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Summary The temporal modulation of light from halophosphate, triphosphor and multiband fluorescent lamps (controlled by a conventional choke circuit) was measured as a function of wavelength. Within each category, all lamps had similar functions for peak–peak modulation. At the short-wavelength end of the visible spectrum all lamps showed a modulation near 100%. Halophosphate and multiband lamps had a low modulation at the long-wavelength end of the spectrum and gave the lowest overall modulation. Certain deluxe lamps had a modulation greater than 80% throughout the spectrum. The modulation of photopic energy, and energy transduced by the photoreceptors was calculated. Triphosphor lamps gave greater modulation than halophosphate, the lowest modulation being from warm-white halophosphate lamps.

Modulation of light from fluorescent lamps

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1 Introduction

Fluorescent lamps usually pulsate in brightness twice with each cycle of the AC electricity supply (for example, in Europe at a frequency of 100 Hz). The rapid pulsations are not perceived as flicker but they are nevertheless resolved by subcortical visual structures in man[1,2] and animals[3]. Lamps can now be controlled by high-frequency circuits which remove most of the 100 Hz modulation. The incidence of eye-strain and headaches in offices lit by the high-frequency lighting is less than half that in offices lit conventionally[4].

Fluorescent lamps can be classified according to phosphor composition: namely, halophosphate lamps, triphosphor lamps, deluxe lamps of various kinds and the recently introduced multi-band lamps. The modulation of light varies from one type of lamp to another because of differences in the persistence or afterglow of the phosphors.

The following study is divided into two parts. In the first, the modulation for a variety of lamps has been measured as a function of wavelength in order to facilitate the development of a lamp with more persistent phosphors (since it will be some time before all installations are changed to high-frequency ballast). In the second part, the physiological effectiveness of modulation from halophosphate and triphosphor lamps are compared, to assist those who might wish to choose lamps with minimum pulsation from those that are currently available.

2 Modulation

2.1 Method

A fluorescent lamp was mounted in a 4 or 5 ft (1.2 m or 1.5 m) batten and controlled by conventional 240 V 50 Hz rated lagging circuit using a 4μF power factor correcting capacitor operated from the domestic 240 volt AC supply. A pipe with a matt black inner surface was used to direct light from a circular section of the surface of the lamp to the entrance slit of a monochromator. The pipe had an inner diameter of 17.5 mm and its open end was covered by an ultraviolet filter (to eliminate any possibility of second-order diffraction) and placed against the glass surface of the horizontally mounted lamp, at a point equidistant from the ends. The length of the black tube was sufficient to restrict the entry of the light to an angle less than that appropriate for the aperture of the monochromator (f/3.5), so that nearly all the incoming light was captured by the mirror surfaces. An estimate of the contribution from scattered light was obtained as follows. The luminance of the inner surface of the matt black pipe was measured with a spot photometer at an oblique angle similar to that at which scattered light which had been reflected from the inner surface of the tube could enter the monochromator slit. The luminance was less than 8% of that of the surface of the lamp. At this oblique angle much of the reflection was specular: and partly because of the specular component the variation in reflectance with wavelength was less than 10% between 400 and 700 nm. The scattered light was further attenuated within the monochromator. The fact that it had a negligible contribution in broadening the bandwidth of the monochromator can be judged from the measurements of bandwidth obtained; see below. It was therefore unnecessary to image the source onto the monochromator slit. A silicon photodiode (RS 303-674) was mounted against the exit slit of the monochromator without any interposed optics. The efficiency of the monochromator (Jobin–Yvon H10 UV) was greater at the short-wavelength end of the visible spectrum where the sensitivity of the photodiode was lowest. The current from the photodiode was amplified by a current–voltage converter with a gain of 10 volts per microamp. The output voltage was filtered by an antialiasing filter and sampled at a frequency of 4.3 kHz by a 12-bit analogue–digital converter. The frequency response of the photodiode–amplifier assembly was such that the output was within 3 dB of DC levels up to a frequency of 500 Hz and above 2 kHz was attenuated by more than 12 dB.

The lamp was run for 20 minutes before measurements were taken every 5 nm between 380 and 720 nm. 0.5 mm entrance and exit slits on the monochromator provided a pass band of ±2.5 nm at half height. The pass band was estimated with the mercury lines of a tubular lamp from which the phosphor coating had been omitted (kindly supplied by Thorn Lighting). This lamp was also used to calibrate the monochromator scale, so that minor errors could be corrected. Additional readings were taken when the light output reached a local maximum, that is, at the principal mercury lines (405, 436, 546 and 578 nm).

A computer algorithm calculated the time-averaged voltage and divided the periodic waveform into cycles, each cycle

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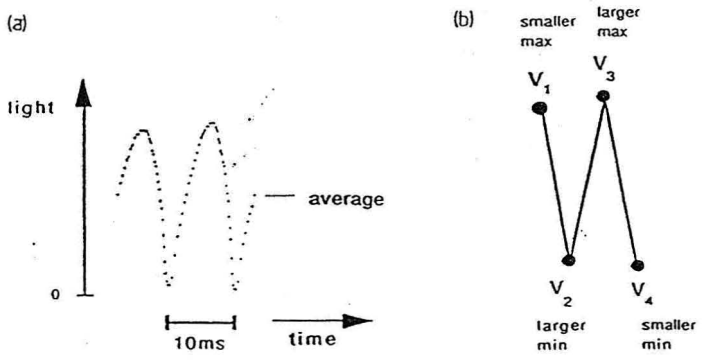


Figure 1 (a) The measurements of light output as a function of time, as sampled by a 12-bit analogue-digital converter at a frequency of 4 kHz, showing the light from one cycle of the 50 Hz AC electricity supply. This recording was taken at a position near one end of the tubular lamp so as to exaggerate the 50 Hz component for the purposes of illustration. The component can be seen as a difference in the height of the two peaks. (b) Schematic to show the four measurements taken for each cycle of the AC supply. The average peak voltages of 10 such cycles were obtained. The voltage obtained with no light was subtracted from the averages. The peak–peak modulation was taken as $(V_3 - V_4)/(V_3 + V_4) \times 100$. The 50 Hz component was estimated as $[(V_3 - V_4) - (V_1 - V_2)]/[(V_3 - V_4) + (V_1 - V_2)] \times 100\%$.

beginning when the voltage of a sample first exceeded the average. The maximum and minimum voltages for each cycle were then obtained. Twenty cycles were analysed in this way and the data divided into ten pairs of successive cycles of light output, each pair resulting from one complete cycle of the 50 Hz AC electricity supply. The maxima and minima for the ten pairs of cycles were then averaged, providing four voltages, two maxima and two minima per cycle of the AC supply. The difference between the largest maximum and smallest minimum was arbitrarily used as an estimate of the peak–peak modulation. Modulation was defined as:

$$(l_{max} - l_{min})/(l_{max} + l_{min}) \times 100\%$$

The difference between the larger maximum and smaller minimum was subtracted from the difference between the smaller maximum and larger minimum to provide an estimate of the (small) contribution from modulation at 50 Hz. Figure 1 illustrates the calculations.

2.2 Results

The peak-to-peak modulation of halophosphate, triphosphor, various deluxe lamps and the new multi-band lamps is shown as a function of wavelength in Figures 2–5. Only data for the range 400–700 nm are shown because the light output outside this range was insufficient to provide reliable estimates of modulation. Between 400 and 700 nm repeated measurements gave estimates of modulation that were generally within ±1% of those shown.

Figure 2 shows the modulation from halophosphate lamps. Note that the curves show only the proportion of variation, and give no indication of the amount of light emitted at each wavelength. The estimate of modulation at the mercury lines depends partly on the pass-band of the monochromator and would have been larger had the pass-band been narrower. Note that the curves from the various lamps are all very similar, showing little modulation at the red end of the spectrum because of the long-persistence phosphors. The warm white lamp shows the lowest modulation at this end of the spectrum.

The triphosphor lamps shown in Figure 3 have a higher modulation at the red end of the spectrum, although the modulation is lower in the range 470–510 nm. The first two lamps listed in the legend are filled with krypton and the third and fourth with argon. The gas filling has little or no effect, perhaps because none of the krypton lamps showed striations when they were under examination.

Other lamps (Figure 4) can show considerable modulation throughout the spectrum. Interestingly, these are usually lamps with a good colour rendering index and relatively full spectrum. The recently developed multi-band lamps (Figure 5) are unusual in having good colour rendering and low modulation.

Measurements were made from the centre of the lamps and the contribution from 50 Hz modulation was less than 3% for all lamps and all wavelengths, with the exception of the True-light lamp for which it varied with wavelength from 5% to 7%.

2.3 Discussion

The modulation curves in Figures 2, 3 and 5 are all similar within type, regardless of the manufacturer or the nature of the gas within the lamp. The differences between types are

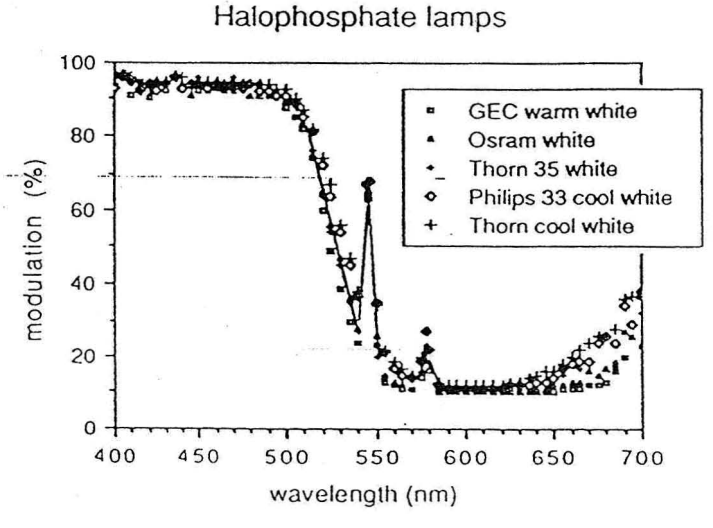


Figure 2 Modulation from halophosphate lamps as a function of wavelength.

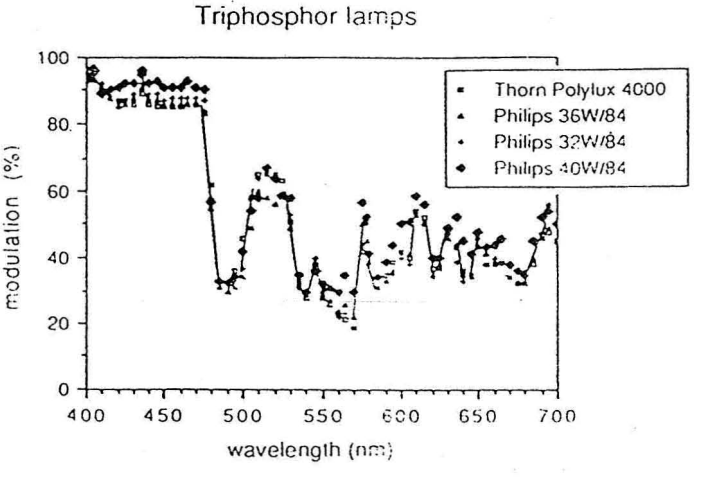


Figure 3 Modulation from triphosphor lamps. The first two listed in the inset contain krypton gas and third and fourth contain argon.

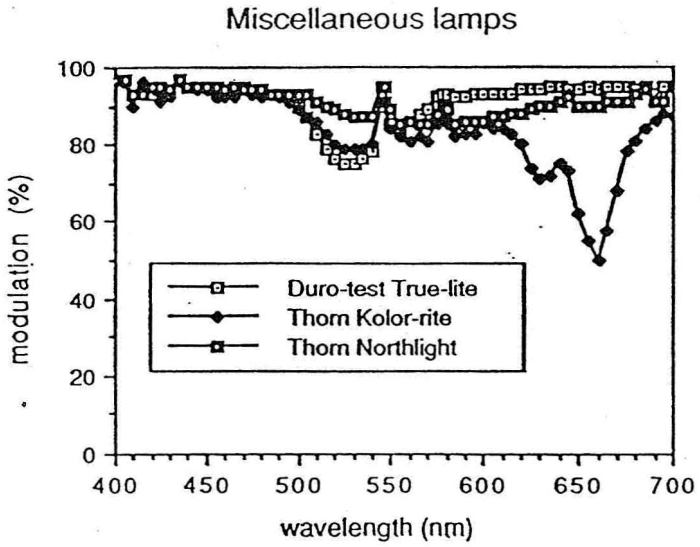


Figure 4 Modulation from miscellaneous lamps with good colour rendering.

very considerable, showing the lowest overall modulation for halophosphate and multi-band lamps.

3 Physiological indices

When a slow red phosphor produces its light, the light output reaches a peak later than the peak due to the mercury direct emission. The calculation of luminance modulation cannot therefore be made directly from the modulation characteristics shown above without taking into account the phase of the modulation at each wavelength. For the miscellaneous lamps shown in Figure 4 the effects of phase can only be slight: the luminance modulation (both photopic and scotopic) must be close to 100%. For the remaining lamps, however, the effects of phase are not negligible.

The variation in light energy with time was measured throughout the spectrum for halophosphate and triphosphor lamps in order to calculate (*a*) the luminance modulation, (*b*) the variation in chromaticity coordinates with time, (*c*) the variation with time in the energy captured by each of the photoreceptors, and (*d*) the variation in colour-opponent signals. The multiband lamps were not included in these

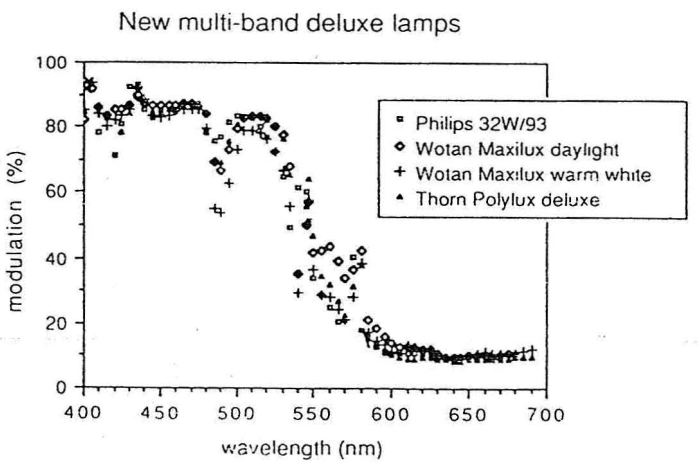
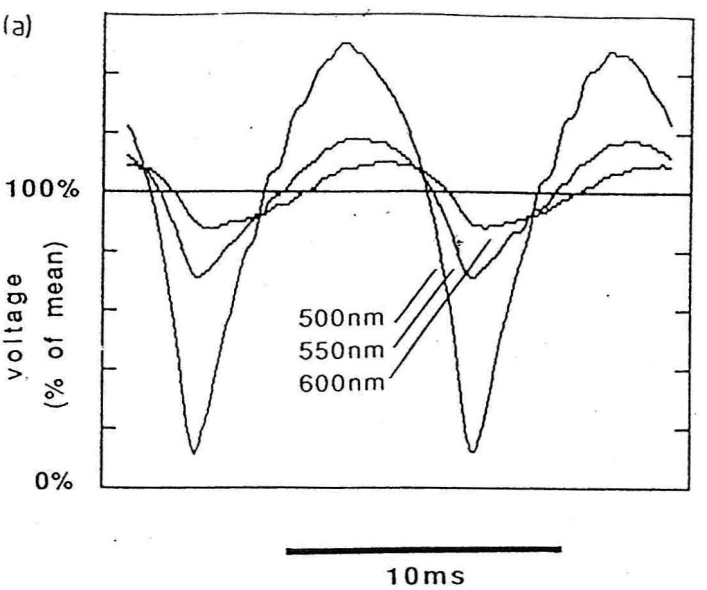


Figure 5 Modulation from new multi-band lamps including a lamp representative of the Philips colour 90 series, sometimes referred to as the 'broad-band triphosphor' range.



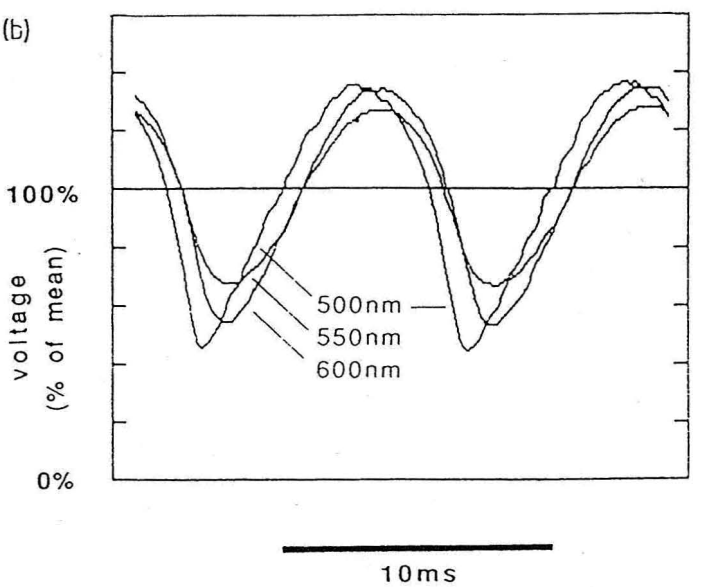


Figure 6 Voltage from the photodiode, expressed as a percentage of the time-averaged mean. (a) F2 halophosphate lamp (Thorn Pluslux 4000); (b) F11 triphosphor lamp (Thorn Polylux 4000). Curves show measurements obtained at 500, 550 and 600 nm.

measurements because they are not in widespread use, having only recently been developed, and the CIE has yet to publish power spectra and make recommendations concerning their use.

3.1 Method

The apparatus was similar to that described in 2.1. The sampling rate of the analogue–digital converter was increased to 12.8 kHz and a second channel of ADC data was added to record the variation in the voltage of the electricity supply. Data were acquired on both channels at random phase with respect to the supply voltage. After acquisition the voltage signal derived from the electricity supply and recorded on the second channel was divided into cycles, each cycle beginning when the voltage of a sample first exceeded the average. The number of samples per cycle varied by 1–2%, depending on the time at which the sampling was initiated and the duration of a period of the supply voltage. Sampling was therefore

repeated until one cycle containing exactly 128 samples was obtained. The corresponding 128 samples from the first ADC channel provided the voltage fluctuation from the photodiode through one cycle of the electricity supply.

Once the lamp had run for 20 minutes, measurements were made every 5 nm between 400 and 700 nm. Various halophosphate and triphosphor lamps were compared, including those with high and low correlated colour temperature.

On some lamps there were low-amplitude, high-frequency components of the light output that were not strongly phase-locked to the electricity supply, and which can be seen as ripple on the waveforms in Figure 6. The data for at least 5 cycles were obtained and averaged, greatly reducing these components, and increasing signal/noise ratio at the extremes of the visible spectrum where the signal was weak.

Initially data were obtained for halophosphate and triphosphor lamps with similar correlated colour temperature (4000 K). The available narrow and wide lamp versions were obtained from two major manufacturers. The quoted characteristics of correlated colour temperature, rendering index and colour coordinates for these lamps (shown in Table 1) closely resemble the characteristics of either CIE lamp type F2 (listed as 4230 K, 64 and 0.3721, 0.3751) or type F11 (listed as 4000 K, 83, and 0.3805, 0.3769).

Measurements were then taken from lamps with lower colour temperature: both halophosphate and triphosphor. The characteristics of these lamps are shown in Table 1.

3.2 Results

Figure 6 shows the voltage for selected wavelengths (500, 550 and 600 nm) as a function of time, each curve expressed as a percentage of the time-averaged voltage (represented by the horizontal line). The data are for one halophosphate and one triphosphor lamp. The change in phase lag with wavelength is obvious. (The curves may be used to provide a rough estimate of the (reduced) modulation that would occur were the lamp run on an electricity supply with a frequency of 60 Hz, although the interactions between the phosphors may differ at this frequency in a way that would be difficult to derive analytically).

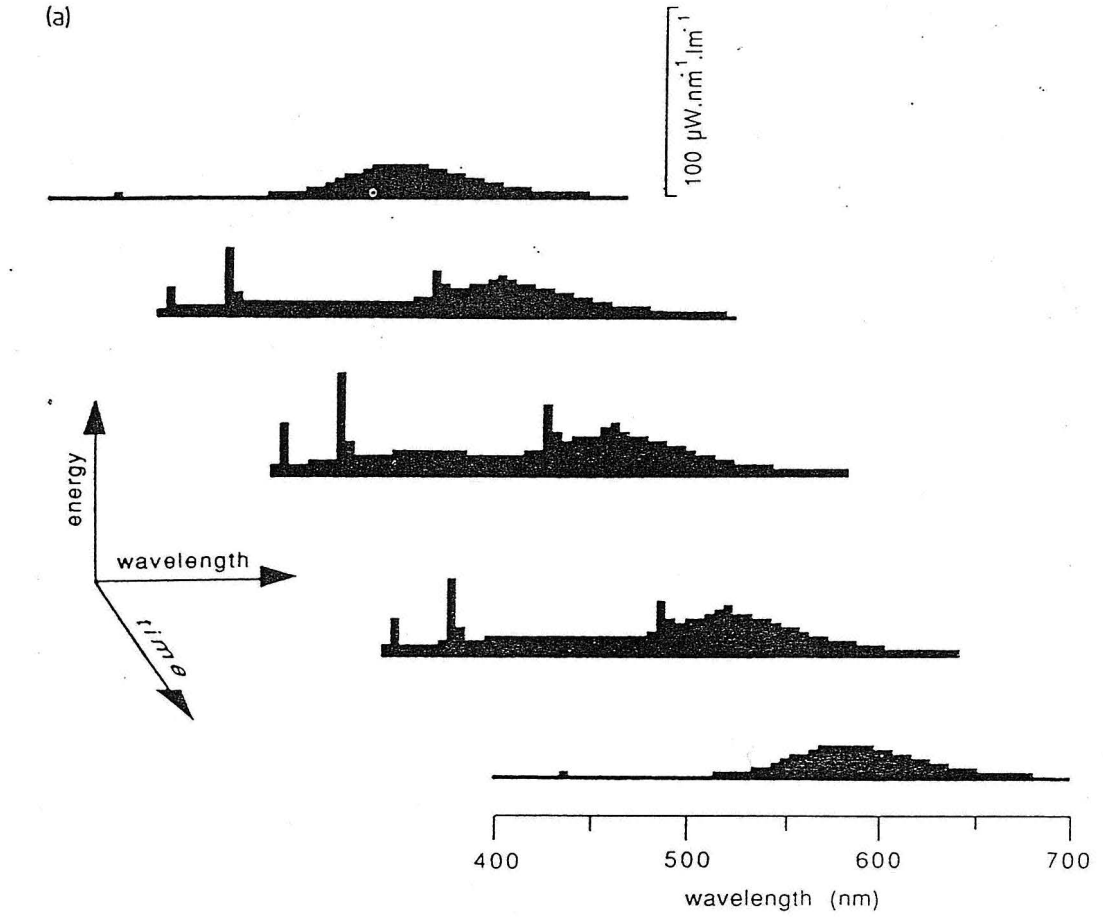
Every 5 nm between 400 and 700 nm the time-averaged voltage from the photodiode was taken as equivalent to the power at that wavelength, as given from the spectral power distribution for the appropriate CIE lamp type. From this was calculated the variation in power with time. Figure 7 shows the calculated spectral power distributions for the lamps over half of one cycle of the electricity supply, beginning when the light from the mercury direct emission was minimal and subsequently at intervals of 2.5 ms.

From the spectral power distributions for one complete cycle of the supply was calculated the variation in photopic luminance over time and these data are shown in Figure 8. Figure 8 also shows, for comparison, the variation in luminance with time measured directly using a $V\lambda$-corrected photodiode (Hagner) connected to the same data acquisition and analysis system. The calculated and measured curves were superimposed, although the trace from direct measure-

Table 1 Characteristics of various halophosphate and triphosphor lamps

CIE category		F2				F3	F4		F11			F12
Lamp brand		Thorn Pluslux 4000	Philips cool white 33	Thorn cool white	Philips 40W/33	Philips 36W/35	Thorn Pluslux 3000	Thorn 40W warm white	Thorn Polylux 4000	Philips colour 84	Philips colour 84	Thorn Polylux 3000
Rated power (W)		36	36	40	40	36	36	40	36	36	40	36
Outer diameter (mm)		25.2	25.8	37.9	37.5	25.9	25.2	37	25.2	25.8	37.5	25.5
Correlated colour temperature (K)		4200	4000	4200	4000	3500	2900	2900	4000	4000	4000	2950
Colour rendering index		58	62	58	62	58	51	51	85	85	85	85
Appearance		Cool white	Cool white	Cool white	Cool white	White	Warm white	Warm white	Cool†	Cool†	Cool†	Warm
Quoted colour coordinates	x	0.372	0.379	0.372	0.379	0.412	0.440	0.440	0.380	0.380	0.380	0.440
	y	0.375	0.384	0.375	0.384	0.392	0.403	0.403	0.377	0.377	0.377	0.402
Luminance modulation (%)												
Photopic As calculated		28.3	27.1	31.4	29.6	21.8	16.9	18.9	36.4	34.9	39.5	34.9
Photopic As measured directly		28.2	27.5	31.0	29.0	21.7	17.4	19.8	37.2	35.1	40.3	35.6
Scotopic		62.3	61.2	68.1	66.1	54.3	46.3	50.6	40.1	38.3	41.9	33.0
Receptor modulation (%)	R	23.7	22.7	26.4	24.8	18.1	14.2	16.0	38.3	36.5	41.7	37.0
	G	30.8	29.5	34.0	32.3	23.9	18.5	20.8	35.2	33.8	38.0	33.5
	B	87.8	87.5	95.0	93.5	86.4	87.0	93.8	79.3	77.5	83.4	75.3
Channel modulation (%)	$R - G$	49.6	48.3	55.9	55.4	23.8	14.6	15.6	73.3	67.1	83.9	57.7
	$-2B + (R + G)$	41.0	42.8	49.3	48.6	22.2	17.7	21.3	53.9	54.5	61.6	35.5

† These are not the conventional terms used to describe colour appearance and are used only as an indication.



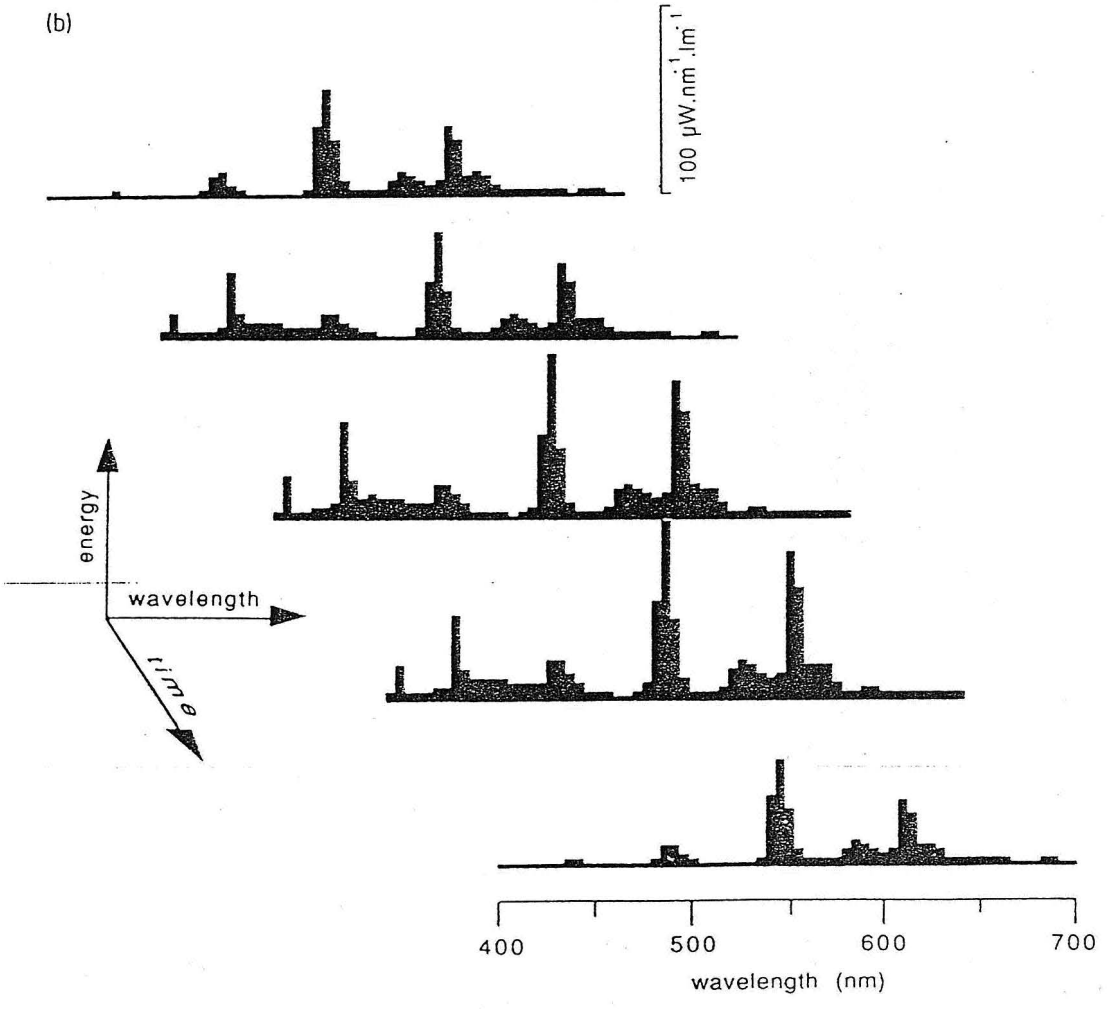


Figure 7 Spectral power distributions computed from CIE data and shown as a function of time over half of one cycle of the electricity supply, beginning when the light from the mercury direct emission was minimal (top histogram) and subsequently at intervals of 2.5 ms. The horizontal axes range from 400–700 nm in bins 5 nm wide. (a) F2 halophosphate lamp (Thorn Pluslux 4000); (b) F11 triphosphor lamp (Thorn Polylux 4000).

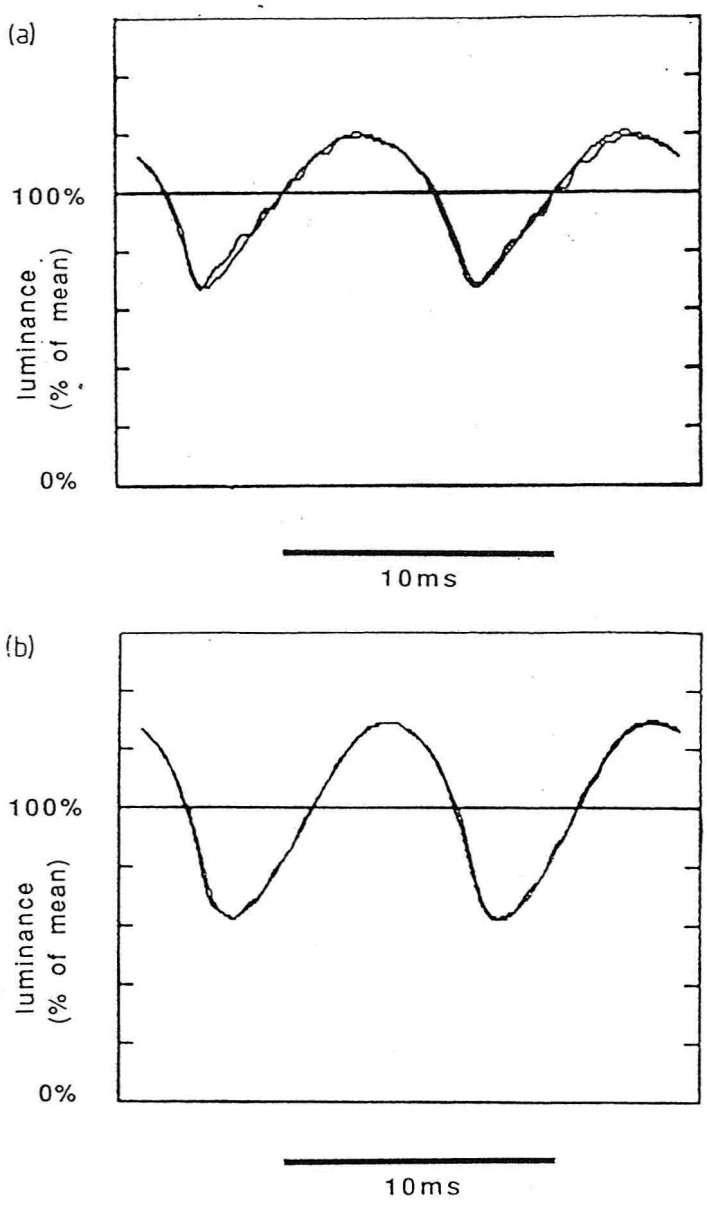


Figure 8 Variation in luminance with time as calculated from data such as those in Figure 7, and as measured directly using a $V\lambda$-corrected photodiode. (a) F2 halophosphate lamp (Thorn Pluslux 4000); (b) F11 triphosphor lamp (Philips colour 84). The trace with high-frequency ripple is that measured with the corrected photodiode and is based on one sweep with no averaging. The ripple was never greater than that shown in (a) and was usually less than that in (b).

ment sometimes showed a high-frequency ripple, most pronounced for the lamp shown in Figure 8(a). As can be seen from Table 1, the direct measurements of luminance modulation $(l_{max} - l_{min})/(l_{max} + l_{min})$ were well within 1% of the calculated values, indicating (*a*) that the choice of spectral power distributions was appropriate, and (*b*) that the ripple had a negligible effect, even though the direct measurements differed from those calculated from the spectral power distributions in that they were not averaged over several cycles of the supply voltage.

Not only was the peak–peak modulation in luminance greater for the triphosphor lamps (type F11) than for the halophosphate (type F2), the variation in luminance with time shown in Figure 8 had a different shape. The variation for the halophosphate lamps approximated a rectified sine wave whereas the variation for the triphosphor lamps approximated a sine wave with no rectification. In terms of Fourier analysis, the power in a sine wave is greater than that in a rectified sine wave of similar peak–peak amplitude. Partly for this reason the luminance modulation for the (type F2) halophosphate lamps had a power in the fundamental Fourier component (at 100 Hz) only about 70% of that for the triphosphor lamps.

The flicker index[5] (area of curve above the mean/area below) for the F2 and F11 lamp data shown in Figure 7 was 21.0% for the halophosphate lamp as compared with 31.2% for the triphosphor. The standard deviation of the sample voltages expressed as a percentage of the mean (another measure of variation) was 17.4% for the halophosphate lamp and 24.8% for the triphosphor.

Using $V\lambda$, the scotopic luminance was calculated as a function of time and gave a peak–peak modulation of about 60% for the halophosphate lamps but only 40% for the triphosphor lamps (see Table 1).

Figure 9 shows the variation in colour coordinates with time for two lamps. The chromaticity coordinates published by the manufacturers are quoted in Table 1. The values are based upon the time-averaged power spectra. Figure 9 shows the variation in colour coordinates with time for two lamps. The time-averages of these values are the same as the chromaticity coordinates quoted in Table 1 provided a weighting for luminance is applied according to the centre of gravity law of colour mixture (see Hunt[6] pp 59–60).

From the x, y, z values the light absorbed by the three classes of cones was calculated using the equations described by Hunt[6] (p 147). The peak–peak modulation in the long-, medium- and short-wavelength cones is listed as R, G, and B respectively in Table 1. Hunt's model[6] describes two chromatic channels, one red–green opponent and the other blue–yellow. The modulation for these channels is also given in Table 1. (The achromatic channel described by the model gave values similar to those for photopic luminance.)

Measurements and calculations were then obtained for halophosphate lamps with relatively low correlated colour temperature, for which the CIE spectral power distributions F3 and F4 are appropriate. As can be seen from Table 1, the modulation is lower for the 'warm white' than for 'white' or 'cool white' halophosphate lamps because of a greater contribution of red light from the persistent phosphor. No such change with colour temperature occurred for the triphosphor lamps. The F12 triphosphor lamp with a colour temperature of 3000 K had a modulation similar to that of the triphosphor lamps with a colour temperature of 4000 K.

As can be seen from Table 1, lamps with large diameter had a slightly greater modulation than those with small.

3.3 Discussion

The light from the triphosphor lamps had a greater photopic luminance modulation than the light from the halophosphate lamps of similar correlated colour temperature. Warm white halophosphate lamps had the lowest modulation.

The modulation in light energy captured by the long-, medium- and short-wavelength photoreceptors was greater for the triphosphor lamps than for the halophosphate. In general, therefore, the findings suggest that triphosphor lamps have greater physiologically effective modulation than halophosphate lamps. It remains to be determined whether the differences between the lamps are physiologically significant. For example, it is not yet known whether, in

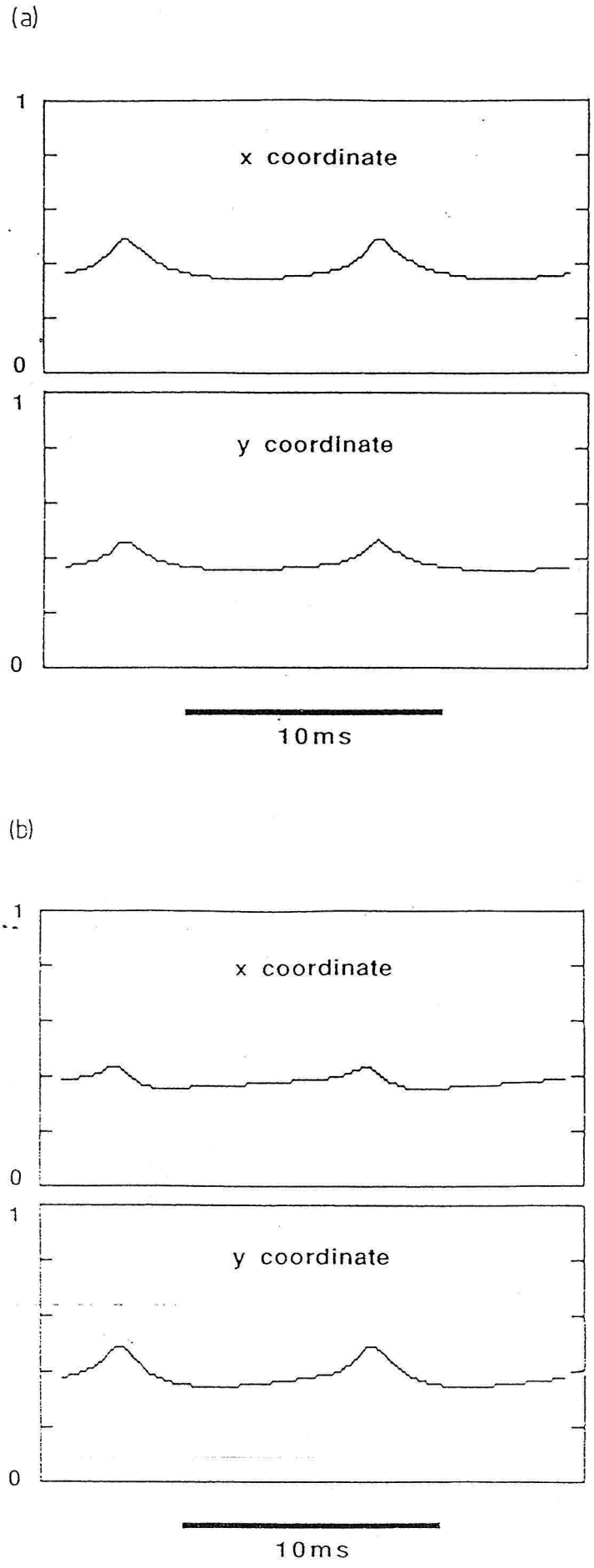


Figure 9 Variation in colour coordinates with time. (a) F2 halophosphate lamp (Thorn Pluslux 4000); (b) F11 triphosphor lamp (Thorn Polylux 4000).

installations fitted with low-frequency ballast, changing from triphosphor to halophosphate lamps would effect a reduction in headaches and other symptoms.

Over the last two decades, improvements in colour rendering have been achieved at the expense of greater modulation, a trend only recently reversed. Lamps with good colour rendering have been associated with greater apparent 'visual clarity' than lamps with relatively poor colour rending and similar illuminance. For example, Boyce[7] found that when Kolor-rite lamps illuminated an office scene they required an illuminance 0.7 times that for white halophosphate lamps in order to produce a match in which the lighting from both types of lamps was judged equally satisfactory. Any aversive effects of flicker might be expected to increase with illuminance and perhaps offset improvements in clarity, and this might be one (of several) reasons why Kolor-rite lamps were judged equally satisfactory at lower illuminances.

It might prove possible to create a new lamp by combining phosphors that are more persistent than those currently used. It is doubtful whether such a lamp would have as high an efficacy or as good maintenance properties as those currently available. However, any consideration of economics should, of course, include the contribution to employees' health. A 5–10% improvement in productivity dwarfs all other economic parameters.[8]

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