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The Effects of Screen Refresh Rate on Editing Operations Using a Computer Mouse Pointing Device

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Two experiments are described in which subjects attempted to locate a specified target word in a short text using a cursor controlled by a computer mouse pointing device. The task was performed at screen refresh rates of 50 Hz, 75 Hz, and 100 Hz. In Experiment 1, both the timing and accuracy of the cursor movement was influenced by screen pulsation. During the early phase of the movement, performance was worse at 100 Hz, whereas in the later, visually guided phase, performance was worse at 50 Hz. In Experiment 2, eye movements were recorded as the task was performed. The results show that the cursor movement is typically preceded by an eye movement and that subjects do not directly inspect the cursor in the early stages of its movement. In the later phase of the movement the cursor is tracked for considerable periods of time. The data suggest that adverse effects of screen pulsation on the control of cursor movement are inherited from penalties incurred during the process of target computation but may also be influenced by concurrent eye movements.

It has recently been established that pulsating illumination has systematic effects on eye movement control during reading. Compared to an appropriate control condition of stable illumination, the extent of the first saccade to enter a word is shorter when text is read under conditions of pulsed illumination. The effect is associated with an increase in the probability of making within-word refixations (Kennedy & Murray, 1991, 1993a). A recent study examining word identification in a task mimicking the dynamics of normal reading under four different refresh rates, from 50 Hz to 125 Hz, suggests that the pulsation-induced reduction in saccade extent increases at least up to 100 Hz (Kennedy & Murray, 1993b). These specific effects on reading performance are consistent with

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other reports of perceptual distortions and interference with eye movement control associated with pulsation from refreshed displays (Neary & Wilkins, 1989). It seems likely that they also relate to the discomfort, headache, and general visual disturbance associated with the use of VDU display terminals (Kennedy, 1993; Rossignol, Morse, Summers, & Pagnoto, 1987; Wilkins, 1991), although the only clearly established adverse effect on *performance* associated with the use of refreshed displays is a speed decrement, comparing reading from a screen with an equivalent hard-copy condition. Even this literature has long been controversial (Oborne & Holton, 1988), but a recent cautious review (Dillon, McKnight, & Richardson, 1988) concludes: " . . . despite methodological weaknesses in many of the investigations, evidence continue(s) to mount supporting the case for a general speed decrement" (p. 458).

As changes in reading speed must relate to changes in the number and/or duration of the reader's eye fixations, the search for mechanisms that might account for adverse effects on reading performance has shifted from necessarily indirect indices of "visual fatigue" to direct studies of eye movement control itself. In this context, an important consideration has been the demonstration of a relationship between the initial point of fixation within a word and the efficiency of lexical access: the so-called Optimal Viewing Position hypothesis (O'Regan, 1989, 1990; O'Regan & Levy-Schoen, 1987). For a word of given length, there is a marked curvilinear relationship between initial landing position and the probability that a word will require more than one fixation for identification (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Pynte, Kennedy, & Murray, 1991; Vitu, O'Regan, & Mittau, 1990). Changes in saccade extent induced by pulsation are likely to reduce the proportion of initial fixations landing at the Optimal Viewing Position. This will, in turn, produce changes in processing time because of an increase in the number of within-word "corrective" saccades. Such a mechanism would be adequate to explain increases in reading time, but it is less clear as an explanation of "visual fatigue". However, as small changes to viewing position (*within* the word) probably index shifts of attention, an association between refixation and discomfort becomes plausible, because attentional resources are limited (Wilkins, 1991). Indirect support for such a view can be gained from studies of reading strategy. Whether or not a deviation from the optimal position triggers re-fixations appears to depend on the reader's tolerance of an inappropriate landing position, with "tolerance" defined either by reference to reading strategy or to the use made of contextual information to reduce the need to fixate (Kennedy, 1993; Vitu, 1991). In other words, the optimal viewing position itself may be considered less as a defined location and more as a zone, whose width may vary as a function of strategic or task demands. For example, Kennedy and Murray (1993a) showed that although screen pulsation induced changes in saccade size in a sample of professional typists, only those subjects characterized as "cautious" readers demonstrated equivalent changes in the probability of making additional within-word saccades. Interestingly, it was professional typists in this category who were most likely to complain of visual discomfort associated with the use of refreshed screens.

Attempts to reduce the adverse effects of refreshed screen displays have tended to focus on the need to reduce *visible* flicker. For example, the Consultative Document issued by the Health and Safety Commission (1992) in the United Kingdom in response to a European Community Directive (Commission of the European Communities, 1990) states that "the image on the screen should be stable, with no flickering or other form of instability". The principal difficulty with this approach is that although the screen refresh rate of most modern displays comfortably exceeds traditional definitions of "critical flicker fusion" (Brown, 1965), this has not led to a reduction in complaints. In fact, it is becoming increasingly evident that pulsation need not be visible for the visual system to be perturbed. A stimulus undergoing rapid pulsation (i.e. any point on a refreshed screen) is spatially stable so long as the eyes do not move. However, during a saccade, such stimulus will not present a continual retinal "smear" but, rather, a series of discrete streaks whose form will depend on a number of factors, including pulsation frequency, saccade velocity, and phosphor decay-rate. Macknick, Fisher, and Bridgeman (1991) consider such a visual configuration in an experiment on the detection, *during a saccade*, of small displacements in a pulsating target. Detection accuracy varied systematically over the range between 33 Hz and 260 Hz with a minimum at some point less than 130 Hz, but greater than 66 Hz (i.e. above fusion). Macknick et al. suggest that pulsation interferes with normal saccadic suppression, implying that " . . . one of the causes of visual complaints associated with prolonged video display terminal use may be a stress on the space constancy mechanism" (p. 2063). That is, because pulsation changes spatial sampling, the viewer may become less confident of the spatial location of a given target (Hershberger, 1987, makes a similar suggestion). Such an account points to a possible *global* effect of screen pulsation on eye movement control, caused by disruption to the process of saccadic suppression. However, certain additional assumptions must be added if this mechanism is to predict the typical outcomes when the task is reading rather than target detection. Breitmeyer (1980, 1991) undertook this task, arguing that perceptual segmentation in reading depends on a form of "transient-on-sustained" inhibition in the visual system (a transient response occurs each time a saccade sweeps across the patterned surface provided by the printed text). This response will be disrupted if saccades are made over text that is undergoing continual pulsation, as the field will be blank (or effectively so) for a proportion of the duration of the saccade. If pulsation acts to disturb the process of normal saccadic suppression, successive fixations will be inadequately segmented; the location of some fixations will be ambiguous; and, from the reader's perspective, the screen image may appear to be globally degraded. A likely response to this assault will be a change in reading strategy, in which smaller saccades compensate for the poorer quality of information available from any given fixation. The proposition that reading pulsating text might be difficult because of disturbance to the transient system is clearly consonant with the observation that subjects with transient system deficits frequently experience reading difficulties (Lovegrove, 1992; Lovegrove, Heddle, & Slaghuis, 1986). Indeed, Lovegrove and his co-workers have suggested that mechanisms underlying transient-on-sustained channel inhibition are not fully operative in 60% of subjects characterized as "reading disabled" and that, as a result, such subjects show poor temporal segregation of fixations and behave as if the spatial location of visual targets was ambiguous.

To summarize, the global effects described so far arise as a result of the influence of pulsation on the eyes as they move. That is, they will adversely affect performance in any task where an observer makes eye movements under conditions of pulsating illumination. Text editing using a VDU screen falls into this category, and the experiments reported here attempt to capture some significant aspects of this skill. The experiments measured the speed and accuracy of the execution of cursor movements made over text under the control of a computer "mouse". We examined the effects of refresh rate variation on performance in this task, which involved both normal reading and careful inspection of the refreshed screen.

We turn now to consider the influences of screen pulsation on performance when the eyes are not moving. We refer to these as *local* effects. If a subject is attempting to maintain steady fixation under conditions of pulsating illumination, saccades may be triggered prematurely by abrupt stimulus onsets or offsets near to the point of fixation. Eye movement control involves the successive "latching" and "unlatching" of attention (Henderson, 1992), and such a process is particularly vulnerable to transient stimulus events. It should be noted that, on the plausible assumption that end-point computation is refined spatially outwards from the current fixation point over time (O'Regan, 1990), such "premature" saccades will also tend to fall short of their intended target. More generally, there is evidence that sustained fixation of the stimulus configuration typical of displayed text (i.e. a high-contrast striped surface with a spatial frequency of about 3 cycles per degree) is highly unacceptable to some subjects. At the extreme, such a patterned surface can induce visual disturbances of various kinds, and these are exacerbated if the stimulus flickers or is viewed under flickering illumination (Wilkins, 1991; Wilkins & Nimmo-Smith, 1984, 1987). What distinguishes these local sources of influence from the global effects defined above is the relative stability of the eye: global effects of pulsation come about because the subject is executing saccadic eye movements over a "flickering" field; local effects occur when the subject attempts to maintain steady fixation in the same circumstances. Cursor movement under the control of directed hand movements with a mouse pointing device provides a promising way of teasing these two processes apart, as the task involves frequent and large saccades, but also steady fixation.

The control processes governing hand movements from one position to another are relatively well understood (Fisk & Goodale, 1985; Fleischer, 1989; Howarth & Beggs, 1985; Sheridan, 1984) and have been plausibly extended to the movements involved when using a mouse to control a cursor (Baccino, 1991). Movements of this kind have two components (Mohrmann-Lendla & Fleisher, 1991): (1) an early phase (sometimes referred to as a "ballistic" phase), during which velocity increases smoothly and rapidly as a previously programmed motor command is executed, resulting in a fast movement in a given direction; and (2) a positioning phase, characterized by a rapid deceleration, during which visual feedback plays an increasingly important role. Thus, the effects of changes in refresh rate on cursor control can be assessed on two phases of a task involving text editing: (1) on the accuracy or stability of the specified target on the initial hand movement, *following* inspection of the text; and (2) on the accuracy and timing of fine positioning movements under direct visual guidance.

The task simulated a common editing operation. Subjects read four lines of text, located near the top of a display screen, and were then asked to "click" a mouse button to expose a target word at the foot of the screen. An area of blank screen separated text and target, and subjects moved the mouse as rapidly as possible to "capture" the defined word in the text by locating its exact centre with the cursor and then clicking on it. The two phases of this task tap differentially into the global and local processes as defined.

(1) The overall accuracy of the cursor trajectory will depend on the computation of target position during prior inspection of the text. That is, the accuracy of the smooth ballistic movement of the cursor towards the target can be used as an index of the quality of the visual information specifying the target. (2) In the final ("visually guided") phase of the movement, when subjects must maintain steady fixation on or near the target position, the accuracy and timing of cursor movements will reflect local influences.

A linguistic variable was used to manipulate the degree of spatial uncertainty associated with the target. Different experimental texts contained two different nouns that either were or were not co-referential. If two spatially separated text items co-refer, subjects are uncertain in a later detection task as to precisely *where* in the text a particular target (e.g. one of two co-referential nouns) was displayed (Baccino, 1991).

The task made use of materials of the following form (the key nouns were not presented in italic type in the task itself):

The smart shop was always open late
In the window a *diamond* sparkled
Cecile asked to see *the/a jewel*
It was brought for her inspection

Target: *diamond/jewel*

Text fragments of this kind have been extensively studied by Baccino and co-workers (Baccino, 1991; Baccino & Pynte, 1994; Baccino, Pynte & Kennedy, 1990). It will be noted that there is a subordinate/superordinate relationship between the indicated nouns in the second and third lines. In different versions of the texts, the superordinate was preceded by a definite or indefinite article. The definite article has the effect of establishing an anaphoric relationship between the two nouns: that is, from the reader's perspective, the second noun (*jewel*) is taken to be co-referential with the first (*diamond*). In contrast, the indefinite article triggers no such link, and the reader is invited to see the second noun as establishing a new discourse topic (Stenning, 1978). Materials like this are of particular interest in the present context, as the presence or absence of a co-referential link directly influences the ease with which a spatial representation of the target can be established. Presented with the word *diamond* or *jewel* as a target in the definite article case, readers are slower and less accurate in identifying where the word is located (Baccino & Pynte, 1994). The explanation for this is fairly evident: if the second noun is introduced with the definite article, it may act to invoke its anaphor at the time of reading (i.e. when a different text location is being inspected). In consequence, when a particular target is presented, subjects are less certain as to its precise location.[1] Investigation of these psycholinguistic effects was not the main objective of the study: however, manipulation of a variable likely to modulate "spatial uncertainty" also fulfilled a methodological

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[1] This is an over-simplification of the situation. In particular, the mechanism through which anaphors might act to "reactivate" their antecedents is controversial (Sag & Hankamer, 1984; Tanenhaus & Carlson, 1990). However, this linguistic debate is not directly relevant to the present experiment if the minimal assumption is accepted that the use of the definite article is likely to increase spatial uncertainty in a later detection task.

purpose as a means of deflecting or defeating objections that might be raised against a pattern of results that showed only main effects of pulsation.

Two primary hypotheses were tested: (1) following previous studies of eye movement control in subjects reading pulsating text (Kennedy, 1993; Kennedy & Murray, 1991), it was predicted that there would be an effect of refresh rate variation in mouse control, with a *decrement* in performance over the frequency range employed (50 Hz to 100 Hz). This prediction rests on the assumption that the early phase of a pointing movement, such as that used to control the mouse, is invariably preceded by a saccadic eye movement to the target (Mohrmann-Lendla & Fleisher, 1991). Effects of refresh rate on the timing and/or accuracy of movements of the mouse must ultimately reflect disturbance to a *prior* process of spatial computation (Kennedy, 1992), the outcome of a pattern of eye movements made over the text as a whole. (2) It was predicted that pulsation would influence later phases of the movement, while the subject is engaged in directly monitoring cursor position. On the balance of the evidence it is likely that low-frequency pulsation (or flicker) in this situation will exert an adverse effect. The experiments also tested subsidiary hypotheses relating to the manipulation of the type of article: (3a) spatial uncertainty, as reflected in the mouse trajectory, should be greater in texts containing the definite article; (3b) this effect should interact with the screen refresh rate, acting to amplify adverse effects of pulsation on the derivation of a spatially coded target position.

EXPERIMENT 1

Method

Subjects. Twenty-four subjects participated in the experiment. They were student volunteers, paid £4.00 for their services. All were native English speakers, were right-handed, and had normal or corrected-to-normal vision.

Design. The 30 experimental items were treated as three sets of ten and assigned to the different refresh rates such that, over the complete design, each set was presented at all three rates. The 24 subjects were divided into three groups of eight, each receiving all experimental items and all three conditions of refresh rate, but in different orders of presentation determined by a Latin square. Twelve filler texts were distributed evenly over the three sets. Allocation of different sets of five of the texts from each group of ten to either the definite or indefinite article was counterbalanced between sub-groups of subjects. To increase power in the design, the whole experiment (apart from the practice materials) was run twice for each subject, with only the order of presentation of the materials changing between trials. The design thus had two dummy between-subjects factors: order of presentation of refresh rate and allocation of texts to article. The principal experimental variables were all within-subjects: trial (1 vs. 2); refresh rate (50, 75 and 100 Hz); and article (indefinite vs. definite).

Materials and Procedure. Thirty sets of four-line texts of the form described in the Introduction were constructed. Target nouns were randomly selected to be either superordinates or subordinates, and position of the targets within a line varied. The filler texts were constructed with an arbitrarily chosen noun, located on one of the four lines, defined as the target. There were also three practice sets. The materials were presented on a Manitron display (using a monochrome P4 phosphor) interfaced to a Control System Artist 1 graphics card mounted in a 386AT computer. Refresh rate of the display was controlled by writing specified parameter values to the graphics controller card. Three rates were achieved in this way: 50 Hz, 75 Hz, and 100 Hz. It is important to note that the horizontal and vertical resolution of the visible part of the screen (i.e. 1024 × 465 pixels) was identical under all conditions of refresh rate, as were all other physical parameters (e.g. horizontal and vertical blanking times). All that differed between conditions was the rate at which this effective "frame" was written to the screen: variation in refresh rate produced no changes in the size or shape of the displayed characters.[2] Standard "Artist" graphics routines were used to access mouse movement and cursor position. The cursor took the form of a 16 × 16-pixel cross-hair. During the course of the experiment, mouse position was sampled every 10 msec and stored for later analysis. Text was presented in positive polarity (i.e. black characters on a white background), with the display screen masked off to the size of the area visible in the 100-Hz condition (340 mm horizontal × 154 mm vertical). At the viewing distance of 525 mm, 3.5 characters subtended 1° of visual angle. Luminance of the background was 54.3 cd/m^2 and of the characters, 0.1 cd/m^2. Refresh rate settings were verified by means of direct recordings at the screen surface using a photocell and oscilloscope. Brightness was adjusted during the experiment to achieve an equal luminance display at each refresh rate. The adjustment was by means of ten-turn potentiometers to settings previously verified using an SEI spot photometer. The experiment was carried out in low-level DC background illumination (approximately 0.3 cd/m^2).

At the beginning of each trial, the text appeared in a box (the "text box"), 173 mm × 31 mm, horizontally centred on the screen, 2 mm from the top of the visible region (see Fig. 1). Initially, each letter was replaced by the letter *x*. At this stage, no mouse cursor was visible. Subjects clicked the mouse button with the right hand to display successive lines of text. The click following the fourth and final line led to the appearance of a small box (the "target box"), 31 mm × 19 mm, centred 16 mm from the bottom of the visible region of the screen. The vertical distance from the top of the target box to the line defining the bottom of the text box was 86 mm. Simultaneously with the display of the target box, a cross-hair cursor appeared on the screen. The target box was divided by a horizontal line into two equal parts, and the subject was asked to use the mouse to locate the cursor in the upper part and then click the mouse button. This produced a target word, centred in the lower part of the box. (The separation of cursor and target in this way ensured that the target could not be partly masked by the cursor.) Subjects were instructed to read the target word and then move the mouse as quickly as possible to position the cursor on the identified word in the text displayed in the upper part of the screen. It was emphasized that the task called for accurate location, with the cursor positioned on the *exact* centre of the word (i.e. in the case of even-length words, on the space between two letters or, for odd-length words, on the centre letter itself). A click at this point produced a signal tone from the computer and allowed the next trial to appear. Subjects were asked to continue trying to click on the exact centre if their first attempt failed to capture the target. At appropriate points, subjects were allowed a rest period while the display refresh rate was changed and the brightness adjusted. Subjects were not told that refresh rate was being manipulated, and this would not have been evident from casual observation.

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[2] A referee has asked for reassurance that this was, in fact, the case. Long-exposure (4 sec in positive polarity and 15 sec in negative polarity) high-definition photographs were taken of the display at the three different refresh rates. These were presented to five judges in a forced-choice discrimination. All judges performed at chance and all pointed out that the stimuli appeared identical.

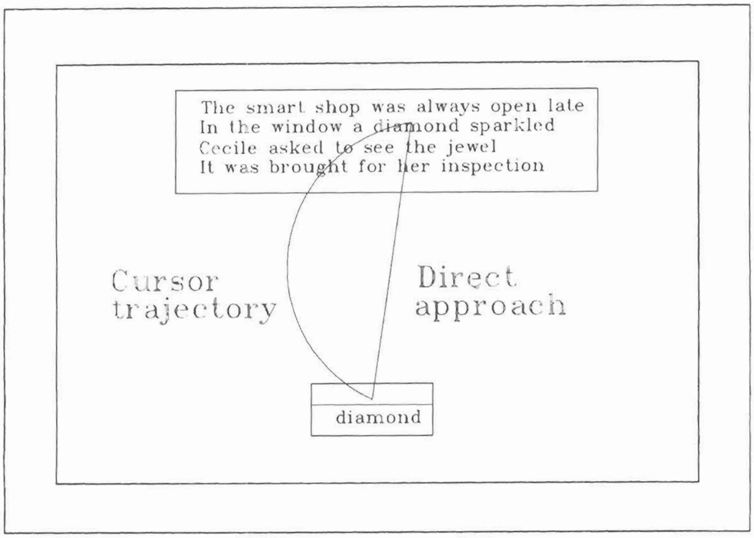

FIG. 1. A schematic diagram (not to scale) showing key elements of the display.

Results and Discussion

Movement Times. Measurements were made of the time taken to traverse four zones (medians computed over the five texts in each sub-condition for each subject): (1) from target onset to the exit of the target box; (2) from the target box exit, across the (blank) screen, to the lower boundary of the text box; (3) from the text box boundary to the point of intersection with the line of text containing the defined target; and (4) from the intersection of the target line to the point at which the target was "captured". As an overall analysis of variance (ANOVA) showed a significant high-order Zone × Refresh Rate × Article interaction, $F(6, 108) = 4.94$, $p < 0.001$, separate analyses were carried out on the data for each zone. There was no significant effect of refresh rate, and no interactions involving this factor, in analyses of the time to exit the target box (50 Hz: $M = 526$ msec; 75 Hz: $M = 537$ msec; 100 Hz: $M = 543$ msec) and of the time to traverse the screen to the text box boundary (50 Hz: $M = 823$ msec; 75 Hz: $M = 818$ msec; 100 Hz: $M = 872$ msec). The time taken to traverse the text to the intersection of the target line showed a significant effect of refresh rate, with increasing times as a function of refresh rate (50 Hz: $M = 341$ msec; 75 Hz: $M = 391$ msec; 100 Hz: $M = 479$ msec), $F(2, 36) = 4.68$, $p = 0.015$. Follow-up analyses using the Newman-Keuls procedure showed two significant contrasts: 50 Hz versus 100 Hz, $p < 0.01$, and 75 Hz versus 100 Hz, $p < 0.05$. In contrast, the analysis of the time taken to capture the target showed a tendency for longer times at 50 Hz, although the overall effect of refresh rate failed to achieve significance (50 Hz: $M = 2401$ msec; 75 Hz: $M = 2110$; 100 Hz: $M = 2008$ msec), $F(2, 36) = 2.12$, $p = 0.12$. The outcome appears to reflect a difficulty synchronizing eye and cursor when the rate at which the screen is updated is slow relative to the time to sample mouse position. Indirect support for this interpretation can be found in an analysis of the number of clicks necessary to capture the target. These data (50 Hz: $M = 1.64$; 75 Hz: $M = 1.47$; 100 Hz: $M = 1.50$) show a significant effect of refresh rate, $F(2, 36) = 5.01$, $p = 0.017$, with the adverse effect restricted to the lowest refresh rate. Post-hoc Newman-Keuls tests showed that more clicks were required at 50 Hz than at either of the other two frequencies, $p < 0.05$.

In summary, the results show no detectable change in timing attributable to screen pulsation as the cursor was moved across the blank (pulsating) screen. This is consistent with the presumption that subjects did not actually inspect the cursor as it moved towards the target. Hypothesis 1, concerning the stability and accuracy of the representation of the final target, makes reference to "performance", but it is clear that, in fact, no prediction regarding the *time* to execute the movement can be made. The speed with which the cursor approaches a particular target (under the control of a ballistic movement) will be unaffected by whether or not the target position has been accurately specified. However, once the cursor is in the vicinity of the target, screen pulsation clearly does exert an effect on timing, as cursor control at this point is sensitive to disturbance to concurrent eye movements. The form of the relationship in the data confirms Hypothesis 1, with a decrement in performance associated with higher refresh rates, and parallels results of direct eye movement measurement which also show performance decrements at pulsation frequencies well above fusion (Kennedy & Murray, 1991, 1993b). Thus, although it may be possible to consider the difficulty in locating the target centre as a "flicker" effect (i.e. it is manifest at the relatively low frequency of 50 Hz), the more general adverse effects, at relatively high refresh rates, appear to be mediated by mechanisms unrelated to *perceived* flicker (Kennedy, 1993).

Trajectory Dispersion. The question of the accuracy of the spatial code derived prior to mouse movement was assessed by examining the deviation of the obtained trajectory from the best line of approach. Trajectory dispersion was defined as the area between a hypothetical straight line from the initial point of departure of the mouse to the target centre and the trajectory itself. The final approach to the target was often quite variable and reflected idiosyncrasies of movement (for example, loops or curves extending above the text box). For this reason, the measure of dispersion was derived only up to the point at which the trajectory crossed the text box boundary (extended, if necessary, by imaginary lines to the screen border). An ANOVA showed a significant difference in area between Trial 1 (14,737 square pixels) and Trial 2 (12,308 square pixels), $F(1, 18) = 7.09$, $p = 0.015$, reflecting an overall improvement in accuracy over the two trials. Trajectory dispersion was greater for targets specified in the definite article case (definite: $M = 14{,}356$ square pixels; indefinite: $M = 12{,}689$ square pixels), $F(1, 18) = 9.46$, $p = 0.007$. This confirms Hypothesis 3(a), which predicted greater spatial uncertainty associated with the definite article (Baccino, 1991). It will be recalled that Hypothesis 3(b) also predicted that the spatial uncertainty associated with the definite article should be amplified by variation in screen refresh rate. The data confirm this, with a significant Article × Refresh Rate interaction, $F(2, 36) = 3.20$, $p = 0.05$. There was no effect of refresh rate for the indefinite article case (50 Hz: $M = 12{,}665$; 75 Hz: $M = 12{,}891$; 100 Hz: $M = 12{,}421$ square pixels), $F < 1$, but a highly significant effect in the case of the definite article (50 Hz: $M = 12{,}852$; 75 Hz: $M = 14{,}026$; 100 Hz: $M = 16{,}192$

square pixels), $F(2, 36) = 5.68$, $p = 0.007$. The form of the relationship is greater error at higher refresh rates, with post-hoc Newman-Keuls tests showing significant contrasts between 50 Hz versus 100 Hz, $p < 0.01$, and 75 Hz versus 100 Hz, $p < 0.05$. It should be kept in mind that these data reflect the stability of target co-ordinates derived from *prior* inspection of the text (Preblanc, Echallier, Komilis, & Jeannerod, 1979); they are highly unlikely to reflect concurrent eye movements. We may conclude that a global decrement in accuracy is "inherited" from adverse effects of high-frequency screen pulsation on eye-movement control.

The experiment permits at least one conclusion of some practical significance to be drawn; screen pulsation affects both the timing and accuracy of cursor control. This outcome is of interest because, at least in part, the effects appear to be unrelated to perceived flicker. Performance in some phases of the controlled cursor movement was significantly worse at higher refresh rates. However, this interpretation rests on an assumed parallel between directed hand movements and the movements made to control a screen cursor. In particular, it has been assumed that the initial phase of the aimed hand movement is effectively ballistic (Mohrmann-Lendla & Fleischer, 1991) and not subject to on-line correction. One indirect check on this is to examine the form of the velocity function of the cursor movement over the screen (Fig. 2). The trajectory cannot be described as typical of a ballistic movement. It is, rather, a series of "pulses", or sub-movements, superimposed on phases of acceleration and deceleration. This is potentially embarrassing for the central argument, as it fails to rule out the possibility that direct observation (or even tracking) of the cursor might take place as it is moved. Were that the case, of course, the obtained performance decrements may relate *not* to global inaccuracy in target specification, induced by the prior execution of saccades over the pulsating text, but to *direct* effects of screen pulsation in some way influencing the accuracy with which a cursor can be tracked. In practical terms such an outcome would remain of interest, but it is clearly important to discover which of the two possible explanations is correct. This can

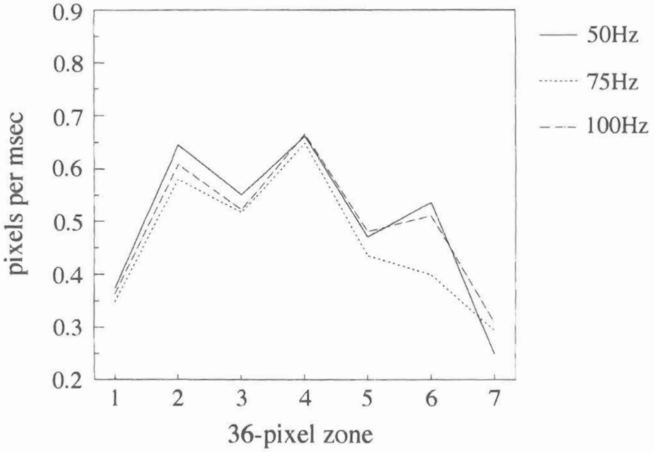

FIG. 2. Velocity profile of the mouse movement (Experiment 1) over seven 36-pixel zones. Each zone subtended approximately 1.3° of visual angle.

only be achieved by examining the interacting dynamics of mouse movement and eye movement control. Experiment 2 set out to do this.

EXPERIMENT 2

Method

Subjects. The subjects were 24 students volunteers, paid £4.00 for their services. All were native English speakers, were right-handed, and had normal vision (i.e. could read without optical correction). None of the subjects had participated in Experiment 1.

Design. Eye movement measurement (particularly in two dimensions) involves time-consuming calibration procedures, and it was necessary to simplify the experiment design to accommodate these. The factor of trial was removed—subjects read each text once only. As a compensation for the loss of power in the analysis of the refresh rate factor (i.e. doubling the number of texts per refresh rate), type of article was treated as a between-subjects factor. As in Experiment 1, order of presentation of refresh rate was a dummy between-subjects factor.

Materials and Procedure. The 30 sets of experimental items were treated as three sets of 10 and assigned to the different refresh rates as in Experiment 1. The 24 subjects were divided into three groups of eight, each receiving all experimental items and all three conditions of refresh rate, but in different orders of presentation, determined by a Latin Square.

As far as possible, the experimental procedure was identical to that used in Experiment 1. Subjects' eye movements were recorded (from the right eye) using a Dr Bouis pupil-centre computation Oculometer interfaced to a 12-bit A-D device sampling X and Y position every 10 msec. The Oculometer had a resolution of better than 0.25° over the calibrated range. A dental wax bite bar and chin rest were used to minimize head movements. This procedure (which was necessary to achieve stable calibration) made direct inspection of the hand and mouse impossible.

Prior to presentation of each experimental item, the eye-movement recording device was calibrated. This involved subjects fixating in turn on a series of letters displayed as a 3×3 matrix on the screen, which was otherwise blank. The top row was coincident with the position of the top line of the text box; the bottom row was coincident with the position of the bottom line of the target box; a third row was centred beween these. Each row spanned the horizontal extent of the screen. X–Y eye position was recorded for each experimental item from the time at which the target word was displayed until the subject located (i.e. clicked) the exact centre of the defined word in the text box. Eye movement data were normalized prior to analysis using the algorithm described by Mason (1976) and software based on an implementation by Kliegl (Kliegl, 1981; Kliegl & Olson, 1981). This rescaled the eye-movement data to the same co-ordinate system as the cursor position record. Dynamic plots of eye and cursor position in real time were examined to verify the accuracy and stability of the rescaled data. Even allowing for the relatively slow sampling rate, the eye-movement record was stable enough to allow for sensible comparisons of the timing and accuracy of mouse and eye trajectories in critical phases of the task.

Results and Discussion

Mouse Movement Times. An ANOVA carried out on the median times to traverse the four zones defined in Experiment 1 showed a similar Zone × Refresh Rate interaction, $F(6, 108) = 4.79, p = 0.004$. Separate analyses were carried out on the data for each zone.

There were no effects of refresh rate and article, and no interactions involving these factors, in analyses of the time to exit the target box (50 Hz: M = 597 msec; 75 Hz: M = 593 msec; 100 Hz: M = 564 msec) and of the total time to traverse the screen (50 Hz: M = 551 msec; 75 Hz: M = 580 msec; 100 Hz: M = 567 msec). As in Experiment 1, the analysis of the time to traverse the text to the target line showed a tendency for longer times associated with higher refresh rates (50 Hz: M = 174 msec; 75 Hz: M = 172 msec; 100 Hz: M = 289 msec), but this failed to achieve significance,[3] $F(2, 36) = 2.12$, $p = 0.13$. It will be noted that these times are in general considerably faster than the equivalent times in Experiment 1, a point that will be taken up later. There was a significant effect of refresh rate in the time to capture the target, $F(2, 36) = 5.56$, $p = 0.008$, with a pattern of means very similar to that found in Experiment 1 (50 Hz: M = 2153 msec; 75 Hz: M = 1777 msec; 100 Hz: M = 1946 msec). Again, these data can be related to the actual number of clicks-to-capture (50 Hz: M = 1.31; 75 Hz: M = 1.15; 100 Hz: M = 1.23), $F(2, 36) = 3.60$, $p = 0.034$.

Trajectory Dispersion. Analysis of the trajectory dispersion data (medians computed over sets of 10 texts) showed an overall effect of refresh rate (50 Hz: M = 16,419; 75 Hz: M = 13,659; 100 Hz: M = 16,324 square pixels), $F(2, 36) = 3.54$, $p = 0.038$. The apparent curvilinearity in the data is intriguing, but may be no more than a reflection of random variation in rather noisy data, given that post-hoc Newman-Keuls tests showed that the contrast between 75 Hz and 100 Hz was significant, $p < 0.05$, but that between 50 Hz and 75 Hz, albeit with a greater difference between the median values, only marginally so, $p = 0.07$. Although, the effect of refresh rate appeared to differ for the two articles, statistical analysis failed to support this: definite article (50 Hz: M = 18,451; 75 Hz: M = 13,733; 100 Hz: M = 16,762 square pixels), $F(2, 32) = 2.78$, $p > 0.05$; indefinite article (50 Hz: M = 14,385; 75 Hz: M = 13,584; 100 Hz: M =15,886 square pixels), $F(2, 36) = 1.91$, $p > 0.05$.

Summary of Mouse Movement Control. Several aspects of the results demand comment. The results confirm Hypothesis 2, predicting an adverse effect of low-frequency pulsation in the final phase of the task where fine positioning is demanded. Hypothesis 1, predicting poorer performance at higher refresh rates in the earlier phase of the task, fares rather less well with regard to cursor timing, with a non-significant tendency for longer times at 100 Hz as the cursor approaches the target (but see Footnote 3). However, this hypothesis is supported in the measure of trajectory accuracy. An unexpected outcome serves to complicate the picture. There is a substantial difference in overall speed in the two experiments. Figure 3 shows the velocity function for Experiment 2. It has the same irregular form, but with a peak velocity some 0.2 pixels per msec faster than in Experiment 1. It is possible that the experimental procedures associated with eye movement measurement changed subjects' strategy, leading to a greater emphasis on speed. The fact that trajectory dispersion was somewhat higher overall is consistent with this view. This complicates comparisons between the two Experiments. If it is assumed that the cursor is only moved towards the target at some point after the eyes have begun

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[3] There was, in fact, a significant effect of refresh rate as the cursor approached the text box boundary across the final 32 pixels (50 Hz = 92 msec; 75 Hz = 117 msec; 100 Hz = 123 msec, $F(2, 32) = 3.55$, $p = 0.038$).

to inspect items in the text box, the precise timing of the movement may be critical and may be reflected in the (non-significant) curvilinearity in the relationship between refresh trajectory dispersion. Two extreme possibilities can be considered. If the cursor is left immobile until the specification of its target position is fully computed, timing and accuracy of the subsequent movement should reflect only the outcome of a process of prior inspection. But if the delay is short, the mouse movement may actually be initiated while the text is still being inspected. Performance in this case may reflect the accuracy of the specified target location and, in addition, any adverse effects of pulsation on *concurrent* eye movements, either on the displayed text or even on the cursor itself. To pursue this further, more data are needed on the timing of eye and mouse movements, respectively, and this is taken up in the following Section.

Inspection Times (Eye Movements). The size of the displayed text relative to the calibrated area ruled out an analysis of text processing in terms of the usual measures of fixation location and duration. However, the rescaled scan-paths readily allowed four key issues to be addressed: (1) the precise position of the eyes at the point in time when the cursor was moved from the target box and the temporal lag between these events; (2) the total time during which the cursor was directly inspected as it was moved across the screen surface; (3) the degree to which the obtained decrements in performance at high refresh rates echoed similar effects on eye movement control over the relevant region of text (i.e. in the vicinity of the target line); (4) the relationship between the time spent in actual inspection of the cursor in the text box and variations in refresh rate.

With regard to Question 1, the cursor left the target box on average 585 msec after the target word was displayed. Measurement of the eye trajectory showed that the eyes crossed the text box boundary 238 msec after target display and crossed the target line 199 msec later. Thus, on average, the eyes began inspection of the displayed text before the mouse movement was initiated. The obtained lag of approximately 350 msec is consistent

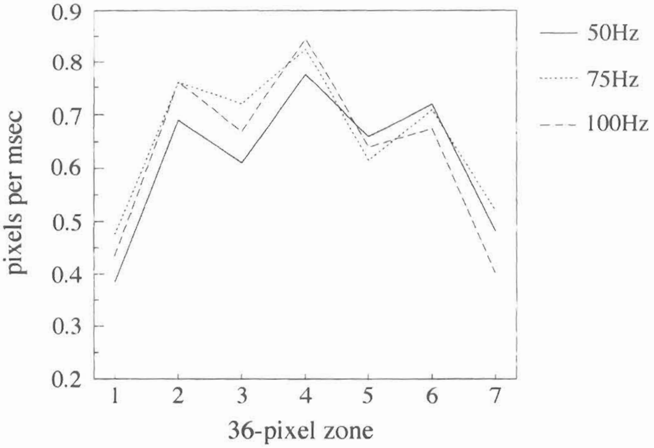

FIG. 3. Velocity profile of the mouse movement (Experiment 2) over seven 36-pixel zones. Each zone subtended approximately 1.3° of visual angle.

with observations of "aimed hand movements" in general (Mohrmann-Lendla & Fleischer, 1991) and illustrates that the mouse is moved after one, or possibly two, prior fixations of the text. (These represent, of course, a second inspection, as the target appears after the text as a whole has been read.) This may have been sufficient reinspection to code target position, on the assumption that subjects retained in memory a specification of potential target location following the initial reading. However, the possibility that revision of the cursor trajectory took place as the text was inspected is left open.

To deal with Question 2, the question as to whether direct fixation of the cursor took place as it was moved across the screen, a count was made, for each 10-msec epoch, of those occasions when the eyes were within ±0.6° of visual angle of the displayed cursor (this was equivalent to 16 pixels and was chosen to provide reasonable compensation for calibration errors). The measure was made between the boundaries of target and text boxes. Converting this to a measure of time yielded a mean of 7.9 msec, confirming that virtually *no* fixations of this kind took place (there was no hint of an effect of refresh rate in the data: 50 Hz: $M = 8.6$ msec; 75 Hz: $M = 8.9$ msec; 100 Hz: $M = 6.3$ msec, $F < 1$).

The 10-msec sampling rate made it difficult to deal with Question 3 by computing velocity functions for the eye movement data. Instead, a parallel analysis to that carried out on the cursor movement was performed, using as data the times for the eyes to traverse the four defined zones. This revealed a significant Refresh Rate × Zone interaction, $F(6, 108) = 5.19, p < 0.001$. (There was no effect of article or interaction involving that factor.) Times did not vary in the first two zones, but the time to cross the text to the target line showed a significant effect of refresh rate (50 Hz: $M = 151$ msec; 75 Hz: $M = 170$ msec; 100 Hz: = 270 msec), $F(2, 36) = 3.13, p = 0.05$. Post-hoc Newman-Keuls tests showed a significant contrast between 50 Hz and 100 Hz, $p < 0.05$. These data provide the necessary confirmation of adverse pulsation effects on eye movement control, with poorer performance at higher rates. (It should be emphasized that these times are median "transit times", *not* fixation durations.)

Question 4 was approached by deriving a measure of the total time that eye and cursor position were within 16 pixels of each other within the text box. There was a highly significant effect of refresh rate (50 Hz: $M = 825$ msec; 75 Hz: $M = 669$ msec; 100 Hz: $M = 463$ msec), $F(2, 36) = 7.67, p = 0.002$, with much longer inspection of the cursor at 50 Hz than at the other two rates, $p < 0.05$. These data are, of course, a reflection of the difficulty subject encountered in locating the target centre under conditions of relatively low-frequency pulsation. However the remaining time spent within the text box, when subjects were *not* actually inspecting the cursor, shows a clear tendency for longer inspection at higher refresh rates (50 Hz: $M = 1278$ msec; 75 Hz: $M = 1108$ msec; 100 Hz: $M = 1434$ msec), $F(1, 36) = 3.62$ $p = 0.036$. Post-hoc Newman-Keuls tests reveal a significant increase at 100 Hz compared to 75 Hz, $p < 0.01$. The two other contrasts were not significant.

GENERAL DISCUSSION

Variation in screen refresh rate has quite different effects on performance in two phases of this task. Typically, on presentation of the target, subjects leave the cursor immobile in the target box and execute a large saccade, or two saccades, to bring the eyes into the vicinity of the target line in the text box. After one, or at most two, fixations on the presented text, the cursor approaches the text box in a series of "pulsed" movements. As the cursor continues its approach, concurrent eye movements scan the text to locate the target word. The cursor itself is very rarely directly inspected as it is moved. Its trajectory is influenced both by a degree of inaccuracy in target specification resulting from pulsation effects on eye movements during prior inspection and by similar effects taking place concurrently as the text is inspected a second time. The form of the effect is broadly in line with previous studies showing disruption at relatively high refresh rates. Direct measurements of eye movements in the vicinity of the text and the "residual" measures of inspection time show a pattern of disruption that is echoed in similar patterns of disruption on both the timing and accuracy of the cursor movement.

In contrast to the apparent de-coupling of eye and cursor during the initial phases of the movement, inspection of real-time plots of eye and cursor trajectories and the data reported here confirm the obvious conclusion that to perform the final phase of the task, subjects directly inspect the cursor. At this point, performance is quite markedly worse at the relatively low refresh rate of 50 Hz. In summary, rapid movements of the eyes across a pulsating surface appear to lead to a global degradation in performance, which increases at higher refresh rates and is unrelated to perceived flicker. A likely explanation of this is the spatial instability brought about by the specific effects of pulsed illumination on retinal "smear". To understand why these should differ for high- and low-frequency pulsation, it is necessary to note the nature of the eye movements engaged in the two phases of the task. In the early phase, subjects engaged in the pattern of fixations and saccades that are characteristic of normal reading. In the later, "visually guided" phase, the eyes were fixed or moved very little. In normal reading a continual re-mapping process must take place, allowing successive fixations to be "glued" into a common stable frame (Crawford & Muller, 1992; Kennedy, 1992), and high-frequency pulsation appears to disrupt this process, as is apparent in the present data showing marked decrements in spatial accuracy as a function of refresh rate as the cursor is moved towards its target. In the final phase of the task, when the eyes are still (or making only very small movements), no such re-mapping is called for. In this case, synchronization of eye and cursor position is critically influenced by low-frequency pulsation. A complete explanation of this is, as yet, unavailable, but at least two possibilities are available for further exploration. Fixating a flickering target is particularly unpleasant (Wilkins, 1985, 1991), and this may influence performance directly. Some support for this idea can be found from observations of the real-time plots of eye and cursor trajectories, which suggest that eye movements in the vicinity of the cursor were, at times, contaminated by small artifacts that normally arise when the subject frowns. Alternatively, the time to re-write the screen (i.e. the displayed text and the cursor) relative to the rate at which mouse position is sampled may make fine positioning in low-frequency pulsation particularly difficult.

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