A Minimum Motion Technique for Judging Equiluminance

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This article evaluates a new technique based on apparent motion (Anstis, 1980) for matching the luminance of different colours. This method supplements the established methods for measuring spectral sensitivity to different hues, namely heterochromatic flicker photometry and minimum-border (Wagner and Boynton, 1972). The minimum motion technique has the advantage of simplicity when used for adjusting colour luminances on television displays.

Consider two coloured square-wave gratings, one made of red and green bars, the other of dark yellow and light yellow bars. If the red/green grating is suddenly replaced by the dark yellow/light yellow grating which is displaced one quarter-cycle (half a bar width) to the right, then the grating will appear to jump to the left if the green bars are lighter than the red bars but to the right if the red bars are lighter than the green. If the red bars were made equiluminous with the green bars, then there is no reason to pair off the dark yellow bars with either the red or the green bars; so no consistent apparent motion will be seen.

A computer-generated television display presented red/green gratings interleaved with dark yellow/light yellow gratings in a four-stroke cycle (Fig. 1) which produced continuous AM to the left or right, or no motion at equiluminance. Subjects found it fairly easy to set the red and green bars to equal luminance, as the direction of the grating motion indicated in which direction a correction should be made in order to approach equiluminance.

The first experiment consisted of matching the luminance of the coloured bars in the test grating (red and green in this case) by adjusting their relative

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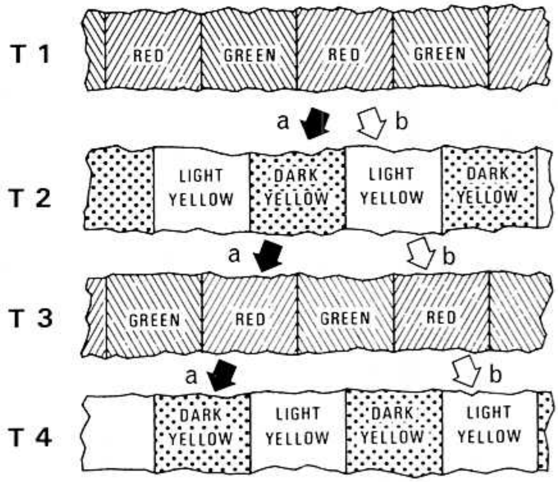


FIG. 1 Four coloured gratings were exposed in a repetitive sequence, at times T1 through T4, on the screen of a computer-controlled TV. Positions of the gratings were superimposed, not displaced vertically as illustrated. Each grating was displaced sideways by one-quarter cycle (half a bar width) from its predecessor. Direction of apparent motion, shown by the arrows, depended on the luminance of the bars. (a) When the red bars were darker than the green bars, the dark red bars in the grating at time T1 (or T3) appeared to jump leftward to the dark yellow bars in the grating at time T2 (or T4). (b) Conversely when red bars were lighter than the green bars they appeared to jump rightward to the light yellow bars.

luminance until no consistent motion was seen, either to the left or to the right. The interleaved light yellow/dark yellow grating that contained the fixed luminance difference was actually a mixture of the two colours to be matched, i.e. yellow in the case of a red/green match. The vertical yellow bars were produced by a dithering technique in which pairs of the 512 horizontal raster lines within each bar were alternated between the red and green of the red/green grating. The horizontal lines within each bar were below the threshold of resolution, so they were spatially summated by the visual system into a metameric yellow. The red and green were made slightly lighter than in the red/green grating to produce the light yellow bars, and slightly darker to produce the dark yellow bars. This procedure ensured that the light/dark (yellow) gratings had the same average hue and luminance as the red/green gratings. This was designed to minimize flicker and hold adaptation level constant, thus optimizing the conditions for motion detection.

Experiment 1: Equating Luminance by Minimum Motion

The luminances of red and green were matched for minimum motion by the method of constant stimuli. A square-wave grating of red and green bars of spatial frequency 2.5 cycles deg^{-1} was set up on the TV screen (P22 phosphor; CIE chromaticity coordinates red $x = 0.68$, $y = 0.32$; green $x = 0.28$, $y = 0.60$). The gratings were 2 deg × 2 deg in a dark surround, and a white cross on a blue 6-min square served as the central fixation point. The gratings were alternated at 5 Hz in a four-stroke cycle of two red/green and two dark yellow/light yellow gratings (Fig. 1). The green bars were held constant at 13.4 cd m^{-2} as measured by a Spectra photometer, and the red bars were set to a range of luminance values between 8 and 12 cd m^{-2}. The contrast of the yellow grating was 6.25% and its average luminance was always equal to the average luminance of the red/green grating. On each trial the red bars were randomly set to one of the test luminance values and the subject reported whether the apparent motion of the stimulus was to the left, right, or neither. The response "neither" was defined to include ambiguous motion, no motion, two superimposed gratings apparently moving in opposite directions, or motionless flicker such as one would see in a counterphase flickering grating. The two authors were the subjects; the technique has also been successfully demonstrated to dozens of observers.

Each luminance value for red was presented a total of ten times in random order. The responses are plotted as psychometric functions in Fig. 2a. The same procedure was used for blue/yellow gratings (CIE chromaticity coordinates blue $x = 0.15$, $y = 0.07$: yellow $x = 0.51$, $y = 0.44$), interleaved in a four-stroke cycle with two gratings of light and dark grey (spatial mixture of blue and yellow) bars. The yellow bars of the blue/yellow gratings were always at 7.9 cd m^{-2} and the luminance of the blue bars was varied.

Results are shown in Fig. 2b. The red and green bars appeared to have the same luminance (PSE) when the luminance of the red bars was 9.54 cd m^{-2} for subject PC and 10.47 cd m^{-2} for SMA. The PSE for the blue and yellow bars was 10.5 cd m^{-2} for PC and 9.41 cd m^{-2} for SMA. Thus PC was relatively more sensitive to longer wavelengths and less so to shorter wavelengths, than SMA. The indifference interval was quite narrow: the number of "neither" responses fell to one-half maximum when the contrast of the red/green grating deviated from its equiluminous value by 1.6%, averaged across both subjects. The corresponding contrast for the blue/yellow grating was 2.8%.

Experiment 2: Effect of Spatial Frequency

We compared the apparent-motion and flicker techniques using square-wave gratings whose spatial frequencies were 0.625, 1.25, 2.5 and 5 cycles deg^{-1}. For minimum flicker the standard CIE stimulus is a uniform field of 2 deg

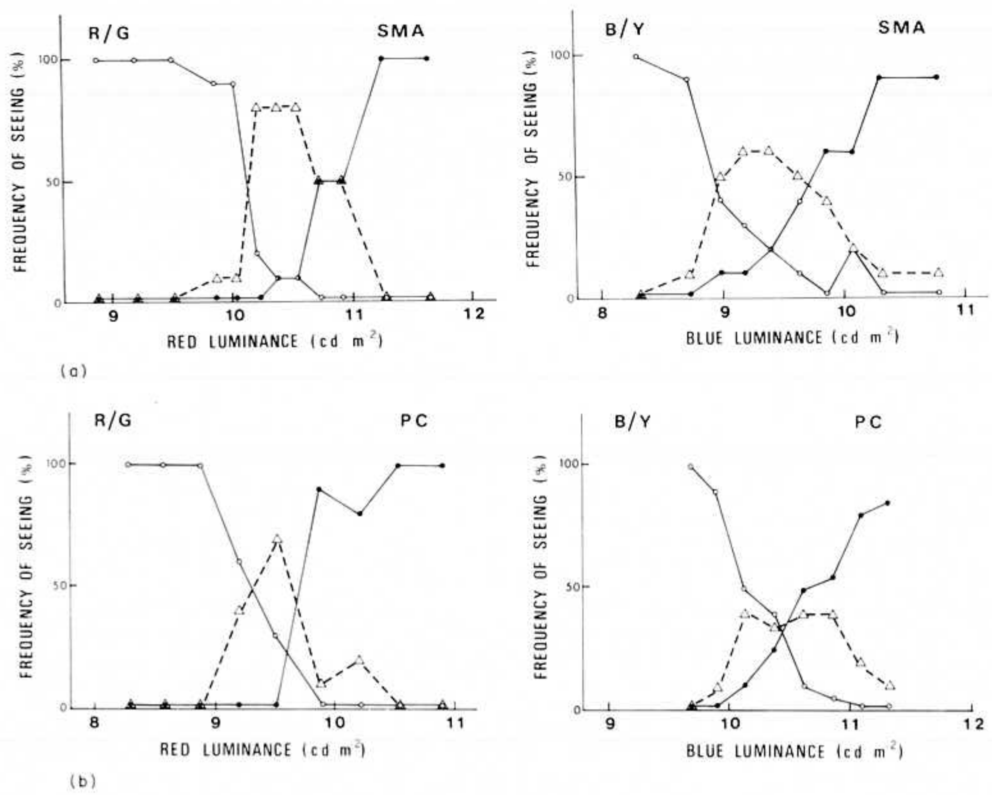


FIG. 2 Left panels: Percentage of reports of apparent motion to the left (open circles), right (filled circles), or neither direction (open triangles), when the luminance of the red bars was varied (abscissa) and green bars were held at a constant 13.4 cd m^{-2}. Display was the four-stroke cycle shown in Fig. 1. Method of constant stimuli.

Right panels: As above for blue/yellow gratings. Yellow bars were kept at 7.9 cd m^{-2} and blue bars were varied. The interleaved gratings (at times T2 and T4 in Fig. 1) were now light and dark grey instead of yellow.

diameter, but in order to evaluate the effects of spatial frequency we used square-wave gratings whose bars were flickering in counterphase between the two colours to be matched. Instead of taking colours in pairs such as red vs. green or blue vs. yellow, we now measured each colour separately, matching the luminance of red to white ($x = 0.30$, $y = 0.30$), then of green to white, then of blue to white. Thus in a grating of red and grey (or white) bars, the red bars suddenly became grey and the grey bars suddenly became red. The alternation rate was 15 Hz, so each grating of the two-stroke counterphase cycle was presented for two TV frames (33 msec). We also included a standard flicker match of each colour in turn against white in a 2-deg uniform field, and each of these three settings was normalized to a value of one in Fig. 3. The temporal rates were matched for flicker and motion, although as we shall see in the next experiment temporal rates are not critical.

For the apparent motion conditions we used the same four-stroke cycle as in Experiment 1. However, the bars of the two coloured gratings in the cycle were now red and achromatic grey, while the bars of the two interleaved gratings were light and dark pink. The grey bars had a luminance of 13.6 cd m^{-2}. The pink was made of equal parts of the red and the achromatic grey, and the light and dark bars had the same hue but differed in luminance so the grating had a luminance contrast of 12.5%. The cycling rate was 15 Hz, so each grating in the four-stroke cycle was presented for a single TV frame (16 msec). This gave equivalent velocities ranging from 3 deg sec^{-1} for the 5 cycle deg^{-1} gratings to 24 deg sec^{-1} for the coarsest gratings: the latter gave very fast apparent motion, which looked like rapidly fleeting shadows.

In both conditions the subject adjusted the luminance of the coloured bars by means of a joystick control until he saw minimum motion or minimum flicker. Spatial frequencies and colours were presented in a counterbalanced randomized order, and six readings were taken for each datum point.

Results are shown in Fig. 3. Luminous efficiencies for each colour were plotted relative to that for the uniform field flicker match. Open symbols show results for minimum motion, closed symbols for minimum flicker. Standard errors (SEs) are not shown as they were generally smaller than the symbols used to plot the graphs; the average SEs in relative units for motion and flicker were ± 0.0103 and ± 0.0125 respectively for PC and ± 0.0120 and ± 0.0159 for SMA. The luminances for the standard uniform field flicker matches for red, green and blue against a 13.6 cd m^{-2} white have all been normalized to unity in Fig. 3, but their actual values were 11.77, 15.0 and 14.68 cd m^{-2} respectively for PC and 12.97, 14.47 and 10.47 cd m^{-2} for SMA. The SEs in cd m^{-2} were ± 0.17, 0.05, 0.28 for PC and ± 0.20, 0.11, 0.35 for SMA.

The findings can be summarized as follows: 1) The means and SEs for motion and for flicker are almost indistinguishable. 2) As spatial frequency was increased, the luminous efficiency, relative to white, went up for red, stayed about the same for green, and went down for blue.

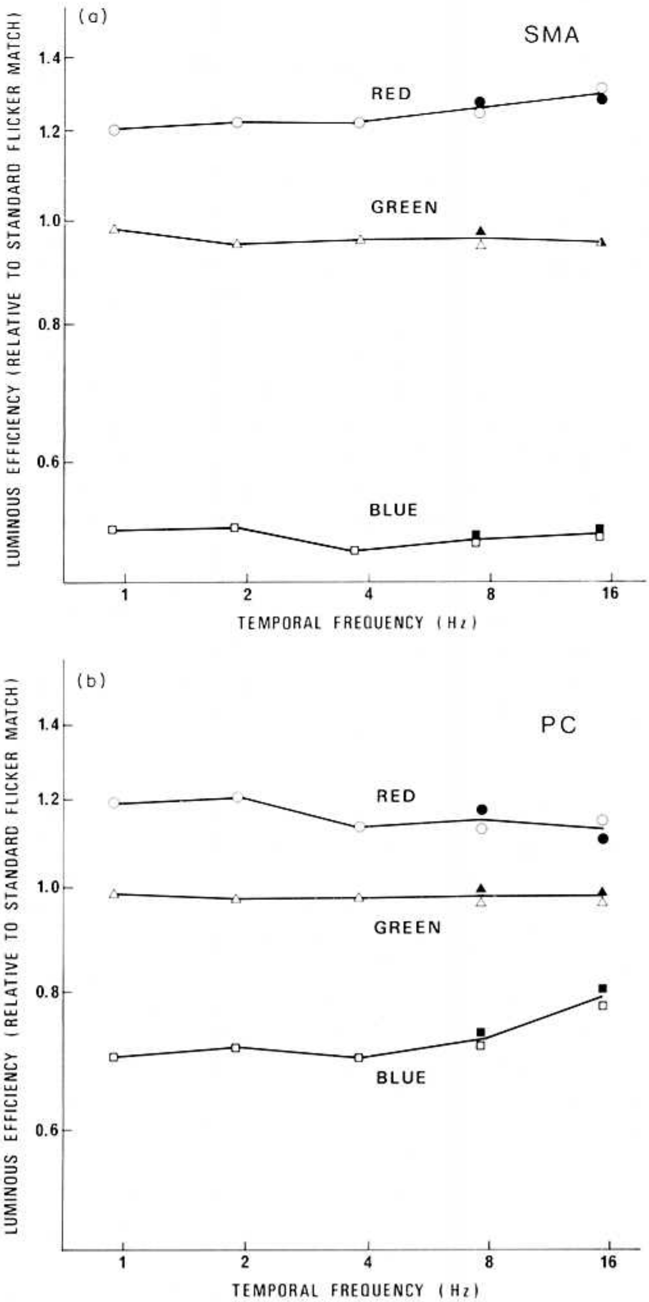


FIG. 4 Effect of temporal frequency on minimum counterphase flicker (filled symbols) and minimum motion (open symbols). Gratings were same as in Fig. 3, except spatial frequency was always 2.5 cycles deg^{-1}. Flicker data could not be collected below 7.5 Hz (see text). Height of each line replotted from 2.5 cycles deg^{-1} condition of Fig. 3.

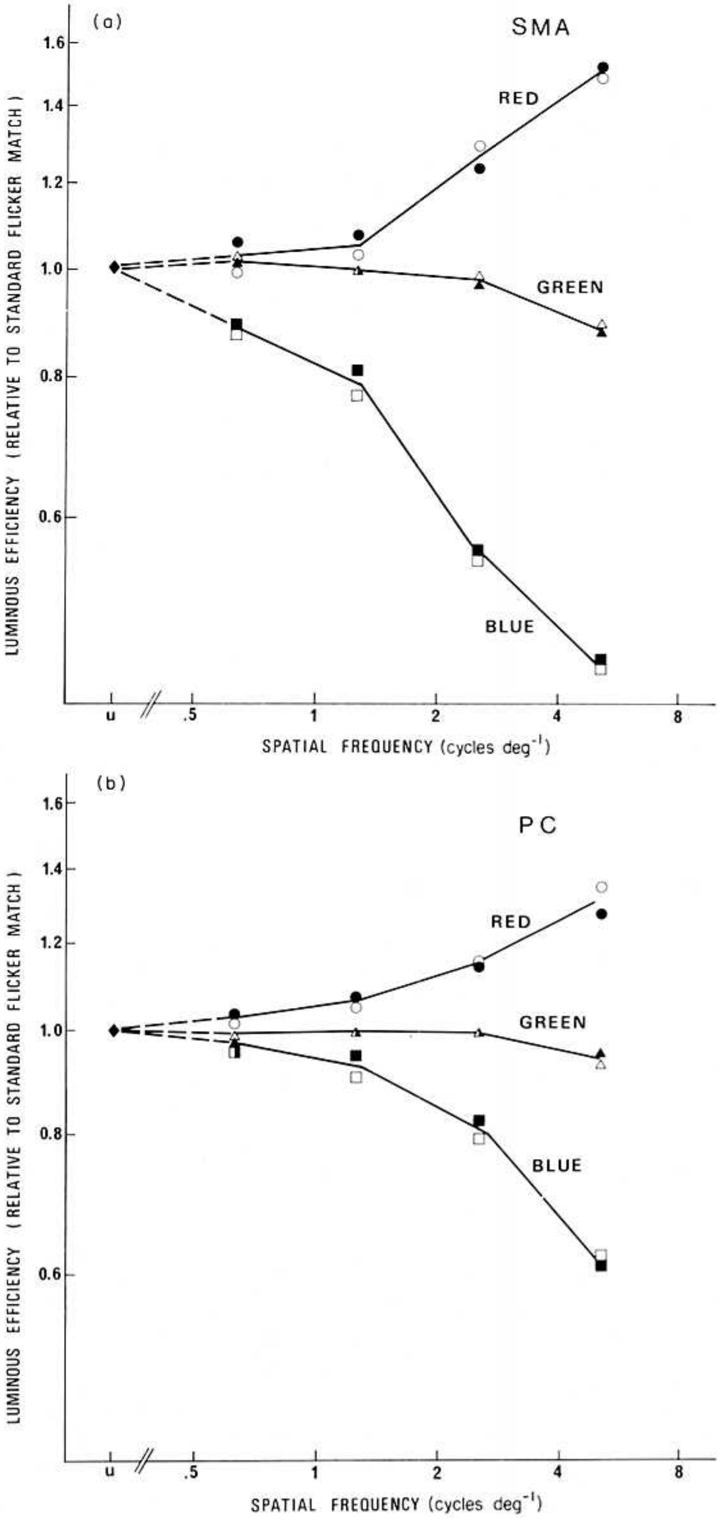
Experiment 3: Effect of Temporal Frequency

In this experiment we compared minimum motion and minimum flicker over a range of temporal frequencies, using similar conditions for the two techniques. We found that minimum motion could be successfully measured over a much wider range of temporal frequencies than minimum flicker could, and in fact gave settings that were largely independent of temporal frequency. The properties of the TV display and the four-stroke cycle limited us to frequencies that were submultiples of 60 Hz (15, 7.5, 3.75, 1.875 and 0.9375 Hz). For the luminance values we were using, good flicker judgements could be made only at 15 and 7.5 Hz. They could not be made at 30 Hz because there was a very wide dead range of luminance settings within which no flicker could be seen, and they could not be made below 7.5 Hz because strong chrominance flicker interfered seriously with judgements of luminance flicker. However, stable judgements of minimum motion could easily be made at frequencies down to 1 Hz or below.

As before, the gratings were red/grey, green/grey or blue/grey, the flicker condition comprised a counterphase flickering grating, and the motion condition comprised a four-stroke cycle. The spatial frequency was held constant at 2.5 cycles deg^{-1}. The temporal frequency of flicker (or drift) was set to 0.9375, 1.875, 3.75, 7.5 or 15 Hz. The effective velocity in the motion condition ranged from 0.375 to 6 deg sec^{-1}.

Results are shown in Fig. 4. Conventions are the same as for Fig. 3. The height of the red, green and blue curves is replotted from the 2.5 cycles deg^{-1} condition of Fig. 3. Where flicker results could be obtained they were virtually identical to motion results. Motion results could be reliably obtained over a much wider temporal range. Temporal frequency, in sharp contrast to spatial frequency, had virtually no effect on the results, since each curve is more or less a flat, horizontal line. The only slight departures from horizontality were not consistent between the two subjects. Red sloped slightly downwards for PC, but upwards for SMA. Blue sloped considerably upwards above 7.5 Hz for PC, but not for SMA.

FIG. 3 (opposite) Effect of spatial frequency. Red was matched to white in minimum flicker condition (filled circles) by square-wave flicker at 15 Hz in a 2-deg uniform field; and in minimum motion condition (open circles) by interleaving red/grey gratings with pink gratings in the four-stroke sequence shown in Fig. 1. Results for green (triangles) and blue (squares) were collected in the same way. Luminous efficiencies for each colour are plotted relative to their minimum-flicker matches against a 2-deg white uniform field.


(a)
SMA
RED
GREEN
BLUE
1.6
1.4
1.2
1.0
0.8
0.6
LUMINOUS EFFICIENCY (RELATIVE TO STANDARD FLICKER MATCH)
u
.5
1
2
4
8
SPATIAL FREQUENCY (cycles deg^{-1})
(b)
PC
RED
GREEN
BLUE
1.6
1.4
1.2
1.0
0.8
0.6
LUMINOUS EFFICIENCY (RELATIVE TO STANDARD FLICKER MATCH)
u
.5
1
2
4
8
SPATIAL FREQUENCY (cycles deg^{-1})

Discussion

Our conclusions are as follows:

1) The identical luminance matches from flicker and motion suggest that the two phenomena are mediated by the same system. Kulikowski and Tolhurst (1973) and Tolhurst (1973) drew similar conclusions from their experiments on sensitivity to gratings.
2) Calibrations. Our spatial frequency results in Fig. 3 show that there are no luminance matches that will hold over the whole range of spatial frequencies. Calibration procedures should be designed with this in mind and should be tailored to match the experimental stimuli. For instance, 2-deg uniform fields would be an inappropriate choice for calibrating an experiment on fine-grained coloured patterns which contained many high spatial frequencies.
3) Spatial frequency. Our red/grey (or red/white) grating in Experiment 2 can be thought of as a red/black grating interlaced with a white/black grating, and the set of equiluminance matches plotted in Fig. 3 shows the relative luminous efficiency of the two interlaced gratings at different spatial frequencies, i.e. the ratio of the red/black CSF to the white/black CSF. The same is true for green and blue. These CSF ratios indicate the relative contributions of red, green and blue stimuli to the luminance channel at different spatial frequencies. (The method ignores the role of the R, G, B mechanism through which the colours pass.) Thus in Fig. 3 the green curve remains horizontal, indicating that green and white stimuli maintain the same relative inputs to the luminance channel from 1 to 5 cycles deg^{-1}. The red and blue curves slope respectively upwards and downwards, indicating a drop in luminous efficiency at low and high spatial frequencies respectively, compared to white or green. Van Nes and Bouman (1967) and Nelson and Halberg (1979) showed that the CSFs of black/white gratings were the same whether they were viewed directly or through a narrow-band or broad-band red or green filter. These CSFs are presumably mediated by luminance, not chrominance channels.

   Our results for red and green cannot be compared to those of Kelly (1974), Green (1968) or Cavonius and Estévez (1975a, b), as they were examining sensitivities of the colour mechanisms and not, as we were, the inputs of coloured stimuli into the luminance channel.
4) Temporal frequency. Our results show that temporal frequency had little effect on equiluminance settings. This is implied as well by the fact that minimum flicker settings made at 10–20 Hz are virtually the same as minimum border settings made at zero Hz (Wagner and Boynton, 1972). Since minimum motion settings could be made reliably over a wide range of temporal frequencies, the experimenter may choose a single convenient frequency and perform all measurements at that value, independently of

stimulus luminance or colour. The same freedom of choice is not available in minimum flicker matches, as the flicker rate must be chosen to maximize luminance flicker sensitivity, which peaks at 10 Hz for moderate luminance levels, and to minimize chrominance flicker sensitivity, which peaks at 2 Hz (Kelly and van Norren, 1977). In particular Kelly and van Norren (1977) state that the presence of chrominance flicker strongly interferes with the detection of luminance flicker.

We found that equiluminance judgements were unaffected by temporal frequency, using minimum-flicker and minimum motion techniques. However, Kelly (1982) reached the opposite conclusion when he measured the luminance ratio that gave minimum contrast sensitivity for a two-colour grating presented in counterphase flicker, and found that the visual system was relatively less sensitive to red at an 8 Hz flicker rate than at 1 Hz. Minimum-flicker matches cannot be made reliably at these low flicker rates so there is no way to know if they are also influenced by rate in this range. Since the minimum motion technique appears to measure the same system response as minimum flicker, but can operate at lower temporal rates, we used it to test Kelly's (1982) claims, with minimum motion standing in lieu of minimum flicker at low temporal rates. Our results are at variance with Kelly's findings.

5) TV vs. optical systems. Methods of equating colour luminance are important whenever the experimenter wishes to study the chromatic channels independently of luminance (Wagner and Boynton, 1972). The spatial characteristics of chrominance channels have been explored with equiluminous pictures which show losses of resolution (van der Horst and Bouman, 1969), borders (Tansley and Boynton, 1976), depth (Lu and Fender, 1972) and motion (Anstis, 1970; Ramachandran and Gregory, 1978). These studies suggest that information about borders, depth and motion is carried mainly by luminance channels.

Computerised TV graphics systems are becoming increasingly popular, and our new photometric method exploits the advantages that TV systems have over optical techniques. The great strength of optical systems lies in their ability to control stimulus wavelengths very precisely. Monochromatic lights of arbitrarily narrow bandwidths can easily be produced in a way that no TV system, with its inherently broad-band phosphors, can hope to emulate. Where colour vision *per se* is the primary concern, optical presentation remains the method of choice. But for studying spatially distributed stimuli which happen to be coloured, TV has significant advantages. For the control of timing there is not much to choose between the methods since both have their good and bad points. Optical devices allow very brief flashes or extended continuous presentations, but often at the price of elaborate and inconvenient mechanical shutters or high-voltage power supplies. Timing on a computer-controlled TV is restricted to a sampling rate of

50 (or 60) Hz, but within this limitation it is quick and easy to control. But it is in presenting spatially extended coloured pictures, either stationary or moving, that TV systems really come into their own.

6) Advantages of minimum-motion technique. (a) over flicker: Our method of colour matching enables inexperienced observers to make straightforward equalization settings of colour brightness. The direction of motion on the screen tells the subject in which direction he should adjust the luminance. Minimum motion can be used at any desired temporal frequency. (b) over minimum-border: Misalignment of the colour guns is a common TV problem which is difficult to eliminate completely. It produces troublesome edge transients which can rule out the use of minimum-border methods. However, judgements of minimum flicker and minimum motion are unaffected by even quite severe misalignments.

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