HUMAN FACTORS, 1986, 28(1), 75–81

Intermittent Illumination from Visual Display Units and Fluorescent Lighting Affects Movements of the Eyes across Text

ARNOLD WILKINS,[1] *MRC Applied Psychology Unit, Cambridge, England*

The size of eye movements across text was measured under conditions in which the text was illuminated by fluorescent light or was displayed on the screen of a cathode-ray tube. Under these conditions of intermittent illumination the high-velocity saccadic eye movements were enlarged. The extent to which they were enlarged depended on the frequency of intermittency, but was generally equivalent to the width of one letter. This disturbance of ocular motor control by intermittent illumination might help to explain why reading is generally slower on computer display terminals than with printed text.

INTRODUCTION

It has been widely reported (e.g., Wright and Lickorish, 1983) that text is more difficult to read when displayed on the surface of computer visual display units than when printed conventionally on paper. Computers typically use a cathode-ray tube to display text, and the text is illuminated intermittently at frequencies in the range 50 to 100 Hz. The following experiments suggest that eye movements across text are affected when the text is intermittently illuminated at these frequencies.

In two experiments volunteers were asked to look at text, fixing their gaze alternately on one specified letter and then on another. In the first experiment a paragraph of text was displayed on the surface of cathode-ray tubes with different refresh rates. In the second (concurrent) experiment, the page of a book was illuminated by two types of fluorescent lighting, one intermittent and the other continuous. In both experiments, saccadic eye movements were enlarged to an extent that depended on the frequency of intermittency.

EXPERIMENT 1

Subjects

Fourteen women on the subject panel of the Applied Psychology Unit, aged between 20 and 35 years, were paid £2.00 per hour for participating. One subject with strabismus and one with a refractive error of −6 diopters were not included, but the subjects were otherwise unselected. All of the subjects had an acuity of 6/9 or better, measured (with correction in 3 cases) using a reduced Snellen chart at a viewing distance of 0.4 m. Stereoacuity, as measured on the Titmus test, was better than 40 seconds of arc in all subjects but one, who showed evidence of suppression in the right eye.

[1] Requests for reprints should be sent to Arnold Wilkins, MRC Applied Psychology Unit, 15 Chaucer Road, Cambridge, CB2 2EF, England.

Apparatus and Stimulus Material

Two Mullard C62 monitors using cathode-ray tubes (CRTs) with white P4 phosphors (having a persistence such that the relative luminance was less than 2% in 10 ms) were driven by a Quantum Data 801A video generator so as to produce a field comprising blurred lines of uniform brightness. One CRT had a frame frequency of 50 Hz and the other 100 Hz. The surface of each tube was covered by an opaque matte black mask in the center of which was a rectangular aperture measuring 0.16 m wide and 0.1 m high. Between the aperture and the screen was mounted a photographic negative of a paragraph of text, typewritten in IBM Letter Gothic (a sans serif typeface). The 22 lines of text were spaced 54 min arc apart. Near the center of the block of text two letters were identified as targets: the *c* and the second *e* in "... article on Drente...." At the viewing distance of 0.5 m, these letters were 12 min arc high, 9 wide, and 132 min arc apart.

Light from the phosphor passed through the clear sections of the negative so as to produce a display of white text on an unlit background. Both displays were viewed in a darkened room and had a space- and time-averaged luminance of about 10 cd/m^2 (measured with an S.E.I. spot photometer). Moiré effects produced by parallax between the contours of the letters and the raster lines beneath were observable during movements of the head, but such movements were not possible during the recordings. The disposition of light over the component strokes of the letters depended on the viewing position, which changed from one recording to the next sufficiently to provide only random variation.

Horizontal eye movements were recorded binocularly with a resolution of about 5 min arc using infrared scleral reflection (A.C.S. Applied Research Developments Ltd.). The data were acquired using a 12-bit ADC (Analogic MP6912) triggered by a 100-Hz strobe phase-locked to the AC supply, and they were subsequently analyzed using an IBM Personal Computer.

Procedure

Subjects bit on a horizontal wooden bar to prevent movements of the head. They wore spectacle frames bearing, on the outside, any lenses necessary to comprise their prescription for reading and, on the inside, the infrared emitters and sensors necessary for measurement.

Subjects were instructed to keep their eyes on one of the letter targets until they heard a tone, when they were to move their eyes and look at the other target. No further instructions were given, other than to refrain from blinking and to avoid anticipating the tone. Subjects were not requested to look at any particular part of the target letters.

Trials began with fixation of the left target and comprised four changes of fixation in response to 4 100-ms tones, 4 s apart. Two trials on each display were presented in *ABBA* order, with a random assignation of a display to the *A* position. At the end of the session subjects were asked to select which of the displays they would choose to read from, guessing if necessary.

Data Analysis

Blinks and attempted blinks produced recognizable artifacts, and all such artifacts were removed by inspection of the records prior to analysis. The records in which subjects moved their eyes in anticipation of the signal were rejected, as were the few technically imperfect records. Otherwise, all data contributed to the calibration and subsequent analysis of the recordings, which was carried out automatically by computer. It was assumed that 1.5 s after the tone had sounded, the eye was fixating the new target, and that fixation was maintained for the subsequent 2.5 s until the next tone. Inspection of the records suggested that such assumptions were amply justified. The measured positions of each eye during fixation of the left target were averaged separately, and the differences between these averages and those for the right target were taken as equivalent to the angular separation of the targets. All recorded movements were scaled accordingly. The calibration obtained under the various conditions of illumination was not compared because the illumination could not be changed from one condition to the other quickly enough to be sure that the head position had been maintained on the bar. As it transpired, the stability of fixation under the various conditions was closely comparable.

The saccades were recognized on the basis that the peak velocity of the movement exceeded 8.3 deg/s. The size of the saccade was determined from the difference between the mean of four samples in the period 100 to 50 ms before and the mean of four samples 50 to 100 ms after the point of maximum slope, and only saccades exceeding 10 min of arc in size were accepted. On the basis of the main sequence (Zuber, Stark, and Cook, 1965) nearly all saccades of such an amplitude should have had a peak velocity greater than 8.3 deg/s. The measure of size was based on the final settling point of the eye, and was thus unaffected by brief, transient saccade overshoots. On the rare occasions that two saccades were separated by less than 100 ms, the algorithm recognized only the first. For each of the four fixation periods per trial, the standard deviations of eye position were averaged to provide a measure of fixation stability.

Results

The average size of the "main" saccade following the signal tone was 11% larger for the 50-Hz display than for the 100-Hz display (see Table 1a). The main saccade was defined as the largest saccade occurring in an observation period of one second that began with and included the first saccade after the signal tone. The main saccade was also the first saccade in 89% of the cases. An analysis of variance based on the mean size for the two eyes of the four successive saccades per trial, with frame frequency and order of presentation as factors, yielded a significant effect of frame frequency, $F(1,13) = 5.78$, $p = 0.03$; 14.2% variance explained. The increase in size under the 50-Hz condition approximated the width of one letter of text.

The number of saccades occurring in the observation period was greater for the 50-Hz display, 2.54, than for the 100-Hz display, 2.26; $F(1,13) = 7.51$, $p = 0.02$; 15.2% variance explained. The sum (without respect to sign) of the sizes of all saccades in the 1-s observation period provided a measure of total saccadic excursion: 193 min arc for the 50-Hz display and 170 min arc for the 100-Hz display, $F(1,13) = 8.92$, $p = 0.01$; 18.1% variance explained. In none of the above analyses were there significant effects of practice or interaction terms. The measure of fixation stability averaged 10.0 min arc for the 100-

TABLE 1

Mean Size and Standard Deviation of Main Saccades (min arc)

A. EXPERIMENT 1

Refresh Rate	*Mean*	*S.D.*
50 Hz	154	38
100 Hz	139	36

B. EXPERIMENT 2

	Target Spacing			
Lighting	*Close*		*Wide*	
Frequency	*Mean*	*S.D.*	*Mean*	*S.D.*
100 Hz	102	53	261	49
20 kHz	97	36	253	51

Hz conditions and 11.7 for the 50-Hz condition. The difference was not significant.

The standard deviation of the difference in the position of the left and right eyes (a measure of vergence) for the period 50 to 550 ms following the main saccade was slightly larger under conditions of 50-Hz illumination (1.8 min arc) as compared with 100-Hz illumination (1.2 min arc), although the difference was not significant.

Eleven of the 14 subjects preferred the 100-Hz display without being able to give consistent reasons; only two preferred the 50-Hz display, and one refused to make any judgment.

EXPERIMENT 2

A page of conventionally printed text was illuminated by a fluorescent tube. Under one condition the tube was driven by conventional circuitry so that it provided intermittent illumination at a frequency of 100 Hz. Under a second condition, the same tube was driven by solid-state circuitry at a frequency of 20 kHz, and at such a frequency the light output of the tube was effectively continuous. As in Experiment 1, the subjects' task was to fixate one of two target letters, but in this experiment two pairs of targets were used, one pair closely spaced and the other more widely separated. The task was performed under two levels of illumination, one twice the other.

Subjects

Twelve of the 14 subjects who participated in Experiment 1 took part, together with an additional three women of similar age and with similar visual acuity.

Apparatus and Stimulus Material

A ceiling-mounted fluorescent tube (40-Watt GEC warm white) was positioned so that it was not visible within the periphery of the subject's visual field. Ten centimeters of each end of the tube were permanently masked so as to eliminate low-frequency light from Crooke's dark space. The power of the light output for frequency components above and below 100 Hz was more than 35 dB lower than the power at 100 Hz, with the exception of a component at 200 Hz, which was 16 dB down. The modulation depth was 36% of peak light output. The measurements of the frequency components and modulation depth were made using an optically filtered "eye response" photodiode and were, therefore, a weighted average of the contribution from different spectral components. The (time-averaged) chromaticity coordinates were virtually independent of the frequency of illumination: 0.4327, 0.4113 with conventional circuitry, and 0.4378, 0.4124 with high-frequency circuitry. The central 1 m of the tube was partially covered with a removable mask so as to provide two levels of illumination, one twice the other.

Two pairs of letter targets were used, one pair 94 and the other 257 min arc apart. The closely spaced target letters were the first *e* and the *c* in ". . . interval scale . . ." and the widely spaced targets the first *c* and the second *s* in ". . . applicability of the statistical. . . ." The word sequences were near the center of a page of text (Siegel, 1956, p. 31), and all of the page was visible. The text measured 170 mm high and 108 mm wide. The lettering had an *x* height of 1.5 mm, and the 39 lines were spaced 3.6 mm apart. At the viewing distance of 0.4 m, the target letters were 12.8 min arc high, although the width varied from one character to the next. The text had a space- and time-averaged luminance of 16 or 8 cd/m^2, depending on condition (measured with an S.E.I. spot photometer).

Procedure

The various conditions of target separation, illumination level, and illumination frequency were administered according to a hierarchical *ABBA* design (illumination frequency nested within illumination level, and illumination level within target separation), so that frequency was the variable most often changed, and the target separation least often changed. In this way, practice had the least effect on the comparison of the frequency of illumination, and the subjects experienced each pair of letters in a block, which enabled them to become completely familiar with the targets and their location.

The remaining aspects of data acquisition and analysis were the same as for Experiment 1.

Results

There were no significant effects of practice or of the level of illumination. As can be seen from Table 1b, the size of the main saccade under conditions of intermittent 100-Hz illumination was slightly larger than under steady illumination, although the effect of frequency was significant only for the widely spaced targets, $F(1,14) = 7.17, p = 0.02$; 4.8% variance explained. Analysis of variance was based on the mean saccade size for the two eyes on the four successive saccades in each trial. The increase in saccade size under conditions of intermittent illumination approximated the width of one letter. The increase for the closely spaced targets was not significant, presumably because the variance in calibration contributed to a larger proportion of the variance in saccade size. The number of saccades during the observation period did not differ significantly as a function of illumination frequency. The measure of fixation stability averaged 9 min arc for the 20-kHz condition and 9.8 min arc for the 100 Hz. The difference was not significant.

DISCUSSION

The results of the two experiments complement one another in demonstrating that intermittent light affects ocular motor control at frequencies and modulation depths at which the light appears continuous, regardless of the style or contrast of the text or the illumination of the periphery of the visual field. The effects of intermittency explained only a small proportion of the experimental variance, although the latter included variance due to measurement as well as physiological factors. Inspection of the distribution of saccade size suggested that the increase in size was not due simply to an increase in the number of relatively large saccades. Under conditions of steady illumination, saccades to the widely spaced targets tended to undershoot the target, whereas the smaller saccades to the closely spaced targets did not, a common finding (e.g., Carpenter, 1977, p. 57). There appeared to be large individual differences between subjects as regards the effects of intermittency, but these differences require further study.

Given the number of saccades made during reading and the possibility that corrective saccades may also be enlarged, the effects of intermittent illumination may be sufficient to explain the widely reported finding that reading is slower on visual display units than on conventional printed text (e.g., Wright and Lickorish, 1983). If so, it may be advisable to increase the availability of display units with long-persistence phosphors. The eye movements observed using the present procedure were similar in size to those during reading, but they inevitably differed in many other respects. For example, during reading, the programming of a saccade is determined by cognitive factors at least as much as by visual ones. The present procedure kept cognitive processing to a minimum so that the visual requirements might be better measured.

The disruption of ocular motor control may be connected with the complaints of visual discomfort with which visual display terminals and fluorescent lighting have been associated, particularly in view of the fact that these complaints are related to the depth of modulation of the light output (Laübli, Hünting, and Grandjean, 1980). In Experiment 1, the majority of subjects preferred the high-frequency display without being able to give consistent reasons why they did so.

The records were calibrated on the assumption that the eyes fixated their target in such a way that there was no consistent position bias as a function of illumination frequency. This assumption can be justified on the basis that (1) no consistent drift during fixation was evident from inspection of the recordings, and (2) the standard deviation of eye position was not significantly affected by the illumination frequency. The eyes moved from left to right as often as from right to left, so any artifactual contamination of the eye movement signal should have produced symmetrical effects that may have contributed to the variance but should not have produced a difference in the mean saccade size. When the size increase was large there was an increase in the number of saccades during the observation period, suggesting that as a result of the dysmetric saccades the subjects found it necessary to correct fixation.

West and Boyce (1968) investigated the distribution of the size of microsaccades occurring during fixation under conditions of steady and intermittent light. At frequencies of intermittency above those at which flicker was perceived, the distribution of saccade size was not identical to that for steady light, although West and Boyce do not comment on the statistical significance of the difference apparent from their graphs.

Saccades are sometimes held to be ballistic, or at least preprogrammed, and not subject to feedback control (e.g., Carpenter, 1977). If the present data are interpreted on the basis of current theory it is necessary to assume that high-frequency intermittent illumination had its effect more than 80 ms prior to the flight of the eye (Findlay and Harris, 1984).

Brindley (1962) showed that the beat between visual and electrical stimulation of the retina could be perceived when the frequency of stimulation was as high as 120 Hz and above that at which either form of stimulation would on its own produce a sensation of flicker. Evidently, high-frequency intermittent light is resolved by the human visual system (at least at the level of the retina), and it may give rise to uncharacteristic phase-locked excitation in the lateral geniculate nucleus similar to that observed in the cat by Eysel and Burandt (1984). As Eysel and Burandt point out, all subcortical structures receiving inputs from lateral geniculate neurons via short neural chains should receive phase-locked inputs. Such structures would include the superior colliculus, which is involved in the control of eye movements.

Perhaps there is another level of explanation. When the eye moves from one point of regard to another, the retinal input is "smeared" during the movement. If a display is intermittently illuminated with repeated brief flashes, clear images of the display will occur at different retinal positions while the eye is in motion, and in general the "smear" will be reduced. There are circumstances under which the smear can be used to provide information as to the magnitude of eye movement (Festinger and Holtzman, 1978). It remains a possibility that the brain controls eye movement using visual information acquired both before and during the flight of the eye (Hallett and Lightstone, 1973, as discussed by Howard, 1982, p. 319).

ACKNOWLEDGMENTS

The studies reported herein follow pilot experiments performed in collaboration with John Findlay and Roger Carpenter, who were most generous with their time and with the use of their recording facilities, and whose valuable advice contributed extensively to the subsequent work. Roy Patterson and Peter Stone kindly helped with the measurement of the characteristics of the fluorescent light. Thanks are also due to Kenneth Amore, Michael Barrett, Peter Boyse, Peter Collinge, Michael Gatrell, and Derek Gent for electronic expertise, Ben Craven for an extensive literature search, Derek Simmonds for photography, and Sharon Basham for preparing the manuscript. The work was supported by the Medical Research Council, the Electricity Council Research Centre, and IBM UK Ltd.

REFERENCES

Brindley, G. S. (1962). Beats produced by simultaneous stimulation of the human eye with intermittent light and intermittent or alternating electric current. *Journal of Physiology* (London), *164*, 157-167.

Carpenter, R. H. S. (1977). *Movements of the eyes*. London: Pion.

Eysel, U. T., and Burandt, U. (1984). Fluorescent tube light evokes flicker responses in visual neurons. *Vision Research*, *24*, 943-948.

Festinger, L., and Holtzman, J. D. (1978). Retinal image smear as a source of information about magnitude of eye movement. *Journal of Experimental Psychology: Human Perception and Performance*, *4*, 573-585.

Findlay, J. M., and Harris, L. R. (1984). Small saccades to double-stepped targets moving in two dimentions. In A. G. Gale and F. Johnson (Eds.), *Theoretical and applied aspects of eye movements* (pp. 71-78). Amsterdam: North-Holland.

Hallett, P. E., and Lightstone, A. D. (1973). Corrective saccades and visual inflow during the prior saccade. *Journal of the Optical Society of America*, *63*, 1311.

Howard, I. P. (1982). *Human visual orientation*. Chichester, U.K.: Wiley.

Laübli, T., Hünting, W., and Grandjean, E. (1980). Visual impairments in VDU operators related to environmental conditions. In E. Grandjean and E. Vigliani (Eds.), *Ergonomic aspects of visual display terminals. Proceedings of the international workshop, Milan, March 1980* (pp. 85-94). London: Taylor and Francis.

Siegel, S. (1956). *Nonparametric statistics* (international student ed.) Tokyo: Kogakusha.

Wright, P., and Lickorish, A. (1983). Proof reading texts on screen and paper. *Behaviour and Information Technology*, *2*, 227-235.

Zuber, B. L., Stark, L., and Cook, G. (1965). Microsaccades and the velocity-amplitude relationship for saccadic eye movements. *Science*, *150*, 1459-1460.

West, D. C., and Boyce, P. R. (1968). The effect of flicker on eye movements. *Vision Research*, *8*, 171-192.