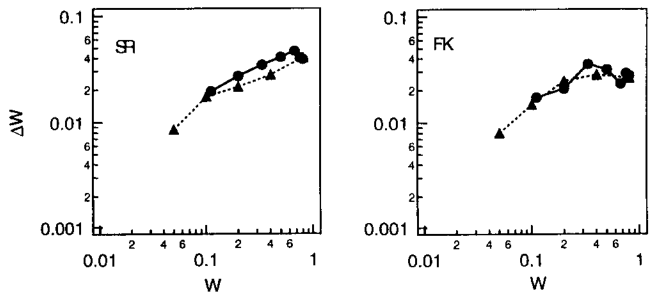

FIGURE 7. Results for the decrement-bar CSGs from Experiment 1 (triangles) and Experiment 2 (circles) expressed in terms of bar Weber contrast. See text for details.

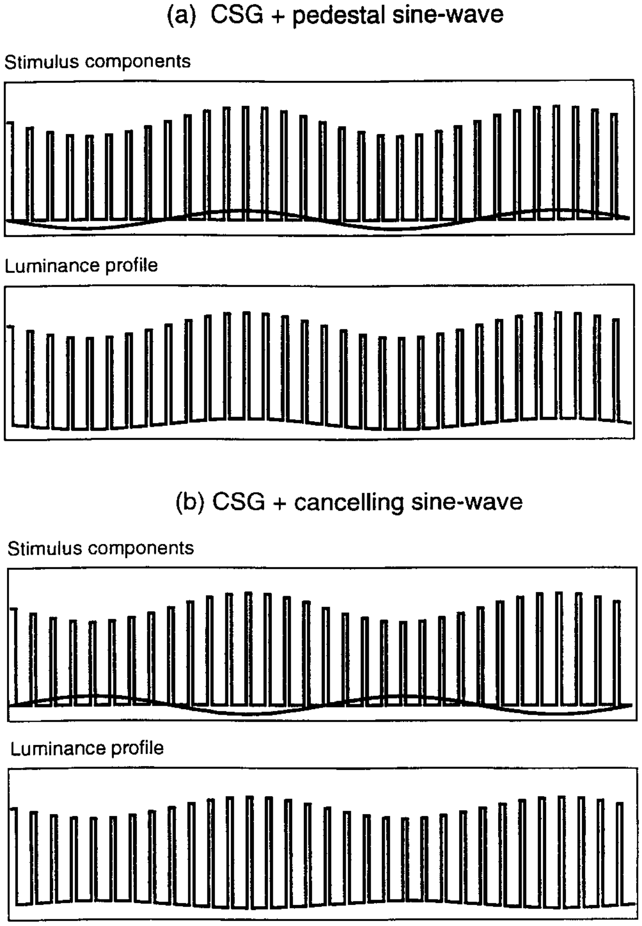

FIGURE 8. Stimulus components and luminance profiles of the stimuli used in (a) Experiment 3; and (b) Experiment 4. In (a) a pedestal sine-wave grating of variable contrast is added in phase to the fundamental in the CSG. In (b) a sine-wave grating of identical amplitude to the fundamental in the CSG is added out of phase, to precisely cancel the fundamental.

the background information would be a constant factor throughout.

We tested this theory by recasting the results of the decrement-bar CSG conditions in both experiments in terms of the contrast threshold for detecting the modulation of the sample bars, rather than for the fundamental. An appropriate metric for such an analysis is Weber contrast, *W**, defined as $\Delta L/L_b$ where ΔL is the peak-to-trough amplitude of the bar, and L_b its background luminance. The mean contrast of the sample bars in a CSG can now be expressed as *W*, and the increment threshold level of modulation, ΔW. Figure 7 plots ΔW against *W* for the 0.0625 cpd decrement-bar CSG data in both experiments. As can be seen, the data now quite neatly superimpose. Both sets of data show a systematic increase in ΔW with *W*, presumably reflecting the underlying contrast-based compressive nonlinearity common to the processing of the stimuli in both experiments. The apparently contradictory results of the decrement-bar CSG data in the two previous experiments is, therefore, reconciled once one assumes that the visual system detects CSGs by directly comparing the contrasts of the bars in the display, and ignoring the background information which would otherwise be integrated by a mechanism detecting the fundamental. Moreover, the pattern of decrement-bar CSGs has been modeled using a metric of contrast in which the divisive gain factor due to light adaptation is background luminance rather than mean bar luminance.

We have not attempted to apply this model to the increment-bar CSG data, since our aim was to show that the decrement-bar CSG data of Experiment 1 were in fact perfectly consistent with a contrast-based nonlinearity, which was not at issue for the increment-bar CSGs. Moreover, to apply the Weber contrast metric to the increment-bar stimuli would require making an assumption about the level of "dark noise" (Barlow, 1957) at the near-zero luminance background (otherwise *W* equals infinity when $L_b = 0$).†

*It is important not to confuse the W used here for representing Weber contrast, with the W used by Whittle (1986) defined as DL/L_{min}, where L_{min} is the minimum luminance in the stimulus.

†We could have analysed both the increment and decrement data using a model incorporating both subtractive and divisive inhibition. However, such a model has up to now only been applied to increments, and its applicability to decrements has yet to be given a solid empirical foundation.

Experiment 3. Are unsampled and compressively sampled gratings detected by different mechanisms?

In the previous experiment we showed that the visual system appeared to detect the variations in the contrast of the sample bars directly, rather than incorporate those variations into the fundamental, together with background luminance. This implies a different mechanism for detecting CSGs than unsampled gratings. The third experiment aimed to test this idea. We used a well established technique for establishing whether two stimuli are detected by the same mechanism, namely whether one can facilitate the detection of the other. Low contrast "pedestal" gratings facilitate the detection of in-phase "test" gratings of the same spatial frequency, producing the well known "dipper function" (Campbell & Kulikowski, 1966; Foley & Legge, 1981; Legge & Kersten, 1983; Bradley & Ohzawa, 1986; Ross & Speed,

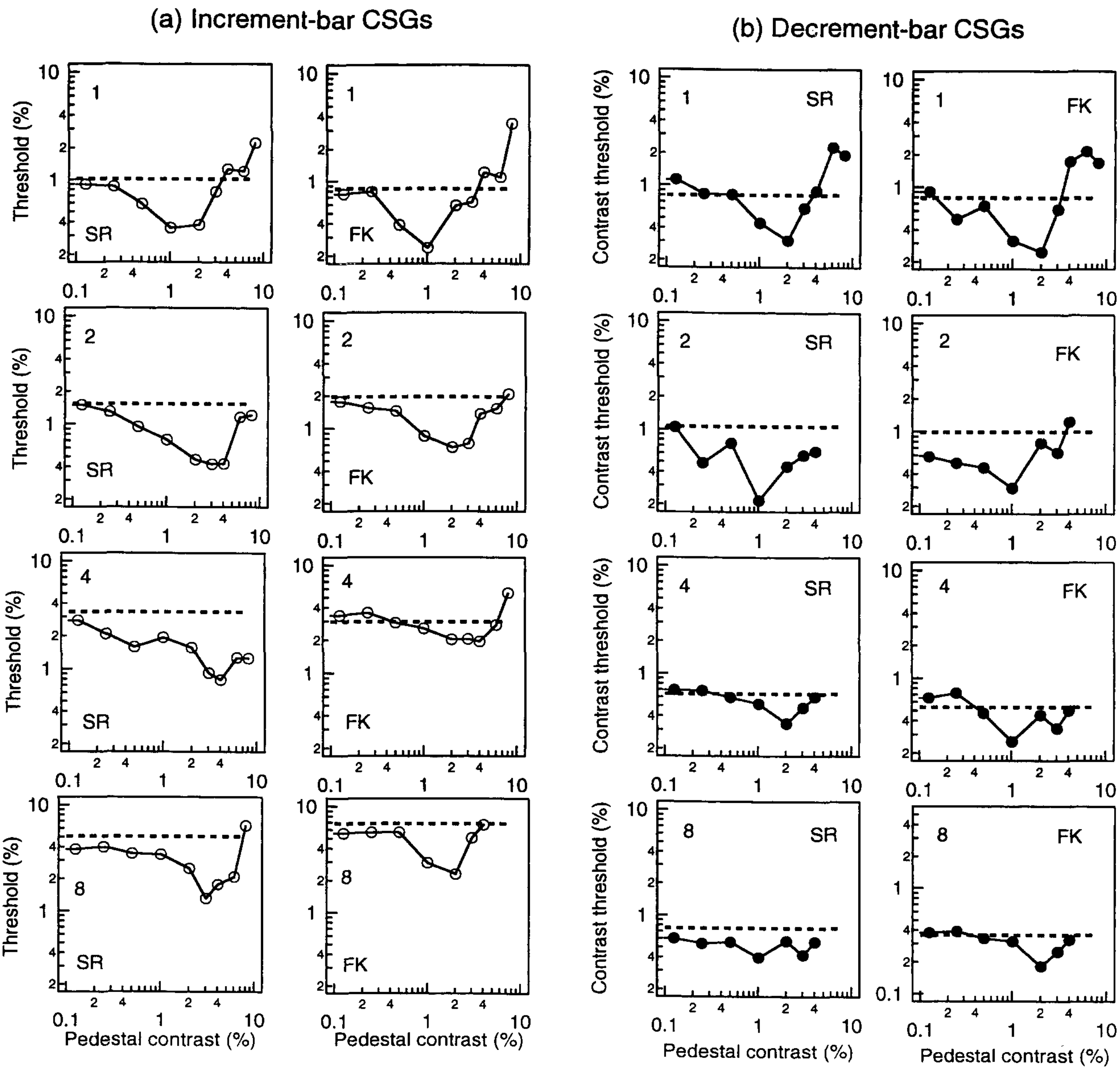

FIGURE 9. Results for Experiment 3. The stimulus arrangement for this experiment is shown in Fig. 7(a). Each plot shows contrast thresholds as a function of pedestal contrast for (a) increment-bar CSGs; and b) decrement-bar CSGs. The dashed line in each plot gives the contrast threshold for the CSG in the absence of a pedestal.

1991; Foley, 1994). The presence of such facilitation is widely accepted as an indication that the test and pedestal stimuli are processed by the same mechanism (e.g. see McCourt & Kingdom, 1996). If unsampled gratings and CSGs are detected by fundamentally different mechanisms, then one would predict an absence of facilitation between them. To test this we measured contrast thresholds for both increment-bar and decrement-bar CSGs in the presence of an unsampled pedestal grating of the same spatial frequency and phase. In the case of the increment-bar CSGs it was necessary to make the background luminance greater than near-zero, in order to accommodate the added unsampled grating pedestal. Background luminance was therefore set to 5% max. and mean luminance 15% max. For the same reason, background luminance was set to 95% max. and mean luminance 85% max. for the decrement-bar CSGs. The arrangement of the stimuli is illustrated in Fig. 8(a) for the period-to-bar-width ratio of eight conditions.

The results are shown in Fig. 9(a) and Fig. 9(b), respectively for the increment-bar and decrement-bar CSGs. Each graph plots CSG thresholds as a function of the contrast of the unsampled grating pedestal. The dashed line shows CSG thresholds in the absence of a pedestal. As in previous figures, the number in each panel refers to the period-to-bar-width ratio. The top panel in each figure shows the results for an unsampled grating test. All plots appear to show a dipper function, in which thresholds are lower in the presence, compared with the absence, of the pedestal. Moreover, the depth of the dipper is as great in many of the CSG conditions as in the unsampled grating conditions. The weakest facilitation is

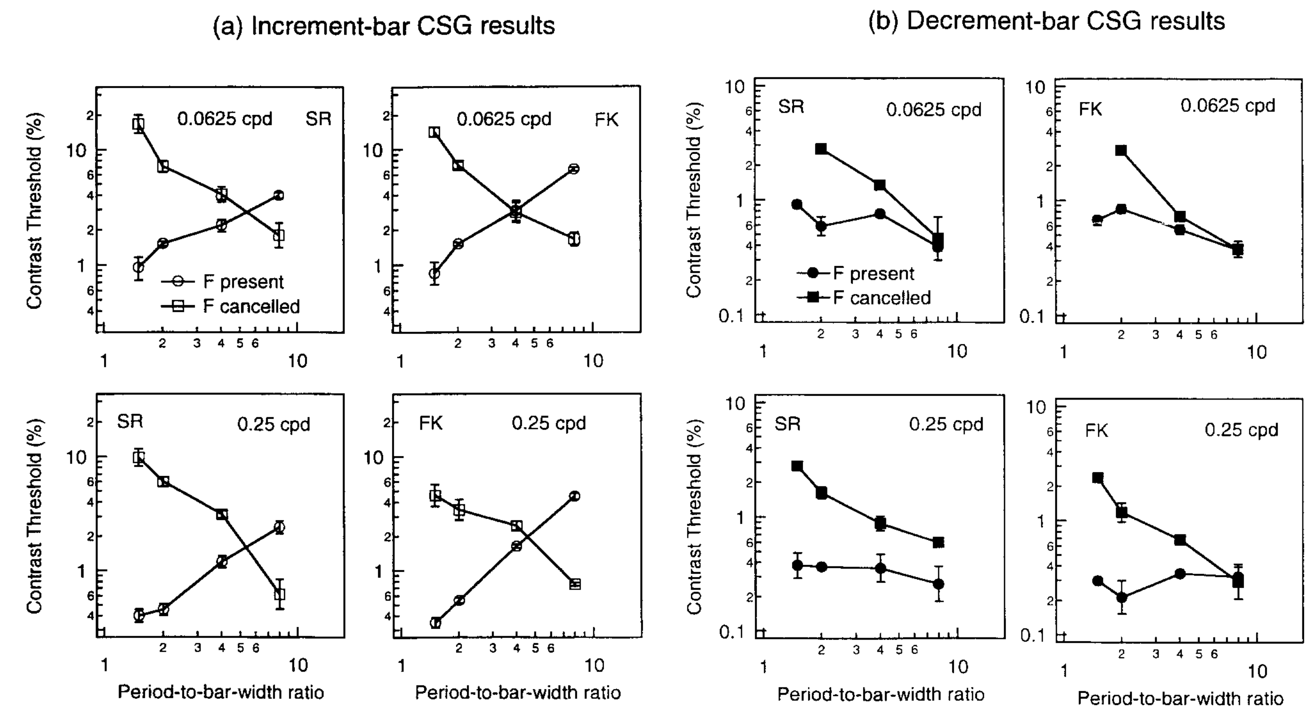

FIGURE 10. Results for Experiment 4. The stimulus arrangement for this experiment is shown in Fig. 7(b). See text for details.

in the most compressively sampled decrement-bar CSGs (period-to-bar-width ratio of 8). Taken together, these results do not support the view that CSGs are detected by different mechanisms from those detecting unsampled gratings.

These results were not expected, given our earlier conclusion that detecting variations in bar contrast underlay CSG detection. We therefore decided to perform another test for independence of CSG and unsampled grating detection, as described below.

Experiment 4. Can CSGs be detected as efficiently with the fundamental cancelled?

If CSGs are detected by processing the spatial variations in bar contrast, it follows that thresholds should be unaffected if the fundamental is removed, provided the higher harmonics and their phase relationships remain intact. This situation is illustrated in Fig. 8(b). In the figure a sine-wave of the same spatial frequency and amplitude has been added 180 deg out of phase to the fundamental in order to cancel it. In this experiment we measured thresholds for fundamental-present and the fundamental-cancelled, increment-bar and decrement-bar CSGs.

The results are shown in Fig. 10. Note that thresholds for both the fundamental-present and fundamental-cancelled conditions are plotted in the same units, namely the contrast of the fundamental. For the fundamental-cancelled condition this is the amount of fundamental that would have been present were it not cancelled, which we argue is the most suitable basis for comparison. As the figure shows, the two conditions produce very different results. At low degrees of compressive sampling, thresholds for the fundamental-cancelled condition are much higher than for the fundamental-present condition, for both increment-bar and decrement-bar CSGs. With high degrees of compressive sampling the fundamental-cancelled condition produces lower thresholds than the fundamental-present condition, whereas for the decrement-bar CSGs the data from the two conditions appear to merge. These data imply that whatever the mechanism responsible for detecting the fundamental-cancelled CSGs, it is not the same as that which detects the fundamental-present CSGs, except perhaps in the case of the highly compressively sampled decrement-bar CSGs. These data therefore reinforce the conclusion from the previous experiment, namely that the fundamental is under most circumstances a critical component of CSG detection, and that CSGs and unsampled gratings are detected by the same mechanism.

Experiment 5. Is the contrast-based compressive non-linearity static or dynamic?

The final question we consider is whether the contrast-based nonlinearity we have isolated in CSG detection is static-compressive, or has a dynamic gain control component. A well known paradigm for demonstrating the presence, time course and advantage to vision of luminance and contrast gain control was first employed by Crawford for light adaptation (Crawford, 1947). In this paradigm, detection thresholds for a brief test stimulus are measured at various times after the onset of an adapting background. If when the test is presented simultaneously with the onset of the background thresholds are higher than when presented at a suitable SOA

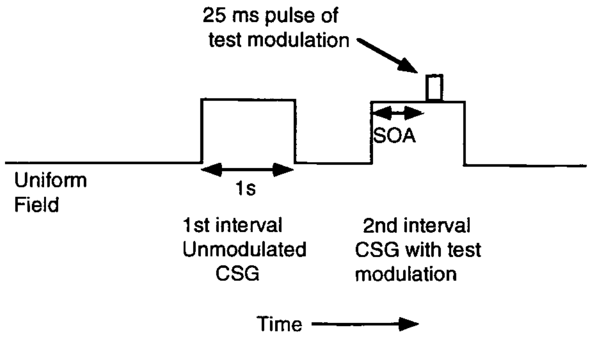

FIGURE 11. Temporal arrangement of stimuli used in Experiment 5. See text for details.

(stimulus onset asynchrony), this is taken as evidence that the background adjusts the gain of the mechanism responding to the test stimulus. The effect of the background in this case is to allow the test stimulus to be transduced by a less compressed part of its response function, thus rendering it more detectable than otherwise.

To test for the presence of a dynamic gain control mechanism in the contrast-component of CSG detection we employed the temporal arrangement of stimulus presentation shown in Fig. 11. The CSGs employed had a period-to-bar-width ratio of 8, and a spatial frequency of 0.125 cpd (producing 2 cycles per screen). They were identical to those portrayed in Figs 1 and 2, respectively for the increment-bar and decrement-bar CSGs. Thus, for the increment-bar CSGs the stimulus had a mean luminance of 5% max., a background of near-zero luminance and a mean sample bar luminance of 40% max. For the decrement-bar CSGs the stimulus had a mean luminance of 95% max., a background luminance of 100% max., and a mean bar luminance of 20% max. The "adapting background" was a 1 sec presentation of an unmodulated CSG presented in both intervals, and the test a brief 25 msec pulse of CSG modulation presented at various SOAs during one of the intervals. In between the intervals the screen was filled with a uniform field. In the case of the increment-bar CSGs the uniform field was 5% max., whereas in the case of the decrement-bar CSGs it was 100% max. To isolate the contrast-gain component of CSG detection, one needs to use a uniform field in between the test intervals equal to that of the background luminance of the CSGs, in order to ensure there is no change in the luminance adaptation state when the CSGs are presented. The use of a 5% rather than near-zero uniform field for the increment-bar CSG condition did not therefore conform to this principle. The reason for this was that the 5% uniform field was chosen initially to address a different question from that reported here. To ensure that this was not a critical factor in the results reported below, a control experiment was run on one subject (FK) with a near-zero uniform field, and the results were not significantly different from the 5% max. condition. Finally, data for an unsampled grating control condition were also collected. In this case the adapting background presented in the two intervals was a uniform field of 40% max. and at all other times the screen was filled with a uniform field of 5% max.

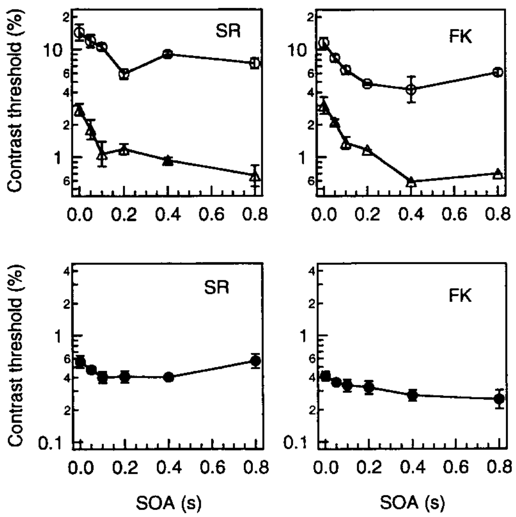

FIGURE 12. Results for Experiment 5 for increment-bar CSGs (top) and decrement-bar CSGs (bottom). The open triangles (top) data are for an unsampled sine-wave. See text for details.

Figure 12 shows contrast thresholds as a function of SOA. In the case of the unsampled control condition (open triangles) there is a rapid improvement in thresholds over the first few hundred milliseconds, revealing the dynamic gain control mechanism of light adaptation. In the case of the increment-bar CSGs a similar though less marked pattern improvement in thresholds is observed, while in the decrement-bar CSGs there is only the barest hint of an improvement. These results show that a dynamic gain control mechanism is involved to some extent in increment-bar CSG detection, and that the contrast-based nonlinearity isolated in the previous experiment is not wholly static. The possible source of this gain control mechanism will be discussed later.

SUMMARY OF FINDINGS

The principle findings of this study are as follows:

1. For increment-bar CSGs on a dark background, contrast thresholds rise approximately proportionally with the degree of compressive sampling. This confirms the previous report by Burr *et al.* (1985).
2. For decrement-bar CSGs on a bright background, contrast thresholds fall slightly with the degree of compressive sampling.
3. The effects of compressive sampling are similar for both constant-bar-width and constant-period-width CSGs.
4. For both increment-bar and decrement-bar CSGs, changing background luminance while holding constant mean bar luminance significantly alters thresholds.
5. The decrement-bar CSG data from different experimental conditions come together when thresholds are measured in terms of the difference in Weber

contrast for discriminating the bars, plotted against the mean bar Weber contrast.

6. Unsampled grating pedestals of the same spatial frequency and phase as the fundamental in CSGs facilitate CSG detection, though to a reduced degree with CSGs that are highly compressively sampled.
7. Contrast-thresholds for increment-bar CSGs in which the fundamental harmonic has been cancelled show a very different pattern from CSGs in which the fundamental is present. For decrement-bar CSGs the pattern is also different except at high degrees of compressive sampling, where the data appear to come together.
8. There is a dynamic gain control component to detecting increment-bar, but not decrement-bar CSGs.

DISCUSSION

Luminance gain control or a contrast-based compressive nonlinearity?

The results of these experiments demonstrate that the elevation of contrast thresholds observed when sine-wave gratings are compressively sampled into a set of bright bars on a dark background, results primarily from a compressive nonlinearity in transduction of the contrasts of the sample bars. They do not support the position that the threshold elevation is due to localized light adaptation to the luminance of the bars, as originally proposed by Burr *et al.* (1985), and supported by our first experiment employing decrement-bar CSGs (Kingdom & Rainville, 1995). The definitive evidence against the local light adaptation hypothesis was that background luminance had a profound effect on CSG thresholds when mean bar luminance was held constant. This implied that the luminance gain of the mechanisms sensitive to the bars was primarily set not by the luminance of the bars themselves, but by the luminance of the spacing in between the bars. When the results from the experiments using decrement-bar CSGs were recast in terms of the Weber contrast threshold for discriminating a bar at the peak of its modulation from one at its mean, they showed a pattern consistent with an explanation in terms of a contrast-based nonlinearity. Mulligan & MacLeod (1991), in their study of conventionally sampled gratings, concluded that a nonlinear saturation of spatially opponent mechanisms sensitive to the individual sample patches primarily determined detection threshold. Given that spatially opponent mechanisms are widely believed to underlie contrast detection and discrimination, our results are therefore in keeping with those of Mulligan & MacLeod.

Other possible explanations

In the Introduction, we suggested that the elevation of thresholds with increment-bar compressive sampling might be due to problems encountered with interpolating the sparsely distributed sample bar information. The results from the constant-period-width conditions, in which the number of bars per cycle was held constant, were very similar to the constant-bar-width CSGs. The constant-period-width and constant-bar-width experiments differ on a critical parameter: in the first experiment the number of samples is constant for all degrees of compressive sampling, whereas in the second the number of samples varies inversely with compressive sampling. Interpolation should therefore be facilitated by a greater number of tightly packed sample bars and adversely affected when samples are sparse. Since constant-bar-width and constant-period-width produce virtually identical threshold elevation curves despite significant differences in their respective number of sample bars, this precludes the possibility that spatial interpolation is a significant factor in explaining our results. This is consistent with the results of Morgan & Watt (1982, 1984) which demonstrate that interpolation fails at a roughly 200 sec of arc, a value well below that needed to integrate CSG bars in any of the conditions we have used.

Another possibility was critical band masking. The amplitude spectra of the CSGs are shown in Fig. 4. Of the higher harmonics introduced by compressive sampling, the one arguably of most interest is the one closest in spatial frequency to the fundamental, since this will have potentially the greatest masking effect. We will refer to this as the second harmonic. The ratio of the spatial frequency of the second harmonic to that of the fundamental is equal to the number of bars per cycle of the fundamental. As can be seen from inspection of the left-hand column in Fig. 4, the second harmonic in constant-bar-width CSGs approaches the spatial frequency of the fundamental with increased compressive sampling. In the worst case for the stimuli in our study, the 0.25 cpd period-to-bar-width = 16 condition, there were 4 bars per cycle of the fundamental, making the second harmonic only 2 octaves away from the fundamental. Given that the second harmonic is an order of magnitude greater than the fundamental at threshold, as Fig. 4 also shows, masking is a priori a distinct possibility. There is evidence in the data of some critical band masking. An examination of Fig. 5 shows, in general, higher thresholds for the 0.25 cpd condition compared with the 0.0625 condition, even when the data are normalized to the unsampled grating thresholds. Mulligan & MacLeod (1991) also provided evidence that at relatively high spatial frequencies there was some critical band masking in their conventionally sampled stimuli.

The question, however, is whether critical band masking can account for the main body of results. Three arguments suggest it cannot. Firstly, Burr *et al.* (1985) have already provided evidence against critical band masking in CSGs. They found that scrambling the phases of the higher harmonics reduced the magnitude of threshold elevation substantially. Secondly, it is difficult to see how our results with the decrement-bar CSGs, in which thresholds were slightly lowered by compressive sampling, are compatible with an explanation in terms of critical band masking. Thirdly, the results with the constant-period-width CSGs argue against such an explanation. In these stimuli, the number of bars remains constant, and so therefore also does the spatial frequency of the second harmonic, as the right-hand column in Fig. 4 shows. The fact that the constant-period-width CSGs showed a very similar pattern of thresholds as the constant-bar-width conditions, suggests that the "approaching second harmonic" explanation advanced above is unlikely to be correct.

A common mechanism for detecting unsampled and compressively sampled gratings?

The second issue that we addressed was whether the mechanisms responsible for detecting CSGs were ultimately those responsible for detecting the unsampled gratings from which they were derived. Having provided evidence that CSG detection appeared to involve a comparison of bar contrasts, rather than a detection of the fundamental *per se*, we were surprised at how well unsampled grating pedestals facilitated CSG detection. Moreover, our demonstration that cancelling the fundamental in most cases significantly altered thresholds reinforced the idea that the fundamental was a critical component in CSG detection. These results imply that CSGs are unlikely to be processed by the type of nonlinear mechanism believed to be responsible for the detection of amplitude modulated gratings and beat patterns (Derrington & Badcock, 1985; Zhou & Baker, 1993). Instead, they appear to be processed by mechanisms sensitive to relatively low spatial frequency sinewaves, but in a way which apparently ignores the non-signal, background luminance information contained in the spaces between the sample bars, information which would perhaps be expected to be integrated with the bar signals. How the visual system might accomplish this will only be understood after further research.

Dynamic or static nonlinearity?

We showed that there is a dynamic component to the compressive nonlinearity underlying increment-bar (though not decrement-bar) CSG detection. We found a reduction in thresholds when the test modulation was presented at a variable SOA after the onset of an unmodulated CSG background. Given our evidence that the nonlinearity underlying CSG detection is contrast-based, this result implicates at least some degree of contrast-gain control. Rapid contrast gain control has been demonstrated both physiologically (Shapley & Enroth-Cugell, 1984) and psychophysically (Bowen & Wilson, 1994). A contrast-gain adjustment, if retinal, may however be partly synonymous with the multiplicative (though not subtractive) component of light adaptation isolated for increments (Hayhoe, personal communication). For an increment on a dark background, the effect of dividing the response by some function of its contrast would be mathematically similar to the effect of dividing its response by some function of its luminance. The dynamic component of CSG detection isolated here for increment-bar CSGs might also be synonymous with the mechanism isolated by MacLeod *et al.* (1992), which mediated bleaching by high contrast difference frequency gratings. Both subjects in the experiments described here noticed afterimages from the CSGs, particularly with the increment-bar CSGs.

The measurement of adaptational pooling size

We began with the issue of adaptational pools, and specifically with the question of whether CSGs could validly be employed to measure the pooling area of luminance gain control, as suggested by Burr *et al.* (1985). Our key finding that luminance gain appears to be set primarily by the luminance of the background between the bars, rather than by the luminance of the bars themselves, suggests that CSGs cannot be used for this purpose. The estimates of adaptational pooling size provided by Burr *et al.* (1985) are therefore most likely to be estimates of bar resolution i.e., visual acuity.

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Acknowledgements—This research was supported by an NSERC Fellowship to Stéphane Rainville, and grant No. MT11554 from the Medical Research Council of Canada awarded to Fred Kingdom.