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Flicker of video display terminals (VDTs) has several consequences for visual function: space perception is distorted, and reading is slowed. We first tested the hypothesis that the flicker of VDTs interferes with visual space constancy, the perception that the world remains in the same place despite eye movements. Space constancy was probed by moving targets during eye movements, and noting a difference in movement threshold that depended upon whether a target jumped in the same direction as the eye or the opposite direction. Flicker rates up to 260 Hz distorted perception in a direction that implies breakdown of space constancy. Another experiment investigated the roles of color and luminance mechanisms in space constancy. The conclusion was that perception is actively suppressed during eye movements. The suppression depends on channels in the visual system that are insensitive to chromatic differences. Reading with 60 Hz flicker was 3.05% slower than with 500 Hz flicker. The result is consistent with a hypothesis that under flicker the eye 'parks' following an eye movement, until a new sample of text appears. Processing then proceeds in the usual way. The results allow quantitative predictions of reading speed at any flicker rate.

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SPACE CONSTANCY ON VIDEO DISPLAY TERMINALS

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28 April 1994

Final Report

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Summary

Flicker of video display terminals (VDTs) has several consequences for visual function: space perception is distorted, and reading is slowed. We first tested the hypothesis that the flicker of VDTs interferes with visual space constancy, the perception that the world remains in the same place despite eye movements. Space constancy was probed by moving targets during eye movements, and noting a difference in movement threshold that depended upon whether a target jumped in the same direction as the eye or the opposite direction. Flicker rates up to 260 Hz distorted perception in a direction that implies breakdown of space constancy. Another experiment investigated the roles of color and luminance mechanisms in space constancy. The conclusion was that perception is actively suppressed during eye movements. The suppression depends on channels in the visual system that are insensitive to chromatic differences.

Reading with 60 Hz flicker was 3.05% slower than with 500 Hz flicker. The result is consistent with a hypothesis that under flicker the eye 'parks' following an eye movement, until a new sample of text appears. Processing then proceeds in the usual way. The results allow quantitative predictions of reading speed at any flicker rate.

Based on these results, we recommend a 120 Hz minimum refresh rate for VDTs.

Space Constancy

Introduction

During the project's first year, we tested the hypothesis that the flicker of video display terminals interferes with visual space constancy, the perception that the world remains in the same place despite rapid exploratory eye movements. Space constancy was probed by moving targets during eye movements, and noting a difference in movement threshold that depended upon whether a target jumped in the same direction as the eye or the opposite direction. Flicker rates up to 260 Hz distorted spatial perception, with larger distortions at the slower rates, in a direction that implies breakdown of space constancy. A second experiment investigated the roles of color versus luminance processing systems in the processing of position during eye movements, at 70 Hz flicker. "Chromatic" targets were defined only by their color contrast, with the luminance of target and background always remaining the same. Thresholds for detection of target movement during eye movements were raised only for luminance targets; there was no direction-specific suppression of the detectability of target movement for chromatic targets. This implies that suppression of movement detection during eye movements is an active process that depends on channels in the visual system that are insensitive to chromatic differences. The goal of this project was to measure quantitatively the effects of temporal sampling (flicker) on space constancy, in preparation for later planned work aimed at ameliorating those effects. Flicker, interpreted as temporal sampling of a visual image, implies that at a given instant in time, perception relies not on presently available information but rather on visual persistence from the previously flashed sample. When the eye is moving relative to the image, this delay results in reduction of retinal smear and in spatial distortion.

Method

Effects of flicker on space constancy were measured by moving a flickering target during rapid (saccadic) eye movements. Small targets were flickered at 33, 66, 130, or 260 Hz. Using a 2-interval forced-choice design, sensitivity to displacement was about twice as great when the target was moved in the direction opposite the eye movement as when it was moved in the same direction, a result consistent with a subthreshold reduction of the suppression during saccadic eye movements that ordinarily aids in space constancy. There was also less suppression at lower flicker rates. Both effects were smaller with higher flicker frequencies. Results imply that both masking and extraretinal signals are important in saccadic suppression of target displacement, and that flicker on VDTs may distort space perception.

The process of saccadic suppression of image displacement (SSID) is an essential part of the mechanism that gives us space constancy. SSID makes up for errors in extraretinal signals, suppressing retinal motion that otherwise would cause perception of displacement of the visual field with each saccadic eye movement. This paper addresses the question: how sensitive is SSID to the dynamic structure of the image during a saccade?

The target stimulus was displayed on the screen of a HP 1351 vector display with a fast p31 phosphor. The screen was placed 58.5 cm away from the subject's eye, and was 43.5° wide and 32.2° in height. The display was controlled and timed by a PDP 11/23 computer via a HP 1351 vector graphics display buffer. Eye movements were recorded with a photoelectric infrared

eye-tracking system and sampled by the computer. A Wavetek digital function generator served to trigger the sampled input. Subjects responded on a button box assembly, signalling the computer. The subject's head was restrained with a bite bar assembly to which the eye tracking infrared LED and photocells were attached. Experimenters monitored all eye movements during trials with a second oscilloscope.

Using a two-interval forced choice paradigm, we tested displacement discrimination in either direction during a saccade in a flickering environment. The target was displaced without motion; once a saccade was detected, the target was extinguished and redrawn at a different position. The stimuli varied in flicker frequency, displacement distance, direction of displacement, and position on the screen for each trial (Figure 1).

The subject's task was to report in which interval displacement occurred. The 576-trial experiment comprised 4 flicker frequencies (33Hz, 66Hz, 130Hz, and 260Hz) X 3 displacement sizes (2.67° , 1.33° , and 0.67°) X 2 directions of target displacement (left and right) X 12 stimulus positions X 2 trials of each type. Stimulus position was varied to eliminate the (admittedly unlikely) possibility that some sort of egocentric position cue could inform subjects whether the target had moved by monitoring the post-displacement position of the target. Trial order was randomized over all parameters.

Saccades were detected on-line as movements that exceeded $75^\circ/\text{sec}$ for 16msec. Every msec, this interval was probed by comparing the present digitized eye position sample with the sample collected 16msec earlier. Target offset occurred 100 msec after saccade detection.

The eye movement monitor was calibrated before each session by presenting each of the 12 pre-saccade and 12 post-saccade fixation points in order. The subject fixated each point in turn, pressing a button when fixation was achieved. The computer picked up 100 eye position samples 2 msec apart, calculated a mean position and a standard deviation to estimate fixation instability, and illuminated the next point. Unstable fixation resulted in an automatic restart of the calibration procedure. During the experimental sequence, piecewise linear interpolation was used to determine eye position between the calibration points.

Saccadic errors were detected on-line by the computer and defective trials were redone. If the saccade was too short, too long, a double saccade occurred, or no saccade occurred, the subject saw an error message on the screen describing one of these 4 error conditions, and the trial was repeated later. If fixation remained outside the region of the initial fixation target, the subject received a "calibration problem" message on the screen. With some practice, most subjects could progress through the trials with relatively few error messages.

Results

Data, as reported in the manuscript, were based on 3,456 trials in 6 subjects. Generally, displacements were easier to detect at low flicker frequencies than at high flicker frequencies. This occurred despite the fact that all flicker conditions appeared similar, except that some subjects were aware of more flicker at the slowest rate, and subjects generally did not know which flicker rate was being presented or even that flicker rate was an independent variable. Finally, target displacements in the opposite direction from the saccade were more easily detectable than target displacements in the same direction. Sensitivity to displacement was about twice as great when the target was moved in the direction opposite the eye movement as when it was

moved in the same direction (Figure 4). This would be expected from a partial break-down of space constancy – the world should seem to jump in the direction opposite to an eye movement. Even if a suppression of displacement detection during saccades prevents the jump from being perceived, it should be easier to detect a target displacement in the direction opposite the eye movement than in the same direction: when movement is opposite, the imposed displacement adds to the illusory displacement, making detection easier. Displacements were more easily detected at lower flicker rates. Details of the results are in the accompanying published papers.

The results imply that both masking and extraretinal signals are important in suppressing the detectability of target displacements during saccades, and that flicker on video display terminals may distort space perception. Further, information concerning retinal smear affects saccadic suppression of displacement. By flickering the display at different frequencies, we have decreased smear by different amounts; at low flicker frequencies saccadic suppression of target displacement is incomplete, while at high flicker frequencies (by allowing more smear) target displacement suppression is maintained. Thus flicker results in what can be interpreted as a partial breakdown in space constancy, and such complaints as 'eyestrain' may result from the continual need to achieve constancy despite this disturbance. "Eye fatigue" is the most frequently reported visual complaint for both transient and persistent complaint groups in surveys of VDT users. It may be possible to design VDT display formats that do not result in distortions of space constancy, and that will be easier and less fatiguing to use.

Saccadic suppression of Displacement at Isoluminance

Introduction

Until now, all experiments in saccadic suppression of displacement have been performed with stimuli differing in brightness from the background. These experiments have consistently shown a large increase in threshold for detectability of target displacement during saccades, but the mechanism of the effect remains obscure. It seems probable based on a number of findings that both visual masking and active internal signals are involved, but we need to know more about the mechanisms of the suppression to be able to interpret its effects on space constancy.

Stimuli differing from one another only in chromatic content ('equiluminant stimuli'), with luminance held constant across the entire visual field, can be used to probe the kinds of channels in the visual system that mediate saccadic suppression of displacement. Such stimuli, and the expertise needed to calibrate and use them, came to the PI's laboratory by a fortuitous coincidence. Stephen Macknik, an exceptionally capable student working in the laboratory, was simultaneously pursuing a project on equiluminant stimuli with Prof. Eugene Switkes of the UCSC Chemistry Dept. Macknik brought the equiluminant capability into our laboratory, and we were able to design an experiment whose conditions overlapped at one condition with those of the experiment above. If suppression was found with equiluminant stimuli, we would know that parvocellular channels in the visual system are capable of supporting the suppression process, because the magnocellular channels would be blind to the stimuli. Lack of suppression of displacement during saccades under isoluminance would imply that the suppression normally depends upon the magnocellular channels, a system of

large, fast-conducting but color-insensitive neurons that work in parallel with the parvocellular channels.

Method

The experiment relied almost entirely on programs and equipment already at hand in our laboratory, using a color monitor on an IBM PS/2 computer as the stimulus presentation device. Therefore the experiment could be run at relatively little cost, and it was not included in the original proposal budget. Stimuli for the experiment consisted of 1° squares. Two of them, separated by 20° , served as fixation and saccadic goal areas. The target square, centered between the fixation areas, was displaced 0.1 to 3.0° during a photoelectrically detected saccadic eye movement, using programs from the experiment above. Isoluminant red and green were calibrated with heterochromatic flicker photometry: since the maximum temporal frequency for detecting flicker is much lower for chromatic than for luminance stimuli, two chromatic stimuli can be alternated within a window at a rate faster than chromatic flicker fusion, but slower than luminance fusion. The relative brightnesses of the red and green stimuli are then adjusted until flicker seems to disappear: this is the equiluminant point, which must be set separately for each subject. The two brightnesses and colors alternated in the window are then used as target and background fields respectively during the suppression experiment.

Results

There is much less suppression of displacement in the equiluminant condition, and what suppression there is does not depend on relative direction of eye and target motion as it does for the luminance targets used as controls in the same experimental runs. Luminance results (using the same program, but reducing the brightness on one color channel to zero) were comparable to those found in the corresponding condition in the experiment above.

We can conclude that the neurological mechanism of saccadic suppression of displacement depends upon visual channels sensitive to luminance-defined, but not chromatically-defined edges.

Saccadic Suppression of Displacement with High-speed Flicker

This is an extension of Part One, Experiment I of the AFOSR proposal. Spatial distortions in flickering fields were found to be reduced at high flicker rates in the first experiment above, but there was still some residual asymmetry of suppression when comparing target motion in the same direction as eye movement and in the opposite direction. Therefore we repeated the experiment with flicker rates up to 960 Hz, using multiplex programming techniques on our HP vector-driven display. The design is otherwise similar to that of the first experiment, using flicker rates of 960 Hz and submultiples down to 30 Hz.

Like study #1, the question being asked in this study is how flicker changes space constancy. By flickering the target object the temporal component of space constancy is manipulated, and by displacing the target in the visual field the spatial component can also be probed. The amount of flicker can be varied while oculomotor demands and the appearance of the image during fixation remain the same. A flickering target remains spatially constant as long as the eye is fixating the target, so that location is defined. During a saccade the information available about stimulus location

will lag behind eye position (Macknik, 1991). Because information from a flickering stimulus is not present during the off period of the duty cycle, visual perception must utilize information from the most recent flash. If the eye is moving, this sample will lag behind the actual eye position. Also, a flickering stimulus does not leave a continuous smear on the retina, but rather a series of spatially discrete samples. The study was designed to further explore the effects that flicker has on the ability to detect movement during a saccade. By including flicker rates of 480 and 960 Hz, faster than those used in study #1 above, we determine whether the temporal pattern of sampling, or merely the fact that the image is discontinuous, is important in maintaining space constancy.

Methods

Apparatus: Subjects were dark adapted for 10-15 min with the left eye occluded. With head restrained by a bite bar, the subject sat with the right eye at the center of a HP 1351 vector screen onto which targets were displayed. This device can present stimuli 980 times per sec and has a medium-short persistence p31 phosphor that decays exponentially to 1% brightness in .02 to 2 msec. Since we ran our display at a brightness of 2 log units over threshold, the stimulus always decayed to invisibility in 2 msec or less. This brightness level also prevents any long-persistence phosphorescence of the screen from affecting perception. The screen was 58.5 cm from the subject's eye. It was 44 deg wide and 32 deg in height, and was of uniform brightness. Ambient light level at the observer's eye was 0.12 cd/m². The display was controlled by a computer via a HP display buffer. Duty cycle was held constant at 50%. Horizontal saccadic eye movements were recorded with a photoelectric infra-red eye tracking system and sampled by the computer. An infrared LED illuminated the viewing eye, and paired photocells were aimed at the iris-sclera border.

Design and Procedure: The subject fixated the leftmost target (fig. 1A) and signalled readiness by pushing a button. Both the left and right targets then disappeared, leaving only the middle target on the screen (fig. 1B). Subjects had been instructed to saccade at this time to the position where the right target had been (fig. 1C). When the eye passed through the first 7 deg the computer triggered the central target to move in either direction. Targets were 1 degree outline squares. Saccades were on average 40 msec in duration. Upon reaching the right target spot, if the saccade was of proper length and duration, the screen blanked and was replaced with a question asking whether the target had moved or not. If the saccade was inaccurate, the subject was informed with visual text whether the error was caused by an undershoot, overshoot, or double saccade. Subjects responded by pressing either yes or no on a response box. Since the fixation points had been extinguished, the target jumped in an unstructured visual field. The response was made without either right or left fixation points on the screen. Therefore, no intentional reference frame was provided for the subject.

A Modified Binary Search (MOBS) system was used to control the trial sequence. The standard binary search method utilizes information gained with each stimulus presentation to determine the next step in the search. The search begins by sampling the midpoint of the range of possible values. Depending on the outcome, a boundary is established that eliminates half the range. The midpoint of the remaining range is sampled next, and the process is repeated. Regular binary search fails when the target drifts outside the defined boundaries. MOBS (Tyrrell and Owens 1988) uses a sampling range

defined by two boundaries made up of two stacks. The goal of MOBS is to minimize the number of trials before establishment of threshold. MOBS achieves this by presenting each trial at the assumed threshold. Each stimulus presentation is presented at the value midway between the two stacks. After each presentation one of the boundaries is updated. This information is saved and used if the response drifts beyond the boundary. When two consecutive responses are the same, an alternative test is implemented to confirm the validity of the opposite boundary. This tests whether the target is within the active range. If the target drifts beyond a boundary, the invalid boundary is reset to its previous value. This continues until two termination criteria are met. Criterion 1: A certain number of reversals occur. Reversals are consecutive opposite responses. Criterion 2: The last step is less than 5% of the total range. This controls for large drifts in the last response. If these criteria are not met, then the threshold detection procedure continues. The variance within the range has a lawful relationship with the number of reversals. Upon satisfaction of these two criteria, the mid-point is selected as the subject's threshold. Displacement of the target was determined by MOBS and started between 0 and ± 3 degrees.

Stimuli: The middle target in figure 1 was flickered at one of 6 frequencies, 30, 60, 120, 480, or 960 Hz, and had a 50% duty cycle. Before testing the subject held a 99% filter in front of the right eye. Each stimulus was presented to the subject, who alerted the experimenter when he saw the target. At this point the brightness threshold was set and the filter removed. Each flicker frequency was then presented and adjusted for equal brightness. During the practice phase of the test each subject was instructed to tell the experimenter if any afterimage had appeared on the screen. If a report was given, the session was stopped and brightness calibration was continued.

Analysis: Analysis of variance (ANOVA) was carried out using standard statistical package (CRUNCH ANOVA). Two factors, flicker frequency and direction of displacement, were analyzed.

Results

No evidence was found that these high flicker rates have advantages over slower rates, though some technical issues were resolved.

The main effect of flicker frequency on the threshold boundary was established by MOBS. There was no overall main effect of flicker frequency ($df=5,15$ $F=1.14$ $p=.377$). A negative bias was found in all but one (120 Hz) of the flicker rates. This result suggests that the flicker biases detection of movement in the direction opposite the saccade by forcing the original zero position (where the target actually started on the screen) in the direction opposite the saccade. Figure 2 illustrates the flicker-x-direction of movement interaction. This figure shows the range between the thresholds measured in both directions in which no movement was detected. No significant interaction was uncovered. Saccadic suppression was equally effective no matter what the flicker frequency or direction of displacement. Despite these tests, the midpoint of the range was less biased at 30 Hz than other frequencies (Figure 3). The range nonlinearity masked the significance of this result from the linear ANOVA fit. Asymmetry of suppression at the low end of the range is condensed by some 70%.

Thus far all analyses have been performed on thresholds measured relative to the initial position of the stimulus. If the position of the fovea is taken to be the reference from which measurements are to be taken instead of

the position of the stimulus, then statements about the distance and time required for the stimulus at the fovea to reach threshold can be made. To do this, all threshold measurements were referenced to the position of the fovea at the moment it passed the trigger (3° before arriving at the stimulus) and an ANOVA was performed on this measured distance. Results of this analysis show that the fovea was significantly closer to the stimulus for displacements in the direction opposite the saccades ($df=1,4$ $F=130$ $p=.0003$). This difference may result from the sparser spatial sampling on the retina for the stimulus moving in the direction opposite the saccade. There was a smaller probability of the target flickering in the fovea while moving in this direction. The displacement took place when the fovea was closer to the target in the opposite-direction trials than in the same-direction trials. All of these sampling properties reflect what happens on computer terminals that flicker during normal use.

Thresholds from the stimulus-bound and fovea-based reference frames showed that these two points of reference were significantly different ($df=1,4$ $F=22.76$ $p=.008$). The threshold value for each direction of displacement relative to the starting point of the stimulus was combined with the eye movement needed to detect such displacement, measured relative to the trigger, and formed into a ratio value. Movements in the direction opposite the saccade had significantly different threshold/ eye movement ratios than did those in the same direction as the saccade ($df=1,4$ $F=11.7$ $p=.026$). This result is further evidence that those movements in the direction of the saccade had more time to start/finish their duty cycles while the fovea was near the target location.

Discussion

Our results suggest that flickering the target object at high frequencies has no significant effect on the ability to detect movement in the visual field, as long as the flicker exceeds about 60 Hz. However, direction of movement of the stimulus is a discriminating factor. It has been shown (Bridgeman & Fisher 1990) that displacement suppression is symmetrically distributed around the center of the target. All flickers shifted the detection area from a symmetrical distribution to an asymmetrical one. The distance between the two threshold values remained quite constant over all flickers except for 30 Hz. In flicker studies #1 and #2 the results suggest that no matter what the direction of the saccade, thresholds are biased such that target movements to the right are easier to detect than movements to the left (Figure 4). This may be related to the more frequent saccades to the right during reading. When both groups of data were subjected to the same analyses using a stimulus bound reference frame, a foveal based reference frame, and a ratio measure, no statistically significant difference between the two groups was found other than the vantage point offered by the different saccade directions. The original study's threshold values were on average 40% greater than those reported in this study. This suggests that with MOBS a more sensitive measure of threshold was made in the present study. Both the frame-based and foveal-based data suggest similar suppression in both studies.

Movements in the direction of the saccade had more space and time to accomplish a full duty cycle when threshold was measured from the fovea along its movement to the displaced target. Flickers of less than 120 Hz had a high probability of being in the off phase of the duty cycle at this time.

Flickers greater than 120 Hz left similar smears on the retina and are suggested to have been processed in the same way. The probability that these stimuli achieved both an on and off phase of their duty cycle while passing through the fovea was high, so that the subject always had both spatial and temporal information at the fovea. If this were the case then a simple match/mismatch distance equation could answer the question of whether the stimulus moved.

Interaction of Reading Speed and Flicker Rate

Another consequence of flicker on computer terminals may affect not space constancy but reading speed. As a reader makes successive saccades on a flickering screen, the eye may land on a new word at a time when the display has not been refreshed. Does the eye 'park' at this location until a refresh occurs? And would this slow down total reading speed? The predicted effect of these timing differences is small, but may be of practical significance because of the large amounts of time spent reading from computer terminals.

A pilot study was designed to answer these questions. We examined reading rates on CRT screens at 60 and 500 Hz.

Pilot Study

Methods

Apparatus: Reading experiments used the apparatus described above. Text files stored in the IBM PC were fed to the HP graphics buffer and display system. Characters were displayed at 60 or 500 Hz. All other display characteristics, including brightness, type font, and character size were equal at the two flicker frequencies. The subject saw a line of text on the screen, and pressed a button to move to the next sample of text.

Procedure: Subjects read a series of graded and standardized passages from "Individual Evaluation Procedures in Reading" by T. A. Rakes, J. S. Choate, and G. L. Waller (Englewood Cliffs, N. J.: Prentice-Hall, 1983). Each passage was about 200 words long. Reading rate was measured for 12 passages in each subject; data from the first 2 were discarded as practice passages. The passages were graded to be at the 10th grade level, well below the reading level of our college subject sample. Subjects were instructed to read as fast as possible consistent with comprehension, and they answered a few simple questions about each passage before moving to the next, to assure that the material had been read.

Results

Reading speeds varied greatly both between subjects and between passages. The faster rate resulted in reading that was on average 0.6 msec faster, a difference that is neither statistically reliable nor of practical consequence. Technical problems in this pilot study were addressed in another study, using more subjects and a larger and more difficult sample of reading material, with photoelectric eye movement monitoring and an automatized screen refresh procedure.

Main Study

Several artifacts may have obscured any effects in the study reported above. First, the material was so easy for our college student sample that some readers merely skimmed it. Second, the procedure of pressing a button to obtain the next sample of text was unfamiliar, and slowed the reading of some subjects because some new lines required a button press while others required only a return saccade. Third, the sample of text was too short to obtain a reliable reading speed estimate at each flicker rate. To correct these deficiencies, a second study was run.

Method

The same hardware was used, but the samples of text and procedure differed. Text was the first chapter of a college textbook in physiological psychology. The chapter consisted of about 7,000 words. Flicker rates were varied without the subjects' knowledge in an ABAB paradigm, following a practice session to familiarize them with the procedure.

Design and Procedure

Calibration: The subject fixated the leftmost of three targets located 10° apart and signalled readiness by pushing a button. If a stable record was recorded the subject received a written confirmation on the screen, and fixated the middle target. The process was repeated for the right target.

Target temporal sampling properties reflect what happens on computer terminals that flicker during normal 60 Hz use.

Subjects read a chapter from a textbook in physiological psychology (Bridgeman, B., *The Biology of Behavior and Mind*. New York: Wiley, 1988). Standard difficulty measures place the reading level at about grade 14. Subjects were instructed to read as fast as possible consistent with comprehension. The text was displayed one full-length line at a time, and each new line was called by a button press. With this method every return involves the same procedure, and the task can become automatized so that it requires minimal time and effort. The chapter consisted of about 7,000 words. Flicker rates were varied without the subjects' knowledge in an ABAB paradigm, following a practice session of 50 lines to familiarize them with the procedure. Incomplete lines of text were not scored. Also, lines on which a blink or interruption of reading occurred were deleted from the sample before statistical analysis.

Saccades were analyzed on-line and divided into four categories: 1.) Small forward saccades, advancing 1 word through the text. These were the most common type. 2.) Large forward saccades, advancing more than 1 word. 3.) Small reverse saccades, moving backward a word in the text. 4.) Large reverse saccades, regressing more than 1 word. Return saccades to the start of a new line were not counted in this category. Dynamics of individual saccades were not stored, to reduce the volume of data. Only the saccade time and size were recorded.

Results

Reading speeds varied greatly both between subjects and between passages. Speed was faster with the higher flicker frequency. Because individual differences are significant in an overall analysis of variance, 20

subjects were run. Overall, the reading rate for all subjects with 60 Hz flicker was 262 words/min, and with 500 Hz flicker was 270 words/min. While this difference is small, it has practical significance in the real world when compared to the 100 million hours/day spent reading on terminals. A difference of this magnitude corresponds to about 2 million hours/day wasted by terminal flicker in the US alone. The difference amounts to a 3.05% deficit at 60 Hz, which compares favorably to the 3% deficit predicted by the 'parking' hypothesis. This quantitative agreement increases our confidence that the parking hypothesis accurately describes the microstructure of the subjects' response to the sparse temporal samples available on flickering screens.

With practice at the reading task, readers increased their speed in the 60 Hz condition until it equalled the speed in the 500 Hz condition. At 500 Hz, the increase in reading speed across the study was not statistically significant. The subjects accomplished this acceleration by changing the frequencies of their eye movements, making more use of large forward saccades and less use of reverse saccades. More than 107,000 eye movements were analyzed.

In the 500 Hz condition, the mean reading rate averaged across subjects was 269.9 words/min. This rate, combined with our eye movement data and the stimulus sampling theory outlined above, can be used to make a quantitative prediction of reading speed at any screen refresh rate. We begin by defining the relevant variables and their empirically derived values, where f is flicker frequency and S is reading speed in words/min.

Empirically derived values:

W = words/fixation = 1.1295

P = processing time = 250 msec (at 500 Hz)

The model makes the following assumptions:

D = delay/fixation = $1/2 (1000/f) = 500/f$

T = time/fixation = $P + D$

Combining these parameters into the definition of reading speed,

$S = \frac{W}{T}$, we obtain

$$S = \frac{W}{P + D}$$

Substituting our empirically derived values and converting to minutes,

$$S = \frac{1.1295}{250 + \frac{500}{f}} \times 60,000 \text{ msec/min.}$$

This function is plotted in figure 5. Values are calculated every 20 Hz, and intermediate points are interpolated with a curvilinear algorithm. The behavior of the function can be further characterized by evaluating S after substituting important values for f . When f is infinite the term $500/f$ drops

out, resulting in an asymptote of 271.1 words/min under continuous illumination. The minimum of the function occurs when $f = 0$. Then the $500/f$ term becomes infinite, $S = 0$, and reading ceases.

The curve in figure 5 was plotted by combining the stimulus sampling model with the empirical data that we obtained at the 500 Hz flicker rate. We can now evaluate the reading speed data from our 60 Hz condition to see how closely the model matches the observed values. The result is shown in figure 6. Also included in figure 6 is the empirically derived reading rate at 500 Hz. There was a reliable difference in reading rate between the flicker frequency conditions ($F(1,19) = 3.983$, $p < .05$). Reading at 60 Hz is 3.05% slower than at 500 Hz.

Details of the results, statistical analysis, and further discussion are in the two appended manuscripts (appendix papers #1 and #2). Paper #1 has been submitted to *The Journal of Experimental Psychology: Applied*, while #2 is a proceedings paper published in connection with the 1992 SPIE/AS&T meeting in San Jose, Ca.

Sustained reading under continuous illumination

In evaluating the results of the above experiment, we intended to compare our results on saccade patterns to those in the literature. We found, however, that no studies of sustained reading had been carried out even under continuous illumination under conditions comparable to ours (large sample, one-line display). Therefore we undertook a study of extended reading under continuous illumination, using the same text materials that we had used for the flicker studies.

Methods

Subjects read text one line at a time. The pre-printed text was fed through a dot-matrix printer that was used only to advance the text, one line at a time, when the subject pressed a button. Masks above and below the text presented a window, so that only one line of text could be seen at a time. Thus the reading conditions were made as similar as possible to those in experiment 1, where only one line of text was displayed at a time on a monitor. The same textual material was used in experiments on the screen and on paper. In each case, subjects took about 40 minutes to read the entire text, including a 50-line practice section that was not scored.

Eye movement monitoring apparatus and procedure were the same as those in experiment 1, except that calibration took place on marks printed in the text.

Results

Changes in the pattern of the four types of saccadic eye movements defined above are smaller than the changes noted in experiment 1. In three of the four saccade types, there was a greater frequency of saccades under continuous illumination, as the 'parking' hypothesis would predict. The only exception is in the large forward saccades.

Overall, the saccade results look similar to those recorded at the 500 Hz flicker speed on the terminal. From the first half of the experiment to the second, the frequency of small forward saccades declined slightly while the frequencies of the other three types of saccades increased. This matches the

500 Hz results previously obtained, except for the large reverse saccades. These saccades are by far the least frequent of the four types, however, at well under one saccade/line of text, so they do not significantly affect the overall results.

Reading rate increased from the first half of the experiment to the second as it did in the CRT studies.

Reading on Flickering versus Continuous Screens

In the reading studies above, we were limited to display of one or a few lines of text at a time. There was no choice of font, and displays were in a green-on-black format that is no longer used in modern computers. A new study, supported by the AASERT supplement to the main grant, is now underway comparing reading on a color CRT screen and a color active-matrix screen, both using identical Macintosh operating systems and display format. The active-matrix display, purchased from non-AFOSR sources, does not flicker like the CRT display.

Method

To equate brightness, chroma and contrast on the two displays, a mirror apparatus was constructed to make a region of the two displays appear to be adjacent. Subjects then equated the displays, using the method of adjustment, until there was no visible contour at the boundary between the displays. Subjects read the same text as used in the previous reading experiments, but now a screenful (about 200 words) at a time. This task simulates more closely the conditions encountered by users of current displays, and is more comparable in appearance to a paper format.

Analysis methods are similar to those used in the experiments above.

A New Theory of Visual Stability

During the grant period a major theoretical paper on the subject of constancy of visual direction during successive fixations was prepared, underwent a major revision, and was accepted for publication as a target article in *Behavioral and Brain Sciences* (appendix paper #3), presently the most cited journal in the behavioral sciences. The paper, coauthored with Lex van der Heijden of Leiden and Boris Velichkovsky of Moscow, reviews the three dominant theories of direction constancy and concludes that all are inadequate. We then propose a new 'calibration' theory, maintaining that the visual system uses the current values of retinal and extraretinal signals to determine visual direction without regard to previous fixations. Thus no correction must occur. This theoretical effort is a major step in interpreting the space constancy phenomena investigated in the experiments described above, and draws heavily on that work for its empirical base.

Saccadic Suppression and Voluntary Movement

Also appearing in *Behavioral and Brain Sciences* (appendix paper #4) will be a commentary on a target article by Alex Wertheim on visual localization and visual-motor coordination during smooth eye movements and locomotion. The commentary links Wertheim's ideas with another empirical project completed in the PI's laboratory during the review period, a collaboration

with Jean Blouin of the University of Laval, Quebec, Canada, who worked in Santa Cruz during the spring of 1992. A separate description of these studies has been submitted for publication (appendix paper #5).

Method

The experiments involved perceptual detection of the displacement of a target that was jumped horizontally during a saccadic eye movement. On some trials the subject would not only detect the jump, but would also hit the target with an abrupt, ballistic jabbing motion. In a subset of the hitting trials, the subject's arm was mechanically restrained just after it began to move. On these trials, the efference copy for the movement is already established, but proprioception of arm position cannot contribute to the perceptual estimate of position.

Results

We found that motor behavior was accurate even when perception of displacement was masked by the saccade, as others have found. In addition, we discovered that the act of hitting the target increased the threshold for perception of the displacement, an example of an extraretinal signal not related to movement of the eye or head affecting visual perception. We further discovered that interrupting the movement in mid-course did not alter these effects, suggesting that efference copy rather than muscle proprioception is responsible for them.

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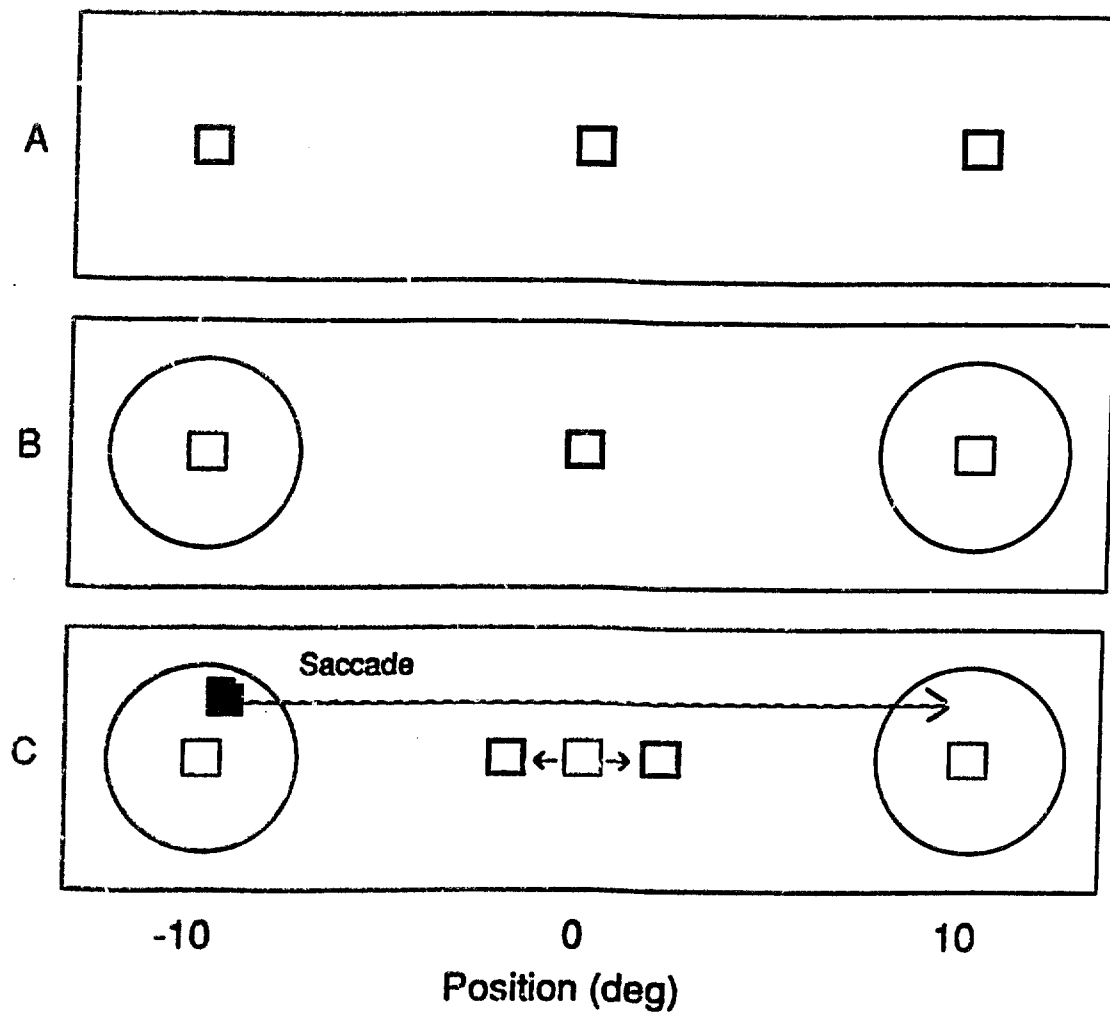
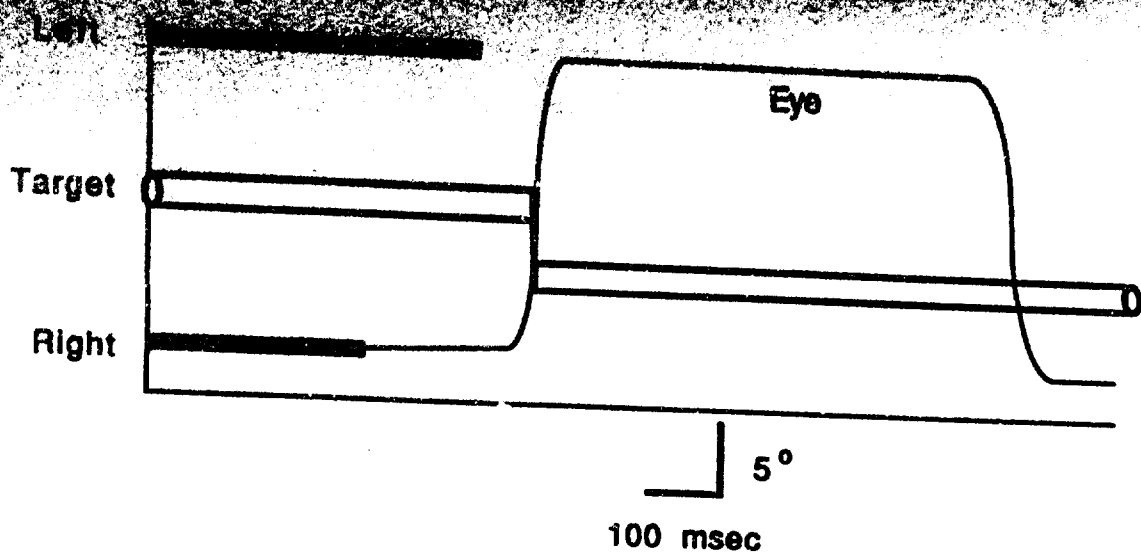


Figure 1.

ratio of
displacement threshold/eye movement

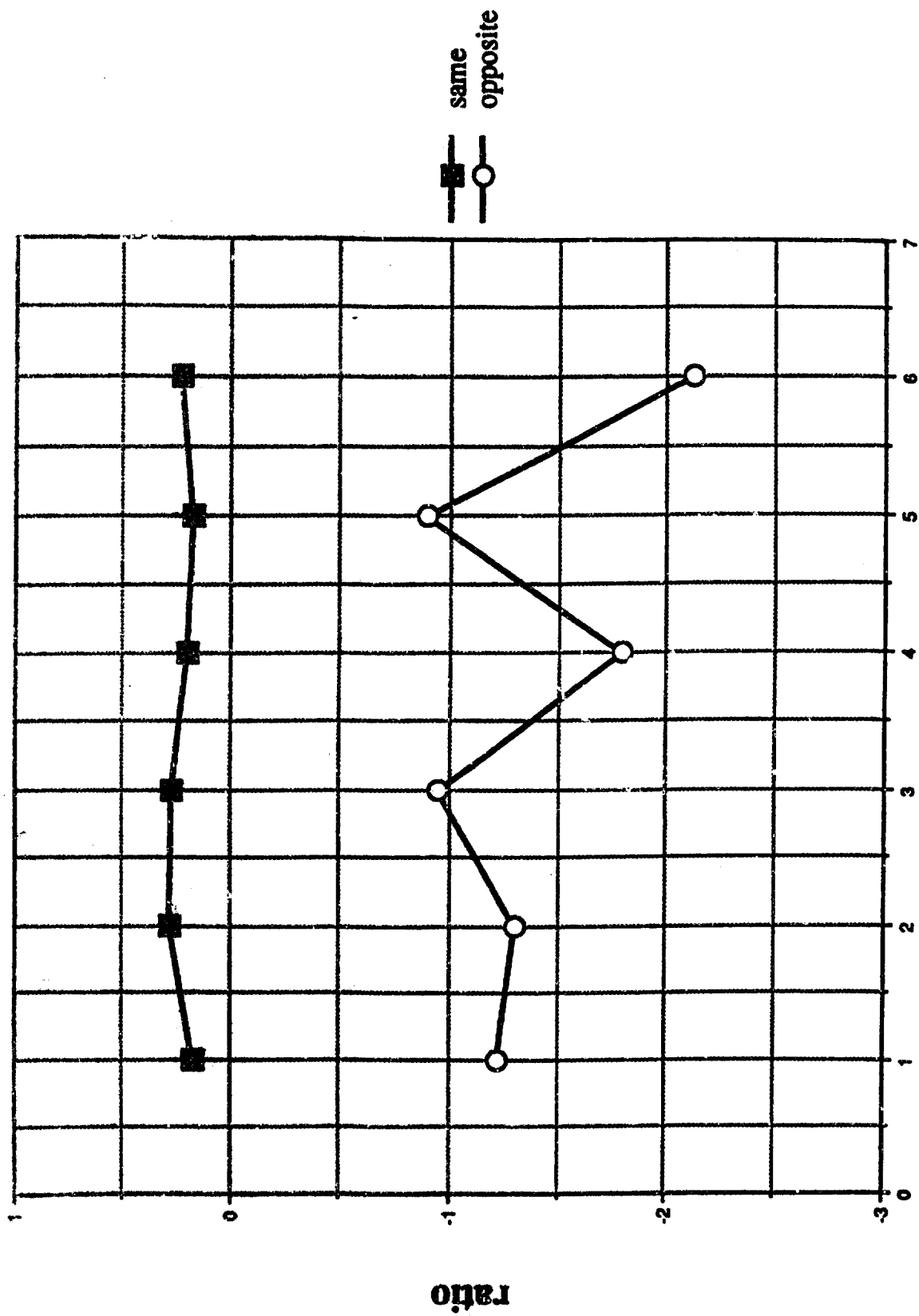


Figure 2.

flicker frequencies
30, 60, 120, 240, 480, 960 Hz

total range in space and time of
saccadic suppression as measured
distance between left and right
threshold boundaries

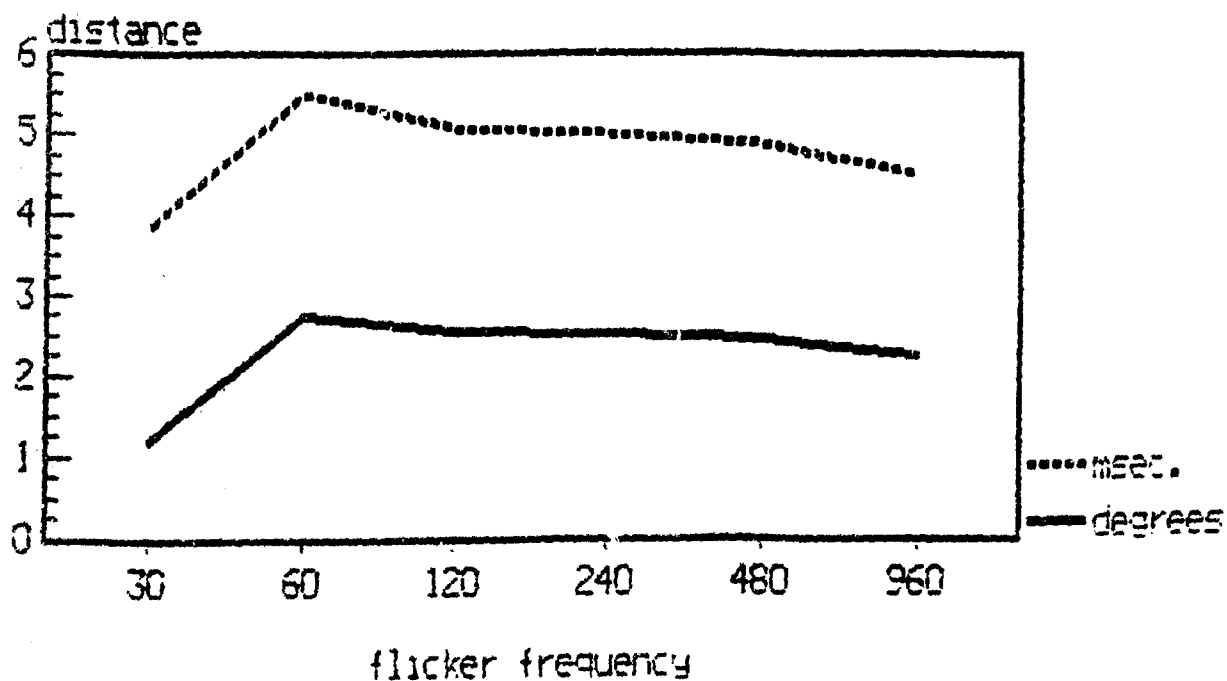
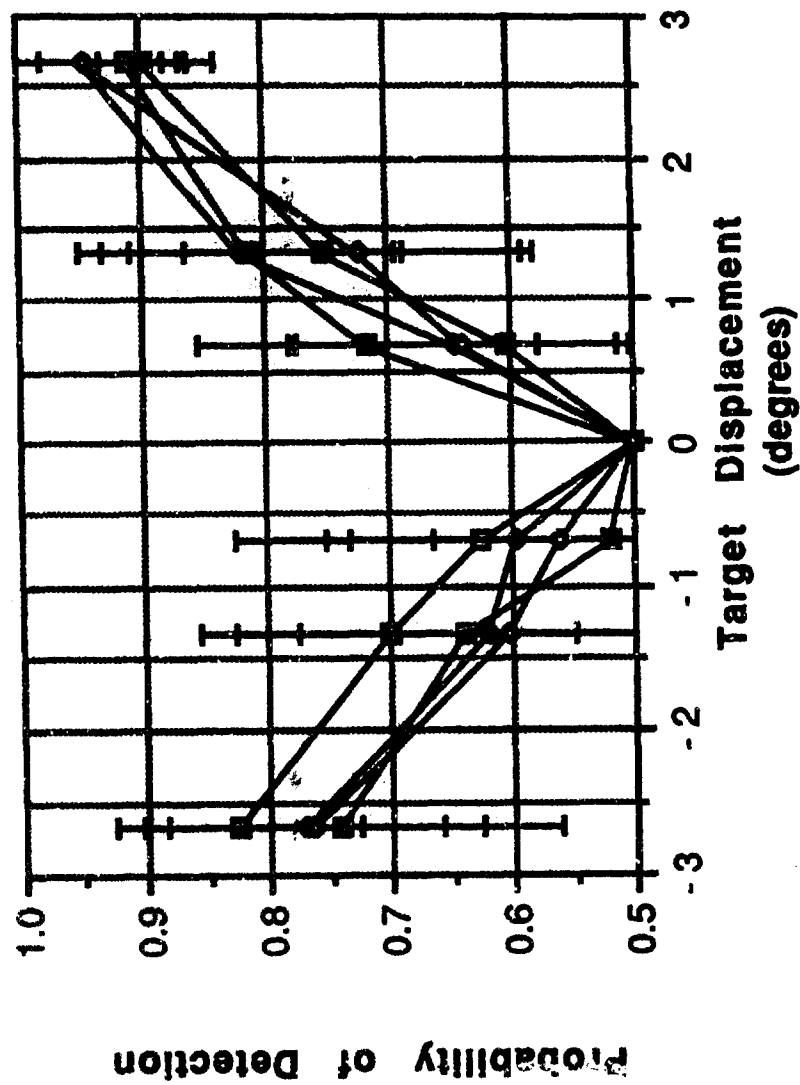


Figure 3.

Detection vs. Displacement



Flicker Frequencies

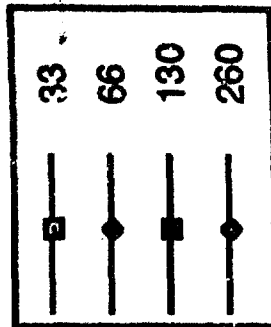


Figure 4.

Stimulus Sampling Model

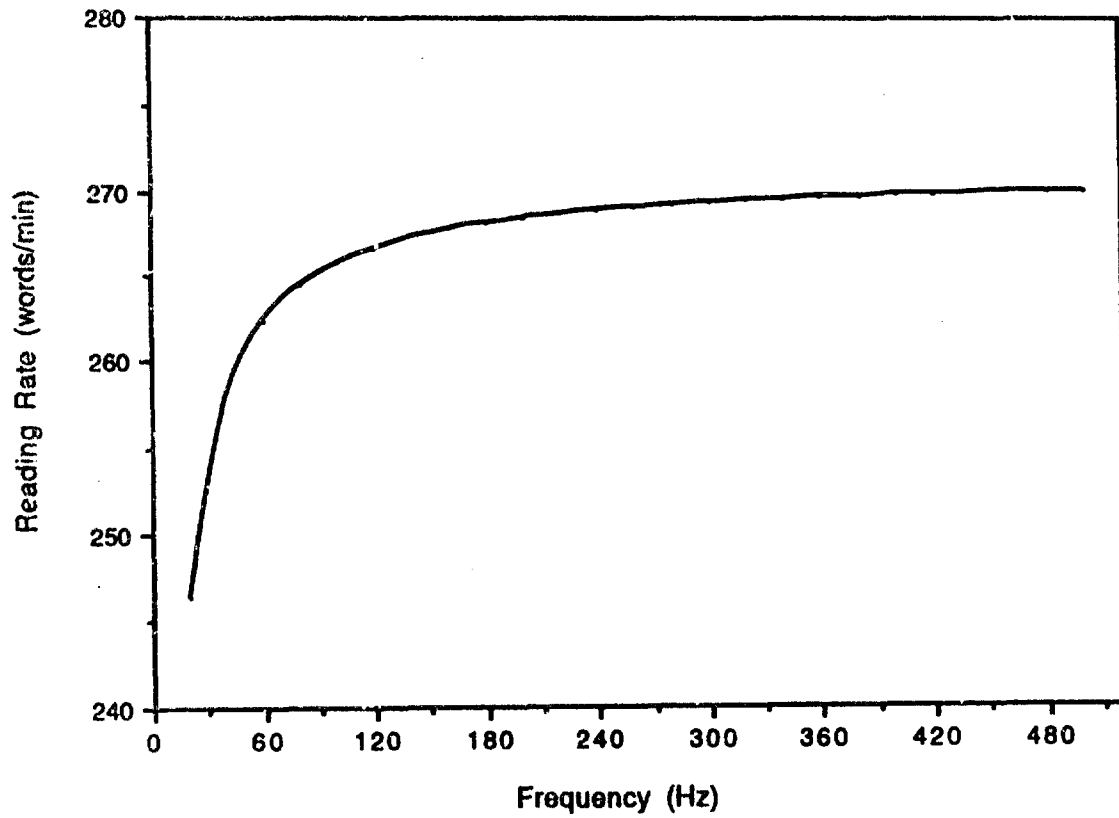


Figure 5.

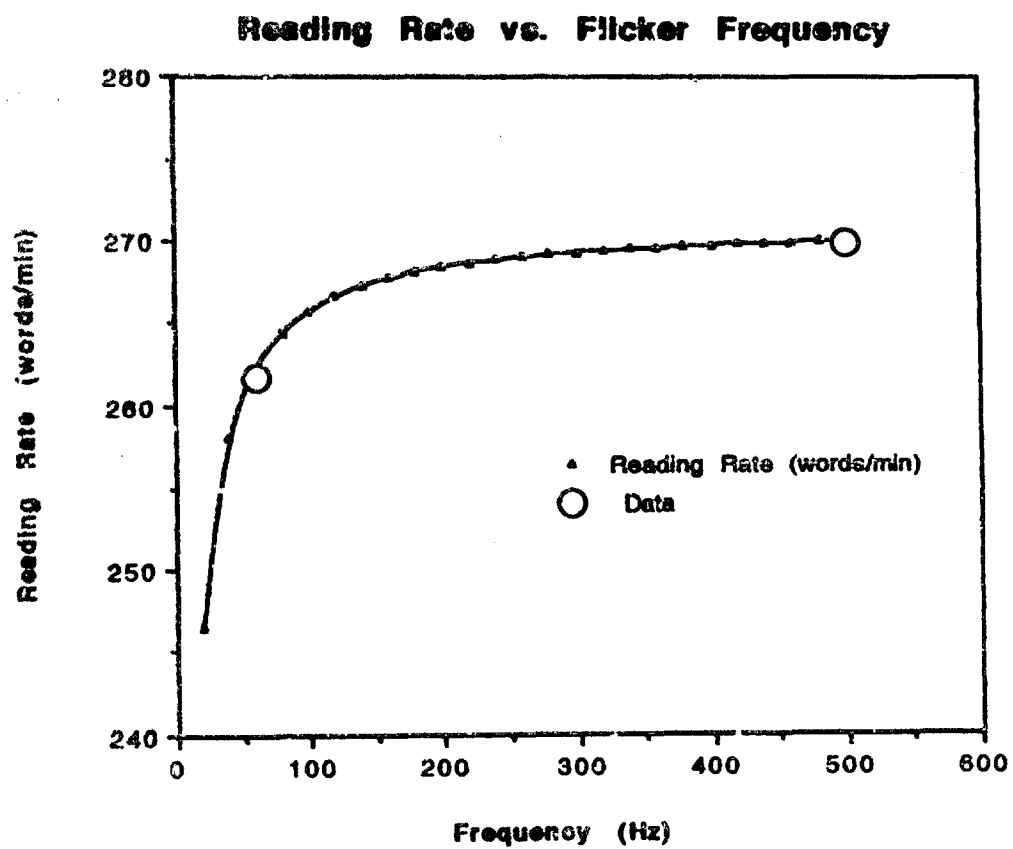


Figure 6.