Perception, 1989, volume 18, pages 257-264

Effects of phosphor persistence on perception and the control of eye movements

Catherine Neary, Arnold J Wilkins
MRC Applied Psychology Unit, 15 Chaucer Road, Cambridge CB2 2EF, UK
Received 11 February 1988, in revised form 12 August 1988

Abstract. When a rapid eye movement (saccade) is made across material displayed on cathode ray tube monitors with short-persistence phosphors, various perceptual phenomena occur. The phenomena do not occur when the monitor has a long-persistence phosphor. These phenomena were observed for certain spatial arrays, their possible physiological basis noted, and their effect on the control of eye movements examined. When the display consisted simply of two dots, and a saccade was made from one to the other, a transient ghost image was seen just beyond the destination target. When the display consisted of vertical lines, tilting and displacement of the lines occurred. The phenomena were more intrusive for the latter display and there was a significant increase in the number of corrective saccades. These results are interpreted in terms of the effects of fluctuating illumination (and hence phosphor persistence) on saccadic suppression.

1 Introduction

Cathode ray tubes are typically used to display material on computer visual display units (VDUs). The material is illuminated intermittently, once with each screen refresh, but the time course of the illumination varies considerably, depending on the nature of the phosphor coating on the screen. Figure 1 shows the time course of the illumination of a pixel on screens with two commonly used phosphors: one with short persistence (P31), and one with long persistence (P39). Figures 1a and 1b have linear scales. (Note that the abscissa in figure 1a is expressed in microseconds and in figure 1b in milliseconds.) Although the long-persistence phosphor (curve P39) retains its light more than one hundred times longer than the one with short persistence (curve P31), it has nevertheless lost about half its light in 16.7 ms, the interval between successive scans on visual display units which use a 60 Hz refresh rate. In figure 1c, which shows the curves on logarithmic coordinates, it can be seen that the P31 phosphor has a peak light output about eighty times greater than that of the P39 phosphor when the screens have similar brightness.

The short- and long-persistence phosphors can have very different perceptual effects. In this paper we describe the effects, their possible physiological basis, and show that they depend on the spatial characteristics of the display and the nature of the movement of the eyes across it. We also show that, under certain circumstances, the use of short-persistence phosphors can affect ocular motor control, and argue that these motor effects are due to the perceptual effects.

1.1 *Nature of the perceptual effects and preliminary observations*

The perceptual differences between screens with short- and long-persistence phosphors can be demonstrated, in normal room illumination, with a very simple display consisting of two isolated dots. When the observer directs his or her gaze from one dot to the other, thus making a very rapid eye movement (a saccade), a transient ghost-like image may sometimes be seen in the vicinity of the dot to which the saccade is directed, usually beyond it. A more striking display is provided by a thick vertical line. When the observer makes a saccade from one side of the line to the other the line may appear momentarily to tilt, leaning in the direction of the eye movement. These perceptual anomalies are seen on screens with a short-persistence phosphor, but not on those with a long-persistence one. We have observed such phenomena on monitors with frame rates as high as 100 Hz (white P4 phosphor), and when the display is light on a dark background or the reverse contrast.

Saccades have a duration (about 30 ms for a 5 deg saccade) such that the screen is refreshed only a few times whilst the eye is in flight. The ghost-like images are due to the perception of visual input during the flight of the eye. The line appears to tilt because the top of the screen is lit before the bottom and the light from the line stimulates positions on the retina which correspond to those which a tilting line would stimulate were the eye fixating. Normally we are unaware of the visual stimulation that occurs during a saccade, a phenomenon known as 'saccadic suppression' (see Matin, 1974, for a general review), so it is necessary to explain why the perceptual effects we have just described occur, as well as why their visibility should be affected by phosphor persistence.

The first and most obvious consideration is that the peak light output from a screen with a short-persistence phosphor is extremely bright. To determine whether a simple explanation of the perceptual differences between the two phosphors is possible in terms of brightness, two monitors (both Taxan Model KX12), one with a P31 and the other with a P39 phosphor, were compared. Both received an identical video signal from a microcomputer, so as to display the spatial array shown in figure 2. The time course of the luminance of a pixel on each monitor was measured using a photomultiplier and is shown in figure 1. From figure 1c it can be seen that the peak luminance of a pixel on the short-persistence phosphor is about eighty times greater

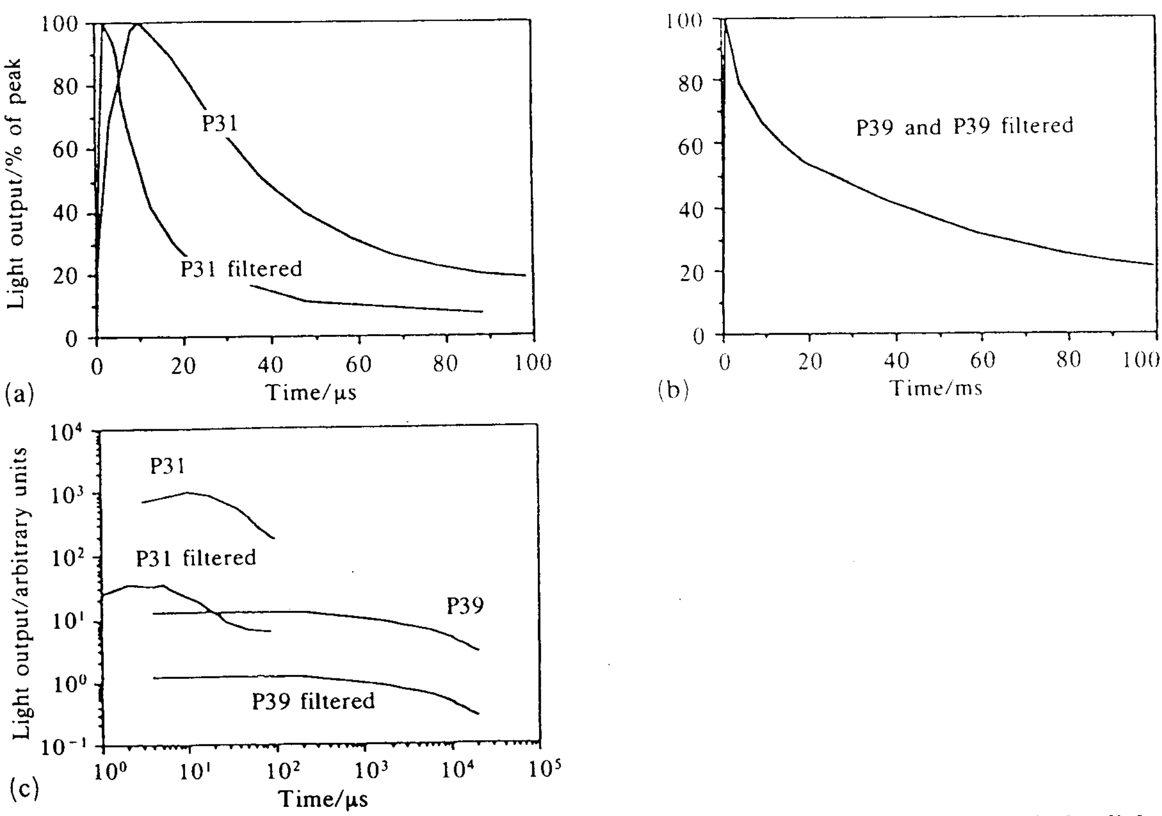


Figure 1. The decay characteristics of two phosphors. A photomultiplier collected the light from a single pixel on the screen of a monitor with a P31 (short-persistence) phosphor and the screen of a similar monitor with a P39 (long-persistence) phosphor. In (a) and (b) the coordinates are linear [note that the units of the abscissa are microseconds in (a) and milliseconds in (b)]. In (c) the same curves are plotted on logarithmic coordinates. Note that when a green gelatine filter (Wratten 74) is interposed between the screen and the photomultiplier the light output from both phosphors is reduced and the peak of the output on the P31 phosphor occurs earlier.

than that on the one with long persistence. The monitor with the short-persistence phosphor was therefore viewed in a darkened room through a neutral density filter, which transmitted only 1% of light and reduced the luminance slightly below that of the monitor with the long-persistence phosphor (Wratten ND 2.0). Under these viewing conditions four naive observers with normal or corrected-to-normal vision (aged 24-32 years) reported that the perceptual effects were still present, though attenuated, and that they were seen only on the screen with the short-persistence phosphor. The perception of visual effects on the short- but not on the long-persistence phosphor is not therefore simply attributable to the difference in peak light output.

Saccadic suppression is known to be affected by the duration of a stimulus presented during a saccade. Matin et al (1972) flashed a vertical slit of light during the course of a 4 deg saccade and found that when the flash was short subjects perceived an elongated smear to one side of the slit. As flash duration increased, the perceived length of the smear also increased, reaching a maximum at 20 ms and decreasing thereafter, to disappear when flash duration was similar to that of the eye movement. (Exposure duration has also been shown by Burr, 1980, to affect motion smear.) The mechanisms responsible for the effects of flash duration are still controversial (Breitmeyer 1984), but the dependence of the intrasaccadic percept on flash duration suggests that one possible reason for the perceptual differences between the short- and long-persistence phosphors is the time course of the light output.

The appearance of a tilting line is one of a family of perceptual effects that are apparent when identical displays on screens with either short- or long-persistence phosphors are compared. The vertical line produces one of the most powerful perceptual effects because the direction of the raster scan ensures that the intrasaccadic retinal stimulation elicits a percept of a tilting line. A tilting line is qualitatively different from the percept seen before and after the saccade. One of the mechanisms of saccadic suppression, namely masking, may possibly occur less efficiently if the intrasaccadic percept differs qualitatively from that present before and after the saccade. The effectiveness of a visual stimulus as a mask is known to depend on the similarity between the stimuli (eg Campbell and Kulikowski 1966; Kolers 1962). Some support for this view comes from preliminary observations showing the influence of the direction of the eye movement in relation to that of the raster scan.

Eight naive observers with normal or corrected-to-normal vision made a 12 deg saccade between two fixation points positioned 6 deg either side of the centre of a line 10 deg in length. The line was displayed at an angle of 0, 15, 45, 60, 75, and 90° to the vertical on a monitor with a short-persistence (P31) phosphor either placed in an upright position or turned on its side. When the monitor was upright and the line vertical or when the monitor was on its side and the line horizontal all observers reported seeing the tilting of the line. The tilting became increasingly less prominent as the line departed from vertical (or horizontal when the monitor was on its side), and when the line was horizontal (or vertical when the monitor was on its side) no tilting was observed. Instead a momentary line parallel to the actual line was seen. Seven of the eight observers reported that the perceptual anomalies were most intrusive when the tilting was most apparent.

In order to determine whether the perceptual phenomena correspond simply to retinal stimulation, six naive normal observers made a 12 deg saccade across a rectangle 7 deg wide and 5 deg high, or across an isosceles triangle with vertical and horizontal sides of 5 deg. Two observers reported no perceptual effects. Two observed the vertical lines to tilt, and two reported that the rectangle became a parallelogram, but that the triangle moved as a whole. Evidently the perceptual reports may depend on the 'figure-like' quality of the stimulus configuration and not simply upon the geometry of the retinal stimulation whilst the eye is in flight.

Whatever the mechanisms by virtue of which we are normally unaware of intra-
ccadic retinal stimulation, the mechanisms were developed to work within a contin-
usly-illuminated environment, and it is therefore perhaps not surprising that they fail
der conditions of fluctuating illumination.

2 *Influence of the perceptual phenomena on eye movements*
rceptual phenomena can affect eye movements: apparent motion, for example, can be
sponsible for slow eye movements (Lamontagne 1973; Steinbach 1976). West and
yce (1968) and Haddad and Winterson (1975) reported that intermittent illumina-
n interferes with fixational eye movements, at least at frequencies at which flicker is
rceptible. High-frequency intermittency may also affect eye movements. Wilkins
986) compared cathode ray tube displays with a short-persistence phosphor and
fresh rates of either 50 or 100 Hz. He measured the size of saccades made between
o letters, 132 min apart, embedded in a line of text. At the 50 Hz rate the saccades
re enlarged and a greater number of corrective saccades were seen. Given that a
ccade towards a target may be associated with the perception of a transient ghost-like
age in the vicinity of the target and usually beyond it, it is possible that the results
tained by Wilkins may have been due to these perceptual effects.
Considerations such as the above led us to evaluate the simplest possible display: two
lated dots. In the first experiment we compared the saccades made between point
gets displayed on screens with either short- or long-persistence phosphors. Our
lure to demonstrate effects of phosphor persistence on ocular motor control, despite
ferences in perceptual effects, prompted us to carry out a second experiment, in
ich we used a spatial array for which the perceptual effects were more pronounced.
this experiment the screen with the short-persistence phosphor was associated with a
nificantly larger number of corrective saccades than the one with the long-persis-
ce phosphor.

Experiment 1

Method

.1 *Subjects.* Seven female observers, ranging in age from 20 to 35 years, served as
jects. All had 6/6 visual acuity at near and far (normally or after correction), and no
own ocular or ocular motor pathologies. All subjects were naive with respect to the
n of the study.

.2 *Monitors and stimuli.* Two Taxan KX12 monitors were controlled by an IBM
rsonal computer. The monitors were structurally the same, except that one had a tube
h a short-persistence phosphor (P31) and the other a tube with a long-persistence
osphor (P39). The screen of each monitor was covered by an opaque matt black card
the centre of which was a rectangular aperture measuring 17 deg wide and 11.5 deg
h. Calibration lights (high-intensity light-emitting diodes 8 min in diameter) were
ached to the black card and all stimuli were displayed on the monitor within the
tangular aperture of the card. The stimulus configuration consisted of two illumi-
ed pixels, each 6 min in diameter and 12 deg apart.

.3 *Procedure.* The subject sat in a darkened room facing one of the two monitors at
iewing distance of 66 cm. Head movements were restrained by a wooden bite-bar.
l stimuli were viewed monocularly through a Wratten 74 filter to equate spectral
mposition. (The filter attenuated more light from the P31 phosphor, and altered its
cay characteristics slightly. The decay of light from the short- and long-persistence
osphors after the addition of the filter is shown in figure 1.) Trial lenses were placed
ore the eye to compensate for any refractive error. At the beginning of the session,

the subject matched the subjective brightness of the P31 screen to that of the P39 screen.

Horizontal eye position was recorded with the aid of an infrared scleral reflection system with a resolution of about 5 min visual angle and an output linear to within a few per cent over a range of ±10 deg. Eye position analogue voltages were fed through a 80 Hz low-pass antialiasing filter to a 12-bit analogue-to-digital converter (ADC). The ADC, under the control of the personal computer, sampled eye position every 5 ms. The digitised voltages were stored on disk and analysed off-line.

Before and after each experimental trial the eye position signal was calibrated by requiring the subject to look at the calibration lights located 10 deg to the right and left of straight ahead. During the calibration procedure the rectangular aperture on the black screen was covered.

Trials began with fixation of the left target and comprised five changes in fixation in response to five 100 ms tones, 1.5 s apart. The subject was instructed to move her eyes as quickly as she could without anticipating the tone. Four trials on each monitor were presented in ABBA order, with a random assignment of a monitor to the A position, giving a maximum of forty refixations on each monitor.

Immediately after the recording the subject was asked whether she had noticed any differences between the stimuli displayed on each monitor. The monitors were then placed side by side, the Wratten filter removed, and the subject instructed to move her eyes from target to target, first on one screen and then on the other, reporting any differences between the two displays.

2.1.4 *Data analysis.* Only trials in which the following criteria were met were analysed: (i) the calibrations before and after data collection changed by less than 5%; (ii) the subject did not look away during the trial and moved her eyes approximately in time with the tone; and (iii) few blinks occurred. The number of usable trials and hence refixations varied from subject to subject but no subject had fewer than twenty analysable refixations on each monitor. The digitised eye position samples were analysed by means of a computer algorithm which detected and measured saccades. The detection of saccades by the algorithm was confirmed by inspection of the eye movement records, and only saccades that fell on the main sequence (Bahill et al 1975) were included in subsequent data analysis. For both the P31 and P39 monitors, the mean size of the largest (main) saccade following each tone, and the mean size and mean number of subsequent saccades larger than 0.25 deg and occurring within 0.75 s of the main saccade were determined.

2.2 *Results*

Immediately after the experiment, two of the seven subjects reported that as they moved their eyes across the screen of the P31 monitor they saw a transient ghost-like image just beyond the target to which their gaze was directed. For example, as they looked from the left to the right target on the P31 monitor they briefly saw an additional target just to the right of the right-hand target. Six of the seven subjects reported the same

Table 1. Means and standard deviations for size of main saccade and size and number of corrective saccades across the seven subjects, for the two visual display monitors, in experiment 1.

Phosphor	Main saccade size/deg	Corrective saccade size/deg	Corrective saccade number
P31	10.96 ± 0.86	1.30 ± 0.55	2.18 ± 0.50
P39	11.13 ± 0.77	1.24 ± 0.43	2.08 ± 0.51

ɜnomenon on the P31 monitor when the filter was removed and they compared the nitors side by side at the end of the session.

Ihere were no significant effects of phosphor persistence on eye movement control any relation between the reports of ghost images and eye movement control. Table 1 ›ws the mean size of main saccade together with the mean size and mean number of rective saccades (saccades occurring within 0.75 s of the main saccade) across ›jects on the two monitors.

Discussion

hough the majority of subjects saw the perceptual effects on the screen with short-persistence phosphor when they compared the screens side by side, few ›jects experienced the perceptual effects during the experiment, perhaps because the atten 74 filter attenuated the luminance. There was a tendency for an increased nber of corrective saccades on the P31 monitor but the absence of any significant ɜcts may have been due to the weakness of the perceptual phenomena. Therefore, in ›eriment 2 a different display, which produced strong perceptual effects, was used.

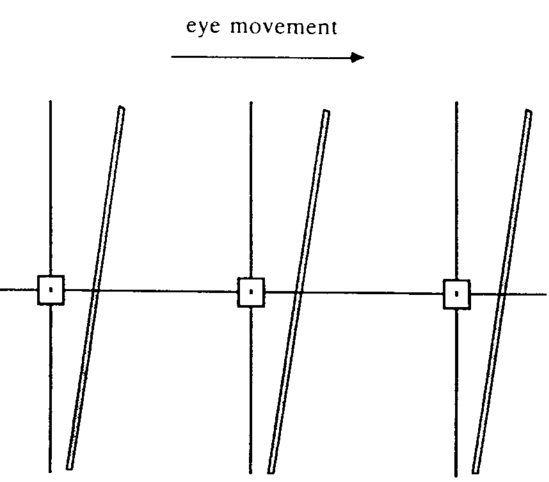
Ɛxperiment 2

Method

.1 *Subjects.* Three of the subjects who participated in experiment 1 took part, ether with an additional twelve of similar age with normal visual acuity.

.2 *Stimuli.* The procedure of experiment 1 was repeated using the display shown in ıre 2, consisting of a horizontal line along which lay three squares with sides ›tending 24 min. Each square had a small (6 min) dot at its centre and was bisected a vertical line. The vertical lines subtended 10 deg from top to bottom and the dots re 5.8 deg apart.

.3 *Procedure.* Trials began with fixation of the dot in the middle of the left square l comprised four changes in fixation to the centre, right, centre, and left dots, in ponse to four 100 ms tones, 1.5 s apart. Six trials on each monitor were presented in ɜBA order, with a random assignment of a monitor to the A position. Both at the end the experiment, and afterwards when viewing the monitors placed side by side



ıre 2. Display used in experiment 2 (solid black lines). It comprised a horizontal line along ch lay three squares with sides subtending 24 min visual angle. Each square had a small nin) dot at its centre and was bisected by a vertical line. The vertical lines were 10 deg from to bottom and the dots were 5.8 deg apart. The three shaded oblique lines are a schematic resentation of the tilting and displacement of the vertical lines reported when a rapid eye vement (a saccade) was made across the display on the P31 monitor in the direction of the ɔw.

(without the Wratten filter), subjects were asked to report any apparent differences between the displays presented on each monitor. Data collection and analysis were as for experiment 1.

3.2 *Results*
Two subjects had fewer than twenty analysable refixations. Immediately after the eye movement recording, eleven of the thirteen remaining subjects reported, on the P31 monitor only, a tilting and displacement of the vertical lines in the direction of eye movement. This is shown schematically by the shaded lines in figure 2. At the end of the session, when the Wratten filter was removed and the monitors were placed side by side, all thirteen subjects reported the same phenomenon on the P31 monitor.

There were no significant differences in the size of the main saccade or the mean size of corrective saccades for the two monitors. However, eleven of the thirteen subjects made more corrective saccades (saccades occurring within 0.75 s of the main saccade) on the P31 monitor, which was significant ($p = 0.01$) on the Student t-test (matched pairs). Table 2 shows the overall mean size of main saccade together with the overall mean size and mean number of corrective saccades on each monitor.

Table 2. Means and standard deviations for size of main saccade and size and number of corrective saccades across thirteen subjects, for the two visual display monitors, in experiment 2.

Phosphor	Main saccade size/deg	Corrective saccade size/deg	Corrective saccade number
P31	5.80 ± 0.40	0.54 ± 0.22	1.52 ± 0.45
P39	5.82 ± 0.35	0.55 ± 0.15	1.37 ± 0.43*

* Significant ($p = 0.01$) on Student t-test.

4 Discussion
The results of this study clearly indicate that intermittently illuminated visual display monitors interfere with the mechanisms which suppress perception of retinal stimulation whilst the eye is in flight. Perceptual phenomena resulting from this disturbance in saccadic suppression are more marked with vertical linear spatial arrays than with simpler arrays. When comparing the monitors with short- and long-persistence phosphors nearly all subjects (six out of seven in experiment 1 and all thirteen in experiment 2) reported seeing perceptual phenomena when they moved their eyes across the screen with the short-persistence phosphor. A transient ghost image was seen just beyond the destination target for the dot array used in experiment 1, and a tilting and displacement of the vertical lines in the direction of eye movement was witnessed for the array used in experiment 2.

When the perceptual phenomena were marked, eye movement control was affected, suggesting that perceptual phenomena resulting from a disturbance in saccadic suppression may influence the control of eye movements. An increase in the number of corrective movements has also been reported by Wilkins (1986), who found an effect of intermittent illumination on eye movements made across text. The appearance of ghost images in the vicinity of the target to which a saccade is directed may, when the images are prominent, disturb the corrective saccades that act to foveate the target. The fact that the images are usually seen beyond the target may also explain the increase in saccade size reported by Wilkins, although no such effect was observed in the present study.

An important factor which may contribute to the perceptual phenomena under investigation is the existence of extraretinal signals which carry information about eye sition or change of eye position. Matin and coworkers (eg Matin and Matin 1972; atin et al 1972) have examined the role of these signals in contributing to the stability the visual world despite dramatic changes in the retinal image space whenever the es move over a stationary display. They have found that this extraretinal compensa-y signal is most notably imperfect for information that impinges on the retina in the ef period just before, during, and after a saccade. Usually the resulting spatial tortion produced by this imperfection in the system is, as argued by Matin (1976), minated by saccadic suppression. However, with a short-persistence phosphor, such ppression would not be effective, and any resulting imperfections in the extraretinal mpensatory system may manifest themselves.

Most visual display units in everyday use are intermittently illuminated, usually at a e higher than that at which flicker is apparent, and typically at 60 Hz. It should be ted that the perceptual phenomena reported here occur at frequencies as high as 0 Hz. It is possible that these perceptual phenomena and their effect on ocular motor ntrol contribute to the complaints of visual discomfort with which VDU use has been ociated, particularly in view of the fact that these complaints are related to the nporal characteristics of the light output (Harwood and Foley 1987; Laubli et al 1981). e design of a visually comfortable display may be one with a refresh rate and modula-n depth that is not only well above critical flicker fusion but also such that perceptual omalies are no longer apparent with the spatial arrays that are to be displayed.

knowledgements. This work was supported by the Health and Safety Executive. The compu- algorithm used to analyse the digitized eye position samples was written by B Craven, partment of Communication, University of Keele. The measurements of phosphor persistence re made with the help of BMUK Ltd.

erences

hill A T, Clark M R, Stark L, 1975 "The main sequence, a tool for studying human eye movements" *Mathematical Biosciences* **24** 191 - 204

itmeyer B G, 1984 *Visual Masking: An Integrative Approach* (New York: Oxford University Press)

r D, 1980 "Motion smear" *Nature (London)* **284** 164 - 165

npbell F W, Kulikowski J J, 1966 "Orientational selectivity of the human visual system" *Journal of Physiology (London)* **187** 437 - 445

ddad G M, Winterson B J, 1975 "Effect of flicker on oculomotor performance" in *Basic Mechanisms of Ocular Motility and their Clinical Implications* eds G Lennerstrand, P Bach-y-Rita New York: Pergamon Press) pp 489 - 493

rwood K, Foley P, 1987 "Temporal resolution: an insight into the video display terminal (VDT) problem" *Human Factors* **29** 447 - 452

ers P, 1962 "Intensity and contour effects in visual masking" *Vision Research* **2** 277 - 294

nontagne C, 1973 "A new experimental paradigm for the investigation of the secondary system of human visual motion perception" *Perception* **2** 167 - 180

ubli T, Hunting W, Grandjean E, 1981 "Postural and visual loads at VDT workplaces. II. Lighting conditions and visual impairments" *Ergonomics* **24** 933 - 944

tin E, 1974 "Saccadic suppression: a review and an analysis" *Psychological Bulletin* **81** 899 - 917

tin E, 1976 "Saccadic suppression and the stable world" in *Eye Movements and Psychological Processes* eds R Monty, J Senders (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 113 - 119

tin E, Clymer A, Matin L, 1972 "Metacontrast and saccadic suppression" *Science* **178** 179 - 182

tin L, Matin E, 1972 "Visual perception of direction and voluntary saccadic eye movements" *Bibliotheca Ophthalmologica* **82** 358 - 368

nbach M J, 1976 "Pursuing the perceptual rather than the retinal stimulus" *Vision Research* **16** 1371 - 1376

st D C, Boyce P R, 1968 "The effect of flicker on eye movements" *Vision Research* **8** 171 - 192

kins A, 1986 "Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text" *Human Factors* **28** 75 - 81