Pergamon

0042-6989(93)E0060-K

Vision Res. Vol. 34, No. 16, pp. 2093–2101, 1994

0042-6989/94 $7.00 + 0.00

Speed, Spatial-Frequency, and Temporal-Frequency Comparisons in Luminance and Colour Gratings

G. B. HENNING,* A. M. DERRINGTON†

Received 13 October 1993; in revised form 8 December 1993

The perceived speed, temporal frequency, and spatial frequency of matched colour and luminance gratings were compared in separate experiments. The large factor by which colour gratings are perceived to be slower moving than matched luminance gratings cannot be explained by systematic differences in the perceived spatial frequency or in the perceived temporal frequency of the two types of grating.

Motion Colour Luminance Isoluminance Equiluminance Speed Spatial frequency Temporal frequency

INTRODUCTION

Differences in the perceived speed of luminance and colour gratings of the same spatial frequency moving at the same speed are well documented (Cavanagh, Tyler & Favreau, 1984). Unlike differences in the perceived speed of luminance gratings of different contrast (Stone & Thompson, 1992), large differences in the perceived speeds of luminance and colour gratings occur when they are presented successively and when both are presented at contrasts that are the same factor above their respective "thresholds" for motion detection.

The differences in apparent speed are interesting in themselves but, in the experiments reported here, we attempt merely to use the differences in perceived speed between luminance and colour gratings to explore the more general problem of how the motion of objects is represented in our visual systems.

Consider a two-dimensional graph in which to represent the one-dimensional translation of objects‡: the horizontal axis shows the spatial frequency of the object (c/deg) and the vertical axis, its temporal frequency (Hz). If the effects of spatial truncation on spatial frequency and temporal truncation on temporal frequency are ignored, then moving sinusoidal gratings are simply points in this space. The ratio of the temporal frequency to the spatial frequency of any such point gives the direction and speed of movement of the object represented by the point.

If information about spatial and temporal frequency is used to determine velocity, any error in the representation of temporal or spatial frequency will, in the absence of cancelling errors, lead to mis-estimation of speed (and/or direction) of motion (Henning & Derrington, 1988).

Suppose, for example, that, unlike motion models derived from Reichardt detectors (Adelson & Bergen, 1985; Reichardt, 1961; van Santen & Sperling, 1985; Watson & Ahumada, 1985), separate mechanisms are used to extract estimates of the spatial and temporal frequency of moving gratings. If either estimate is wrong, then a speed estimate based on their comparison may also be wrong. In particular, if, for a given speed of motion, the spatial frequency of a colour grating is overestimated relative to that of a luminance grating of the same spatial frequency, or if the temporal frequency of the colour grating is underestimated, then the colour grating would be seen as moving slower than the luminance grating of the same speed.

The question of whether speed and temporal frequency estimates are perceptually separate (McKee, Silverman & Nakayama, 1986; Smith & Edgar, 1991) is, of course, quite relevant; although unlikely, the determination of motion may involve separate estimates of spatial and temporal frequency without these estimates being perceptually available to the observer. However, we shall assume that if separate estimates of spatial and temporal frequency enter into the determination of perceived speed, then perceived spatial and temporal frequency give reliable estimates of that factor's contribution to the determination of speed.

The following experiments were carried out to explore, under comparable conditions, observers' estimates of the

*Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, England.

†Department of Psychology, University of Nottingham, University Park, Nottingham NG7 2RD, England.

‡An example, which will be discussed subsequently, is given in Fig. 4.

speed, the spatial frequency and the temporal frequency of colour and luminance gratings.

METHODS

General

Three observers (including the authors) served in experiments in which the perceived speed, the perceived rate of flicker and the perceived spatial frequency of luminance and colour gratings were compared. All the experiments used the method of constant stimuli described below.

Stimuli

The stimuli were horizontally orientated, sinusoidal gratings viewed binocularly with suitably corrected vision; they had either luminance or colour variation, were generated by the method of Schade (1956) using a one-dimensional display controller (Cambridge Research Systems VSG2/1) with three 14-bit digital-to-analogue converters (DACs) and displayed on a Barco CDCT6551 colour monitor. At the viewing distance of 1.37 m, the display subtended 12.1 deg of visual angle horizontally (10.0 deg vertically) at the observers' eyes. The unmodulated screen produced uniform grey fields with a luminance of $44.2\,\mathrm{cd \cdot m^{-2}}$ (CIE chromaticity coordinates: $x = 0.333$, $y = 0.477$) and neither the mean luminance nor the mean chromaticity of the display was altered by the presentation of the gratings.

The gratings—1 c/deg, horizontal luminance or colour gratings—were produced by modulating the luminances of the phosphors of the display as follows:

$$L(y) = L_m(r,g,b) + M(r,g,b) \times \cos[2\pi(fy + gt) + v]W(t), \quad (1)$$

where f is the spatial frequency (c/deg) and g the temporal frequency (Hz) of the grating and v is a phase term. The mean luminance, L_m, was produced by summing the contributions from the r, g, and b phosphors, $L_m(r)$, $L_m(g)$ and $L_m(b)$, in the proportions 0.208, 0.661, and 0.131, respectively. $W(t)$ is a raised cosine temporal envelope in which

$$W(t) = \begin{cases} 1 + \cos 2\pi(t - 0.5) & 0 < t < 1 \\ 0 & \text{otherwise,} \end{cases}$$

and $M(r,g,b)$ represents the luminance modulation of the three phosphors of the display.

A luminance grating of a given contrast was produced by setting the modulation of each phosphor to be the product of the required contrast, C, and the contribution of that phosphor to the mean luminance, $L_m(p)$. Thus, for each phosphor in a luminance grating,

$$L_p(y) = L_m(p)\{1 + C\cos[2\pi(fy + gt) + v]\}W(t). \quad (2)$$

Equation (2) defines a grating of contrast C on each phosphor. Since, in a luminance grating, all the gratings for the phosphors have the same spatial and temporal frequencies, and the same contrast and phase, the relative contributions of the three phosphors are unchanged by the modulation and thus the grating has only luminance variation.

The colour gratings were produced by modulating the luminance of the r and g phosphors in antiphase with modulations of equal luminance so that

$$M(r) = -M(g). \quad (3)$$

and

$$M(b) = 0.$$

This produced spatial variations in chromaticity but not luminance. The chromaticity variation was along an axis close to the "constant blue" axis of Derrington, Krauskopf and Lennie (1984).

Photometry: checks on equiluminance. The display luminance calibrations were carried out using a UDT model 61 photometer with a photometric filter and lumi-lens. However, because equiluminance planes vary slightly from observer to observer, and because the photometer deviates slightly from the V_λ spectral sensitivity, we determined equiluminance points for each observer at different temporal rates. A 1-c/deg "colour" grating was presented under the same conditions as all our stimuli. The grating was presented as a sinusoidal grating counter-phase flickering at rates of 4, 8 or 16 Hz. The observers had levers which allowed them to add a luminance grating to the coloured grating and to adjust its contrast and sign until the perceived flicker was minimized. At this point we assume that the added luminance grating cancels any residual luminance in the colour grating introduced by variations in the equiluminance plane from observer to observer, or by chromatic aberration. In all experiments using that colour grating for that observer, the appropriate proportion of luminance contrast was added to it in the appropriate phase; the mean of six settings under each condition determined the appropriate contrast save that the cancellation task was too difficult (or too variable in its results) at lower temporal frequencies so we used the value measured at 4 Hz for the temporal frequencies used in this study.

Direction-of-motion discrimination. The discriminability of direction-of-motion as a function of contrast for our three observers had been measured previously using the luminance and colour gratings of this experiment (Derrington & Henning, 1993). There, following the suggestions of Lennie and D'Zmura (1988), we expressed the magnitudes of the modulation of our chromatic and luminance gratings as the mean of the unsigned modulations in excitation of the R and the G cones produced by the gratings and called that quantity the "contrast" of both types of stimuli. "Contrast", thus defined, is just the familiar Michelson contrast for luminance gratings and provides a suitable and readily determined basis for comparing luminance and colour gratings. We use the contrasts corresponding to 75% correct direction-of-motion discrimination as the direction-of-motion "thresholds" in our present experiments. Unless otherwise noted, all gratings were presented at a contrast 1.0 log units above their respective direction-of-

TABLE 1. Contrasts of colour and luminance gratings used for the different observers in this study

Observer	SAL	AMD	GBH
Luminance	0.014	0.012	0.012
Colour	0.019	0.010	0.014

The threshold measurements on which these were based have been published (Derrington & Henning, 1993, Fig. 2).

motion-discrimination "threshold"—i.e. 10 times the contrast that led to 75% correct direction-of-motion discrimination with that grating. The contrasts used are shown in Table 1.

Comparisons between luminance and colour gratings

The main experiments involved comparisons of various attributes of luminance and colour gratings. Each trial consisted of two observation intervals, 1 sec long, separated by a pause, and defined for the observers by bursts of audible noise. Whatever attribute was to be compared, a standard grating was in the first observation interval with probability 0.5 on each trial. For the other interval in each experimental session, five different comparison stimuli were used, randomly chosen from trial to trial subject to the constraint that none was used for the nth time until all had been used $n - 1$ times. The session lasted until each stimulus had been used on 25 trials. In experiments involving comparison of an attribute between luminance and colour gratings (main experiments), this process was repeated four times to give five points (each point based on 100 judgements) for each observer on the function relating the percentage of correct responses to a measure of the attribute being compared; measurements involving only luminance or only colour gratings (subsidiary experiments) were based on 50 observations per point. No feedback was given in either the main or the subsidiary experiments.

Speed of motion. In these experiments, one observation interval contained the standard, a 1-c/deg colour grating drifting at a fixed temporal frequency of 2 Hz (2 deg/sec). In the other observation interval of the main experiment, the comparison gratings were luminance gratings presented at one of five drift rates selected at random from a set chosen such that the luminance grating was sometimes seen as drifting faster, and sometimes slower, than the colour grating. The observers' task was to choose the interval with the more quickly moving grating and psychometric functions relating the speed of the luminance grating to the proportion of times that it was judged to be moving faster than the colour grating were obtained. In one type of subsidiary experiment, both the standard and variable gratings were luminance gratings, and in the other type, both were colour gratings.

Rate of flicker. In one observation interval of the main experiment, the observers viewed a standard counterphase-flickering colour grating, and in the other, a counterphase-flickering luminance grating; both gratings had the spatial frequency and contrast used in the speed-of-motion comparisons. The flicker rate of the colour grating was 2 Hz and the flicker rate of the luminance gratings was randomly selected from a set of five chosen so that the luminance grating was sometimes seen as flickering faster and sometimes slower than the colour grating. The observers' task was to choose the interval with the more rapid flicker. As with the speed-of-motion experiments, subsidiary experiments with only luminance gratings (and with only colour gratings) were also performed.

Spatial frequency. In one observation interval the observers viewed a standard colour grating drifting upward at a temporal frequency of 2 Hz. In the main experiment, the other interval contained a luminance grating drifting in the same direction and at the same temporal frequency as the colour grating. Both gratings were presented at the contrasts they had in the motion discrimination task. The spatial frequency of the colour grating was fixed at 1 c/deg while that of the luminance grating was randomly selected from a set of five chosen so that it was sometimes seen as having higher and sometimes lower spatial frequency; the observers' task was to choose the interval containing the grating of higher spatial frequency. As with the speed-of-motion experiments, subsidiary experiments with only luminance gratings (and with only colour gratings) were performed.

RESULTS AND DISCUSSION

The functions relating performance to the parameter manipulated were reasonably well fit by Gaussian functions using the routines of Foster and Bischof (1991). We use the means and standard deviations of these fits in our discussion but, for clarity and because no useful information is gained by plotting the fitted curves, they are omitted from the graphs.

Speed comparisons

Figure 1(a–c) shows the percentage of times that the observer reported a test (luminance) grating, whose speed varied from trial to trial, to be moving faster than the standard (colour) grating (drifting at 2 deg/sec) as a function of the speed of the test grating. The half-solid symbols show the results from the main experiment, i.e. the percentage of times the luminance grating was judged to be drifting faster than the standard colour grating as a function of the speed of the luminance grating. Results from the subsidiary experiments are shown either as solid symbols (standard and comparison gratings both luminance gratings) or as open symbols (colour gratings). Each figure shows the results for a single observer.

Consider first the results of the subsidiary experiments, which, although based on only 50 observations per point, clearly show that the observers can perform the task: the results indicate that physically equal stimuli produce approx. "50%" judgements (note that if the errors are binomially distributed; ± 1 SD covers a range

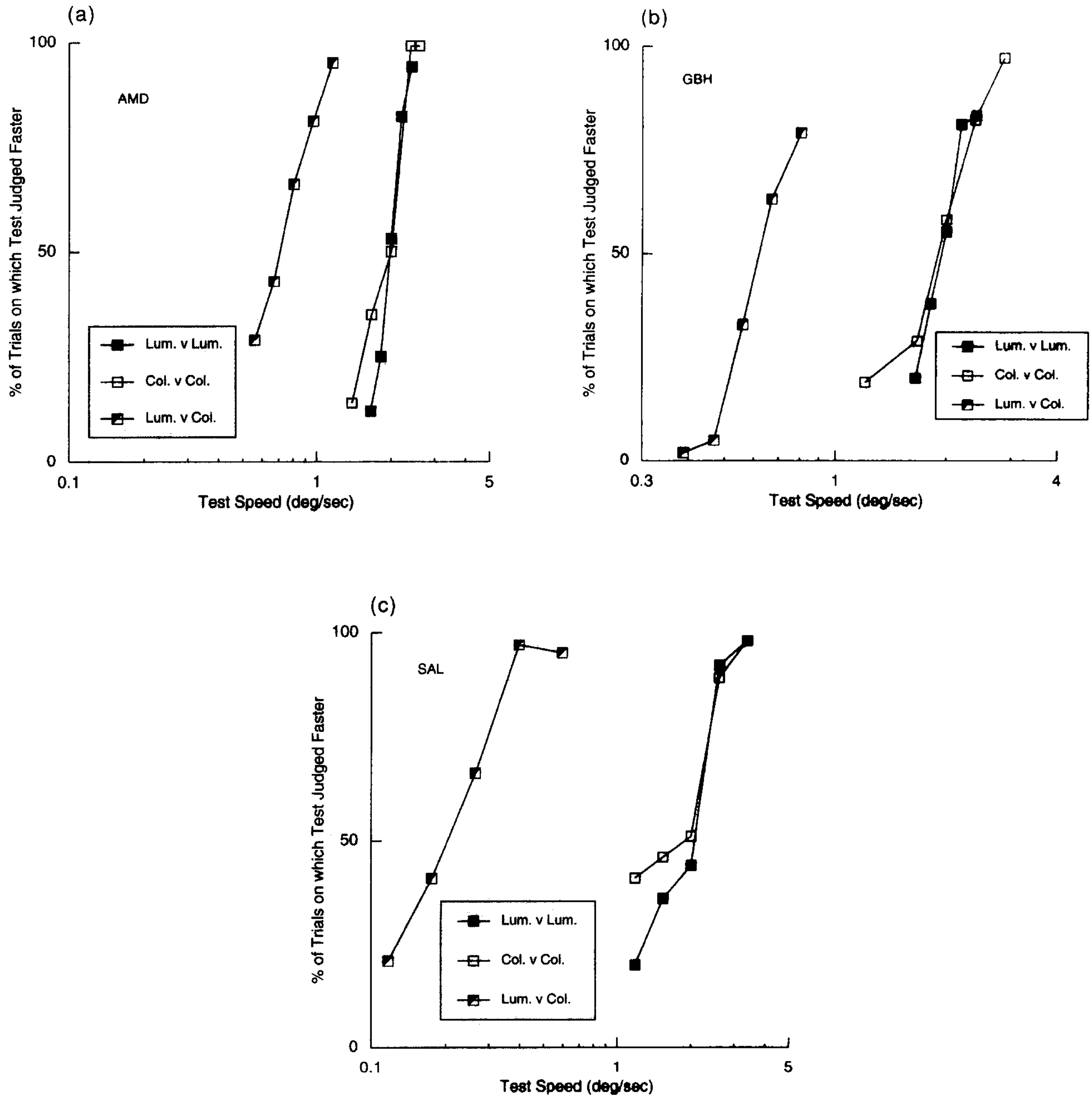

FIGURE 1. (a–c) The percentage of times an observer judged the test grating to move faster than the 2-deg/sec standard grating as a function of the speed (deg/sec) of the test grating. For the half-solid symbols (based on 100 judgements per point) the standard was a colour grating and the test was a luminance grating; in the other conditions (based on 50 observations per point) the test and standard were the same—both colour gratings (open symbols) or both luminance gratings (solid symbols).

of 7%). There is also a suggestion, from the relative shallowness of the psychometric functions of the colour tests (open symbols), that the precision of speed judgements is slightly less with colour gratings than with luminance gratings as has been shown previously (Cropper, 1994).

Comparisons between colour and luminance gratings (half-solid symbols) are different. In agreement with Cavanagh and Favreau (1984), colour gratings are seen as moving more slowly than luminance gratings of the same physical speed. With the conditions of our experiment, the observers judge the two sorts of grating to have equal speed when the luminance grating moves at speeds that are factors of approx. 0.38 (AMD), 0.32 (GBH), and 0.1 (SAL) times the physical speed of the colour grating.

Flicker-rate comparisons

The results of the same observers asked to judge the temporal frequency of flickering gratings are shown in Fig. 2(a–c). Only for one of the observers (AMD) is there a suggestion that the functions obtained with luminance gratings (solid symbols) are steeper than those obtained with colour gratings (open symbols), indicating higher precision in the luminance-based representation of flicker rate.

In comparisons of flicker rate across luminance and colour, however, the results from the different observers

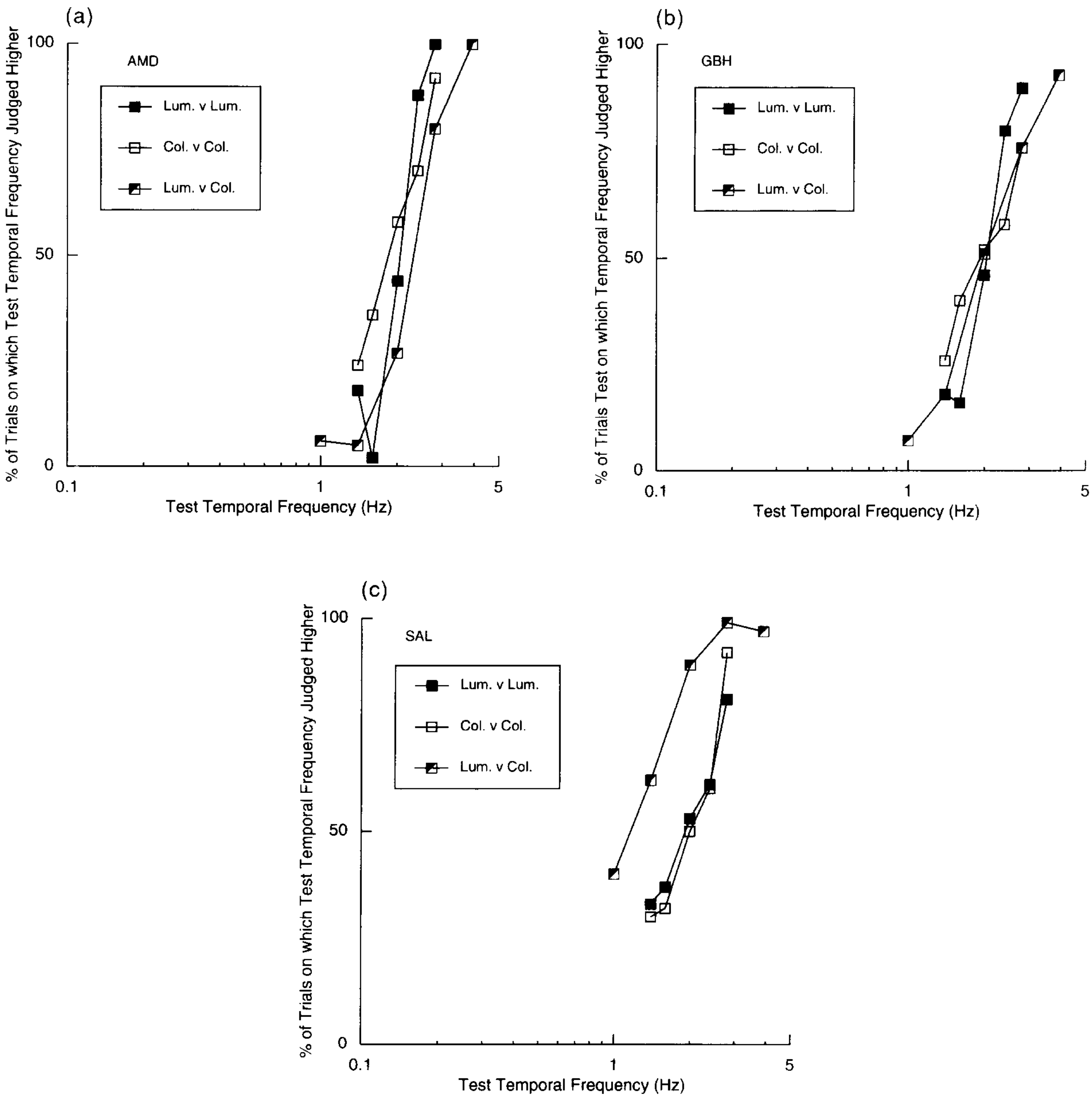

FIGURE 2. (a–c) The percentage of times an observer judged the counter-phase flickering test grating to flicker faster than the 2-Hz standard as a function of the rate of counter-phase flicker (Hz) of the test grating. For the half-solid symbols (based on 100 judgements per point) the standard was a colour grating and the test was a luminance grating; in the other conditions (based on 50 observations per point) the test and standard were the same—both colour gratings (open symbols) or both luminance gratings (solid symbols).

are different, and not much help in explaining the differences in perceived speed between luminance and colour gratings. As with the speed comparisons in Fig. 1, the frequency with which the luminance grating was perceived to have higher temporal frequency than a standard colour grating flickering at 2 Hz, is plotted as a function of the temporal frequency of the luminance grating. Observer SAL [Fig. 2(c)] is the only one of the three who shows a difference in perceived temporal frequency between colour and luminance gratings that is in the direction appropriate to explain the difference in perceived speed. She requires the luminance grating to be flickering more slowly than the colour grating by a factor of about 0.7. However, this is a long way short of the factor of about 10 that would be required to account for the difference in perceived speed between colour and luminance gratings of this observer. Observer GBH [Fig. 2(b)] sees the luminance and colour gratings as having equal flicker rate when their flicker rates are physically equal. Observer AMD [Fig. 2(a)] shows a small difference in perceived flicker frequency between luminance and colour gratings, but the difference is in the wrong direction to explain the difference in perceived speed shown in Fig. 1. He sees them as equal in flicker rate when the luminance grating flickers at approx. 1.2 times the rate of the colour grating.

Spatial-frequency comparisons

Judgements of spatial frequency are shown in Fig. 3. The differences in perceived spatial frequency are in the

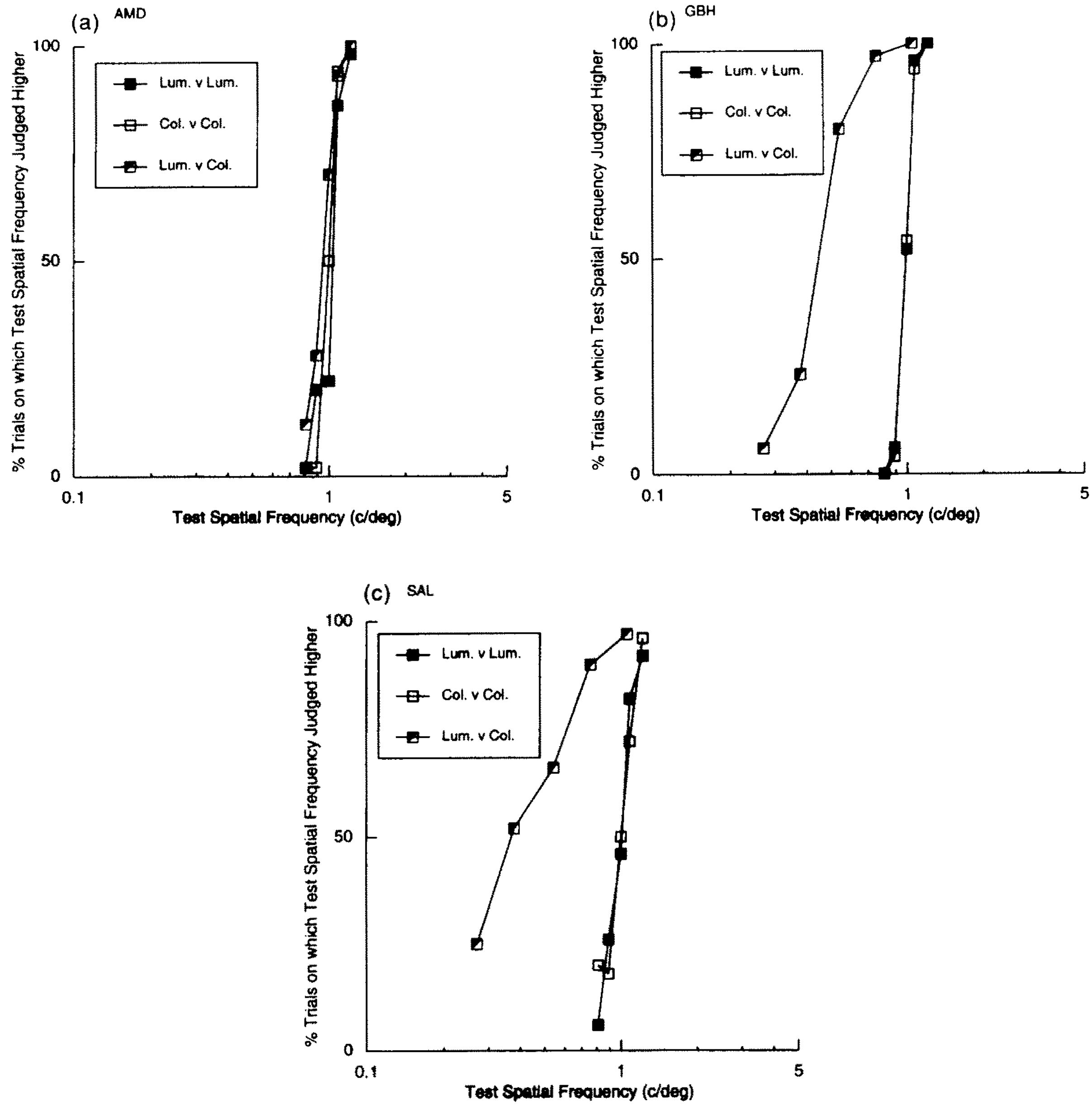

FIGURE 3. (a–c) The percentage of times an observer judged the test grating to have a higher spatial frequency than the 1-c/deg standard as a function of the spatial frequency (c/deg) of the test grating. For the half-solid symbols (based on 100 judgements per point) the standard was a colour grating and the test was a luminance grating; in the other conditions (based on 50 observations per point) the test and standard were the same—both colour gratings (open symbols) or both luminance gratings (solid symbols).

wrong direction to account for the fact that colour gratings appear to move at lower speed than luminance gratings: all three observers require the luminance grating to have a lower spatial frequency than the colour grating for the spatial frequencies to appear equal. The size of the difference is different for the three observers. For AMD [Fig. 3(a)], the effect is small—approx. 10%. Observers SAL [Fig. 3(c)] and GBH [Fig. 3(b)], on the other hand, show a relatively large effect, requiring the luminance grating to be *lower* in frequency by factors of about 3 and about 2 respectively.

It has been reported both for successively presented stimuli (Diener, Wist, Dichgans & Brandt, 1976) as well as for simultaneous comparisons (Smith & Edgar, 1990) that stimuli of physically different spatial frequency moving at the same physical speed have different apparent speeds in that the stimulus of higher spatial frequency appears to move slower. The effect at the low spatial frequencies we use, however, is either negligible or in the wrong direction to predict our results (Smith & Edgar, 1990).

It is also worth noting that the judgements of spatial frequency differ from the judgements of speed or temporal frequency in that, for all three observers, the slopes in experiments involving just colour gratings (open symbols) or just luminance gratings (solid symbols) are virtually identical. This indicates that the underlying precision of representing spatial frequency is the same for luminance and colour gratings.

GENERAL DISCUSSION

Overview

There are two points in the results that seem to us to be worthy of discussion. First, there is the fact that the differences in perceived speed between luminance and colour gratings cannot be related to differences in perceived temporal frequency or perceived spatial frequency. Second, there are inferences about the precision with which different parameters of the stimulus are represented in the visual system that can be drawn from the forms of the psychometric functions in the different tasks.

Speed, temporal frequency and spatial frequency judgements

The results of our experiments clearly confirm that colour gratings appear to move more slowly than luminance gratings of the same spatial and temporal frequency (Cavanagh *et al.*, 1984) and extend the results to the situation where: (1) the contrasts are equal factors above the respective "thresholds" for detecting motion, and (2) the gratings are presented successively rather than simultaneously. Under these conditions also, observers judged colour and luminance gratings to have the same speed when the luminance gratings were moving much more slowly than the colour gratings. The speed ratio differed for the different observers ranging from about 3 to about 10.

The differences in perceived speed do not arise because the observers mis-estimate the spatial and temporal characteristics of the colour gratings. This finding is illustrated separately for each observer in Fig. 4(a–c). In the figures spatial frequency (c/deg) is given on the abscissa and temporal frequency (Hz) on the ordinate. A sinusoidal grating moving at a fixed velocity plots as a point in this space and the slope of the line joining the point to the origin gives the speed and direction of motion. Thus any point on the solid line (including our standard colour grating of spatial frequency 1 c/deg and temporal frequency 2 Hz) represents a stimulus velocity of 2 deg/sec. The solid line thus represents the physical characteristics of the standard.

The dashed line in each figure indicates the speed of the matching luminance grating; for all our observers this line is shallower than that of the standard indicating that the *perceived* speed of the colour grating is slower than that of the luminance test.

The temporal frequencies of the test luminance grating that matched the temporal frequency of the standard colour grating flickering at 2 Hz are shown as dotted horizontal lines in Fig. 4 and the matched spatial frequency are shown as dotted vertical lines. The slope of the line from the intersection of the dotted lines would give the speed of the test grating that matches the standard grating were the observers to use their separate estimates of spatial and temporal frequency to estimate speed. Although all the observers mis-estimate the relative spatial frequencies of colour and luminance gratings, the mis-estimations are in the wrong direction to produce the observed differences in perceived speed. Consequently, whatever the explanation of the differences in the perceived speed of colour and luminance gratings, it does not appear to lie in differences in the ways in which the spatial and temporal characteristics of the stimuli are represented in the visual system.

A further feature of the results that should be noted is the relatively large differences between observers in each of the comparisons between colour and luminance gratings.

Precision of representation of speed, and temporal frequency

An interesting question which our data allow us to address, although not completely to resolve, is the precision with which speed and temporal frequency are represented: on the usual assumptions of detection theory (Green & Swets, 1966; Nachmias, 1972), the maximum slope of the psychometric function (on appropriate coordinates) is inversely proportional to the standard deviation of the dimension on which the variable being judged is represented. We have used this fact in a straightforward way in comparing, within a task and only with stimuli of the same type, the precision with which the properties of luminance or colour gratings are represented. We can use the estimate of the standard deviation (the slope of the psychometric function) to compare precision when the means of the underlying distributions are equal (as for the data in the subsidiary experiments when test and standard stimuli are either both colour or both luminance gratings). But we should like to make comparisons across tasks to estimate the relative precision of the speed and temporal frequency representations. Since the comparisons are of different dimensions, we are forced to use a measure of relative precision (the standard deviation divided by the mean) because this quantity is independent of the (common) unit in which the mean and standard deviation are measured whereas the size of the standard deviation depends on the choice of unit. Table 2 shows this index for all three observers for all the comparisons in which both gratings were of the same type.

The relative precision of the representation of speed is better than that of flicker or luminance (all three observers) and (for two of the three observers) for colour gratings as well. On the surface, this implies that speed is more precisely represented than temporal frequency.

However the direct comparison of speed and flicker data may under-estimate the difference between them: the temporal-frequency (flicker) estimates may be based on an estimate from each of the two components of the flickering grating, one from the upward moving and one from the downward moving component (whereas only one speed estimate is available from the single component of the drifting grating). If two estimates are used by our observers, and if the estimates are independent, then a single temporal-frequency estimate would be less

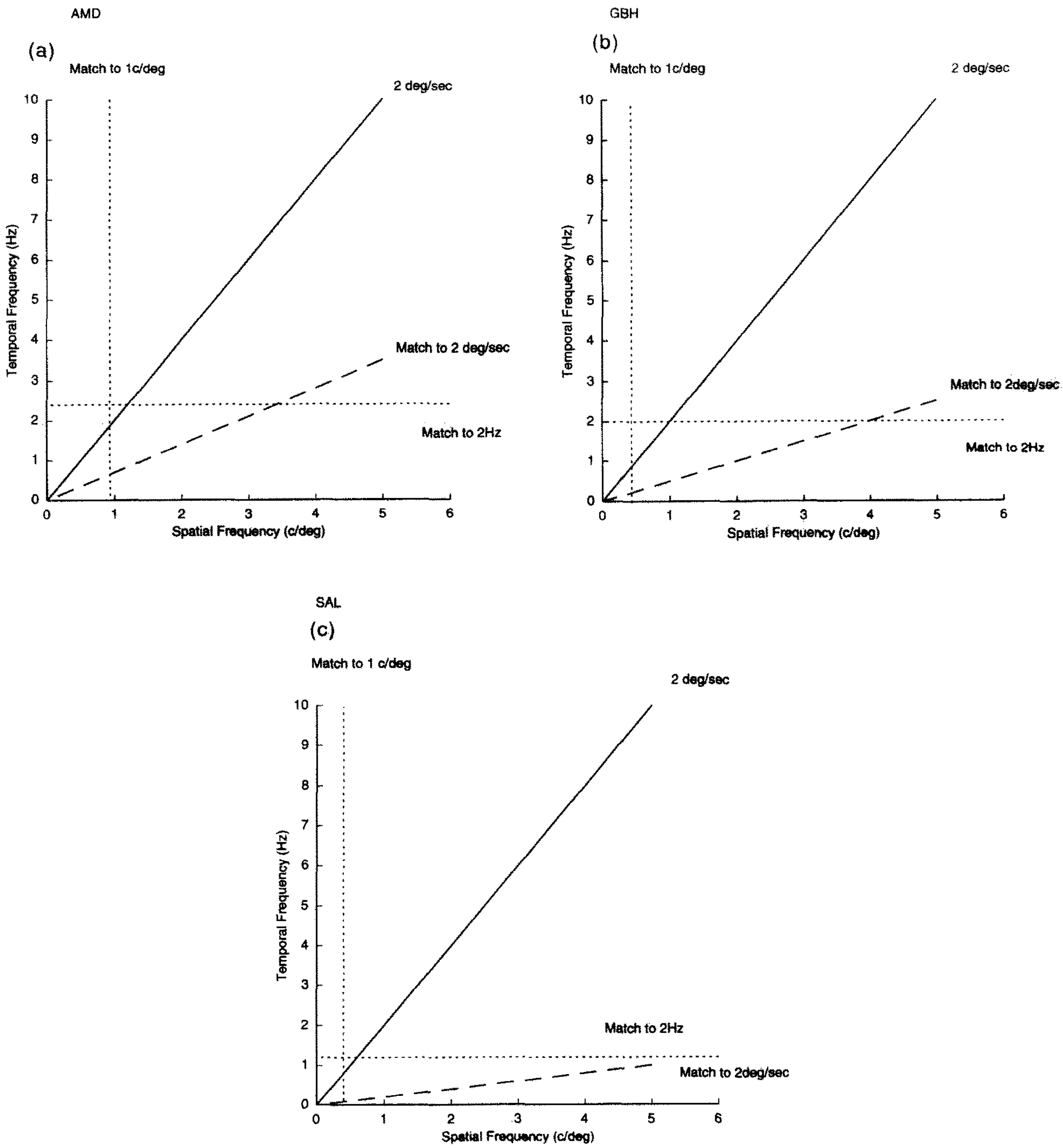

FIGURE 4. (a–c) A summary of the colour and luminance comparisons made by each observer plotted on axes of spatial frequency vs temporal frequency. The solid diagonal line represents the standard velocity of 2 deg/sec. The dashed diagonal line shows the velocity of the moving luminance grating which matches the perceived speed of a chromatic grating moving at 2 deg/sec. The dotted horizontal line shows the temporal frequency of the flickering luminance grating which matched the apparent temporal frequency of a colour grating flickering at 2 Hz, and the dotted vertical line shows the spatial frequency of the moving luminance grating which matches the apparent spatial frequency of a colour grating of 1 c/deg.

precise (shallower slope) than our measurements indicate by a factor of the $\sqrt{2}$. This would further increase the difference in precision between motion and flicker.

We are not in a position to know, of course, whether temporal-frequency estimates from both components of the counterphase flickering gratings are used and, if so, whether the estimates are independent. However, it is difficult to see how, at the speed and spatial frequency we use, speed estimates could be more precise than temporal frequency estimates if the former are based jointly on a less precise estimate of temporal frequency and an estimate of spatial frequency which, however precise it may be, can only add further noise.

Thus our results are not inconsistent with the conclusions of McKee *et al.* (1986), that speed and temporal frequency are coded separately. Further, Fig. 4 shows that the observers' percepts of speed, spatial frequency, and temporal frequency are mutually inconsistent. Thus it is unlikely that any of them could be derived from the other two. Temporal frequency seems as unlikely to be

TABLE 2. Ratio of the standard deviation to the mean of the cumulative Gaussian curve which best fit the psychometric function for the comparisons of flicker rate, speed and spatial frequency for all cases where the two gratings were of the same type

	GBH	SAL	AMD
Luminance gratings			
Flicker	0.28	0.57	0.19
Speed	0.20	0.38	0.13
Spatial frequency	0.06	0.14	0.10
Colour gratings			
Flicker	0.58	0.42	0.38
Speed	0.32	0.61	0.20
Spatial frequency	0.06	0.15	0.06

derived from spatial frequency and speed estimates as the latter is of the former two.

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Acknowledgement—This work was funded by grants from the SERC, GR/G 00730 and GR/G07982 to the University of Newcastle upon Tyne, where the experimental work was carried out.