AERE G4605
PCOMWP (88)P4

The Effects of Display Flicker Rate on Task Performance

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March 1988

Summary

There is evidence that the human visual system responds to intermittent illumination at frequencies above those required for flicker fusion and that flicker can cause the enlargement of high velocity eye movements, necessitating corrective saccades (Wilkins 1986). As a consequence, it is possible that an observers performance of a demanding visual search task will be improved by displaying the task at an increased field rate even though flicker may be minimised at conventional field rates by optimising the viewing conditions. For surveillance or remote viewing by television this may be important.

The experiment described here measured the speed and accuracy with which subjects counted the number of circular targets hidden in a background pattern of random noise, displayed non-interlaced at field rates of 50, 80 and 100 Hz. There were two parts to the experiment; the first compared 50 and 80Hz, the second, using a different display monitor, 50 and 100Hz. Thus there were two 50Hz conditions. The displays were viewed under lighting such that flicker was not noticeable even at 50Hz.

The error rate was found to be constant across the field rates and there was no statistically significant difference in time taken between 50 and 80Hz. At 100Hz subjects performed slightly slower than at 50Hz and the difference was statistically significant. However this difference was small compared to the difference between the two 50Hz conditions, which can probably be attributed to a practise effect rather than any physical difference between the monitors. The difference between the 50 and 100Hz field rates is unlikely to be of any practical importance.

When asked, the subjects reported little difference between the display rates and did not express any preference. Only one of the subjects reported seeing flicker, even at 50Hz.

The hypothesised effect of display flicker on performance was not confirmed; perhaps the effect of intermittent illumination is only strong for the highly ordered eye movements investigated by Wilkins. A second experiment is planned replacing the visual search task with the reading of text.

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1.0 Introduction

CRT based displays are in widespread everyday use, both in work places and for entertainment. Most use field rates in the region of 50 to 75 Hz and will often appear to flicker appreciably. Most people find this annoying and sometimes extremely disturbing.

Flicker can be minimised by careful choice of viewing conditions and display design (Scheiwiller et al 1988), but there is evidence that the human visual system responds to the intermittency of illumination even when no flicker is visible. Tyler (1981) has recorded electrical activity of the brain synchronous with a display field scan at frequencies above flicker fusion. Brindley (1962) has demonstrated the perception of beats between electrical and visual stimulation of the eye at frequencies where either stimulus alone would be invisible. It is possible that these responses have undesirable effects, and although there is no very good evidence that the use of CRT displays causes eyestrain or illness, the intermittency of illumination may be reponsible for the commonly reported finding of a slower reading speed from a CRT than from a piece of paper (e.g. Gould and Grischkowsky 1984).

Wilkins (1986) has shown that flicker can cause the enlargement of saccadic eye movements, the movements made frequently whilst reading. The extent of the enlargement depends on the display field rate and is evident when flicker is not noticeable. At 50Hz, Wilkins found saccades to be 11% larger than at 100Hz. This may necessitate corrective saccades, which themselves might be enlarged. A practical implication may be that accurate fixation of the eyes will be facilitated at a high field rate and a demanding visual search task, involving many changes of fixation, will be performed more quickly and possibly more accurately than at a lower field rate. If the minimum time between saccades is 100msec (Stark et al 1961) then every ten saccades requiring correction will add 1 second to the search time and produce a measurable difference in performance.

The experiment described here compared observer performance of such tasks at display rates of 50,80 and 100Hz. The study is important because a finding of impaired performance at lower field rates, under viewing conditions where flicker is not apparent, would indicate that achieving flicker fusion may not be a good enough criterion for choosing the field rate.

2.0 Visual Search Tasks

The subjects were asked to find and count the number of circular targets hidden in a background pattern of random dots. There were 100 tasks and each contained between 1 and 20 targets. An example, with 20 targets, is shown in photograph 1. For each number of targets (1 to 20) there were five patterns, generated by a microcomputer and stored on floppy disc prior to the experiment. The disposition of the targets was randomised over the screen, but care was taken to ensure that they were evenly distributed between the four quadrants of the screen and that none were less than two targets-widths distant from any other. The resolution of the pattern was 256 by 192 pixels and the targets were drawn in cells 8 by 8 pixels. The background pattern of random dots had approximately equal numbers of black and white dots and was the same for all 100 tasks.

2.1 Apparatus

The experiment was controlled and timed by a BBC Master Series microcomputer, which retrieved the appropriate display pattern from the disc and transferred it as a bit-image, via the user port, to an Acorn ATOM. The ATOM had been modified in several ways and was able to generate video signals at field rates nominally of 50,80 and 100Hz. In addition, it was possible to blank and reveal the picture under program control of the BBC, instantly and without any picture disturbance. This was achieved by switching the output of the ATOM between the picture signal and a train of syncronising pulses derived from the picture signal, or vice versa, during the interval between fields.

The picture was 262 lines, non-interlaced of which 242 lines were active. The actual line and field frequencies for the nominal field rates are shown in table 1. The display had a bright border which was 25 lines wide at the top and bottom, and the equivalent of 58 pixels at either side. This was a feature of the video controller used in the ATOM (Motorola 6847) and was unavoidable in the graphics modes. However under the viewing conditions used for the experiment, even at 50Hz, the border did not flicker noticeably.

It was not possible to obtain a picture monitor capable of displaying 50, 80 and 100Hz, so two monitors were used; a BARCO CD351 to display 50 and 80Hz and a MANITRON VLR20101 for 50 and 100Hz. The BARCO was a colour monitor with a dot-pitch of 0.32mm and a P22 phosphor, whilst the MANITRON was a high quality black and white monitor with a P4 phosphor. Both of these are medium-short persistence phosphors; figure 1 shows the expected decay curves and Appendix 1 gives the derivation of these curves. The P22 red component has a longer persistence than the P4, but at the field rates used here the light output from the excitation of the red phosphor will have decayed to zero long before the next excitation. The overall flicker waveform, when the components have been weighted according to the CIE photopic luminous efficiency curve, is very similar for each monitor.

The scan rate of the BARCO monitor was changed by two internal switches and re-adjusting the scan geometry controls (picture height, width, trapezium distortion etc.) The controls were made accessible from the outside of the monitor by drilling holes in the backplate, and using test patterns generated by the ATOM, the correct settings at each scan rate were established. To achieve the necessary accuracy and repeatability of these adjustments, so that the picture size and shape did not change each time the field rate was changed, the position of each control was marked, from a 3.5" pointer attached to the adjusting screwdriver, onto a paper scale attached to the monitor backplate. Changing the MANITRON monitor from 50 to 100Hz was achieved more easily, by swapping the scan control circuit board with a second, matched board supplied by MANITRON.

2.2 Calibration

Whilst the viewing conditions used in this experiment were probably not typical of those for CRT displays in everyday use, they were chosen to minimise the visibility of the picture line structure which was rather coarse, to make the task suitably difficult and the picture flicker at 50Hz imperceptible.

a) Room Lighting.

The room lighting was subdued throughout the experiment and entirely from overhead incandescent lamps; there were no windows. The illuminance falling on a horizontal surface was 170 Lux where the subject was seated but varied between 160 and 200 Lux for other locations in the room. There were no obvious reflections from the monitor screen and glare was minimal.

b) Viewing Distance.

Although both monitors were of 19" diagonal, it was not possible to arrange for the active picture sizes to be exactly the same. However by adjusting the viewing distance slightly the pictures were made to subtend aproximately the same visual angles at the subjects´ eyes. (As the position of the subject´s head was not constrained there was probably considerably more variation in visual angle due to the subject moving than to any difference between the monitors anyway.) For the BARCO, the viewing distance was 160cm and for the MANITRON monitor 150cm. The actual picture, target and pixel dimensions are detailed in table 2 with the approximate visual angles subtended.

c) Monitor Luminance

To ensure that as far as possible, the pictures were of the same brightness and contrast at the different field rates, the monitors were set up accurately using an EEL Lightmaster photometer to measure the light output from the screen. With the meter´s sensor held against the centre of the screen, and the monitor displaying a black field, the brightness control was adjusted. To set the white level, a completely white field was displayed and the contrast control adjusted. For a high quality monitor these adjustments should be largely independent, but as a small interaction was evident, the process was repeated until satisfactory readings were obtained. These are given in table 3.

Strictly, the EEL meter is an instrument for measuring illuminance, in Lux rather than luminance, in Candela per sq metre, but by holding the sensor against the screen, which is assumed to be a Lambertian surface, the relationship is simply:-

$$L=E/Pi$$

Where L is the screen luminance in cd/m sq and E is the illuminance in Lux. (See Appendix 2 for the derivation.)

Later, measurements were made with a MINOLTA spot photometer to verify the calculations (only the EEL meter was used during the experiment). These are also included in table 3. The agreement is fairly good, but using the spot photometer it was discovered that there were anomolies for each monitor. The BARCO displayed a white field which was not of uniform luminance over the whole screen; there was some shading towards the edges, so table 3 includes centre and edge measurements for the BARCO. (Such measurements were not practical with the EEL meter.) For the MANITRON monitor, it was found that the luminance measured from a homogeneous white field was slightly less than that measured from the white parts of a field made up of black and white squares; again, details are recorded in table 3. (Perhaps this effect was due the monitor's internal power supply being unable to cope with the sustained high beam current). However it was decided that these deviations, and their effects on the picture contrast, were small enough not to influence the results of the experiment.

The contrast inherent in the display can be calculated from table 3, but the perceived contrast will be modified by the effect of ambient light reflected from the display screen. Hence, using the spot photometer, the screen luminance seen from the subjects' view point, under the experimental lighting condition, was measured. Table 4 shows these results and the display contrast ratio for a pattern of black and white squares. (The spot photometer measurements in table 3 were taken with the room lights off and from a closer distance to be comparable with the readings taken during the experiment with the EEL meter.)

d) Display Resolution.

Since the sharpness of the display could affect search times, the resolution was measured.

The ATOM was used to generate linear gratings of different spatial frequencies up to the maximum that was present in the experimental display, where alternate pixels along a line were on. As a measure of system response, the luminance modulation of the display was measured at each frequency. With a close-up lens attached to the spot photometer it was possible to measure the luminance of an area 0.4 mm in diameter, so even at the highest spatial frequency the modulation could be found by measuring the luminance of the black and white bars of the grating. The modulation is then defined as:-

$$M=(L_w - L_b) / (L_w + L_b)$$

Where L_w is the luminance of the white bars and

L_b is the luminance of the black bars.

The results for the four display conditions are plotted in figure 2. Each point is a single measurement and the spatial frequencies are expressed in cycles per degree of visual angle from the subjects point of view.

Comparison with the modulation sensitivity functions of the human visual system puts the differences between monitors and between field rates into perspective. Figure 3 shows the sensitivity functions obtained by Van Meeteren and Vos (1972) for a field, 17 by 11 degrees of visual angle. Sensitivity is defined as the reciprocal of the modulation for which subjects would see, with a probability of 0.75, a grating rather than a uniform grey field. The solid curves are therefore boundaries between seeing a grating and a uniform field. The reciprocal of the modulation measured from the MANITRON monitor at 100 Hz (which can be seen from figure 2 to be the worst case) is plotted to the same scale. The mean luminance used here is about 27 cd/sq m so the modulation of the display, at the highest spatial frequency, is at least 200 times greater than at threshold. Compared to the degradation of resolution that would be necessary to make the task impossible (a factor of about 200), the difference between monitors seems negligible.

2.3 Experimental Design.

As the MANITRON picture monitor was not initially available, the experiment was in two parts; the first compared performance of the search task at field rates of 50 and 80Hz, using the BARCO monitor, whilst the second, one month later compared 50 and 100Hz using the MANITRON. It was expected that the two 50Hz conditions would give a sufficiently similar baseline for the comparison of 80 and 100Hz to be legitimately drawn, and if not it would still be of interest to see whether any differences found in the first part were replicated in the second.

In each sub-experiment the subjects were divided at random into two groups (5 per group). Each subject attended two sessions and completed all 100 search tasks in each. The first of these groups saw the higher field rate in their first session and the lower rate in their second, whilst the second group saw the lower field rate first, and the higher rate second.

Each part of the experiment was timetabled in a way such that, as far as possible, the two sessions for each subject were at the same time on consecutive days. No subject did both sessions on the same day, but one in the first part of the experiment had a days break between the first and second sessions. Most of the subjects took about 50 minutes for a session, but the best performers took about 30 mins, and the slowest around 75 minutes.

2.4 Experimental Procedure

The subject was, for the first half of the experiment, seated on a stool, but by popular demand on a more comfortable draughtman's swivel chair, with a backrest, for the remainder. The subjects' eyelevel, when seated, was about 145cm, depending on posture and stature, and was slightly higher than the centre line of the monitor at 125cm. Meanwhile the experimenter sat some way behind the subject facing a display connected to the BBC computer. On this was displayed the test pattern, the task number, the correct answer, and any responses the subject had made.

A high quality television camera was set up, unobtrusively, about 40 degrees off-axis slightly behind the subjects' monitor. This enabled the experimenter to see, from a monitor on his bench, that the subject was looking at the task and answering conscientiously. (See photograph 2.)

A session was started by the subject, seated in front of the the display monitor, pressing the space bar of the computer keyboard. The instructions (see Appendix 3) were then displayed page by page on the monitor as black characters on a bright background. To display the next page, the subject pressed the space bar. In short the subjects were instructed to count the targets as quickly and as accurately as possible.

Next, five practise trials were presented for familiarisation with the procedure, but from which no data were recorded. After these the subject was given the choice of repeating the instructions and practise trials, repeating the practise trials alone or proceeding with the experiment. None of the subjects repeated the instructions or practise, except by accident. Up to this point the experiment took about 5 minutes, and it was assumed that the subjects' eyes would by now be adequately adapted to the room lighting.

This was followed by presentation of the 100 search tasks. The order of tasks was always the same; a pseudo-random sequence such that no consecutive tasks had the same number of targets. A trial commenced with the screen blanked (i.e. black) whilst the BBC transferred the display pattern to the ATOM. After about 3 seconds the display was revealed and the subject began to count the number of targets. When he had an answer he pressed the space bar and the screen was again blanked. Half a second later he was prompted, on the screen, for the number of targets. The answer was entered via the numeric keypad of the computer and echoed to the screen. As this echo required a transfer of data between the BBC and the ATOM, there was a small delay between pressing a key and the number appearing on the screen. Initially this caused some problems for one or two of the subjects but these were quickly overcome during the practise trials and the delay was easily accepted. The answer was checked to see if it was a number between 1 and 20. If not, the subject was reminded that the answer should be in this range and prompted to re-enter the number.

If the answer was correct, the screen was blanked and the next task presented. However, if the subject had answered incorrectly he was informed thus and the task was repeated. A maximum of three attempts was allowed for each task (although the subjects did not know this) and if the third attempt was unsuccessful the experiment proceded as if the answer had been correct. If, by accident a subject had entered a number he did not intend which was nevertheless a valid answer (e.g 9 instead of 19) he was instructed to tell the experimenter, who made a note of the trial number, so that the error could be corrected later.

The computer recorded, for each task, the number of attempts taken, the time (in centiseconds) for which the task had been displayed and, right or wrong, the subject's actual answer. When all 100 tasks had been presented the subject was briefly asked whether he had noticed flicker in the display and for any comments. After the second session he was also asked whether he had found the session easier than the first, and whether he felt that the picture had been clearer, brighter or no different than before.

2.5 Subjects

Twelve male subjects participated in the experiments; there were 10 per sub-experiment (5 in each group) and eight were common to both parts. None were frequent VDU users, but all watched television. By profession, they were technicians, craftsmen or engineers (staff at UKAEA Harwell), aged between 22 and 36 years, with a median age of 24 years. Within the last three years each had been ophthalmically screened and with one exception had 6/6 or better visual acuity with spectacle correction if worn. The exception had 6/9 acuity in his right eye and 6/4 in his left. All were naive as to the purpose of the experiment.

The two subjects new to the second part of the experiment were put in different groups; one saw the 50Hz field rate in his first session, the other, 100Hz.

3.0 Results, Analysis and Discussion

The data were corrected where subjects had inadvertently entered the wrong answers, and then uploaded to the mainframe computer at University College London, where the following analyses were carried out, mainly using the BMDP package of statistical software.

3.1 Error Rate

In drawing any conclusions from the comparison of response times it is important to take into account the error rate (or indeed the response times when considering error rates). It is possible that subjects trade-off accuracy for a fast performance or vice-versa (Pachella 1974) and therefore a quantitative comparison of response times where the error rate does not remain constant can be misleading since two qualitatively different performances are being compared (slow and accurate vs. fast but inaccurate).

Essentially, the data were analysed with a two-way analysis of variance of the number of errors made, with field rate and the number of targets presented. This was done both for the total number of errors, (the number of incorrect answers on attempts 1,2 and 3) and for the number of errors made at the first attempt.

For the first part of the experiment, 50 vs 80 Hz with the BARCO monitor, the total number of errors is plotted in fig. 4 against number of targets. Similarly fig. 5 shows the number of errors made in the second part (50 vs. 100 Hz). The analysis of variance showed that there was no statistically significant difference in the total number of errors between any of the field rates but, as expected, the number of targets was significant ($F(19,3920)=12.31$; $p<0.0001$ Table A4.1). There was no significant interaction between these two factors. Analysis of the number of errors at the first attempt was very similar (Table A4.2). It is therefore legitimate to compare subject performance by comparing response times.

3.2 Response Times.

Although more of the data collected could have been utilised, only the response time for the first attempt at a task has been used. It is possible that spurious results might have been introduced using the second and third attempts, where subjects may have reasoned their answer could not have been wrong by more than one or two and simply adjusted their first answer.

The response times were examined by calculating the linear regression of mean response time on the number of targets presented (see table A4.12 for a summary of the coefficients). Linear regression was used for both ad hoc and a priori reasons. First, because it is a simple model which fits the data well (typically explaining about 85% of the variance), and second because response time might reasonably be expected to vary in an approximately linear way with number of targets presented. For each trial, there will be a component of response time due to searching the display, a component due to "registering" each target (to fixate and count a target) and a component due to pressing the space bar. Whilst it is difficult to know exactly what cognitive processes are involved with each component, it is reasonable to suppose that the first and third will be largely independent of the number of targets and that the second will be related proportionally. Hence a linear relationship, with a non-zero intercept is to be expected (perhaps with some deviation for the case of 20 targets, where the search need not be exhaustive; once 20 targets have been found there is no need to look for any more). The hypothesised effect of picture flicker could affect either or both of the first two components and hence be manifest as a change of gradient (B in table A4.12) or both intercept (A in table A4.12) and gradient.

If the residual variance, ie. the variance not explained by the regression, was significantly reduced by partitioning the data in some way (e.g. by field rate) and fitting a linear regression, in turn, to the data on each side of the partition, then these linear regressions would be significantly different, in gradient, intercept or both.

Fig.6 show the results for the first part of the experiment. Each point is the mean of 5 trial by 10 subjects and the error bars are plus or minus one standard error of the mean. Similarly, fig.7 shows the results for the second part; 50 vs 100 Hz with the MANITRON monitor. The following significant differences were found:-

Monitor			Difference	p value
BARCO 50Hz	vs.	BARCO 80Hz	50Hz slightly faster	n.s.
MANITRON 50Hz	vs.	MANITRON 100Hz	50Hz slightly faster	p=0.0065
BARCO 50Hz	vs.	MANITRON 50Hz	MANITRON faster	p<0.0001
BARCO 80Hz	vs.	MANITRON 100Hz	MANITRON faster	p<0.0001

(See Tables A4.3, A4.4 and A4.5 for analysis of variance tables for significant results.)

The gradient of the regression for the MANITRON at 50Hz did not differ significantly from that at 100Hz (Table A4.6), whilst for the other two significant comparisons the slope was different. ($F(1,1996)=16.11$, $p=0.0001$, table A4.7 and $F(1,1996)=8.66$, $p=0.0033$, table A4.8 respectively).

The differences between the regressions are reflected in the overall mean response times (10 subjects; 100 tasks):-

Monitor	Mean Response Time (Sec)	Standard Deviation
BARCO 50HZ	10.67	6.78
BARCO 80Hz	11.09	6.45
MANITRON 50Hz	8.89	4.58
MANITRON 100Hz	9.45	5.07

From this it is evident that the difference between the two field rates of the MANITRON monitor was quite small and, by comparison with the difference between the two 50Hz conditions, is probably of no practical consequence.

3.3 Possible Effect of Learning.

The large difference between the two parts of the experiment was unexpected and because of the experimental design, it is not possible to say whether this is due to physical differences between the monitors, or can be entirely explained by a practise effect. Eight of the subjects were common to both parts, and had already completed two sessions before starting the second part.

a) Error Rate

For these eight subjects the error rate (all attempts) was not constant across the sessions ($F(3,3120)=5.13$, $p=0.001$; table A4.9). A Newman-Keuls analysis (table A4.10) showed that for session 4 the rate was no different from session 1, sessions 2 and 3 were not significantly different from each other but differed from sessions 1 and 4. Session 3 and 4 are respectively, the first and second sessions of part 2.

b) Response Times

The regressions of mean response time on number of targets for these eight subjects are plotted session by session in figure 8. The ordering of the lines is certainly consistent with a practise effect; the line for each session lies below that of the previous session and their disposition may well be enough to explain the difference between parts 1 and 2: 80% of the data for the results in fig.6 are drawn from session 1 and 2 of fig.8, and 80% in fig.7 are drawn from session 3 and session 4.

Since the error rate changes from session to session a quantitative comparison of the regressions is dubious, but with practise it might be expected that subjects will perform more quickly, more accurately, or both at each successive session. For the first three sessions this was true:- session 2 was faster and more accurate than session 1; session 3 was faster than session 2 for the same accuracy, but for session 4 there was a different speed-accuracy trade-off; session 4 was the fastest of the 4 sessions, but only as accurate as session 1.

Session	Mean Response Time	Standard Deviation	No. of Errors
1	11.93	6.79	111
2	10.33	5.88	72
3	9.51	4.89	75
4	8.65	4.87	107

This suggests that practise explains the difference between the first three sessions and probably the difference between the two parts of the experiment, but after three sessions has little further effect.

c) New Subjects

If this explanation is correct, then the two subjects new to the second part, might be expected to have performed in a similar way to the ten subjects in part 1.

The error rate (all attempts) for these two subjects, at 50 and 100 Hz was not significantly different from elsewhere in the experiment and there was no interaction with the number of targets.

At 100 Hz, the regression was not significantly different from that at 80Hz in part 1, whereas the regression for all the subjects at 100 Hz differed. However at 50 Hz the regression for the new subjects differed significantly from 50 Hz in part 1 ($F(2,1196)=14.91$, $p<0.0001$; table A4.11) but not from the rest of the subjects in part 2 at 50Hz. Since the higher field rate argues that these two subjects perform in a similar manner to those in part 1, and the lower field rate that they perform like those in part 2, no conclusion can be drawn from this.

Session by session, the error rate for the new subjects (all attempts) did not differ significantly between session 1, session 2, and the error rate of the eight common subjects in their third session. There was no interaction with number of targets in either case.

The regression for the new subjects´ second session was not significantly different from the old subjects´ fourth session, whilst the regression line for the new subjects´ first session lay between the old subjects´ first and second sessions. Therefore the two new subjects started off slower and less accurately than the rest in part 2, but by session 2 appear to performed at the same speed but more accurately than the other 8. This supports a practise effect, but these two subjects learnt quickly and appear to have been particularly good at the task.

3.4 Subject Comments

When the subjects were asked for their comments at the end of each session, none spontaneously mentioned display flicker. Even when asked specifically, only one had noticed any. This subject was one of the eight who participated in both parts of the experiment and after both of the 50Hz sessions reported seeing flicker. In the first part he thought that both sessions were of about equal difficulty, whereas in the second he thought 50Hz the more difficult. However the data from this subject suggest that, in fact, he searched more quickly and more accurately at 50Hz, but as he was in group 1, which saw 50Hz second, for both parts of the experiment, this could just be the effect of practise.

In the first part, all but one of the subjects thought, either that the second session was easier than the first or that they were of equal difficulty. Interestingly, in the second part, whilst the two new subjects found the second session easier, only one of the other subjects thought the second to be the easier session. This supports the practise effect suggested above. Table 5 shows these opinions arranged by field rate, and although the numbers are too small for any reliable statistics to be performed there is no evidence to suggest that the higher field rates were preferred.

Similarly, table 6 and 7 show the subjects´ opinions as to which of the displays was the ´clearer´ and which if either was the brighter. ´Clearer´ meant a subject had commented that in some way the targets were easier to see, and in one case that the display had more contrast. Again , because of the small number of observation and the informal nature of the comparison, it is not possible to read very much into this, but it appears that the slight differences in display resolution were not conspicuous.

4.0 Conclusions

The hypothesised effect of display flicker is not confirmed; there is no evidence from this experiment that subjects performed a demanding visual search task with increased speed or accuracy at display field rates higher than 50Hz.

It is possible that the effects of flicker found by Wilkins are only pronounced for the highly ordered, predictable eye movements found in reading rather than the more erratic ones likely to be found in the search tasks used here. A second experiment is planned where subjects will be required to read text displayed at either 50 or 100Hz.

Curiously, performance at 100Hz was slightly slower than at 50Hz and the difference was statistically significant. Measurements of the display resolution suggest that there was a small difference in sharpness, 100Hz being slightly less sharp than 50Hz, but it was certainly not the case that the smallest details of the task could be seen at one field rate and not the other. A side by side comparison was not possible, but none of the subjects remarked that the 100Hz display was less sharp than any other. In addition the regressions calculated for mean response time on the number of targets did not differ in slope between these two field rates. This would not be expected if degradation of the display was the reason for the 50Hz-100Hz difference. Therefore it is unlikely that a change in resolution is the explanation.

There was a statistically significant difference between the two parts of the experiment. This is most plausibly explained by a practise effect rather than any physical difference between the monitors. Compared to this, the difference between 50 and 100Hz is small, and therefore of little practical consequence.

Although the comparisons were not rigorous, the subjects did not think any field rate easier than any others and on the whole noticed little difference between any of the display conditions.

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Nominal Field Rate	Line Frequency	Actual Field Rate
50 Hz *	14.05 kHz	53.6 Hz
80 Hz	21.02 kHz	80.2 Hz
100 Hz	28.10 kHz	107.3 Hz

* An unmodified ATOM also has a nominal field rate of 50 Hz, but the line frequency is 15.35 kHz and the actual field rate is therefore 58 Hz. This was thought to be too far removed from the nominal value, and thus the ATOM was modified to operate at the line frequency above.

Table 1.

Dimension	BARCO Monitor (mm)	MANITRON Monitor (mm)	Approx. visual angle (degrees)
Total picture width	365	348	13.0
Active picture width	260	242	9.2
Target width	8	7	0.3
Pixel width	1	0.9	0.04
Total picture height	273	269	10
Active picture height	220	213	8
Target height	9	8.8	0.3
Pixel height	1.1	1.0	0.04

Table 2.

Monitor	Pattern	Reading with EEL meter (Lux)	Calculated luminance (Cd/m sq)	Measured luminance (Cd/m sq)
BARCO at 50 Hz	Uniform black field	10	3.2	0.5
	Uniform white field (centre)	170	54.1	51.0
	Uniform white field (edge) *	n/a	n/a	47.0
BARCO at 80 Hz	Uniform black field	10	3.2	0.8
	Uniform white field (centre)	170	54.1	52.0
	Uniform white field (edge) *	n/a	n/a	49.0
MANITRON at 50 Hz	Uniform black field	10	3.2	1.1
	Uniform white field	155	49.3	46.8
	Checkered white field *	n/a	n/a	52.0
MANITRON at 100 Hz	Uniform black field	10	3.2	0.4
	Uniform white field	160	50.9	58.0
	Checkered white field *	n/a	n/a	61.0

* See text

Table 3.

Monitor	Luminance of black squares (Cd/m sq)	Luminance of white squares (Cd/m sq)	Contrast ratio
BARCO at 50 Hz	3.1	55	17.7:1
BARCO at 80 Hz	4.0	62	15.5:1
MANITRON at 50 Hz	2.5	52	20.8:1
MANITRON at 100Hz	2.6	53	20.3:1

Table 4.

Screen luminance, measured at the centre of the screen, viewed from subjects´ point of view under the lighting used for the experiment.

Opinion	Number of Subjects Part 1	Number of Subjects Part 2
Low field rate easier	4	3
High field rate easier	4	4
No difference	2	3

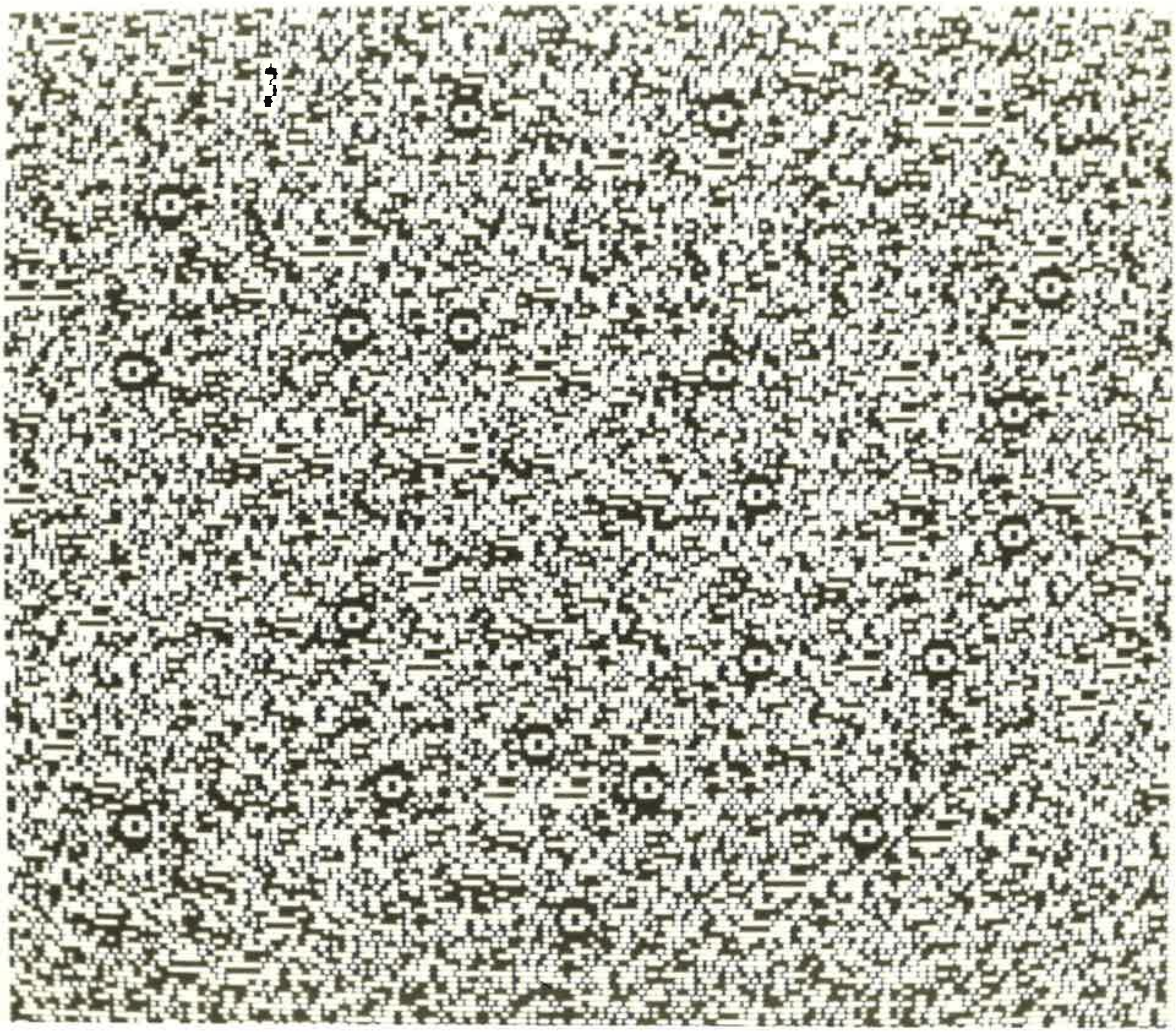
Table 5.

Opinion	Number of Subjects Part 1	Number of Subjects Part 2
Low field rate clearer	2	1
High field rate clearer	2	4
No difference	6	5

Table 6.

Opinion	Number of Subjects Part 1	Number of Subjects Part 2
Low field rate brighter	0	0
High field rate brighter	2	1
No difference	8	9

Table 7.



Photograph 1.

A Typical Search Task

HARWELL LABORATORY
PHOTOGRAPHIC GROUP

HRC 39473

NOT FOR PUBLICATION

Photograph 2. Experimental Apparatus

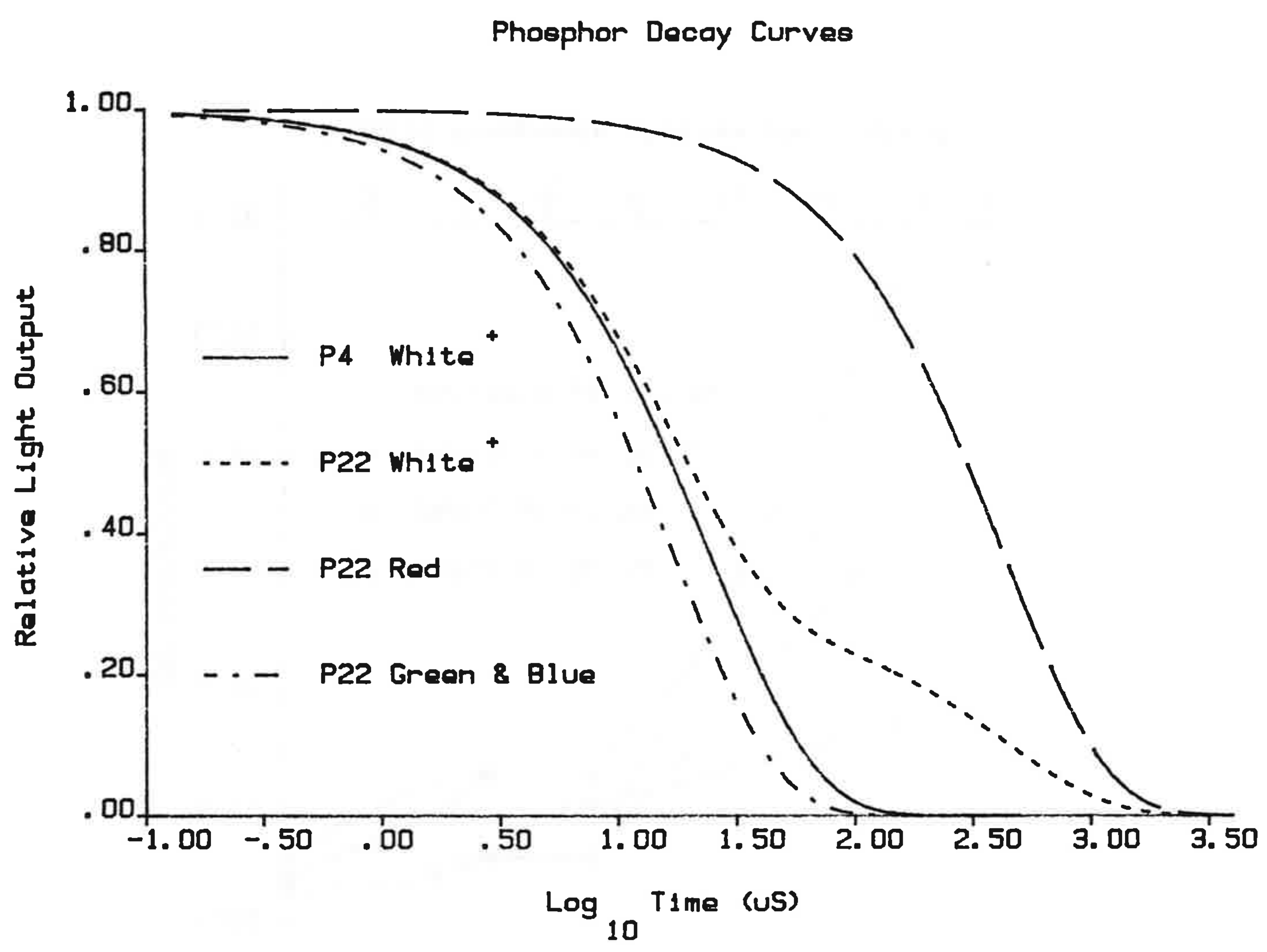


Figure 1.

+ This is the sum of the colour component weighted by the CIE spectral luminosity function. (See Appendix 1).

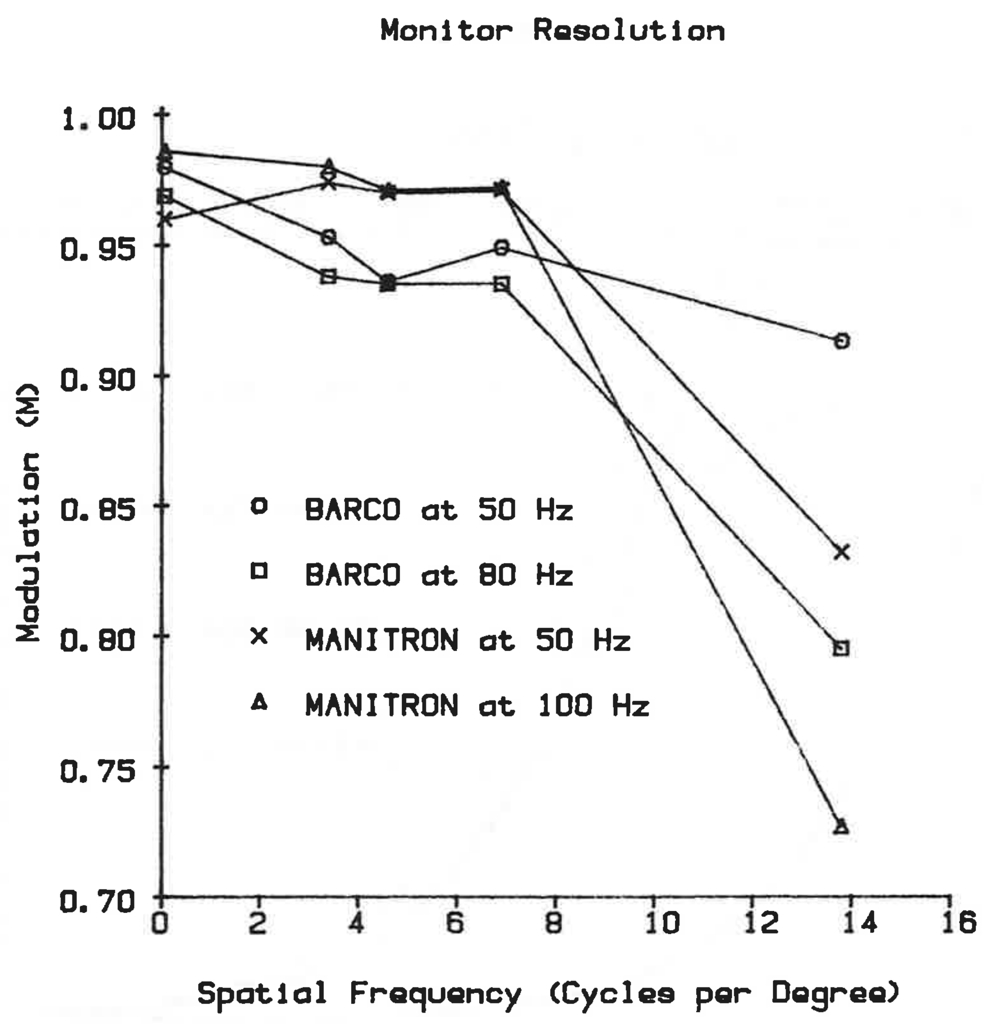

Monitor Resolution
1.00
0.95
0.90
0.85
0.80
0.75
0.70
Modulation (M)
0
2
4
6
8
10
12
14
16
Spatial Frequency (Cycles per Degree)
BARCO at 50 Hz
BARCO at 80 Hz
MANITRON at 50 Hz
MANITRON at 100 Hz

Figure 2.

Monitor Resolution and Modulation Sensitivity Functions.

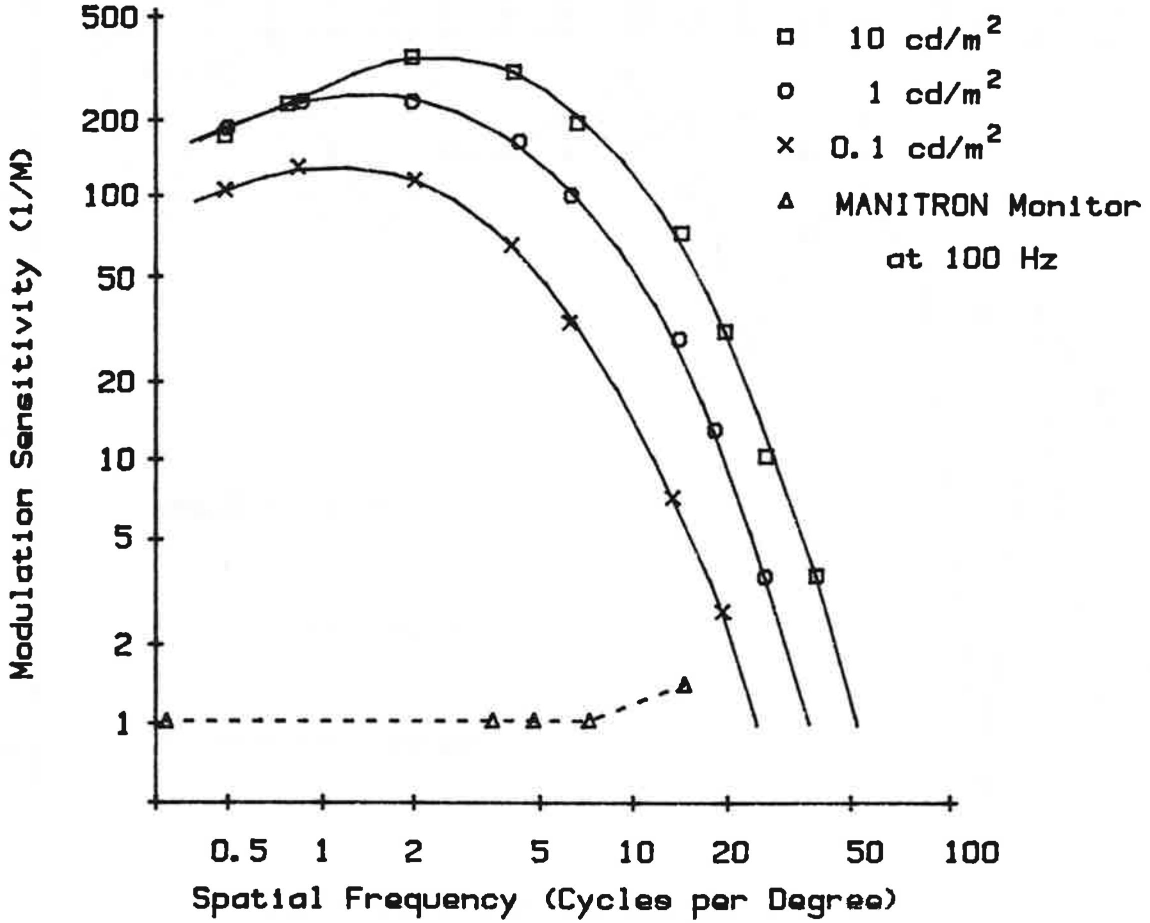


Figure 3.

(Data from Van Meeteren and Vos. 1972)

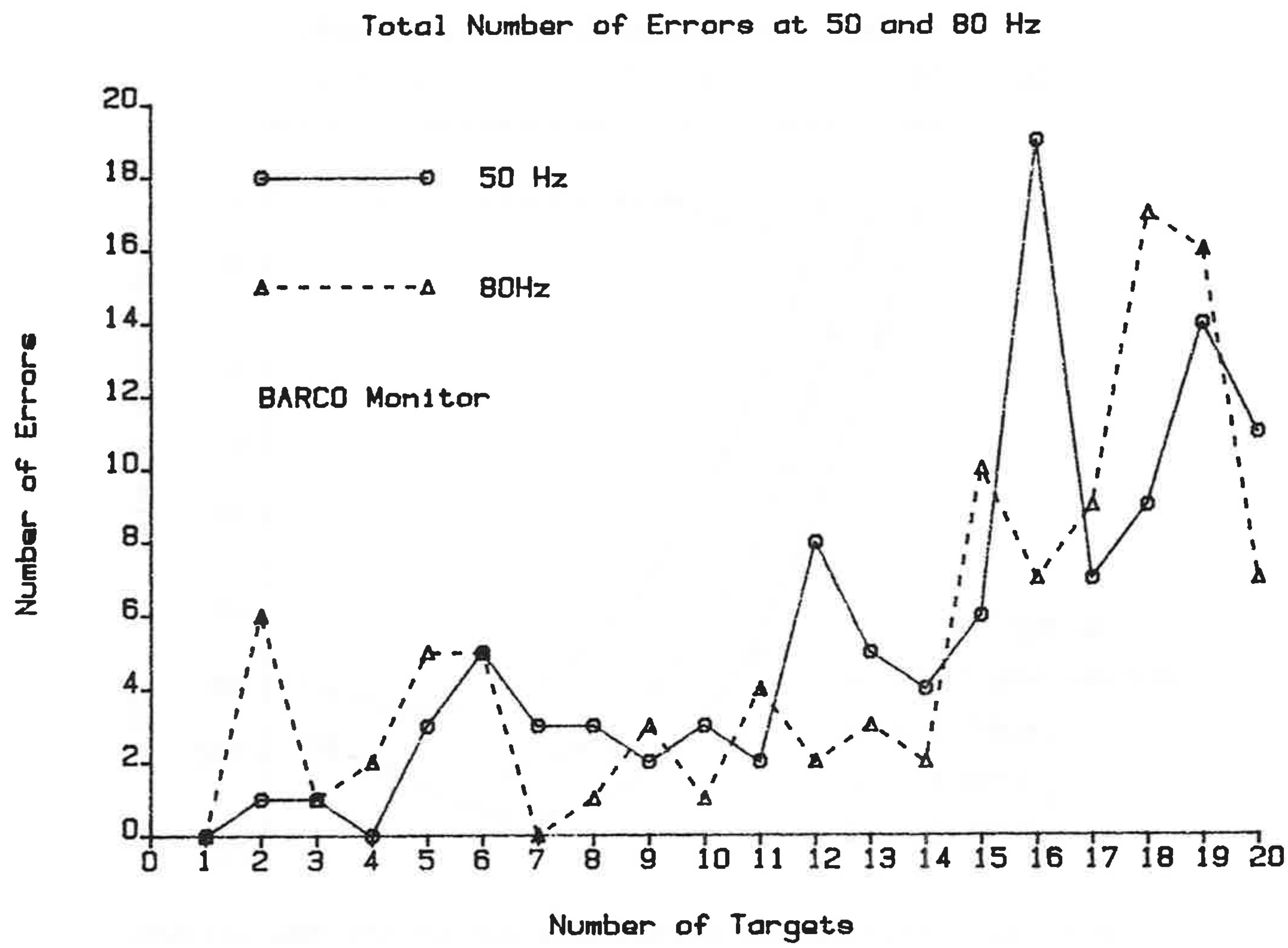

Total Number of Errors at 50 and 80 Hz
50 Hz
80Hz
BARCO Monitor
Number of Errors
Number of Targets
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Figure 4.

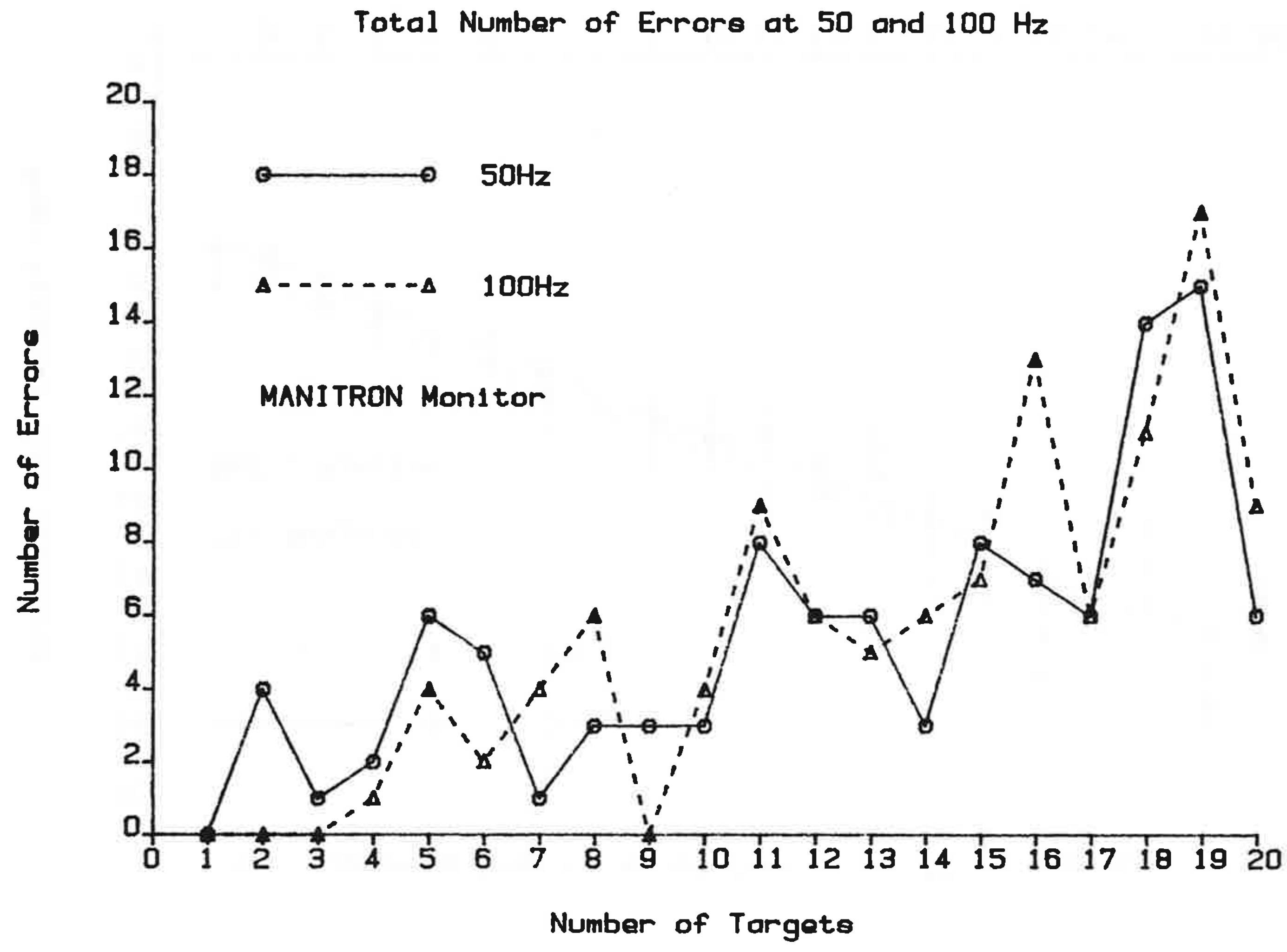

Total Number of Errors at 50 and 100 Hz
50Hz
100Hz
MANITRON Monitor
Number of Errors
Number of Targets
0
2
4
6
8
10
12
14
16
18
20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure 5.

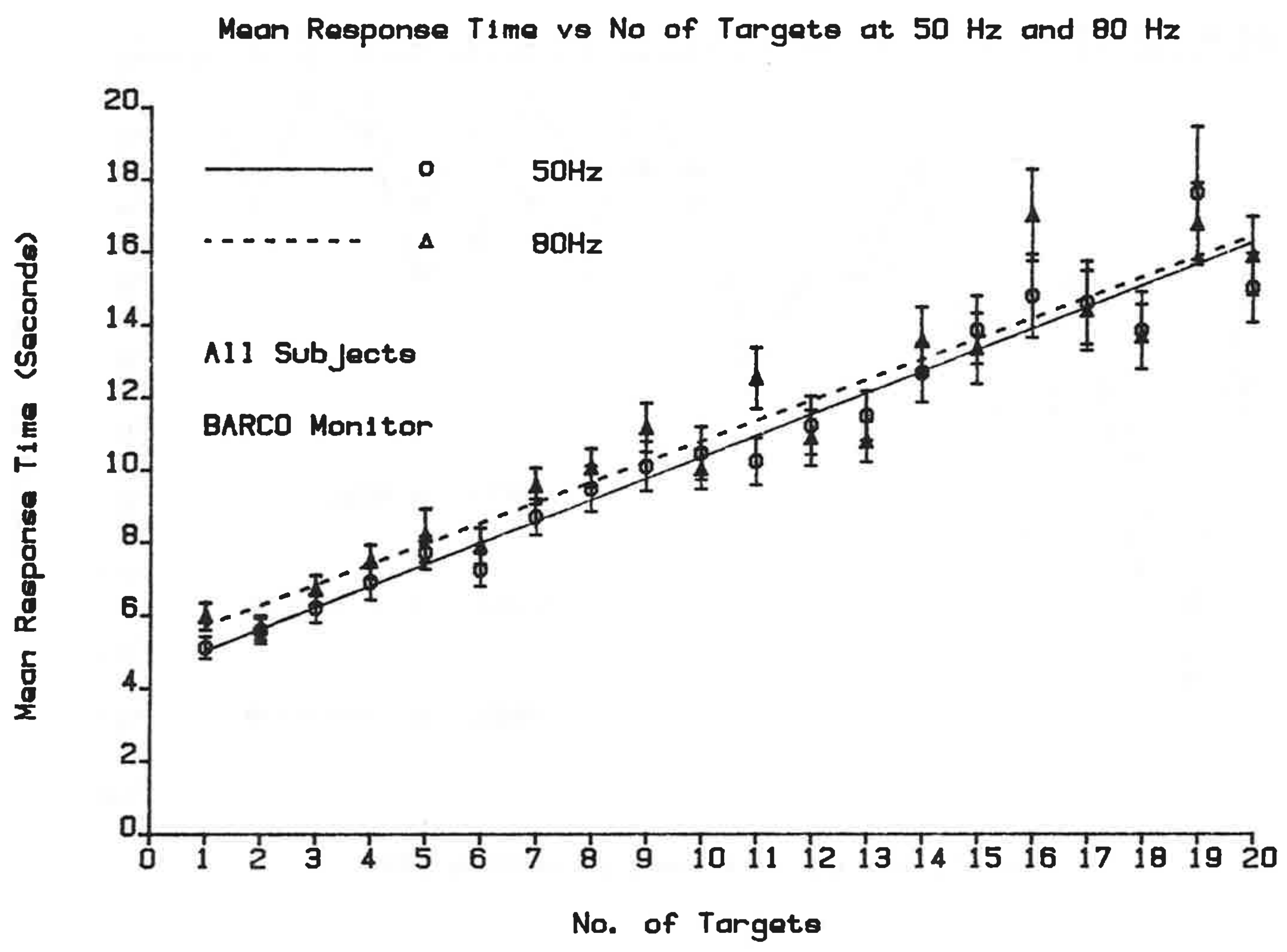

Mean Response Time vs No of Targets at 50 Hz and 80 Hz
50Hz
80Hz
All Subjects
BARCO Monitor
Mean Response Time (Seconds)
0
2
4
6
8
10
12
14
16
18
20
No. of Targets
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Figure 6

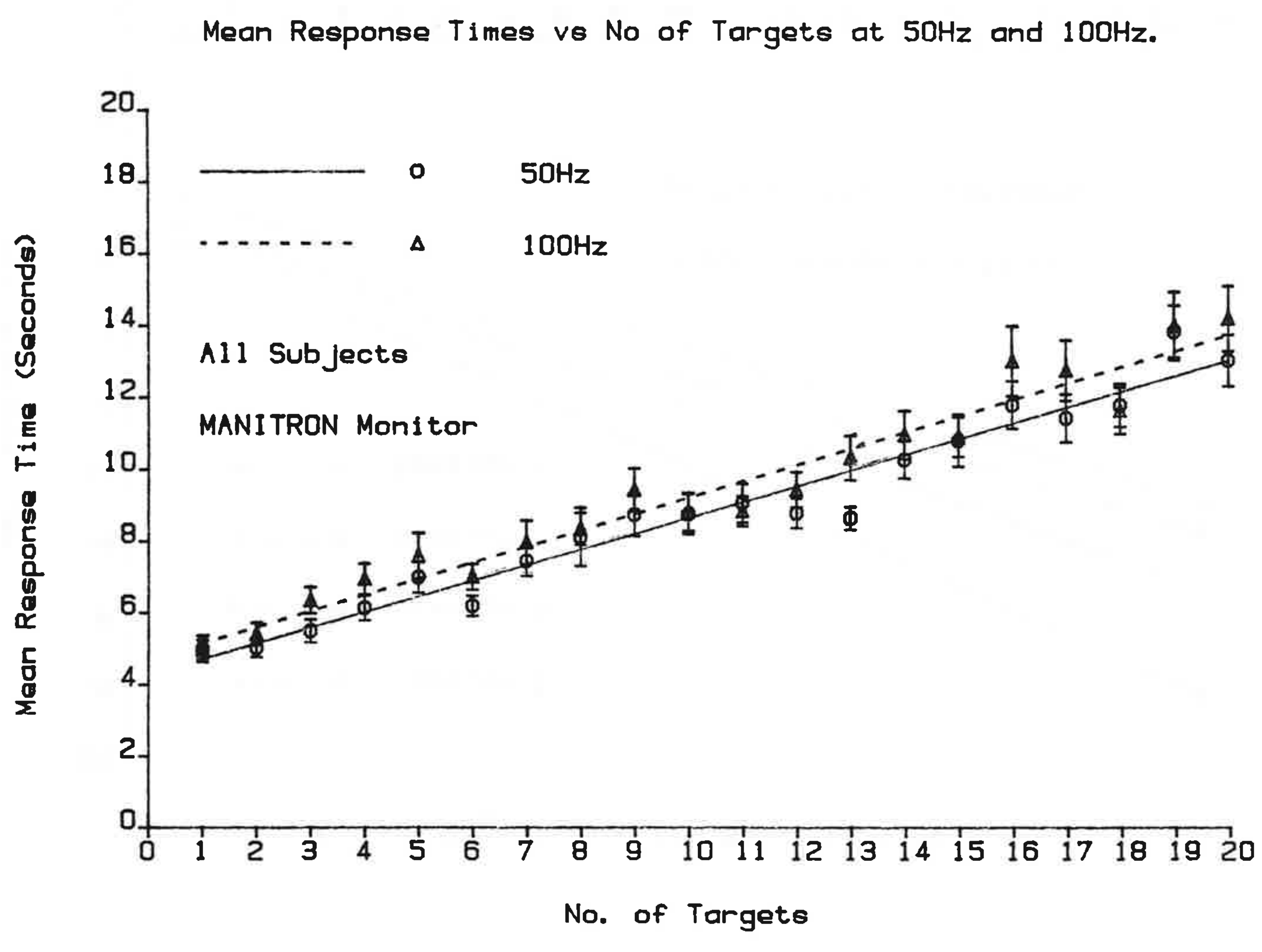

Mean Response Times vs No of Targets at 50Hz and 100Hz.
50Hz
100Hz
All Subjects
MANITRON Monitor
Mean Response Time (Seconds)
No. of Targets
0
2
4
6
8
10
12
14
16
18
20
1
3
5
7
9
11
13
15
17
19

Figure 7

Linear Regressions for Sessions 1 to 4.

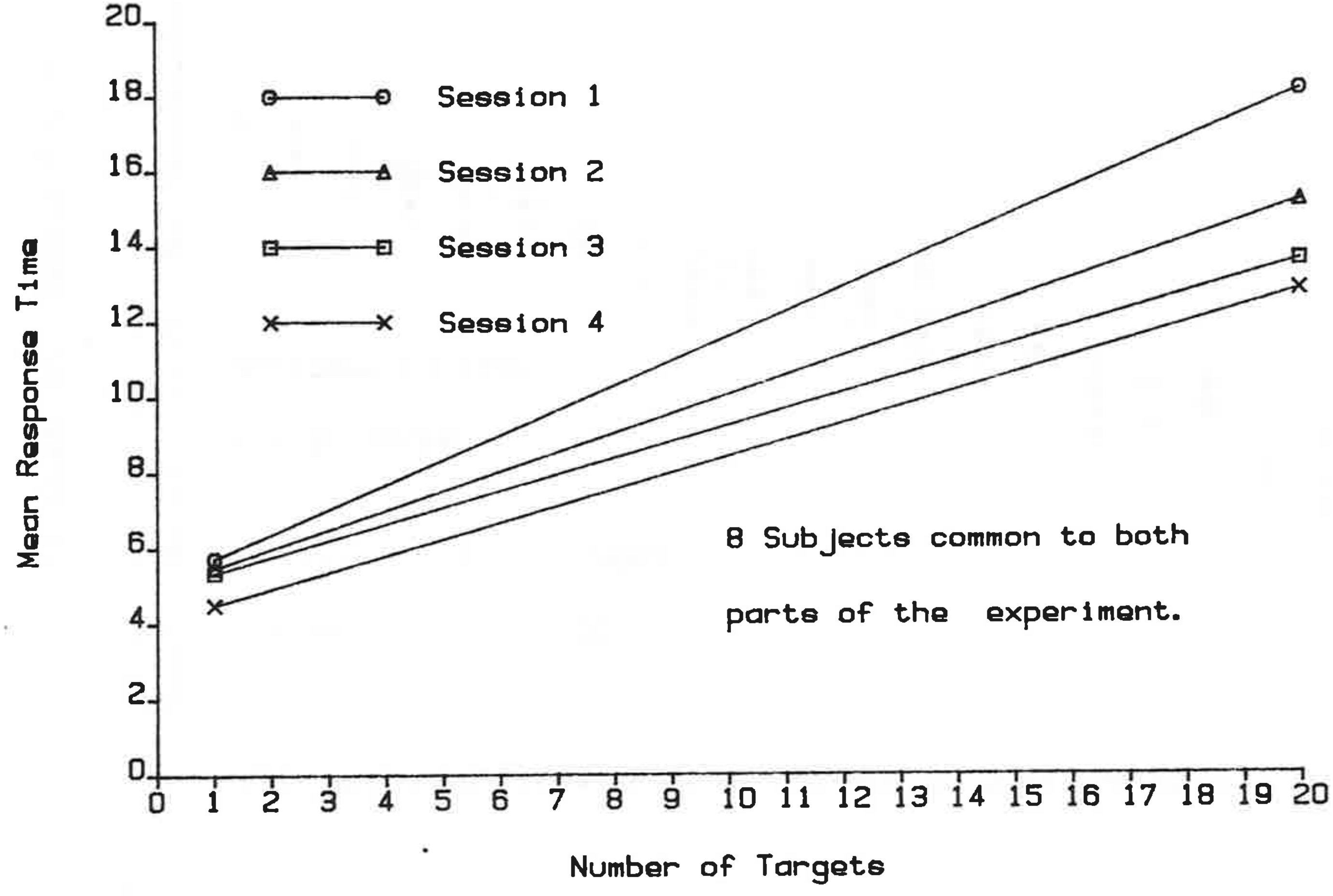


Figure 8.

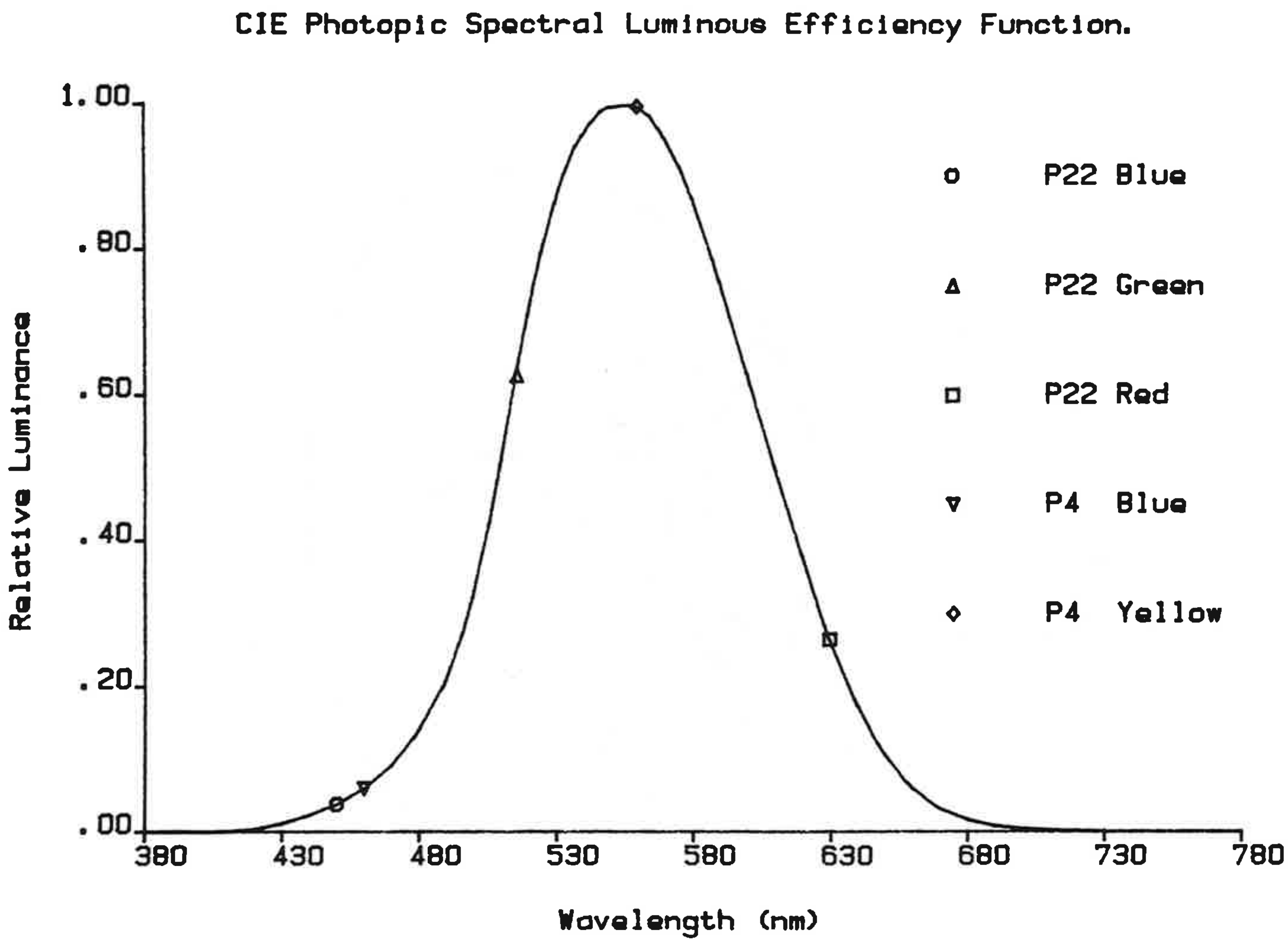

CIE Photopic Spectral Luminous Efficiency Function.
1.00
.80
.60
.40
.20
.00
Relative Luminance
380
430
480
530
580
630
680
730
780
Wavelength (nm)
P22 Blue
P22 Green
P22 Red
P4 Blue
P4 Yellow

Figure A1.

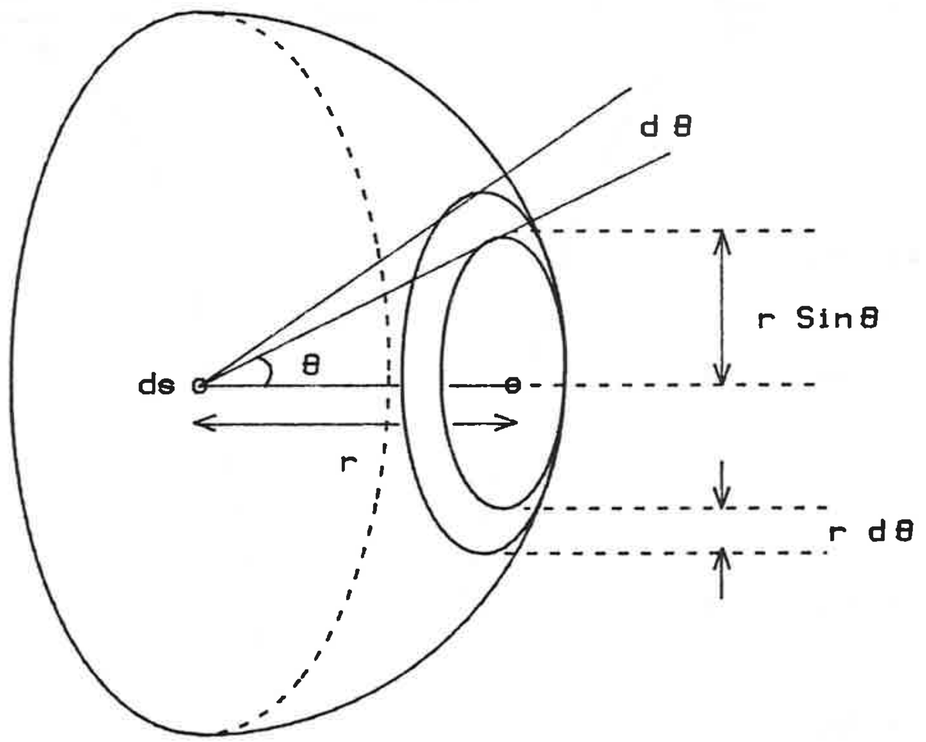


Figure A2.

The Illumination of a Hemisphere by a Small Element of an Emitting Surface

Appendix 1

Explanation of the derivation of the phosphor decay curves of figure 1.

P22 is a set of coloured phosphors; red, green and blue. P4 is a white phosphor, but has two components, blue and yellow. For the P22 and P4 phosphors the decay times to 10% brightness are as follows (JEDEC):-

P4	yellow component	60 usec
P4	blue component	20 usec
P22	blue	40 usec
P22	green	40 usec
P22	red	1 msec

It is assumed that the light output decays exponentially with time after excitation. If the output is measured relative to the peak value, the decay has the form:-

$$L(t) = e^{-kt}$$

Where t is the time in usec, L is the relative light output and k the decay constant.

Setting L = 0.1 and t = the persistence tabled above, the decay constants are:-

P4	blue component	0.115
P4	yellow component	0.038
P22	green and blue	0.058
P22	red	0.002

These are the P22 red and P22 green & blue curves plotted in figure 2. However, so that they can be plotted on the same graph, a logarithmic time scale is used.

To estimate a total decay curve for the P22 phosphor, when the colour white is displayed, the curve from each colour component is weighted by the CIE Photopic Luminous Efficiency Function. (Which is essentially a plot of the relative response of a normal human eye to monochromatic light at different spectral wavelengths.)

For the P22 phosphors the principal spectral peaks are (JEDEC):-

Red	630 (nm)
Green	516 (nm)
Blue	450 (nm)

Figure A1 shows these points on the luminous efficiency curve, and hence the equation for the decay curve is:-

$$L_{tot}(t) = 1.075\,(0.265\,L_{red}(t) + 0.627\,L_{green}(t) + 0.038\,L_{blue}(t)\,)$$

The factor of 1.075 is to make the total output equal to 1 when L_{red}, L_{green} and L_{blue} all equal 1. This is the curve labelled ´P22 White´, in figure 2.

Similarly, for the P4 phosphor the principal spectral peaks are:-

Yellow component	560 (nm)
Blue component	460 (nm)

Weighted by the photopic luminosity function, the decay curve is:-

$$L_{tot}(t) = 0.947\,(0.995\,L_{Yellow}(t) + 0.060\,L_{blue}(t))$$

This is the curve labelled ´P4 White´ in figure 2.

Appendix 2

Derivation of the relationship between luminance and illuminance for a non-absorbing Lambertian surface.

A Lambertian surface is one which appears to be of equal luminance from all directions. For instance a plane mirror illuminated with a collimated light source would not be Lambertian, but a self-luminant surface, such as a CRT face, would be.

Luminous flux (F) measured in Lumen, is a measure of the amount of light emitted, received, or transmitted per second.

Luminous intensity (I), measured in Candela (cd), is a measure of the illuminating power of a light source. For a point source, luminous intensity in a given direction is equal to the luminous flux emitted, in that direction per steradian. (The steradian is a unit of solid angle, such that 1 steradian is the solid angle subtended at the centre of a sphere by an area on the surface equal to that of a square with sides equal to the sphere´s radius.)

Hence:-

$I=F/w$ Where w is the solid angle subtended.

The illuminance (E) of a surface is a measure of the luminous flux (F) falling on the surface per unit area. The unit is Lux, and 1 Lux equals 1 Lumen/ sq metre.

For a surface of area A, distant d from a point source:-

$$E = F/A = I/d^2 \text{ Lux}$$

or if the light source is at an angle of θ to the normal to the surface:-

$$E = (I \cos \theta)/d^2$$

This result is known as the cosine law of illumination.

The luminance (L) is a measure of the luminous flux per unit solid angle, per unit projected area, in a particular direction at a point on the surface. The unit is candela per square metre and :-

$L = I/A \text{ cd/m}^2$ Where A is the area projected in the specified direction

If the luminous flux emitted from a surface, in a direction θ to normal to the surface, varies in proportion to Cos θ, then the surface is Lambertian as the area projected in the direction of θ also varies with Cos θ.

If such a surface has an illuminance of E Lux and is non-absorbing, then a small element of the surface, ds, will emit a luminous flux of:-

E.ds Lumen into a hemisphere (see fig A2).

If the surface luminance is L cd/m^2, then the element will have a luminous intensity of:-

L.ds cd normal to the surface.

This element, by itself illuminates a hemisphere of radius r (fig. A2). An elemental ring on the surface, at an angle θ to the normal has a width of $r.d\theta$ and a circumference of 2π r.Sin θ. The solid angle subtended is:-

$$w = \text{Area}/r^2 = (2\pi r^2 \text{ Sin } \theta \text{ } d\theta)/r^2$$

$$= 2\pi \text{ Sin } \theta.d\theta$$

The ring is subject to luminous intensity of:-

$$L.ds.\text{Cos } \theta \text{ cd}$$

The elemental luminous flux is then:-

$$dF = Iw = 2\pi L.ds.\text{Cos } \theta \text{ Sin } \theta.d\theta$$

The flux emitted into the whole cone of semi-vertical angle θ is:-

$$F = \int_0^\theta 2\pi L.ds.\text{Cos } \theta \text{ Sin } \theta.d\theta$$

$$= \pi L.ds.\text{Sin}^2 \theta \text{ Lumen}$$

For the whole hemisphere $\theta=\pi/2$ radians so the total flux due to area ds is:-

$$F = \pi L.ds \text{ Lumens}$$

But this also equals E.ds, hence:-

$$L = E/\pi \text{ cd/m}^2$$

Appendix 3

Text of the instructions given to the subjects.

The instructions were presented as several screens of text, each ending with the line " Press space bar to continue......". When the subject responded, the screen was cleared and the next section displayed; thus the rate of presentation was paced by the subject.

Instructions

In this experiment you are required to count the number of "targets" hidden in a background pattern.
A "target" looks like this:-

O

Press space bar to continue............

Each screen will contain between 1 and 20 "targets". You are asked to count the "targets" AS QUICKLY AND AS ACCURATELY AS POSSIBLE.

Press space bar to continue............

When you are satisfied that you have found all the "targets" press the space bar. The screen will go blank, and shortly afterwards you will be asked to enter the number you have counted.

Press space bar to continue............

Enter your answer using the key-pad; then press RETURN. There is a small delay between pressing a key and the number appearing on the screen.

Press space bar to continue............

If you have made an error in entering your answer and have not yet pressed RETURN, simply enter any letter before pressing RETURN. You will then be prompted to re-enter your answer.
However, if you have already pressed RETURN then tell the experimenter.

Press space bar to continue.............

If the answer you have entered is correct, then after a short pause the next test will be presented.
If you have answered incorrectly you will be informed and asked to repeat the count.

Press space bar to continue.............

There are 100 such tests and the experiment usually takes about 1 hour.
Before starting press either the space bar to repeat these instructions or press RETURN to run some practise tests.

Appendix 4

Significant results from the statistical analysis and table of coefficients of linear regression.

Source	Sum of Squares	dF	Mean Square	F	p
Field Rate	420.000	3	140.000	0.13	0.9446 ns
Targets	259560.000	19	13661.053	12.31	<0.0001 **
Interaction	60980.000	57	1069.825	0.96	0.5521 ns
Residual	4349600.000	3920	1109.592	-	-

Table A4.1

2-Way analysis of variance of number of errors*100 (all attempts) with field rate and number of targets.

Source	Sum of Squares	dF	Mean Square	F	p
Field Rate	27.500	3	9.167	0.01	0.9984 ns
Targets	192187.500	19	10115.132	12.24	<0.0001 **
Interaction	47422.500	57	831.973	1.01	0.4617 ns
Residual	3239800.000	3920	826.480	-	-

Table A4.2

2-Way analysis of variance of number of errors*100, at the first attempt, with field rate and number of targets.

** indicates a significant result.
ns non-significant

Source	Sum of Squares	dF	Mean Square	F	p
Reduction of residual	169.730	2	84.865	5.0488	0.0065 **
Residual within groups	33554.211	1996	16.811	-	-

Table A4.3
Groups are:- part 2 at 50 Hz and part 2 at 100Hz.

Source	Sum of Squares	dF	Mean Square	F	P
Reduction of residual	1990.414	2	995.207	40.492	<0.0001 **
Residual within groups	49057.230	1996	24.578	-	-

Table A4.4
Groups are:- part 1 at 50 Hz and part 2 at 50 Hz.

Source	Sum of Squares	dF	Mean Square	F	p
Reduction of residual	1557.141	2	778.570	31.160	<0.0001 **
Residual within groups	49872.969	1996	24.986	-	-

Table A4.5
Groups are:-part 1 at 80 Hz and part 2 at 100 Hz.

Reduction of residual is the reduction afforded by grouping the data and fitting a linear regression to each group separately.

** indicates a significant result.

Source	Sum of Squares	dF	Mean Square	F	p
Equality of Slopes	3.356	1	3.356	0.1996	0.6551 ns
Residual within groups	33554.238	1996	16.811	-	-

Table A4.6
Groups are:- part 2 at 50 Hz and part 2 at 100Hz.

Source	Sum of Squares	dF	Mean Square	F	P
Equality of Slopes	396.020	1	396.020	16.113	<0.0001 **
Residual within groups	49057.266	1996	24.578	-	-

Table A4.7
Groups are:- part 1 at 50 Hz and part 2 at 50 Hz.

Source	Sum of Squares	dF	Mean Square	F	p
Equality of Slopes	216.035	1	216.035	8.646	0.0033 **
Residual within groups	49872.996	1996	24.987	-	-

Table A4.8
Groups are:-part 1 at 80 Hz and part 2 at 100 Hz.

** indicates a significant result.

Source	Sum of Squares	dF	Mean Square	F	p
Session	18034.375	3	6011.458	5.13	0.0015 **
Targets	233559.375	19	12292.599	10.48	<0.0001 **
Interaction	54653.125	57	958.827	0.82	0.8338 ns
Residual	3658250.000	3120	1172.516	-	-

Table A4.9

2-Way analysis of variance of total number of errors*100, with session and number of targets for the 8 subjects common to both parts of the experiment.

Group	Mean	Group	Mean	Diff.	p
Session 2	9.000	Session 3	9.375	0.375	>0.05 ns
		Session 4	13.375	4.375	<0.05 *
		Session 1	14.375	5.375	<0.05 *
Session 3	9.375	Session 4	13.375	4.000	<0.05 *
		Session 1	14.375	5.000	<0.05 *
Session 4	13.375	Session 1	14.375	1.000	>0.05 ns

Table A4.10.

Difference in error rate (total number of errors) between sessions for the 8 subjects completing both part 1 and part 2. Newman-Keuls method;

* indicates a significant result.
ns non-significant.

Source	Sum of Squares	dF	Mean Square	F	p
Reduction of residual	898.086	2	449.043	14.905	<0.0001 **
Residual within groups	36031.629	1196	30.127	-	-

Table A4.11

Groups are:- subjects new to part 2 at 50 Hz and all subject in part 1 at 50Hz.

Reduction of residual is the reduction afforded by grouping the data and fitting a linear regression to each group separately.

** indicates a significant result.

Regression	A	B	Standard Error of A	Standard Error of B
BARCO 50 Hz (Fig. 6)	4.450	0.592	0.345	0.029
BARCO 80 Hz (Fig. 6)	5.153	0.566	0.494	0.041
MANITRON 50 Hz (Fig. 7)	4.284	0.438	0.262	0.022
MANITRON 100Hz (Fig. 7)	4.711	0.452	0.280	0.023
Session 1 (Fig. 8)	5.066	0.653	0.546	0.046
Session 2 (Fig. 8)	4.970	0.510	0.301	0.025
Session 3 (Fig. 8)	4.907	0.438	0.369	0.031
Session 4 (Fig. 8)	4.052	0.438	0.246	0.021
New Subjects 50 Hz	4.238	0.414	0.386	0.032
New Subjects 100 Hz	4.906	0.528	0.715	0.059
New Subjects Session 1	5.543	0.509	0.702	0.059
New Subjects Session 2	3.602	0.433	0.407	0.034

Table A4.12.

Coefficients of linear regression.

Equation fitted is:-

Mean Response Time = A + B * Number of Targets

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