Faster Flicker Rate Increases Reading Speed on CRTs

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ABSTRACT

We have investigated whether reading is adversely affected by the flicker of VDTs. We use 60Hz flicker for our low frequency because it is the standard used in most computer monitors, and 500Hz for our upper boundary because it provides nearly constant presentation. 60Hz flicker results in 16.67ms of dead time after every screen write. Therefore there is no useable information at the fixation point for an average of 8.33ms following a saccadic eye movement. We hypothesized that the visual system might have to wait for text to become available after each saccade, slowing reading speed. The 500Hz condition allows 2ms of dead time with an average of wait of 1ms.

Text was displayed one line at a time about 10° of arc below eye level on a HP1351 vector screen. Subjects pressed a key when they were finished reading a line of text, and it was immediately replaced by another line.The types of saccades made on each line were displayed to the experimenter as the subject read. Half of the subjects read four samples at 60 Hz, 500Hz, 60Hz, and 500Hz. In the other half the order was reversed.

Subjects were given 50 lines of practice to automatize the line-advancing procedure, and then read for 45 minutes. In the first half of the experiment reading was 3% (8 words/min) faster at 500Hz, a statistically significant acceleration. Though this difference disappeared in the second half of the study, differences remained between the types of eye movements made in the two flicker conditions. From the first half to the second, subjects at 60 Hz increased the number of large forward saccades and decreased the number of small reverse saccades. Both of these changes make sampling more sparse, compensating for the increased dead time between samples. Differences in these types of saccades were smaller at 500 Hz. Subject were unaware of differences in reading rate and type of eye movement. In addition, no subject expressed knowledge of the two flicker conditions or when they were applied. Thus saccadic scanning patterns were modified without the subject's awareness. The results

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account for some but not all of the slowed reading speed observed in reading from CRT screens.

We suggest an adaptive mechanism driven by a need for efficient information uptake as a reason for these changes. The differences we observe at low flicker frequency indicate an increased processing effort, perhaps explaining some of the fatigue effects observed in reading from CRTs. In addition, the differences indicate a non-conscious optimization of information processing. Though reading speed is slowed only slightly by flicker, the difference is statistically significant and is of practical importance because of the many hours people spend reading from CRTs.

1. PROBLEMS WITH RASTER FLICKER

All CRT-based computer displays currently in use are raster-driven, at rates varying from about 60 to 72 Hz. This results in a flicker of the displays. Because the flicker is above the flicker fusion rate (the flicker rate above which a light source appears to be continuous), it has been assumed that the flicker has no effect on computer users. The latest edition of American Standards for VDTs[8] requires only that the display should be "flicker free" for at least 90% of a sample of the user population. The report further notes that there are no data showing that perceptible flicker adversely affects performance, though it is annoying. This study will show that CRT flicker affects both reading speed and the patterns of eye movements made during reading.

In studies of user populations, proportions of complaints by VDT operators range from 25%[5] to as high as 93%[18]. "Eye fatigue" is the most frequently reported visual complaint for both transient and persistent complaint groups[18, 19].

The complaints undoubtedly have many causes. Visual researchers have concentrated on physical display characteristics such as blur, glare, and contrast[11], and have investigated operator characteristics such as accomodation, AC/A ratio, dark focus differing from VDT viewing distance, and near horizontal heterophoria[6].

After these and other problems are taken into account, however, there remains a residual of unidentified causes of visual VDT complaints. The variables investigated to date concern only static conditions; there has been no attempt to address interactions of operator activities such as eye movements with display parameters. Specifically, the perceptual effects of flicker above the flicker fusion rate have not been studied.

Even among users who do not voice complaints about vision, reading speed is slower on CRT screens than on paper[13]. Because of the growing importance of electronic databases, this characteristic of current VDT formats is of great economic importance. Even the most miniscule disadvantage in reading speed looms large when multiplied by the more than 100 million hours spent daily reading from VDTs in the United States alone.

Flicker has received little attention compared to the physical display characteristics noted above, probably because the 60 Hz terminals in common use operate above the critical flicker fusion frequency (CFF) for most users. Studies of flicker have emphasized conditions that eliminate apparent flicker, raising the display above the CFF. Results have been ambiguous: reverse video (dark characters on a light background), for example, usually results in increased perception of flicker[1] but also provides better readability and greater visual comfort[16]; it also reduces error rate and reaction time in identifying letters[2]. In one of the few studies to vary flicker frequency over a wide range, Nishiyama et al.[14] found a decrease in CFF after exposure to 30 and 60 Hz displays but no change at 90 and 180 Hz. Changes in near point distance, binocular acuity, stereo depth in far vision, lateral heterophoria and far contrast sensitivity were small and inconsistent.

One consequence of flicker is its effect on retinal stimulation during saccadic eye movements, specifically its effect on retinal smear. This has nothing to do with perception of flicker: rather, it affects the processes of early vision. The eye moves so fast during a saccade that a clear image cannot be transduced; instead, a smeared image is painted on the retina during the movement. Normally the smeared image is not perceived; an inhibitory process of backward masking similar to metacontrast prevents perception. The inhibitory process uses the new image, available after fixation is reestablished, to mask the smear[7,12]. Recent work[10] has shown that CRT flicker affects this inhibitory process, and in turn interferes with space constancy, the perception that the world stays in the same place despite shifts of the retinal image caused by eye movements. Suppression of the smeared image may be related to the process of maintaining space constancy in texture-rich, photopic environments. Measures that ameliorate space constancy problems are also likely to improve reading speed on VDTs.

The present study is concerned with another effect of flicker: the sparseness of temporal sampling of the image. It is known that in normal reading, little information is picked up from text that has not yet been fixated. When the eye jumps to a new fixation (usually one fixation per word), information processing normally starts "from scratch". Under continuous illumination, the process begins as soon as the eye comes to rest. Under flicker, such as on a CRT computer screen, however, the raster passes the fixation point only once in every 16 2/3 msec (at a sampling rate of 60 Hz). Though the CRT beam is almost always illuminating some point on the screen in the raster pattern, any one small region is excited for only a few microseconds during each sweep, resulting in a short duty cycle for that region.. Thus when the eye comes to rest at a new fixation point, it is probable that the screen will be blank at that location. The average wait for the "fixated" woard to appear will be 8 1/3 msec, or half of the peak wait, minus the time during which the word is visible due to phosphor persistence.

With this information, and a few assumptions about parameters of the reading task, it is possible to predict quantitatively the reduction of reading speed at various flicker rates. For 60 Hz flicker, an average delay of 8 msec during 4 saccades/sec, a typical saccade rate for reading, means that for 32 msec/sec the eye will be "parked", waiting for visual information to appear. We propose that the visual system begins processing of textual information when that information becomes available in the visual image, and that the next eye movement will have a delay that depends upon the time at which the information becomes available. Micro-waits caused by sparse stimulus samples should decrease reading speed by 32/1000, or about 3% of normal reading speed.

2. METHOD

Twenty subjects read text displayed on a HP135A vector display mounted 57cm from the eyes. The vector-oriented display was used to simulate a raster scan of a single line of text. Since the HP system can display 50,000 vectors/sec, it is no problem to display a line of text at 500 Hz or more. The p31 phosphor decayed to 1% of peak brightness in 0.02 - 2 msec[9]. Text was displayed at 60 Hz in one condition, because this represents the slowest standard rate used in CRT displays and is close (within 20%) to most commercially available display rates. Thus the time between samples was 16 2/3 msec. In the other condition, text was displayed at 500 Hz, resulting in a time between samples of 2 msec and an average wait for the image of 1 msec. Thus delays due to image sampling were negligible in the 500 Hz control condition. Brightness was adjusted so that text appeared the same in both conditions, and subjects were not told that flicker would be manipulated. Since the flicker was always above the flicker fusion rate in both conditions, no subject guessed that flicker was being manipulated.

Eye movements were monitored with a 2-dimensional photoelectric technique (Dr. Bouis Instruments) that offers high temporal and spatial resolution without contacting the eye. The right eye was monitored, but viewing was binocular. Subjects read at the 2 flicker rates in an ABAB design; following 50 lines of practice at advancing to the next line by pressing a key, they read 4 sets of text alternating in display frequency, each of 140 lines. Half the subjects started with the 60 Hz condition and half with the 500 Hz condition, but all read the same text in the same order. In all each subject read about 5600 words, not counting the practice session for which the data were discarded.

Because a large number of saccades was recorded, the saccades were broken down into 4 types for analysis. The most common movements were small forward saccades, defined as movements in the normal reading direction of 4.8 deg or less (4.8 deg was the size of the longest word in the text). Large forward saccades were in the same direction but greater than 4.8 deg in magnitude. Small and large reverse saccades, respectively, met the same magnitude criteria but were in the direction opposite normal reading saccades, i. e. looking back at text already read.

3. RESULTS

3.1 Reading Rate

Because average reading rate increased throughout the experiment, the first and second halves of the expeiment were analyzed separately. Thus each subject had one reading sample in each half of the experiment at each flicker rate. In the first half, the 500 Hz condition resulted in significantly faster reading than the 60 Hz condition (F(1,19) = 3.98, p<0.05) (Figure 1). The 500 Hz reading was 3.05% faster than the 60 Hz reading, consonant with our theoretical prediction. Reading speed increased significantly from the first to the second half in the 60 Hz condition, however, as subjects apparently learned to deal with the sparser stimulus sampling rate (F(1,19) = 15.77, p<0.001). Speed did not change in the 500 Hz condition.

3.2 Saccadic Eye Movements

Saccade data are based on 19,840 saccades in the 20 subjects. The overall saccade distribution is typical for normal reading, though our sample is much larger than that in most reading studies. Most of the saccades (62.9%) were small forward saccades, advancing from one word to the next. Large forward saccades, skipping 1 or more words, were 15.8% of the sample. Small reverse saccades were 17.6%, and large reverse saccades 3.5%.

As reading in the 60 Hz condition caught up in speed to the 500 Hz condition in the second half of the experiment, saccade patterns changed also. The number of small forward saccades decreased slightly in both flicker conditions. The large forward saccades, however, increased more at 60 Hz than at 500 Hz. These saccades were significantly more frequent in the 500 Hz condition at first (F(1,19) = 37.02, p<0.001), but the difference disappeared in the second half. An increase in large forward saccades

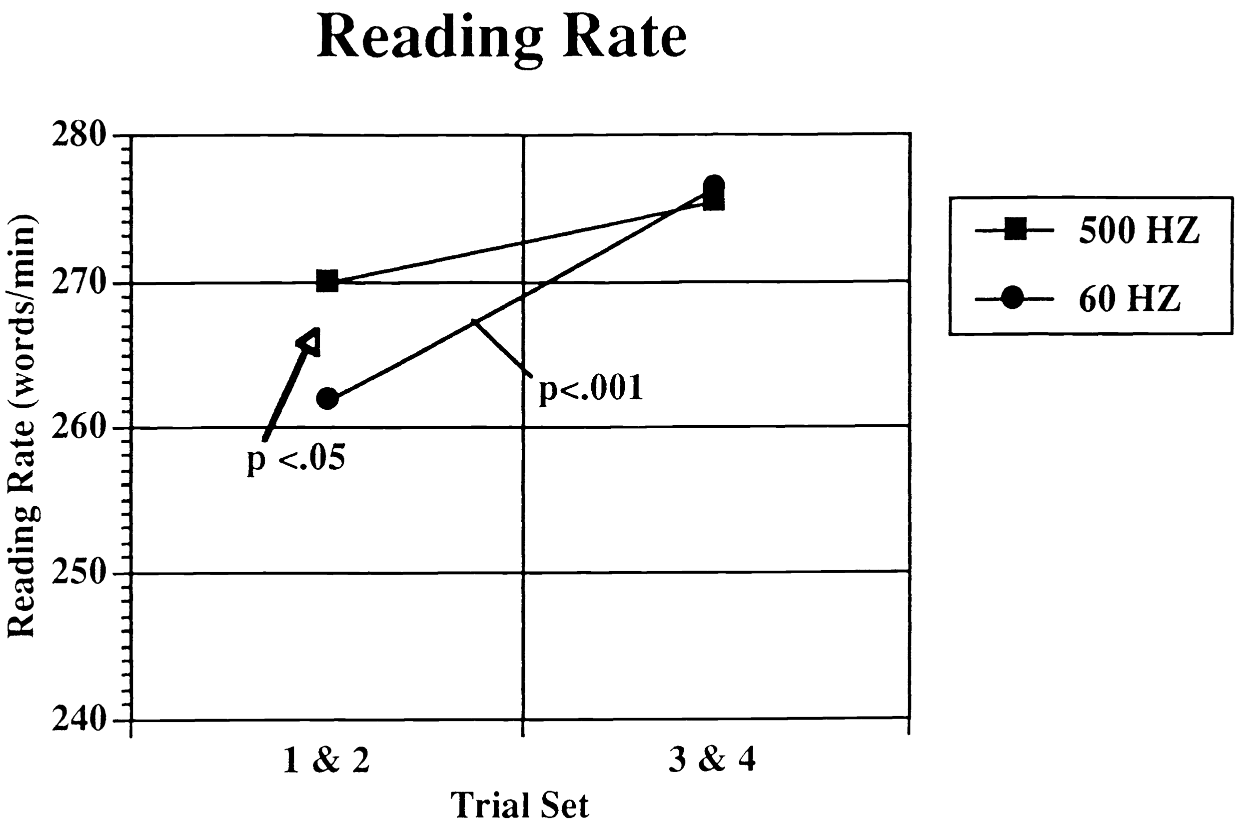


Figure 1. Reading rate in the first half of the experiment (left) and the second half (right).

would tend to speed up reading, compensating for the sparse stimulus sampling by taking in more words per sample (Figure 2).

An analogous picture emerged for the reverse saccades. In the first half, small reverse saccades were equally frequent in the two conditions. In the second half they increased in the 500 Hz condition ($F(1,19) = 13.20$, $p<0.001$), but decreased in the 60 Hz condition ($F(1,19) = 44.12$, $p<0.001$) (Figure 3). The decrease at 60 Hz is also in the direction of a sparser sampling of the text, going backward less frequently. There were also changes in the frequencies of large reverse saccades, but these saccades were so infrequent that they are of little practical importance.

4. DISCUSSION

Reading rate in the first half of the experiment was retarded at 60 Hz by exactly the amount predicted by our theoretical analysis, suggesting that the analysis is useful in predicting the actual conditions of reading. Using

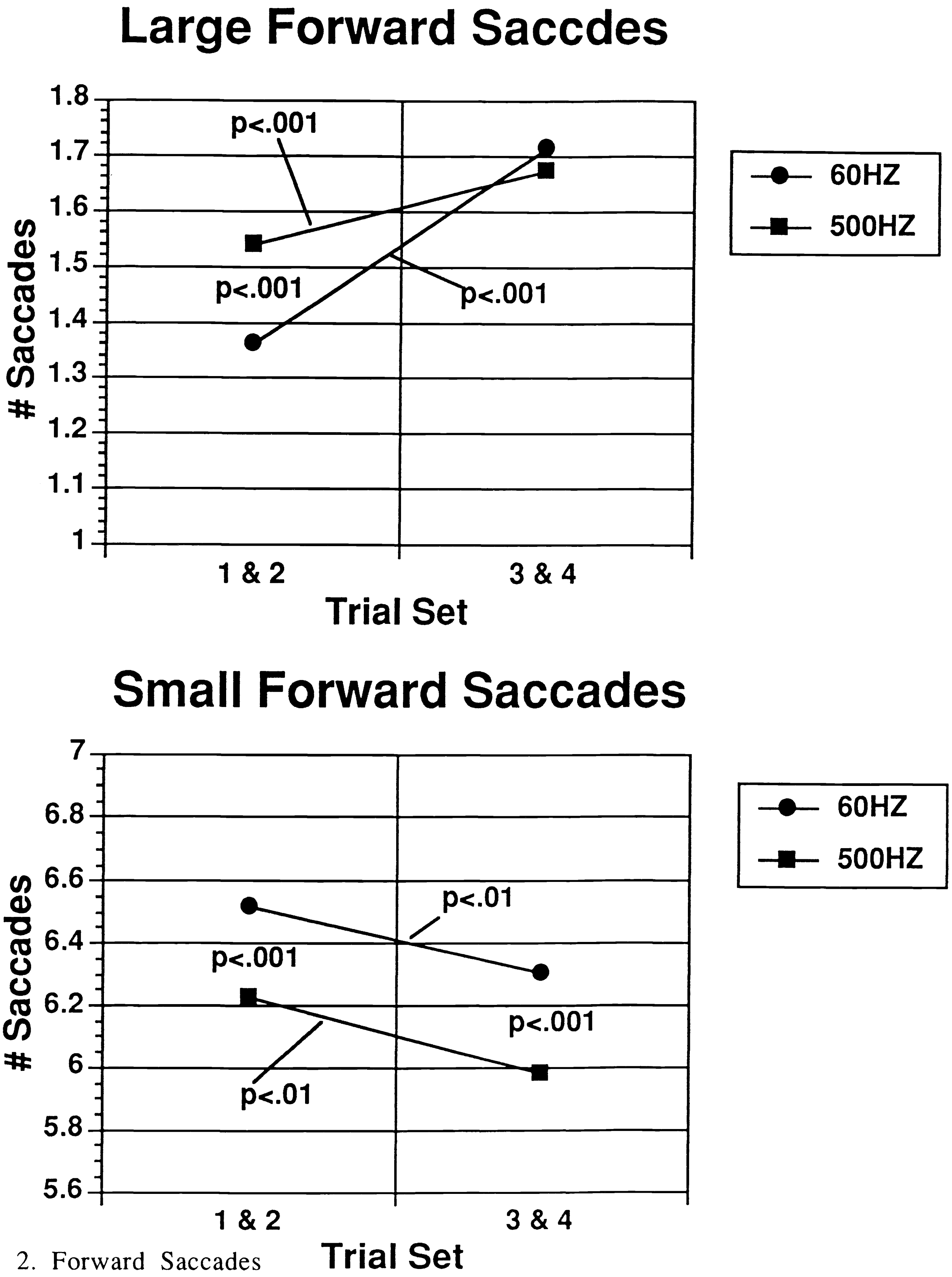
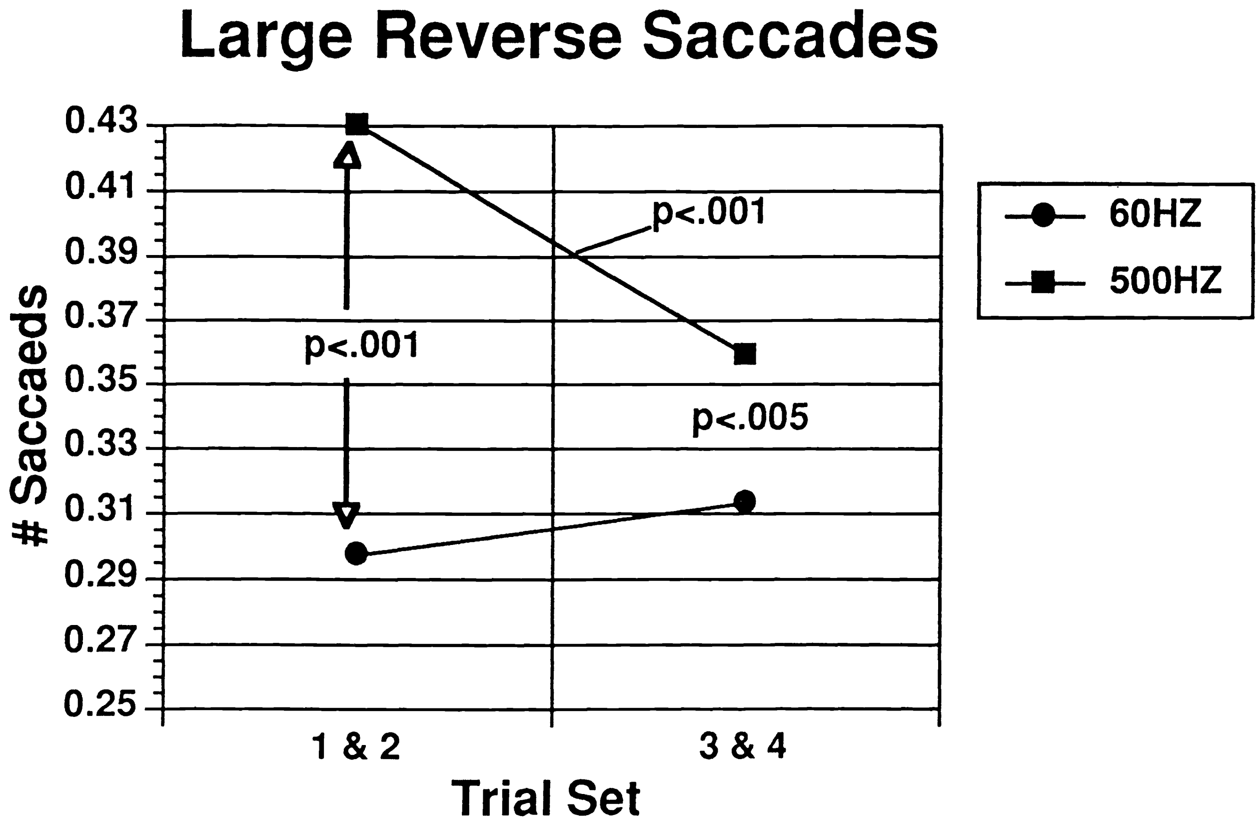


Fig. 2. Forward Saccades



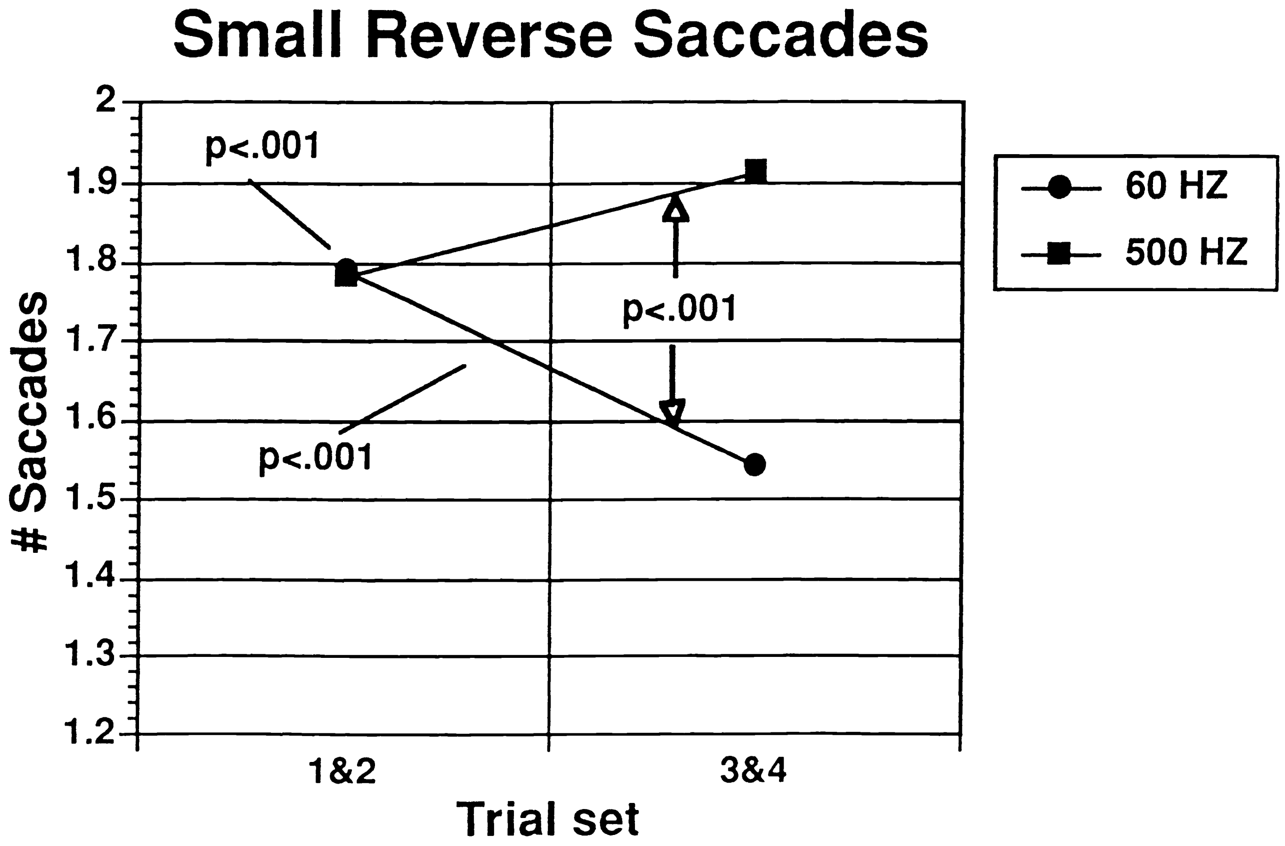


Fig. 3. Reverse Saccades

this analysis, we can predict the reduction in reading rate at any flicker speed (Figure 4). Sampling density alone seems able to account for our initial results. On the basis of these data, we recommend that future CRT displays be designed with a raster frequency of at least 120 Hz. Below this level users pay a significant penalty in reading speed. Above this level gains in reading speed are minor, and technical problems loom larger.

The disappearance of the reading speed difference with practice indicates that the subjects were able to adapt to the sparser sampling at 60 Hz, compensating for it by making more large forward saccades and fewer small reverse saccades. These adjustments in saccade scanning pattern were successful in increasing the reading speed, and represent a sophisticated cognitive adjustment to the adverse sampling conditions. The adjustment of the motor pattern took place entirely at an unconscious level, however, for subjects were unaware that the adjstment was taking place and were unaware even that flicker was being manipulated as they read. The sparser sampling implies that more cognitive processing of the text had to take place, however, and this may be one of the sources of the complaints about fatigue following prolonged use of low-frequency CRT displays.

The finding of an unconscious motor-oriented system engaging in processing separate from the conscious level of perception of the reading material is parallel to other findings that cognitive and sensorimotor systems can process sensory information independently under some conditions[3, 4, 15]. In these experiments subjects were subjected to cognitive illusions of spatial localization by induced motion, the Roelofs effect, or saccadic suppression of displacement. In all three paradigms, reaching toward visual targets remains accurate even though perceived position of the same targets is distorted.

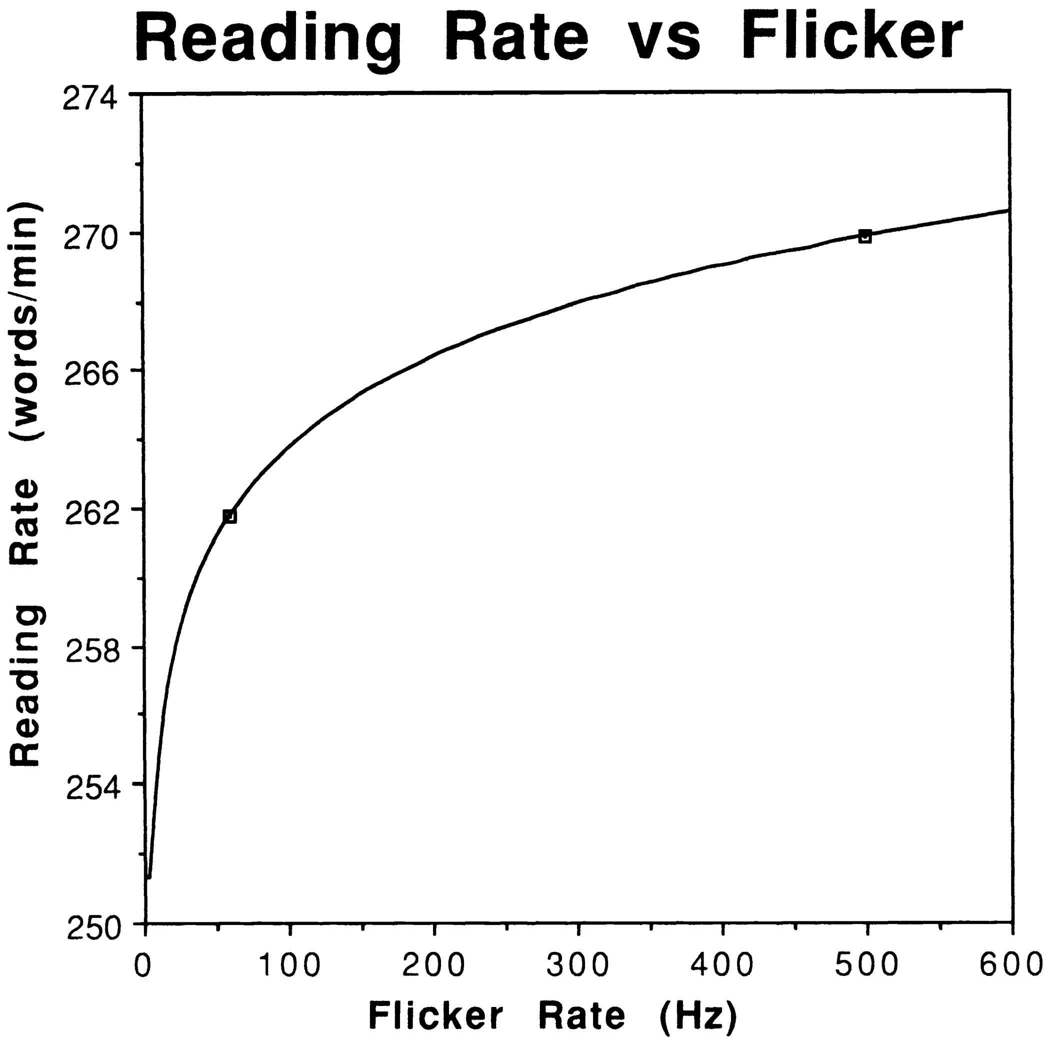


Figure 4. Prediction of reading rates based on the hypothesis that the oculomotor system waits until image information is available, and then immediately starts processing. Predicting the reading rate at 60 Hz from this hypothesis and the 500 Hz data resulted in an experimental error smaller than the size of the symbol.

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