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Blinks, Saccades, and Fixation Pauses During Vigilance Task Performance: II. Gender and Time of Day

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16. Abstract

As operators are required to spend more time monitoring computer controlled devices in future systems, it is critical to define the task and situational factors (i.e., fatigue) that may impact vigilance and performance. Aspects of the gaze system can be monitored relatively unobtrusively, although we used conventional electro-oculographic techniques in this study. Can gaze control measures be used to reflect, and hopefully predict, periods of impaired attention and performance? Gaze control measures (blinks, saccades, and fixations) were recorded while subjects performed on an air traffic control simulation task. Twenty-five subjects performed the task for 3 days at 2 successive hours per day. Blinks and saccades were sampled for 5 consecutive minutes after 10, 30, 50, 70, 90, and 110 minutes of task performance. Significant Time-On-Task (TOT) effects were obtained for all of the 13 variables abstracted. A number of main effects for DAY and a number of interactions involving DAY were significant. TOT effects were obtained for blink rate, blink closing duration, 50% window, blink amplitude, long closure duration blinks, eye closure frequency, blink flurry frequency, number of blinks part of flurries, saccade rate, saccade amplitude, fixation duration, long duration fixations, and performance decrements.

The changes in blink frequency and other blink attributes are interpreted within a framework suggesting a breakdown of inhibitory control as a function of TOT. We believe that this TOT effect is not a tonic one, i.e., a steady decline in the ability to inhibit, but a phasic process, in that periods of poorer inhibitory control increase in frequency and duration as a function of TOT. This conceptual model is akin to one proposed by Bills (1931) dealing with performance "blocks."

Performance declined as a function of TOT but improved over days of task performance. This improvement is mirrored by changes in blink parameters, suggesting that the task had become easier to perform.

17. Key Words

Fatigue	Blinks
Eye Movements	Vigilance
Time-on-Task	

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BLINKS, SACCADES, AND FIXATION PAUSES DURING VIGILANCE TASK PERFORMANCE: II. GENDER AND TIME OF DAY

INTRODUCTION

It has long been our conviction that the gaze control system should reflect time-on-task (TOT) or "fatigue" effects. The literature on which that conviction is based is, at best, spotty. Many occulometric measures have been tested for their ability to detect "fatigue" effects. Most have been found wanting, with respect to reliably demonstrating such effects. For example, the literature on Critical Flicker Fusion Frequency (CFF) as a measure of fatigue finds more studies claiming the absence of an effect than those which report a decrease in CFF as a function of "fatigue." Similarly, studies of steady state, high frequency, brain-evoked response following (i.e., the brain, especially the visual cortex, is "driven" at the frequency or harmonic frequency of the flashed light) in response to sinusoidally (or other waveform) modulated light have occasionally found a reduction in the peak frequency at which such "driving" occurs, but again, the literature is weighted in favor of not finding significant TOT effects. (TOT and "fatigue" effects will be used synonymously.)

It is our contention that TOT effects are best measured while performing the task on which the subject has been "fatigued." Barlett (1943), whom we will quote more fully later, indicated that any change in the nature of the task a subject is required to perform will produce a return to normal or better than normal responding. The fact that recovery from "fatigue" is rapid, though such recovery may be short-lived, has been known for many years, but not appreciated by many investigators who have studied fatigue effects by evaluating, for example, changes in CFF as a function of interposed "work."

Bills and McTeer (1932) report that recovery from fatigue induced by specific task performance is a function of similarity between the condition under which fatigue was induced and the task in which the effect of fatigue is evaluated. The more dissimilar the tasks, the greater the recovery.

Thus, a 2- or 5-minute CFF task administered seconds or minutes after the end of an exhausting 8-hour work day may not show any changes in CFF. Many researchers dealing with aspects of visual activity have reported that a relatively slight change in an experimental situation produced marked changes in the variable under investigation. Ponder and Kennedy (1927) have demonstrated this, for example, for eye blink frequency. ***Thus, we believe that the optimal strategy for demonstrating TOT effects is to record biological variables while the subject is performing the task.***

A second constraint imposed by us in much of our research on aspects of vigilance is that we wish to utilize measures which, if they proved useful in simulation environments, could be readily transferred to field settings. We contend that techniques which remain dependent on the application of electrodes are not acceptable in field settings, both because of technical skills required for the application of electrodes, and non-acceptance of attachment of electrodes on the part of operators.

Thus, rather than recording brain activity (because we are interested in mental "fatigue" and the brain is presumably the place where such fatigue would be best manifested), which for the foreseeable future will require the application of electrodes to the scalp, we selected gaze control variables and the eye blink. Many components of such variables can be recorded without the application of electrodes. Another concern was with "ecological validity." It seemed to us that the air traffic controller's task is visually demanding. Measures that reflect what the eyes are doing would seem to be relevant in generating useful information in subjects performing such tasks for extended periods of time.

Prior research from our laboratory has demonstrated that both frequency and other components of blinking are sensitive to task demands, as well as TOT manipulations (Orchard & Stern, 1991; Fogarty &

Stern, 1989; Goldstein, Bauer & Stern, 1992; Stern, Beideman & Chen, 1976; Stern & Skelly, 1984). We were, thus, reasonably optimistic about demonstrating such effects in the present context. With respect to saccadic eye movements, fixation pauses, and other eye movements, the results from the literature were less reassuring. However, there is evidence of both drug and "fatigue" induced changes in saccade duration and velocity, and in long duration fixation pauses in situations requiring frequent gaze shifts. We thus believed that these measures would also be sensitive to TOT demands.

In the current study, our initial concern was not with identifying gaze control inefficiencies specifically associated with missed signals, but with changes in such variables as a function of TOT. We suspect that some, but not all missed signals, are associated with gaze control inefficiencies. We are also convinced that, if an event to which a rapid response is required occurs concurrent with a period of gaze control inefficiency, then the likelihood is great that the response to that signal will be inappropriate, or that no response will be made. We suggest that most, if not all gaze control inefficiencies, when they occur concurrent with the need to detect and process infrequently occurring information will lead to inappropriate responding. The converse is not true: Inappropriate responses can occur in the absence of gaze abnormalities.

What do we mean by "gaze control inefficiencies," a concept we have introduced a number of times above? We are now on shaky grounds, and to mix metaphors, will climb out on a limb and identify some possible measures.

a. EYE BLINK

Eye blink frequency

Eye blink frequency is related to the visual demandingness of a task. The average blink rate during reading is significantly lower than during rest. Thus, an increase in blink rate during reading and other task performance might index such inefficiency.

Closure duration of blink

Obviously, if an important event occurs during a limited time period and that period is occupied by a blink, the event will be missed when the lid is closed for long, as compared to a short period.

b. EYE CLOSURES

Eye closures are identified if lid reopening, following a closure, does not occur within one-half second. It is obvious that no visual information can be acquired if the eyes are closed.

c. EYE MOVEMENTS

Saccades

Saccade velocity decreases as a function of a number of variables, including TOT. Since information intake for a period preceding, during, and following a saccade is limited (saccade suppression), such intake is likely to be restricted for a longer period of time when saccade duration is extended.

d. COMBINATIONS OF THE ABOVE MEASURES

For example, blinks and saccades.

Blinks and saccades generally occur in tight temporal relationship to each other. If blinks begin to appear with greater frequency during fixation pauses, it might indicate inefficiency. During a blink there is a period of non-seeing, and during a saccade there is also a period of minimal information intake. If the two occur concurrently there is a reduction in the time for which information is not available.

These then, are some examples of gaze control inefficiencies. The model we entertained to account for the increase in missed signals as a function of TOT is, in many respects similar to that proposed many years ago by Bills (1931), and accounts for delayed or missed responses using the concept of "blocks." Bills demonstrated such "blocks" in subject paced tasks. Others (Teichner, 1968) have extended the concept to more complex and not necessarily subject paced tasks. Stave (1977) described blocks in helicopter pilots flying a simulator for several hours. Others (Oswald, 1962 and Williams, et al., 1959) have described similar blocks and invested them with the label "microsleep" or "daydreaming." More recently Kecklund and Akerstedt (1993) have suggested that during vigilance task performance one sees short bursts of EEG alpha or theta activity suggestive of sleepiness. These "bursts" are best seen during the last 2 hours of task performance, and have been reported in studies on long haul truck drivers, train engineers, process operators, as well as in laboratory investigations.

We contend that periods of microsleep and, perhaps, precursors to such periods can be identified from a study of gaze control variables. In prior research (Stern, Goldstein and Walrath, 1984 and Lobb and Stern, 1986), we have demonstrated oculometric variables associated with the operator missing signals. Morris (1984) demonstrated a significant relationship between performance measures associated with flying a GAT-1 simulator for an extended period of time, and aspects of blinking. This work was done in sleep deprived subjects, and one might invoke the concept of microsleep to account for at least some of the results. Thus, gaze control measures may well be effective in demonstrating TOT effects, and such effects may be related to performance deficits.

Whether speaking of blocks, microsleep, or daydreaming we suspect that, during such periods, attention is diverted away from the task at hand. Such periods of inattention should be reflected in gaze control variables in tasks that are visually demanding. Visually demanding tasks require that major portions of the attentional "resources" available to the operator are focused on the task. One thus has to inhibit attending to other aspects of the external or internal environment. We believe that the inability to maintain inhibitory control over attending to other sources of information leads to lapses in attention, and that such lapses in attention to the task are reflected in "gaze control inefficiencies," some of which were described above.

This study is a follow-on to an earlier study using an identical experimental protocol (Stern, Boyer, Schroeder, Touchstone, and Stoliarov, 1994). In the earlier report, the issue of Gender and Time of Day at which the subjects participated was confounded. To resolve questions that were raised regarding the effects of those 2 variables and interactions with certain of the gaze measures, additional data collection was initiated. Thus, the present study is based on data gathered from 12 new subjects and 13 subjects who were included in the previous report. This provided for a more complete and conclusive determination of the role of Gender and Time of Day in changes that occurred in the gaze measures during performance of the vigilance task.

METHODS

Subjects

Twenty-five paid subjects (12 male, 13 female) performed the air traffic control (ATC) task (described below) on 3 separate occasions, 2 hours on each occasion. Half of the subjects performed the task starting at 9 a.m.; half started at 1 p.m. Subject had no prior experience with the task or had been involved in ATC training.

Apparatus and task description

Equipment available to the subject included a 19 inch graphic display terminal, a keyboard attached to the lower right edge and in-line with the CRT, and a joystick. A VAX11/730 computer controlled the display and was used to abstract response information.The task required subjects to continually monitor the CRT display. The display consisted of 2 non-intersecting vectors oriented from the lower right to the upper left side of the CRT. A small rectangle on the flight path defined location of an aircraft (A/C) with 8 A/C displayed on each vector. In an adjacent alphanumeric data block, displayed were A/C identification, altitude, and groundspeed. A/C position and change in alphanumeric information were updated every 6s. The update was done by quadrant, rather than by vector; thus, the displayed information seemed to be continually changing. Subjects were asked to identify and respond to 3 infrequently occurring events:

a) A nontracked unidentified A/C appeared on the CRT as a steady green triangle;

b) An A/C lost altitude information with the numbers reflecting altitude replaced by three X's (XXX); and

c) Two A/C on the same flight path were at the same altitude.

The operator identified the latter event by pressing the appropriate button on the control panel and then returned gaze to the display to determine if the A/C were flying toward or away from each other. If they were flying away from each other, a control button had to be pressed and no further response was required. If, however, they were flying toward each other, the operator was required to press a "conflict" button and to use a joystick to place a cursor over one of the A/C and request reassignment of altitude. If the operator did not detect these latter events within 28s from onset both a visual and auditory "conflict alert" occurred. The visual alert consisted of the 2 A/C targets at the same altitude flashing, the auditory alert presented concurrent with the visual one was a 600hz, 65dB tone pulsed at 2 per s. Forty-four such events were presented over the 2-h period. The minimum interevent time was approximately 1.5 m, the maximum about 4m . Background "noise" consisted of a recording of "normal" activities in an ATC facility.

EXPERIMENTAL PROCEDURES

Subjects were instructed about the task. Each subject participated in three 2-h sessions, approximately 1 week apart. They were given short practice sessions to familiarize them with the task, the nature of the alarms, etc. Rating scales dealing with feelings of attentiveness, tiredness, strain, boredom, and irritation were administered both before and after the 2-hour session. At the end of the 2-h session, additional rating scales relating to perceived task difficulty and amount of effort required to perform the task were completed. The results of the rating scale analyses are not included in this report.

Subjects were prepared for the recording of both horizontal and vertical electrooculograpy by attaching AgAgCl electrodes to the outer canthi of the 2 eyes for the recording of horizontal, and above and below the right eye for the recording of vertical eye movements and blinks. Inter-electrode impedance was generally below 10000 ohms. Where that was difficult to achieve, we made sure that the impedance between the electrode pair from which activity was recorded was approximately the same, when measured against an indifferent electrode. Signals were amplified, with special purpose high common mode rejection amplifiers. Amplifier output was linear from DC to 100hz. The output of these amplifiers was fed into a Kyowa data logger.

The taped data were then digitized and 5-m samples were obtained starting at minute 10, 30, 50, 70, 90, and 110. Data were sampled at either 200 or 100 hz, with all analyses conducted on data sampled at 100 hz. Data analysis utilized a DEC minicomputer and was done semiautomatically, in that a skilled analyst applied our computer based algorithms for detecting eye blinks and saccadic eye movements to the data, and performed editing functions as necessary.

Most editing involved the deletion of saccades not meeting our "eyeball" criteria for acceptance as saccades. Major reasons for rejecting computer identified saccades were the occurrence of a burst of muscle artifact, in which the algorithm detected an occasional saccade, saccades followed by a corrective eye movement, and the identification of a slow eye movement as a saccade (compensatory, pursuit or skin potential change). Eye movements were only evaluated in the horizontal plane.

Editing of eyeblinks was a somewhat more involved process if the blink occurred in conjunction with a major eye (and head) movement in the vertical plane. Such movements occurred when gaze had to be shifted from the CRT to the response panel located to the right and on a level with the base of the CRT. Such movements also occurred with return of gaze to the

CRT. Our algorithm for detecting blinks includes, as part of the algorithm, the instruction that if the voltage level following completion of eye closure does not return to half amplitude of the closure in a specified time period (300 msc.) to not consider that voltage change pattern a blink. The computer thus did not identify many blinks associated with gaze shifts from the response panel to the CRT. (An upward rotation of the eyeball produces a voltage change in the same direction as a lid closure.) Eye position higher in the visual plane at the end of a blink than it was before blink initiation precluded this criterion from being met. These blinks were manually identified by setting blink initiation at the same voltage level obtained after the eyes reopened. These blinks were thus measured as smaller in amplitude and shorter in duration than was really the case.

Some aspects of eyelid motion were manually abstracted. One of the criteria for blink identification requires the operator to set limits to the time between half closure and half reopening. The limit was 300 msec. for this data analysis. If a closure-reopening was not identified on the basis of this criterion and the above process took less than half a second, the event was labeled a long closure duration blink (LCD blink) and independently logged on a data sheet. If the closure-reopening took more than half a second and was accompanied by no horizontal eye movements or slow pendular eye movements, it was identified as a lid closure and its occurrence and approximate duration abstracted.

The editing process allows for the inspection of 1000 consecutive data points in a number of channels. The data were thus edited in 10-s chunks, a time-consuming, but necessary procedure. Five consecutive minutes (or 30 ten second frames) of data were analyzed; the output of this analysis and summary statistic printed. Data from the summary statistics were used for all analyses, except for the blink flurry analysis and the analyses incorporating manually edited and added information. The blink flurry analysis was manually abstracted from the computer print-out of the raw analyzed data.

Measures abstracted and hypotheses concerning change as a function of TOT:

1. Blink rate (average number of blinks per minute).
   Hypothesis: Significant increase.
2. Blink closing duration (average time from blink initiations to full closure).
   Hypothesis: Significant increase in blink closing duration.
3. 50% window (average time from lid being half closed during closing portion of blink to reopening to same level).
   Hypothesis: Significant increase.
4. Blink amplitude.
   Hypothesis: None.
5. LCD Blinks (blinks with 50% window measure between 200 and 500 msec).
   Hypothesis: Increase in frequency of such blinks.
6. Eye closures (frequency of closures in excess of 500 msec).
   Hypothesis: Increase in frequency.
7. Frequency of flurries (a flurry was defined by the occurrence of 3 or more blinks in 3 consecutive seconds).
   Hypothesis: None - post hoc measure.
8. Percent of blinks that are part of a flurry. (Blinks that are part of a flurry divided by all blinks).
   Hypothesis: None - post hoc analysis.
9. Saccade rate (average number of saccades per minute).
   Hypothesis: Reduction in rate.
10. Median saccade amplitude.
    Hypothesis: None.
11. Median fixation duration.
    Hypothesis: Increase in median fixation duration.
12. Fixations in one second time bins.
    Hypothesis: Shift toward longer duration fixations.

TABLE 1
SUMMARY OF ANOVA RESULTS

	MAIN EFFECTS					2 WAY INTERACTIONS								3 WAY I.	
	G	TD	D	TOT	F	Gx TOT	Gx TD	Gx D	Dx TOT	Dx TD	TDx TOT	Dx F	TOTx F	Gx Dx TOT	Gx TDx TOT
BL RATE	.019		.009	.001					.100						
BL CLOSING DURATION			.024	.001					.058					.082	
BL 50% WINDOW				.002				.061	.057					.081	
BL AMPLITUDE				.044										.035	
BL LCD FREQUENCY				.001			.070								.030
EYE CLOSURE FREQUENCY			.015	.046						.011	.071				
BL FLURRY FREQUENCY				.008					.035	.081				.043	
# BLINKS IN FLURRIES				.016					.037					.032	
SACCADE RATE				.001						.081					
SACCADE AMPLITUDE	.003			.001		.011	.014								
FIXATION DURATION				.001											
FIXATION IN 1 SEC TIME PDS				.001	.001							.044	.001		
MISSED EVENTS		.079	.001	.001											
R.T. 1		.019	.004	.001											
R.T. 2	.017		.004				.010								

RESULTS

All analyses utilized ANOVA with 2 within (TOT and Day) and 2 between subject variables (Time of Day and Gender).

Table 1 presents summary data for the 12 ANOVAs involving oculometric measures and the 3 analyses involving aspects of performance. Only effects significant at the p < .05 level will be discussed, though Table 1 presents all effects significant at the p < .10 level and under. Significant TOT effects were obtained for all oculometric and 2 out of the 3 performance variables. As will be described below, these effects were the most robust, with 10 of the 13 analyses significant beyond the .01 level. There were 3 main effects attributable to Gender, 1 to Time of D and 6 to D. Significant 2-way interactions were obtained as follows: 1 for GxTOT, 2 for GxTD and DxTOT, and 1 for DxTD. Significant 3-way interactions were obtained as follows: 3 for GxTOTxD and 1 for GxTOTxTD.

One of the analyses of oculometric variables, involving the fixation duration variable (F), was somewhat different from the above analyses in that fixation durations were classified into fixations less than 1s in duration, those between 1 and 2, 2 and 3, and greater than 3 s in duration. This then became another within-subject variable for these analyses. A significant F was obtained for TOT and significant 2-way interactions involving the DxF and TOTxF variables. The analyses of performance variables averaged these measures over 4 successive 30-m periods.

For most significant results, we have provided figures to describe the effect.

I - BLINK RATE

The significant Gender effect (F(1/21)=6.43, p<.019) is attributable to females blinking significantly more frequently than males. Average blink rate for females was 19.3, while that for males was 12.3 blinks per minute. The significant D effect (F(2/42)=5.30, p<.009) is depicted in Figure 1. There is a significant increase in blink rate over days. Average blink rate on D 1 is approximately 14.5 blinks per minute, and on D 3 is somewhat in excess of 17 blinks per minute.

The significant TOT effect (F(5/105)=12.70, p<.0001) is accounted for by a consistent increase in blink rate from the first to the last sample. These results are presented in Figure 2. It appears that the slope of the blink rate change between successive samples is reasonably constant, with the exception of the shift between the 50-and 70-m samples. The 70-m sample shows a considerably smaller increase than one would expect extrapolating from the previous data points. There were no significant interactions involving the blink rate measure.

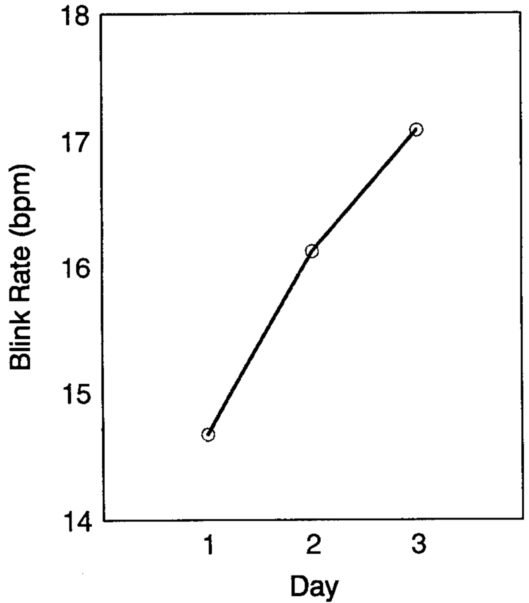

Figure 1. Blink rate as a function of Day.

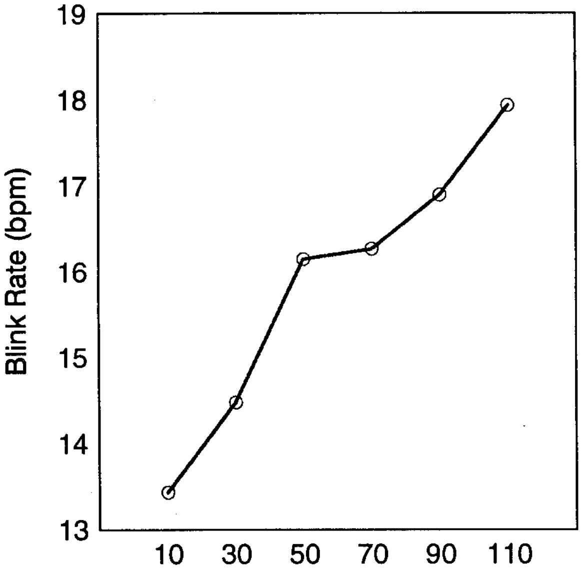

Figure 2. Blink rate as a function of Time on Task.

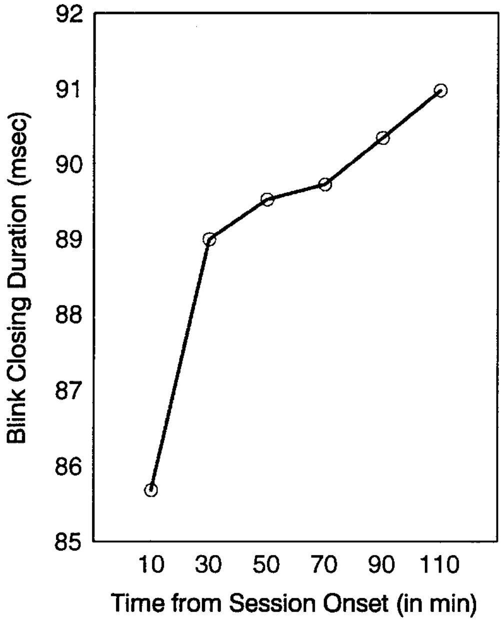

Figure 3. Blink closing duration as a function of Time on Task.

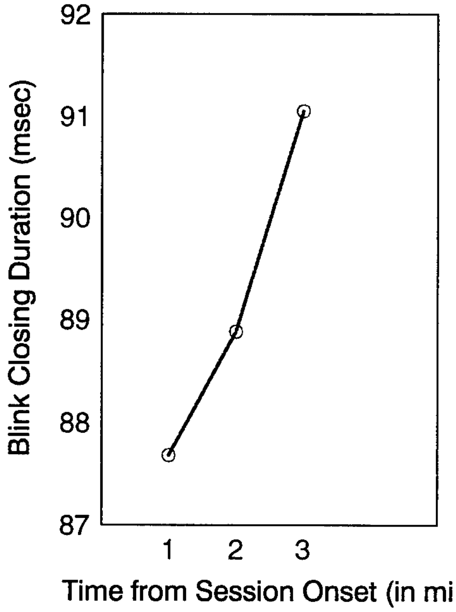

Figure 4. Blink closing duration as function of Day.

II - BLINK CLOSING DURATION

Blink Closing Duration is the time between blink initiation and the lowest point reached by the lid during a blink. There were 2 significant main effects and no interactions. The TOT effect (F(3.66/76.94)=5.98, p<.001) is depicted in Figure 3, the D effect F(1.29/27.18)=4.09, p<.024) in Figure 4. The major shift in the TOT measure occurs between the 10- and 30-m periods, followed by a smaller but linear slope increase over the remaining time periods. The increase over days is, as depicted in Figure 4, small, but linear.

III - BLINK 50% WINDOW

The 50% window measure is the time between the lid being half-closed during the closing portion of the blink and crossing that same level during the reopening phase. There was a significant TOT effect (F(3.91/82.03)=4.87, p<.002). Figure 5 depicts this effect. There is a linear increase in the 50% window variable. Average window duration at 10 m into the recording is approximately 122 ms and 129 ms at time 110 m. There was a 2-way interaction (significant only at p < .06 level) in which females show a consistently lower level over days and less of an increase over days than males. Though not significant, this interaction is depicted in Figure 6.

The D by TOT interaction (F(8.99/188.87)=1.88, p<.057) is depicted in Figure 7. Ds 1 and 2 start at a lower level and demonstrate similar patterns, while on D 3, the increase over time blocks is markedly attenuated.

IV - BLINK AMPLITUDE

The significant TOT effect (F(3.52/73.96)=2.70, p<.044) is displayed in Figure 8. There is a steady increase in blink amplitude over time blocks, with the largest increments occurring late in task performance.

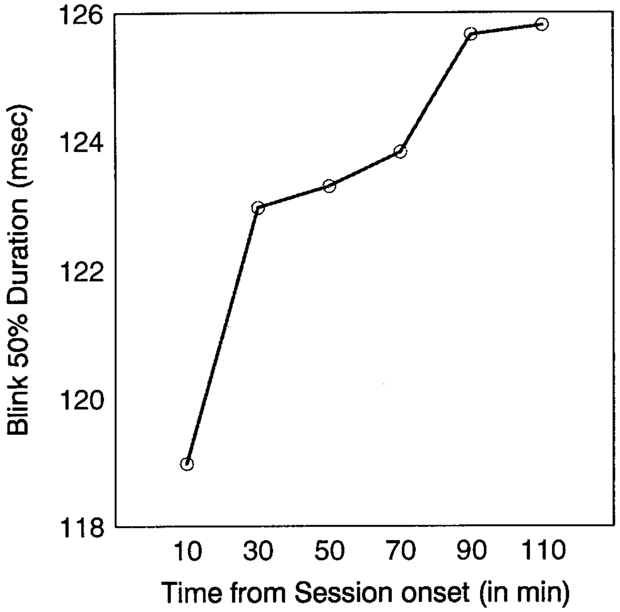

Figure 5. Blink duration (50% window) as a function of Time On Task.

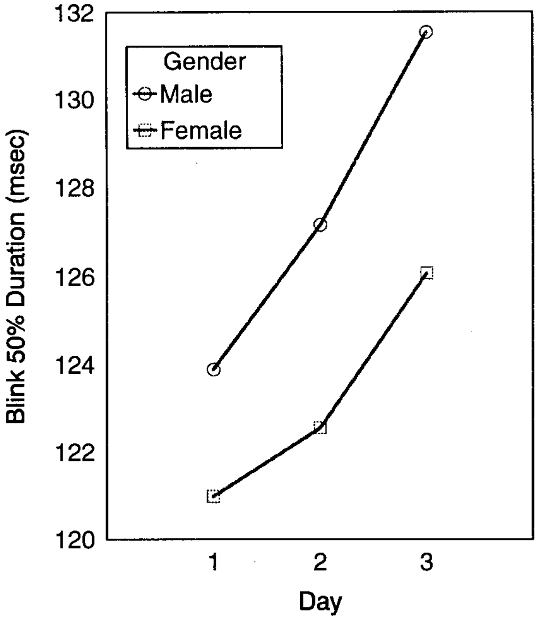

Figure 6. Blink duration (50% window) as a function of Day and Gender.

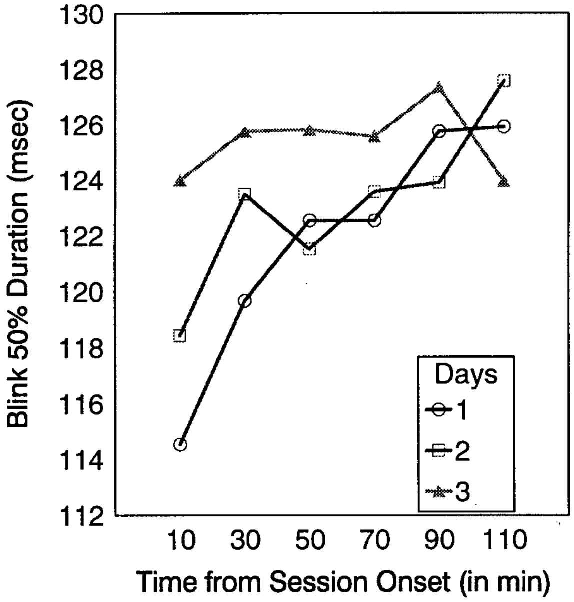

Figure 7. Blink duration (50% window) as a function of Day and Time on Task.

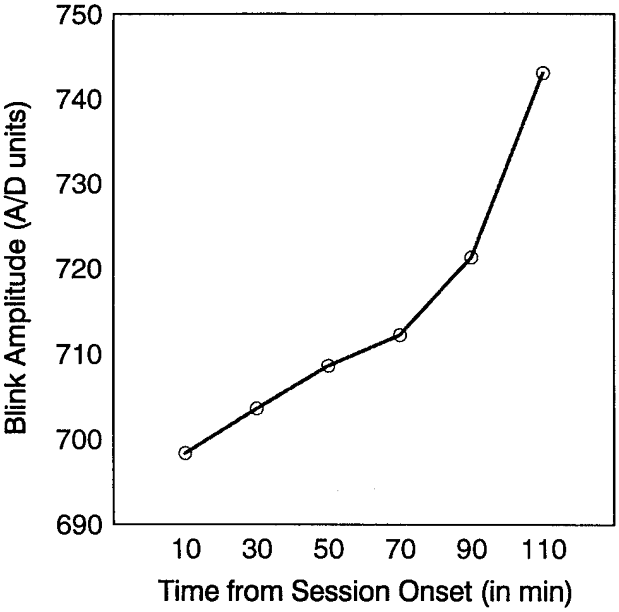

Figure 8. Blink amplitude as a function of Time on Task.

The significant 3-way interaction of GxTOTxD (F(7.37/154.7)=2.19, p<.035) is depicted in Figure 9. For male subjects, blink amplitude appears to be consistently smaller, as compared to females, with the major differences seen on Ds 1 and 3. For females, there is a general increase in amplitude over days. The slope of blink amplitude change over time is steeper for the male than the female groups.

V - LONG CLOSURE DURATION BLINK FREQUENCY

Long closure duration blinks are identified if the 50% closure duration exceeds 200, but is smaller than 500 ms. Blinks with closure durations in excess of 300ms were manually abstracted. Long closure duration blinks increased significantly as a function of TOT (F(3.91/82.07)=6.92, p<.001).

As depicted in Figure 10, the greatest increment occurs between 10 and 30 m, little change between m 30 and 50, and then a return to a continued increase in such blinks over time.

Figure 11 depicts the results of the significant 3-way interaction involving TOTxGxTD (F(3.91/154.19)=2.84, p<.030). The Gender and Time of D components appear to be principally a function of males showing the highest incidence of LCD blinks when run in the afternoon, as compared to the morning. Females, on the other hand, had the highest incidence of LCD blinks when run in the morning. It should be remembered that this effect (AM vs. PM) is a between subjects effect. The TOT component suggests differences in slope between AM and PM runs for both males and females. For males, the steepest slope change occurs in the PM run, while for females, it is found in the group run in the morning. Females participating in the afternoon show little change in this variable over time.

To evaluate whether there was a differential increase in long closure duration blinks compared to the increase in "normal" blinks as a function of TOT, we conducted a further analysis. LCD blinks were expressed as a ratio of all blinks. That data were arc sine transformed and subjected to the same type of ANOVA characteristic of other analysis. No significant effects were obtained, suggesting that the increase in LCD blinks parallels the increase in blinks obtained as a function of TOT.

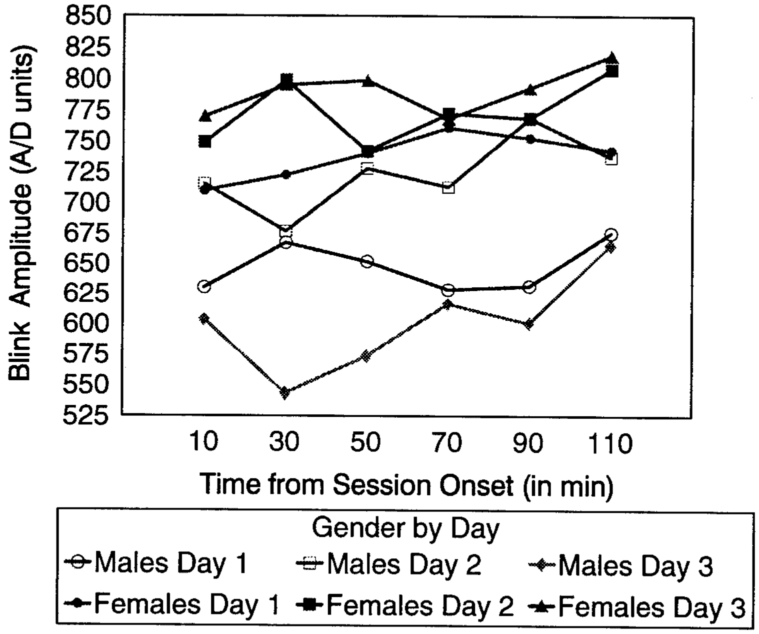

Figure 9. Blink amplitude as a function of Gender, Day, and Time on Task.

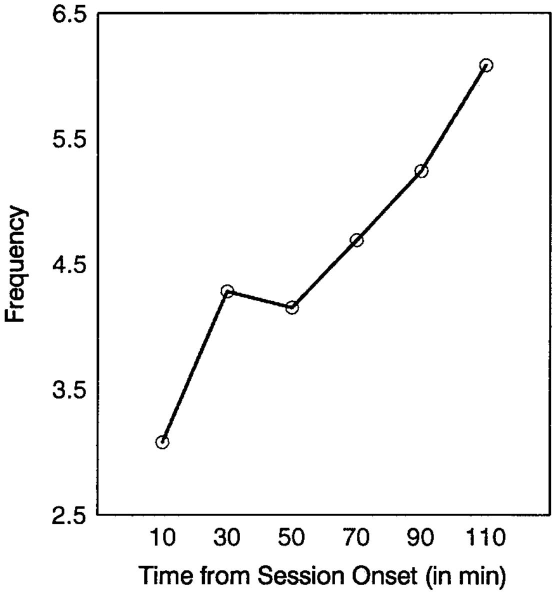

Figure 10. Frequency of long closure duration as a function of Time on Task.

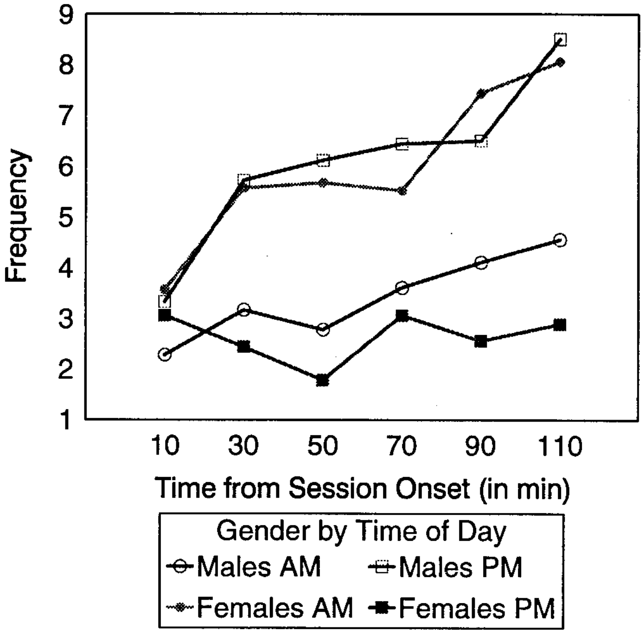

Figure 11. Long closure duration blink frequency as a function of Gender, Time of Day, and Time on Task.

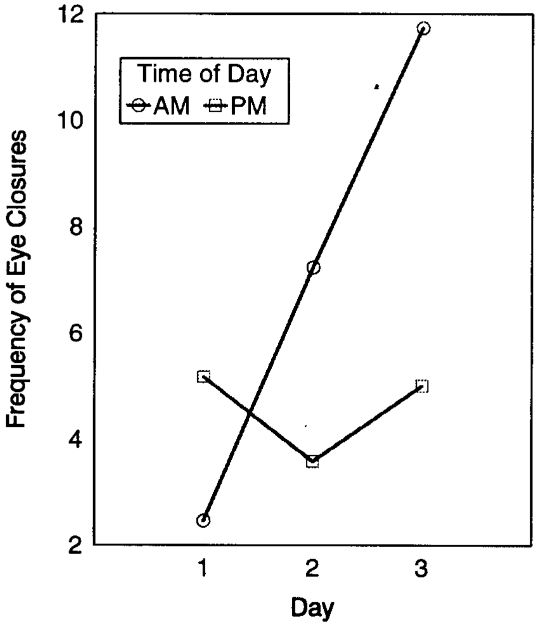

Figure 12. Frequency of eye closures as a function of Day and Time of Day.

VI - EYELID CLOSURE FREQUENCY

Eyelid closures were identified whenever the eyelid remained closed for more than 0.5 seconds. Since lid closures were relatively infrequently occurring events, data were analyzed for the first half, vs. second half of the 2-h session; i.e., data were combined for the 10, 30, and 50 m time samples and for the 70, 90, and 110 m samples. Two significant main effects and 1 significant interaction were found. The significant TOT effect (F(1/21)=4.49, p<.046) is reflected in an average number of closures during the first hour of 5.07, and 6.76 during the second h of task performance. The significant D effect (F(2/42)=4.66. p<.015) coupled with the significant D x TD interaction (F(2/42)=5.00,p< .011) is depicted in Figure 12. There is a significant increase in the frequency of these events over the 3 Ds of task performance. It is principally a function of subjects who participated in the AM.

VII - BLINK FLURRY FREQUENCY

A flurry was tallied if 3 or more successive blinks occurred with an interval of less than 1 s between them. A significant TOT effect (F(4.85/107.92)=3.40, p<.008), a significant 2-way interaction involving D and TOT (F(7.69/161.40)=2.16, p<.035), and a 3-way interaction involving D, TOT, and Gender (F(7.69/161.40)=2.08, p<.043) were obtained. These effects are depicted in Figures 13, 14, and 15, respectively. The effect is accounted for principally by increases in flurry frequency from the first to the second time block, and again from the fifth to the sixth one. From 30 m through 90 m, flurry frequency is asymptotic. The significant DxTOT interaction is not readily identifiable from the graph. It is most likely a function of slope differences between D 1 and the other 2 Ds. The DxTOTxG interaction is accounted for by the greater incidence of flurry activity for females, as well as slope differences. For all 18 (3x6) data points, mean flurry activity is greater for the female, as compared to data sampled at the same TOT and D for the male subjects.

VIII - NUMBER OF BLINKS IN FLURRIES (per 5min)

We initially analyzed the total number of blinks in flurries. The same variables significant in the Blink Flurry Frequency analysis were again significant. Results for the TOT effect (F(4.78/100.48)=3.00, p<.016) are depicted in Figure 16.

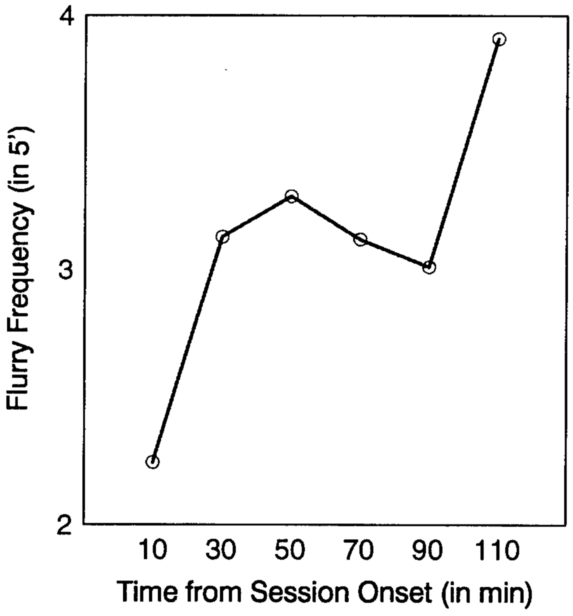

Figure 13. Frequency of blink flurries as a function of Time on Task.

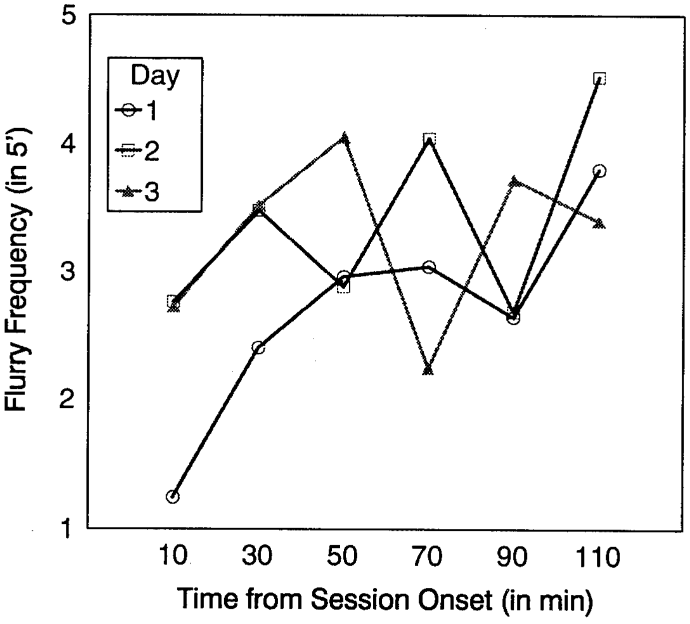

Figure 14. Frequency of blink flurries as a function of Day and Time on Task.

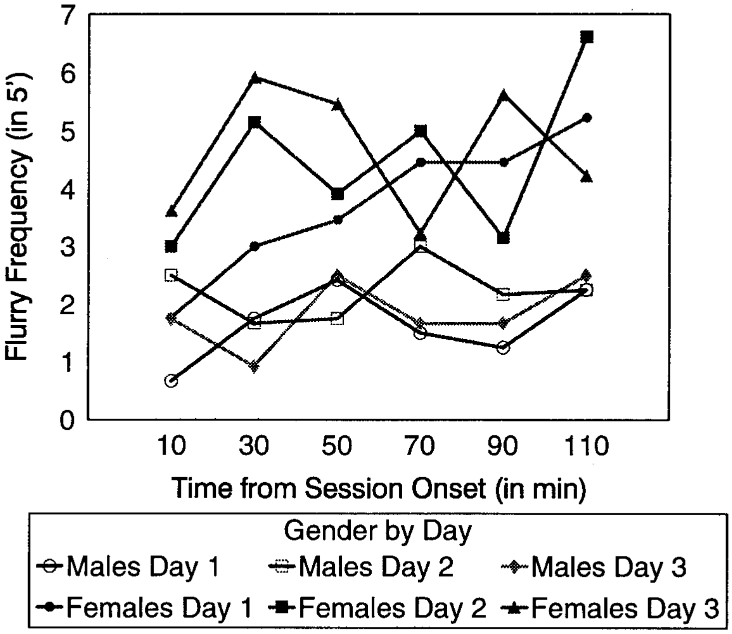

Figure 15. Number of blink flurries as a function of Gender, Day, and Time on Task.

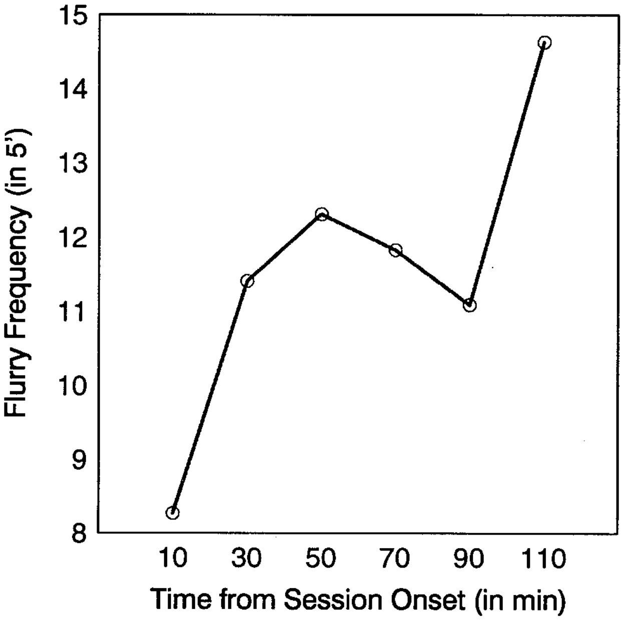

Figure 16. Number of blink flurries as a function of Time on Task.

Those for the D x TOT interaction (F(7.42/155.77)=2.17, p<.037) and the D x TOT x Gender interaction (F(7.42/155.77)=2.22. p<.032) are presented in Figures 17 and 18. Since there were significant effects attributable to flurry frequency and since we were interested in determining whether there was not only an increase in flurry frequency, as a function of TOT, but also whether there was an increase in the number of blinks constituting a flurry as a function of TOT, a further analysis was undertaken. We calculated the average number of blinks per flurry for each subject for each time period, excluding blocks where a subject had no flurries, and a second analysis including such blocks. With these "corrections" to the data, no significant effects were obtained. Thus, there does not appear to be an increase in the number of blinks incorporated in a flurry as a function of TOT.

IX - SACCADE RATE

The only significant effect for saccade rate was a main effect for TOT (F(5/105)=20.66, p<.001). These results are graphed in Figure 19. There is a steady decline in saccade rate from m 10 through m 90, with the m 110 level not appreciably different from the m 90 level.

X - SACCADE AMPLITUDE

There were 4 significant effects for saccade amplitude, 2 main and two 2-way interactions. The main effects were for TOT (F(5/105)=15.57, p<.001) and Gender (F(1/21)=11.71, p<.003). These effects are graphed in Figures 20 and 21. The saccade amplitude effect discriminates the first hour of data collection from the second h in that there is a major increase in saccade amplitude from the 50 m to the 70 m blocks.

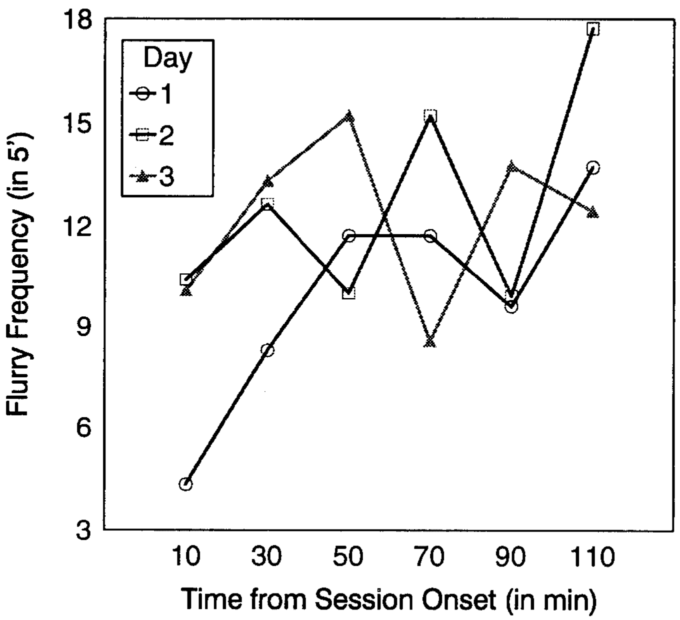

Figure 17. Number of blink flurries as a function of Day and Time on Task.

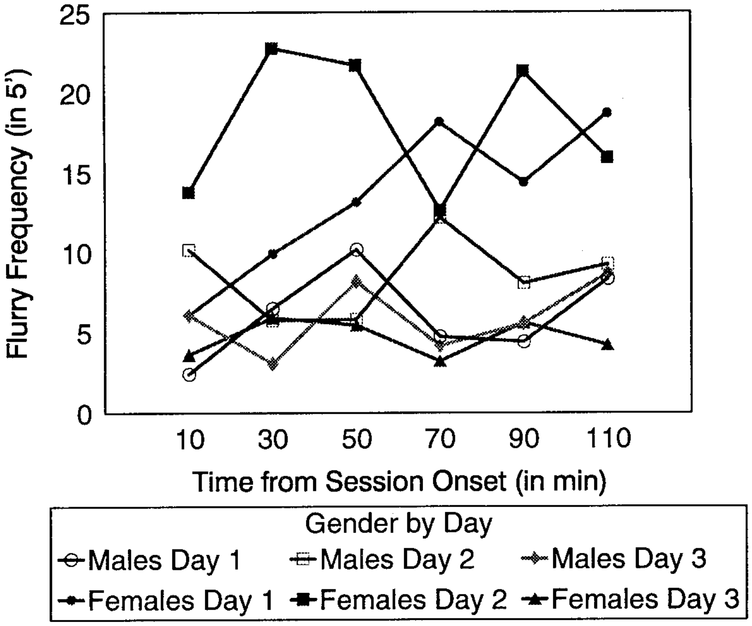

Figure 18. Frequency of blink flurries as a function of Gender, Day, and Time on Task.

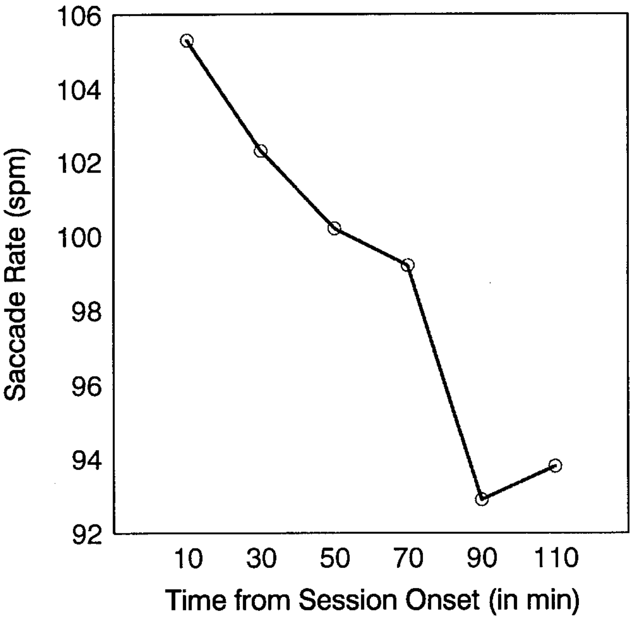

Figure 19. Saccade rate as a function of Time on Task.

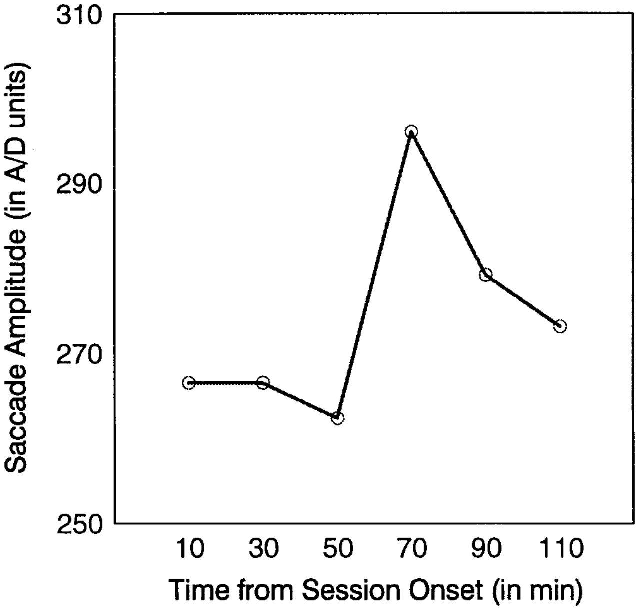

Figure 20. Saccade amplitude as a function of Time on Task.

The gender effect involves larger amplitude saccades for female, as compared to the male subjects. The two 2-way interactions were for Gender x TOT (F(5/105)=3.14, p<.011) and for G xTD (F(1/21)=7.18, p<.014).

Figure 21 depicts the G x TOT interaction, as well as the main effect of Gender. The significant interaction effect involves a greater slope change over time for the female, as compared to the male groups.

The G x TD interaction demonstrates a decrease in saccade amplitude for females run in the afternoon, as compared to the morning hours, while the opposite pattern prevails for the male groups. This effect appears to be quite robust and is graphed in Figure 22.

XI - FIXATION DURATION

Average fixation duration produced a significant TOT effect (F(5/105)=10.05, p<.001). The overall effect is of a steady increase in fixation durations, an effect to be expected from the prior results of declining saccade frequency. The pattern as depicted in Figure 23 is a sawtooth one with the 30, 70, and 110 m samples showing an inversion from the prior sample period.

XII - FIXATIONS IN 1 SECOND TIME BINS

This analysis was concerned with the question of whether the change in fixation pause duration was attributable solely to an increase in average fixation duration, or whether the increase could be attributed to a change in the distribution. Fixations were categorized as falling in the following windows: less than 1 s, between 1 and 2, 2 and 3, and those longer than 3 s in duration. These analyses thus constituted 4x6x2x2x3 in design. The main effect for fixation duration (F) (F(1.15/24.25)=288.96, p<.001) comes as no surprise. By far the greatest number of fixation pauses are less than 1 s in duration.

These results are depicted in Figure 24. The significant TOT effect (F(5/105)=21.83, p<.001) is depicted in Figure 25. There is a decline in short fixation pauses (those less than 1 s in duration) and a slow but steady increase in the other 3 fixation pause duration bins. The TOT x F interaction (F(6.10/128.16)=26.29, p<.001) is also seen in this figure, and is accounted for by the decrease in short duration and an increase in longer duration fixations.

The last 2-way interaction involving D and F (F(6/16)=2.85, p<.044) is depicted in Figure 26. The effect is not readily apparent, but is probably attributable to

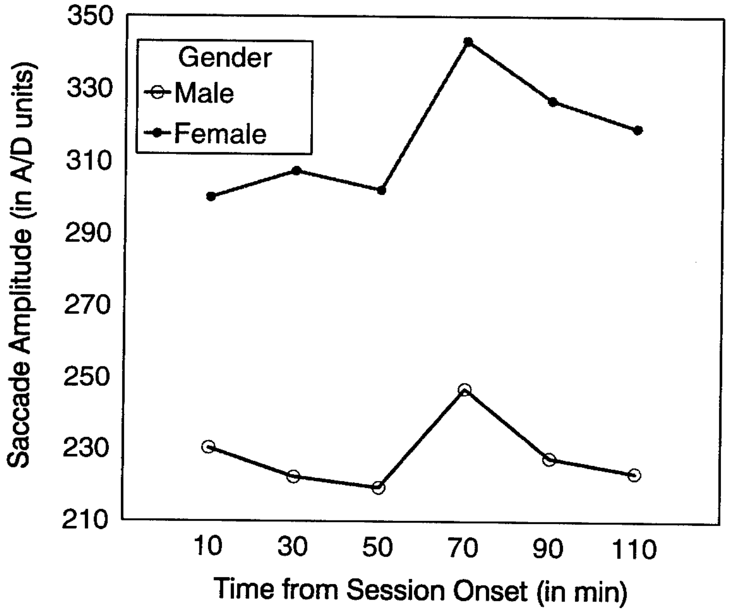

Figure 21. Saccade amplitude as a function of gender and Time on Task.

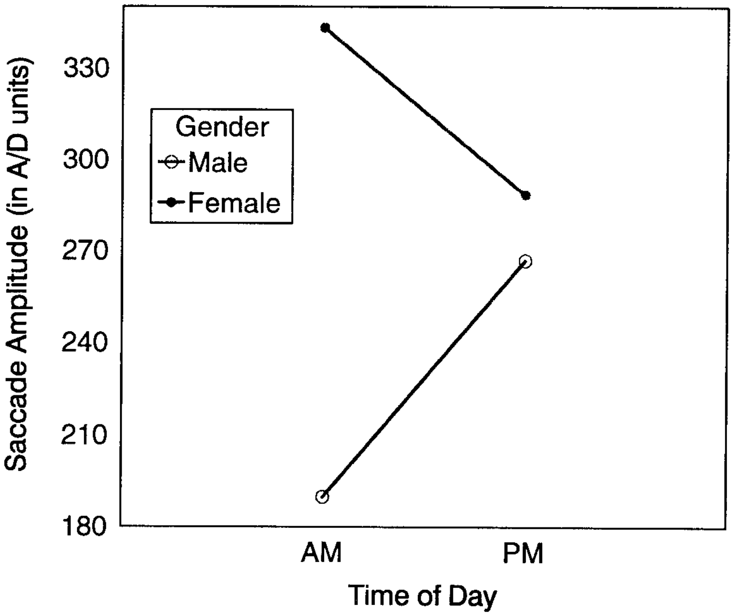

Figure 22. Saccade amplitude as a function of Gender and Time of Day.

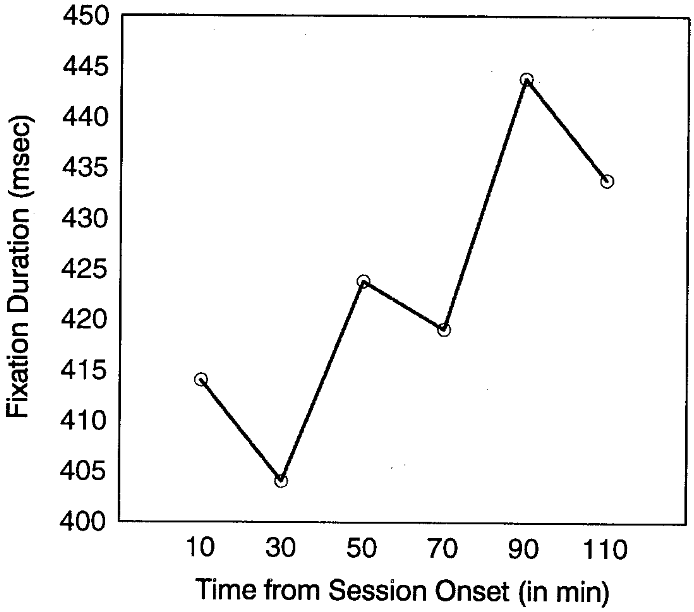

Figure 23. Fixation duration as a function of Time on Task.

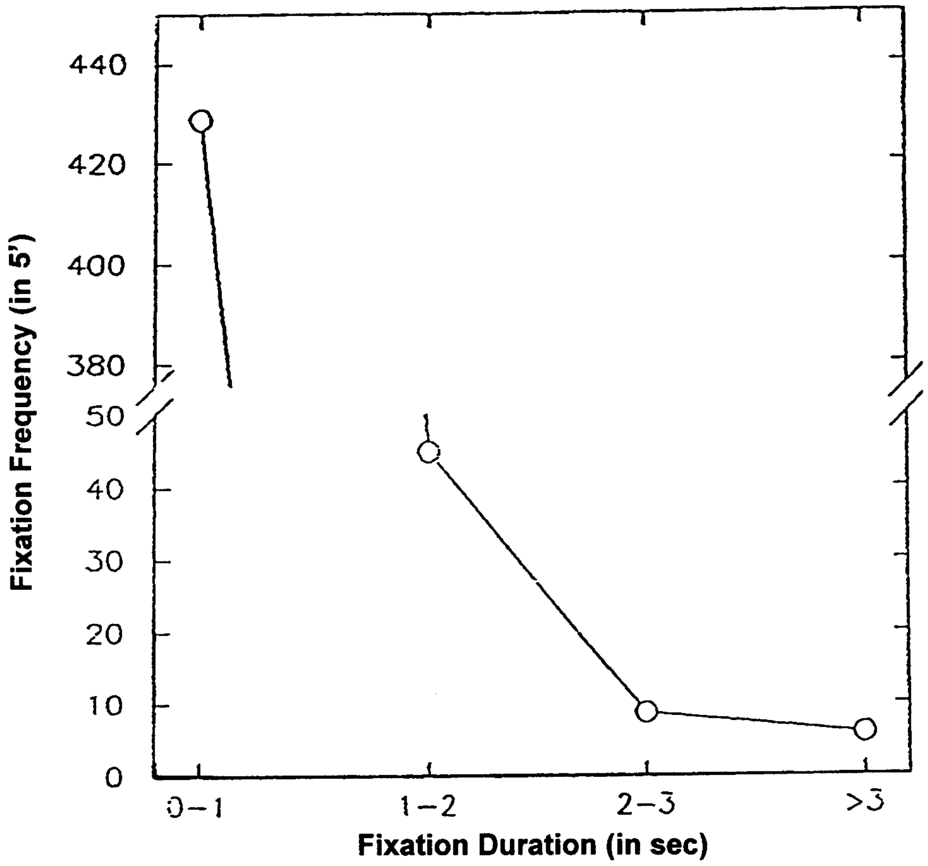

Figure 24. Frequency of fixations in 4 duration bins (0-1 sec, 1-2 sec, 2-3 sec, and > 3 sec).

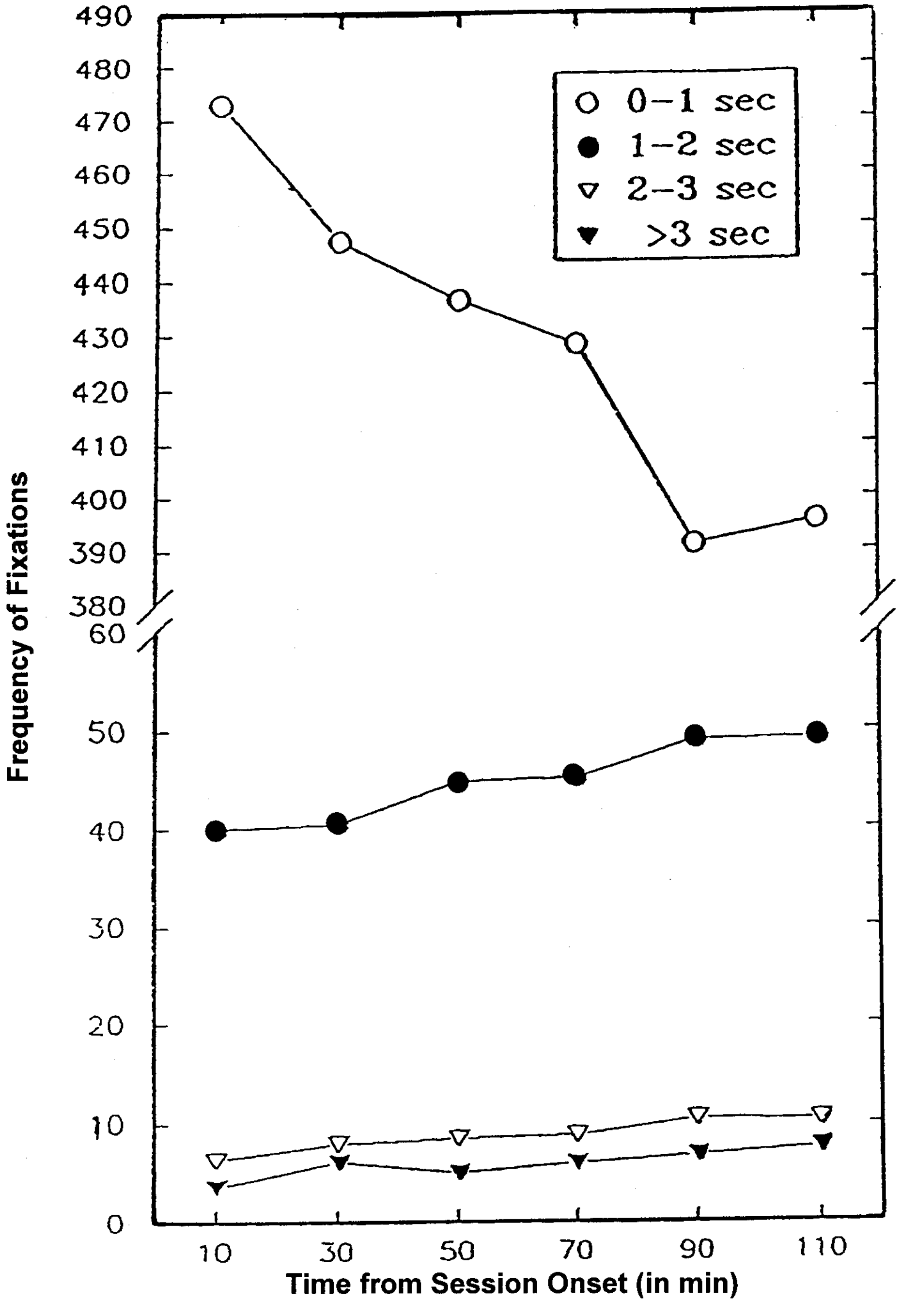

Figure 25. Frequency of fixations in 4 duration bins (0-1 sec, 1-2 sec, 2-3 sec, and > 3 sec) as a function of Time on Task.

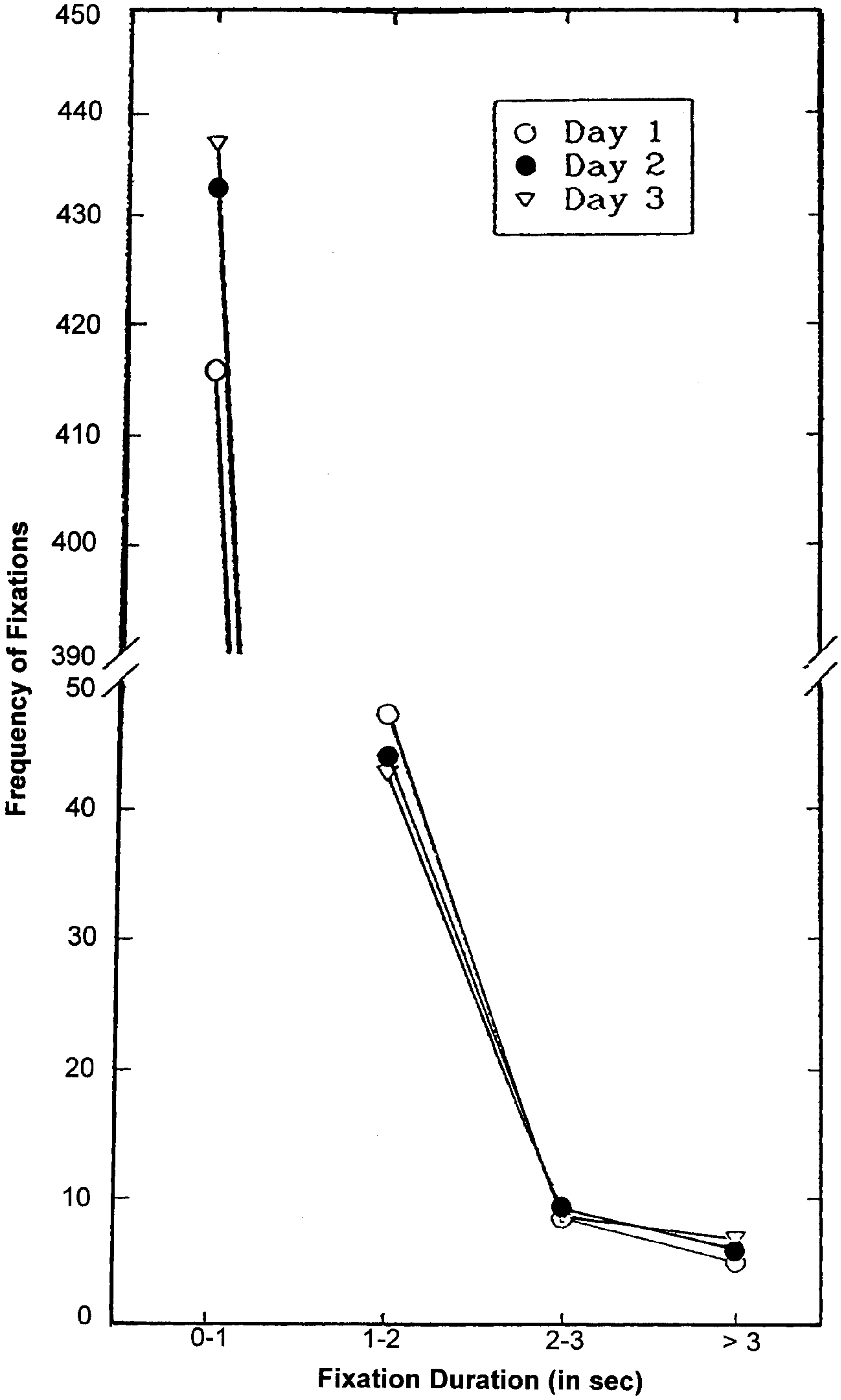

Figure 26. Frequency of fixations in 4 duration bins (0-1 sec, 1-2 sec, 2-3 sec, and > 3 sec) as a function of Day.

the increase in frequency from D 1 to D 3 of fixation pauses falling below 1 s and greater than 3 s, and the consequent increase in total number of fixation pauses over days.

XIII - PERFORMANCE

Three measures of performance were utilized. All demonstrated TOT effects, with 2 also demonstrating D effects. The measures used were: missed signals, and 2 response latency measures. For all 3 measures, data were abstracted for successive 30-m periods, each period containing 11 events requiring a response. The 2 response latency measures were restricted to situations requiring a decision concerning 2 aircraft flying at the same altitude. There were 8 such events in every 30-m period. The first of these latency measures involved the time following presentation of 2 aircraft at the same altitude and the response associated with recognition of that situation. The second response latency was measured from the point in time when the subject had signaled detection of the problem. It signaled the operator's decision that the aircraft were flying toward or away from each other.

Missed events for the conflict-no conflict situation were identified if the subject did not respond to the event within 28 s of its initiation. After 28 s had elapsed, they were "warned" of the event by both an auditory signal, as well as the highlighting of the 2 aircraft at the same altitude.

Unlike the analysis of oculometric variables, where TOT effects were based on data sampled at 6 time intervals; the performance analyses are based on data for successive 30-m periods (4 periods).

a. Missed events

The ANOVA for missed events provided 2 significant effects, a significant TOT effect (F(2.34/49.06)=10.08, p<.0001), and a significant D effect (F(2/42)=9.57, p<.0004). Figure 27 depicts the average number of events missed per 30-m period for each of the 3 Ds of task performance. Two things are readily apparent from this figure: an increase in missed events as a function of TOT, and a reduction in such events as a function of Ds. Differences are also apparent between the AM and PM subjects in that the latter missed fewer events when both TOT and D are taken into consideration. As depicted in Figure 28, for all but 1 of the 24 plotted values (4 time periods by 3 Ds by 2 times of D) the average PM value falls below the AM values.

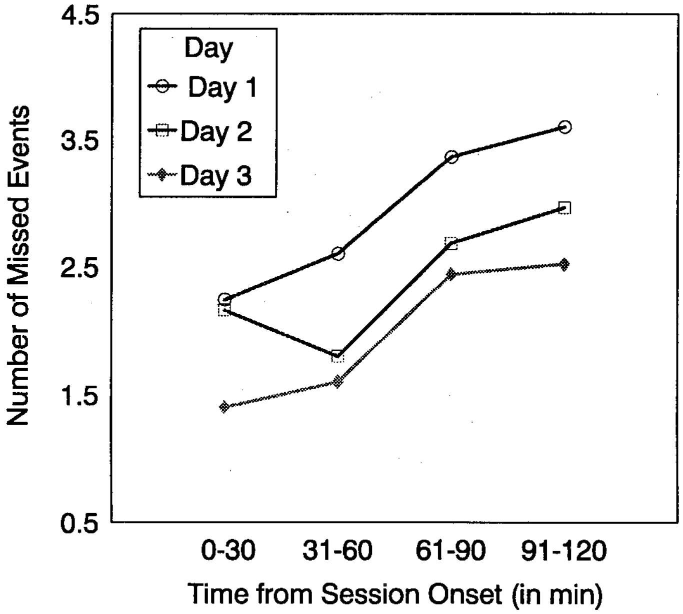

Figure 27. Number of missed events as a function of Day, and Time on Task .

b. Latency of first response

The analysis of reaction time to the first response following onset of 2 aircraft on a vector at the same altitude provided the following significant results. There was a significant TD effect (F(1/21)=6.50, p<.019) with PM latencies shorter than those for AM subjects (AM 17.57 s, PM 15.36 s); a significant D effect (F(2/42)=6.19, p<.004) with decreases in response latencies over Ds (D 1 - 17.53, D 2 - 16.38 and D 3 - 15.62 s); and a significant TOT effect (F(3/63)=8.15, p<.0001) reflecting increases in response latency over time. These results are graphed in Figure 29.

c. Latency of second response

The analysis of time between identification of 2 aircraft at the same altitude and the decision that they were flying toward or away from each other provided the following significant results. There was a significant Gender effect (F(1/21)=6.71, p<.017), with males responding more rapidly than females (5.16 vs 6.69 s); a significant Gender by TD interaction (F(1/21)=8.07, p<.010) accounted for principally by males participating in the PM sessions responding more rapidly than the other 3 groups (males participating in the morning and females participating at either time). The D effect was not significant (F(1/21)=4.04, p<.057); for males, the AM and PM response latencies were 6.61 and 3.72 s, respectively; for females, 6.46 and 6.96. The TOT effect was not significant. Figure 30 depicts the changes in latency of the second response.

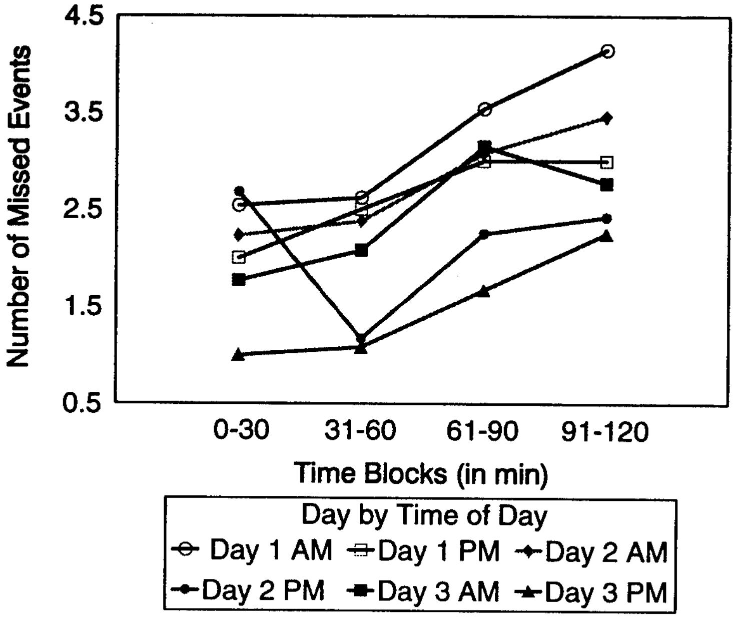

Figure 28. Missed events as a function of Day, Time on Task, and Time of Day.

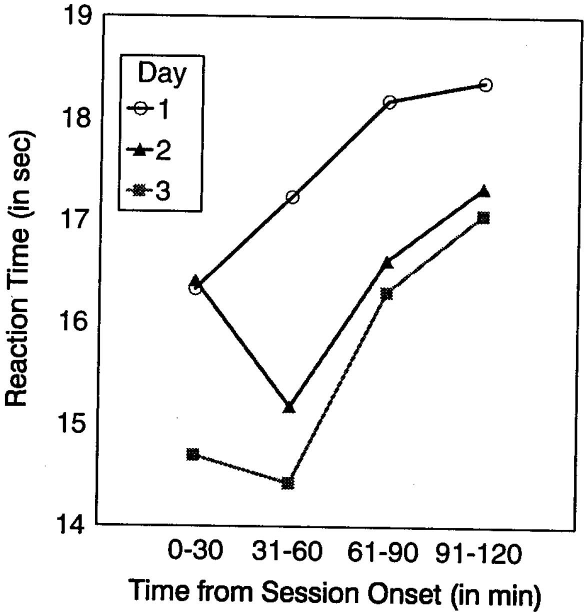

Figure 29. Reaction time of first response as a function of Day and Time on Task.

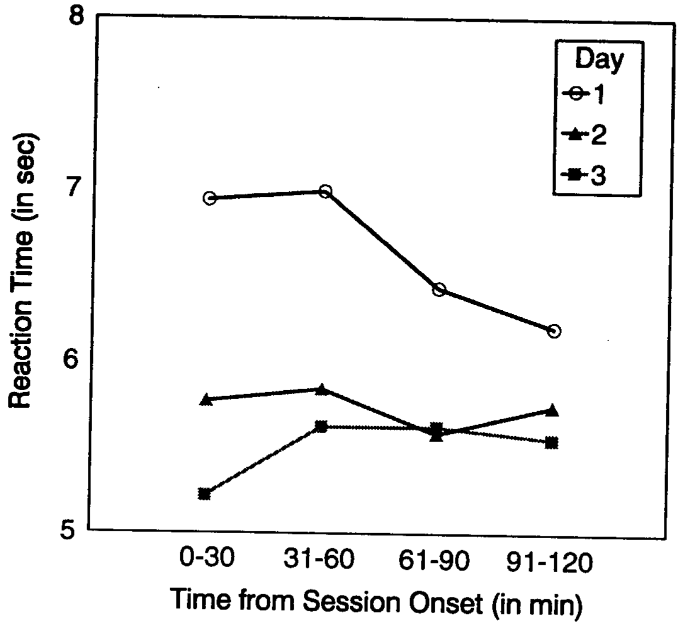

Figure 30. Reaction time of second response as a function of Day and Time on Task.

DISCUSSION

Table 1 summarizes the results of all the analyses. We should point out some possible inflation of effects. A number of measures may be significantly correlated with each other. We chose to ignore this confound, since we expected such correlations to be relatively small. A second reason for not considering this potential confound in our analysis was the supposition that if variables are significantly correlated, they should show similar patterns of change over time. This obviously is not the case. For example, one would expect the pattern of change over time for blink amplitude and blink closing duration to be similar, since there should be some relationship between amplitude and the time taken by the eyelid to cover that distance. For the blink closing duration measure, the greatest change is between the 10- and the 30-m samples (Figure 3) while for blink amplitude, the greatest shift occurs between the 90- and 110-m samples (Figure 8). On the other hand, the relationship between the closing duration and the 50% window duration measure should be closer, since these measures overlap (Figures 3 and 5). Both show similar patterns.

I - BLINK RATE

Our finding of a significant increase in blink rate as a function of TOT is in agreement with much of the literature (reviewed in Stern, Boyer, and Schroeder, 1994). That article, which reviews the literature on blink rate as a measure of "fatigue," concludes that evidence for a TOT effect is compelling, and that for fatigue effects a reasonable inference. The best evidence for fatigue effects comes from studies in which subjects were sleep deprived or in which environmental variables such as lighting were degraded. These studies further suggest that fatigue effects are best seen when the purported measure of fatigue (such as blink frequency) is obtained during prolonged task performance, rather than during "tests" conducted immediately after prolonged performance, especially if these test sessions are of short duration.

Table 2 identifies a few studies demonstrating increases in blink rate as a function of TOT. In the present study, blink rate increased from a mean of 13.4 per m during minutes 10-15 of task performance to 17.8 per m during minutes 110-115. This is an increase of approximately 30% over a 1-h and 40-m period, an increase somewhat less than might have been expected by extrapolating from the results presented in Table 2. However, our first evaluation occurred after 10 m of task performance. Had we used the initial 5 m of task performance as our "baseline" measure, the results would probably be concordant with those reported in the literature. It may only be coincidence, but our results are most similar to the Mourant (1981) study. Both studies had subjects working at a CRT, though the tasks performed were markedly different. It would be nice to be able to say that the increase in blink rate is purely a TOT or "fatigue" phenomenon. However, a number of other variables, also affect blink rate. Before turning to these other variables we will briefly review studies that have demonstrated increases in blink frequency as a function of TOT.

Table 2 demonstrates that a variety of tasks, where duration exceeds half an hour, demonstrates significant increases in blink rate. Thus, driving an automobile, a truck, or airplane simulator, vigilance task performance (Mackworth Clock test), reading, and reading from a CRT, all lead to increases in blink frequency, ranging from 30 to 300%. Studies demonstrating this effect date back at least to 1895, when Katz, using himself as subject, demonstrated increases in blink frequency while reading. He attributed the increase to "retinal fatigue," but also reported that requiring the subject to make frequent changes in accommodation and vergence produced increases in blinking. Our finding of a 30% increase in blink frequency over the 1-h 40-m period elapsing between the first and last 5-m samples evaluated is on the "conservative" side of the changes reported in Table 2.

Not all studies in which subjects were required to perform for extended periods produced increases in blink rate. Carmichael and Dearborn (1947) had subjects read for a 6-h period. No significant increases in blink rate were reported for either college students or high school students reading both easy and difficult text in hard copy or microfilm format. These authors compared their results to those of Hoffman (1946) who, in a study preliminary to the Carmichael and

TABLE 2
TIME-ON-TASK, INCREASE IN BLINK RATE

Author	Nature of Task	Duration (hrs)	% increase
Buettger 1923	reading	4	200-300
Carpenter 1948	vigilance	2	47
Haider*1976	driving simlulator	4	80-100
Hoffman 1946	reading	1	71
		4	268
Luckiesh* 1937	reading, light intensity	1	27
		2	79
		3	257
Morris	GAT-1 flight simlulator	4	268
Mourant* 1981	reading CRT	2	33
Pfaff* 1976	driving, auto	3	167
Stern* 1976	driving, simlulator	0.5	31
Tinker 1945	reading	0.5	38

*only the first named author of the article is identified

Dearborn study, had used the same equipment with students reading for a 4-h period. Hoffman had observed significant increases in blink rate after the initial hour of reading (see Table 2). The major difference between these 2 studies was that in the Carmichael and Dearborn study, tests of comprehension (12-13 per 6-h reading period) occurred after every 20-25 pages of reading. Hoffman, on the other hand, did not utilize comprehension tests; reading material was easy, pay was less, and students were not exhorted to do well. Carmichael and Dearborn came to the conclusion that well motivated subjects do not demonstrate alterations in blink rate as a function of TOT.

We suspect that a repeated measure ANOVA design, such as used by Hoffman (1946) would have found significant increases in blink rate in the Carmichael and Dearborn data. We also suspect that the technique used to analyze the data (critical ratios) was overly sensitive to the large individual differences in blink rate. Carmichael and Dearborn fortunately present some of their summary data in tables. Using their tabled values, we compared blink rate at the start of the experiment with blink rate at 1-hour intervals. There were 6 such comparisons for all reading "events" (easy and difficult; text and microfilm; college and high school subjects). There were thus 2x2x2x6= 48 ratios calculated, 40 of these were positive, 8 negative (negative indicates that blink rate was smaller later, as compared to the initial 5-m period of reading). If there was no significant effect, one would have expected half of the 48 values to be positive and half negative. Forty of the 48 values were positive. The likelihood of this being a chance event is less than .01. We thus concluded that Carmichael and Dearborn's data demonstrate TOT effects. The average increase across all trial blocks was 14%, while the average decrease for the 8 negative values was 1.6%.

Though not stated, we suspect that they sampled their blink rates not at 30-m intervals as suggested, but during the 5 m of reading immediately preceding or following each of the 13 comprehension tests. This might well lead to a lower blink rate in its own right, since Ponder and Kennedy (1927) had demonstrated that any interruption in task performance would lead to an alteration in blink rate. We will not review the acrimonious debate between Tinker (1945) and Bitterman (1945) on one side, and Luckiesh and Moss (1937) on the other side, dealing with blink frequency as a measure of fatigue. Luckiesh, a lighting engineer, presented a considerable amount of data demonstrating that fatigue (as well as lighting conditions) affected blink rate, with an increase in blinking as a function of fatigue. Tinker and Bitterman, both psychologists, presented evidence refuting the Luckiesh findings. Our review of the published results leads us to the conclusion that Luckiesh was correct, while his critics were in error. (Stern et al., 1994).

Our TOT effect on blink rate is at least suggestive of fatigue effects. Corroborating evidence will be elaborated in subsequent sections of this discussion.

Alterations in blink rate also occur as a function of the nature and difficulty of the task being performed. Results of studies demonstrating this effect are presented in Table 3. There is a relationship between blink rate for both visual and non-visual tasks, with the more "perceptually demanding" tasks producing lower blink rates. Wilson (1993) has demonstrated in pilots flying the F4 Phantom A/C that the lowest blink rate and shortest closure duration blinks occur during high workload segments of the tasks. Many authors have demonstrated that the blink rate during reading is significantly lower than during "non-reading" periods (Ponder and Kennedy, 1927). Other situations, such as solving arithmetic problems (Gille et al., 1977; Tanaka & Yamaoka, 1992); vocalizing during vs. quietly solving problems (Schuri and von Cramon, 1981); social vs. non social perceptual tasks (von Cranach, 1969); large vs. small angular gaze displacement (Watanabe et al., 1980); being engaged in discussion vs. listening (von Cramon, 1980); increased levels of muscle tension induced by squeezing a hand dynamometer (King and Michels, 1957; Lovaas, 1960); and easy vs. difficult auditory tracking task (Gregory, 1952) all lead to higher blink rates than the comparison condition.

A number of hypotheses have been invoked to account for the increase in blink rate as a function of TOT. The first suggests that visually demanding tasks, such as reading, lead to blink inhibition. Thus, the increase in blinking over time is attributable to a decrease in the ability to maintain such inhibitory control. A second hypothesis attributes the increase in blinking to increases in muscle tension and/or overt motor activity associated with attempts to sit quietly while performing a task for extended periods of time. A third possibility is that, in complex tasks, such as used in the present study, there is a reduction in task difficulty (learning effect) as a function of TOT. A reduction in the allocation of attentional resources to the task at hand would require less inhibition of blinking. Not only might one expect the task to become easier within a day but one would expect some transfer from day 1 to subsequent days. Such a transfer of training should be manifest in a significant DAY effect or an interaction involving DAY. Significant DAY effects were obtained for 4 oculometric variables: blink rate, blink closing duration, eyelid closure frequency, missed events and response, as well as the time to event detection performance measure. Blink rate, blink closing duration, and eyelid closure frequency increased, while performance measures (the number of missed events and response time to detection of aircraft at the same altitude) improved over DAYS.

To give credence to any of these hypotheses, it would have been desirable to have recorded blinks under "non-task" conditions to determine if task performance, in fact, led to blink inhibition. There is considerable variability in "resting" blink rates across studies. However, the majority of studies reviewed in Table 4 had higher resting blink rates than those obtained early in task performance in our experiment. It thus may not be unreasonable to suggest that performance of the ATC simulation task leads to blink inhibition. Table 4 summarizes studies in which blink rates were obtained under "resting" and at least 1 "task" condition.

The inhibition of blinking associated with demanding visual task performance, such as reading or piloting an aircraft or, in the present context, performing the ATC simulation task, can be accounted for by the "minimal disturbance hypothesis" suggested by Knorr (1924). This hypothesis takes account of the fact that during and bracketing saccades there is "saccade suppression," i.e., a marked reduction in visual acuity. During and surrounding the period of a blink there is also suppression of visual information (Wibbenmeyer, Stern and Chen 1983).

TABLE 3

TASK (DIFFICULTY) AND BLINK RATE

Author	Tasks compared	Effect obtained
Carmichael 1947	reading	N
Clites 1935	logical probs, ment. arith., visual percpetion	Y
Gille 1977	# copying, mental arith., solving	Y
Gregory 1952	non-visual task	Y
Haider 1976	simulator driv. - 3 level diff.	Y
Hare 1971	viewing slides-affect	Y
Holland 1975	count b'wd, memory, rest	Y
King 1957	dynamon, tens. level	Y
Lovaas 1960	dynamon, tens. level	Y
Luckiesh 1937	light intens., ment. arith., reading, conversation	Y
Peterson 1931	reading, unoccupied	Y
Poulton 1952	visual tracking	Y
Schuri 1981	vocabulary and quiet prob.solv.	Y
Stern 1984	pilot vs. copilot aircraft	Y
Telford 1933	mental arith., rest.	Y
v. Cramon 1980	resting, reading, listen, question, discuss	Y
v. Cranach 1964	"social," "non-social"	Y
Watanabe 1980	angular displacement, target	Y
Wilson 1993	pilot high & low workload	Y
Wood 1983	problem solving, easy, diff.	Y

TABLE 4

BLINK RATE AT REST PLUS OTHER CONDITION

Author	Rate rest	Task Condition	Rate
Gregory 1952	22	stylus maze	19
Harris 1966	22	muscle tension	28
Holland 1975	11	count backwards	5
Martin 1958	18	response to questions	34
Peterson 1931	15	reading	4
v. Cramon 1980	12	discussion	27

The co-occurence of these 2 events, then, would produce the least interference with the ability to take in visual information. Knorr found that blinks are inhibited during reading and that those blinks which do occur, occur at points in time where they interfere minimally with information acquisition, such as at the end of a line of text or at the end of a paragraph. Orchard and Stern (1991) similarly report that blinks are more likely to occur in conjunction with line change saccades, and add regressive saccades and fixation pauses preceded by regressive saccades to Knorr's list. In a non-reading context, Watanabe et al. (1980) required subjects to shift gaze from a centrally presented LED to LEDs at various eccentricities, with a return to the central LED after completion of the required gaze shift. They reported that most blinks occurred as gaze returned from the peripheral to the central display, i.e., few blinks occurred while the eyes were moving to the required location. They also reported that blinks were more likely to occur with large, rather than with small angular displacement of the eyes. Fogarty and Stern (1989) have found similar results. Subjects required to abstract and respond to information presented at a peripheral location seldom blinked as gaze shifted to the target location and were most likely to blink as gaze returned to the central location. These authors also noted that the return from a large amplitude gaze shift (40 degree) was more likely to lead to a blink during gaze return than a small amplitude gaze shift (15 degree). Galley (1993) also found blinks to be non-random events. In a driver simulation task, he reported that "probability of a blink is very finely tuned to the end of the interfering inspection of the target field." Our interpretation is that people suppress blinking behavior the nearer they approach the critical target period, and release the blink when target identification is done." (p. 1067). The breakdown of such inhibitory control or the breakdown of the tight time locking between blinks and saccades as a function of TOT is, in our opinion, a reasonable hypothesis to entertain further to account for the demonstrated TOT, or perhaps "fatigue" effect. Bartlett (1943), in his lecture on fatigue, stated:

> In other words, he [the fatigued subject] could, within the limits of fatigue set by the experiment, still carry out the local actions of control as well or better than ever [when task demands were altered]; but he could not maintain the organized, co-ordinated andtimed responses for more than a short period. — P. 253

The finding of greater blink frequencies for female, as compared to male subjects, deserves further exploration. It is possible that this is a "real" effect. On the other hand, it may be secondary, for example, to the wearing of contact lenses, which may be more frequent in females than males. (We, unfortunately, did not record whether subjects wore contact lenses.) Orchard (1993, personal communication) has demonstrated that even soft contact lens wearers engaged in reading have a higher blink rate than non-contact lens wearers. Sex differences have occasionally been described in the literature. Ponder and Kennedy (1928), in their seminal article on blinking, presented some data on differences in blink rate between men and women. Their results indicated no simple relation, but one dependent on the situation in which blinking was evaluated.

The finding that blink rate increased significantly over the 3 days of data collection suggests a number of possibilities. The first is that the task becomes easier over days. Poulton and Gregory (1952), for example, demonstrated that increasing difficulty of a tracking task led to a significant decrease in blink frequency. Stern and Skelly (1984) demonstrated significant differences in blink frequency between the pilot in control of an aircraft (simulator) and the copilot, with the former blinking significantly less frequently than the latter. That study also demonstrated that as the difficulty of flying the aircraft increased, blink inhibition increased. The increase in blink rate over days may thus be associated with a reduction in task difficulty, i.e., learning. Aside from learning how to perform the task more efficiently, they also may have learned from their day 1 experience that infrequently occurring events never occur in rapid successions. Thus, blink rate following the identification of such an event may have increased, accounting for the overall increase.

Clearly, not all types of increases in task difficulty are associated with a decrease in blink rate. In our studies requiring subjects to make temporal discrimination (visually as well as auditorily presented stimuli), we have not been able to demonstrate an association between task difficulty and blink rate, though Poulton and Gregory (1952) reported differences in blink rate as a function of difficulty of a tracking task.

It is also possible that "fatigue" or "motivational" variables contributed to this finding. We think of the ATC task as one requiring the inhibition of blinking. Fatigue or a reduction in motivation, i.e., attention to the task at hand, could well reduce such inhibitory control. We can discard the hypothesis that motivation to perform the task may have waned over days on the basis of improved performance over days, i.e., subjects missed fewer infrequently occurring events on D 3 than they did on D 1, as well as fewer on D 2 than D 1, and response times became faster over days.

II and III -BLINK CLOSING DURATION AND 50% WINDOW

In earlier studies (Goldstein, Walrath, Stern and Strock, 1985; Bauer, Strock, Goldstein and Stern, 1985; Bauer, Goldstein and Stern 1987), where the period of task performance was less than 1 hour, we found that both the 50% closure measure, as well as the closing duration measures, increased significantly as a function of TOT. The effect generally was more robust for the 50% window measure. This measure is also affected by task requirements, with visually demanding tasks leading to shorter 50% window durations than visually or auditorily less demanding tasks.

The closing duration measure, like blink rate, showed a significant effect for both TOT (Figs. 3 and 5), as well as Ds (Figs. 4 and 6) while the 50% window measure only showed the significant TOT effect. For both variables, the greatest increase occurred between samples taken at 10- and 30-m of task performance following the latter point in time increments in both closing duration and 50% window, appear to be quite constant across successive samples. Like blink rate, which showed a significant increase over days, blink closing duration also demonstrated such an increase; the pattern of increase is, however, quite different suggesting that these 2 measures tap different aspects of the TOT phenomena.

Recall that the closing duration measure is an index of the time taken from the initiation of lid closure (associated with a blink) to the point in time where the lid is fully closed, while the 50% window measure is the time between the lid reaching half the full closure and the point in time where the lid returns through that same level during reopening. We should point out that our algorithm for the identification of a closure-reopening as a blink requires that the 50% window measure be completed in a specifiable time frame, which in this study, was set at 300 msec. Eye position shifts during a blink, and quite frequently, the blink does not return to the 50% level during the reopening phase. This occurs because eye position on reopening is higher in the visual field than before closing (for example, blinks occurring as gaze returns from the keyboard back to the CRT). Thus, data had to be edited to allow the computer algorithm to identify such blinks. Such editing involved setting the initiation of blink at the level of the eye position obtained after reopening. Such editing reduced average amplitude, closing duration, and 50% window. The amount of such editing did not change appreciably across time blocks and, thus, did not contribute to TOT effects. Our editing, therefore, artificially reduced these variables. Nevertheless, our TOT variable demonstrates an increase in closing duration and 50% window as a function of TOT. Thus, it is a robust effect.

The 50% window duration measure again is sensitive to TOT effects, but like blink rate, and unlike the closing duration measure, the change over time is a linear one. Though narrowly failing (at $P< .061$ and $P< .057$) to meet our criteria of acceptability for statistical significance, we would like to discuss the two 2-way interactions, both of which involve Ds as one of the variables. The D x Gender interaction (Fig. 6) indicates that, similar to the prior 2 measures, this one also increases over Ds; however, the increase is significantly slower for the female, as compared to the male subjects. The D by TOT interaction (Fig. 7) indicates that the slope changes over Ds. The major effect is that on Ds 1 and 2, the 50% closure duration measure starts from a lower level than for D 3. This measure attains approximately the same level at minute 110 for all 3 days. We suspect that this measure is affected both by TOT, as well as task difficulty or degree of "engagement" of the subject in task performance. The relationship between these 2 variables is not a simple one. If we can take the finding that this variable discriminates D 3 performance from both Ds 1 and 2 as indexing alterations in perceived difficulty, then the finding that all 3 Ds end up at the same level suggests that we are dealing with a ceiling effect or that after about 2 h, task difficulty is perceived similarly across Ds.

We (Bauer et al., 1985 and Stern & Skelly, 1984) have previously demonstrated TOT effects similar to those obtained here. In the Bauer et al. study, subjects performed a visual or auditory temporal discrimination task for 45 m. The 50% window measure changed from 133 msec. early in task performance to 148 msec. for approximately the last 5 m of the 45-m task. The Stern and Skelly (1984) study, performed in a flight simulator with Air Force pilots flying a 5-h bomber mission, also demonstrated significant TOT effects for this measure, as well as significant effects attributable to differences in task demands on the pilot during different flight segments. For example, the pilot in command of the aircraft demonstrated significantly shorter 50% window durations than the copilot. The nature of flight maneuvers also significantly affected average window duration with "weapons delivery" and "threat avoidance," producing significantly shorter window durations than cruising at altitude or "nap of the earth" flying. The present results suggest that performing the ATC simulation task was more demanding of the participant on D 1 as compared to successive Ds, or that subjects had to pay closer attention to task performance early on D 1 than on subsequent Ds.

This measure thus appears to be sensitive to both TOT and motivational effects. To the extent that closing duration and the 50% window measures reflect momentary reductions in motivation (also considered as momentary drops in alertness or attention to task), the monitoring of these variables should allow one to predict that if a brief stimulus requiring a response occurs in close temporal relationship to such a blink, then the likelihood of a performance drop-out or "performance block" (Bills, 1931) is markedly enhanced. We should, however, point out that long closure duration blinks, unfortunately, do not uniquely identify the occurrence of a performance "block." We have also observed longer closing duration blinks while subjects stored and rehearsedinformation. (Stern, 1992; Goldstein, Bauer, & Stern, 1992).

IV - BLINK AMPLITUDE

Blink amplitude has, in our previous laboratory studies, seldom demonstrated TOT effects. The only major finding dealing with this variable demonstrating TOT effects is a study by Morris (1984), in which pilots were sleep deprived and required to fly a 4-h cross country simulated mission the following afternoon. His results demonstrated significant decreases in blink amplitude over time. These results were interpreted as suggesting that, late in task performance, the eyes were partially closed, so that the distance the eyelids had to move during a blink was markedly attenuated. In the current study, we have a significant increase in blink amplitude (Fig. 8) over TOT, and a significant interaction involving Gender, D, and TOT. One rationalization to account for the TOT effect is to suggest a change in head position over time. If there is a significant increase in head droop, i.e., the chin moving closer and closer to the chest as a function of TOT, this would require a wider opening of the palpebral fissure to allow the viewer to see the upper portion of the CRT. Such a wider opening of the eyes would result in an increase in blink amplitude. This change in blink amplitude over time is equally well seen in Fig. 9, where the data are broken down by Gender and D. Males, at comparable points in time, appear to demonstrate smaller amplitude blinks than the female participants in this study. Though females showed less variability over days on this measure, they still demonstrated a reasonably linear increase over Ds with successive Ds starting out and ending with greater amplitude blinks than on earlier Ds. For males, this pattern did not occur.

V - LONG CLOSURE DURATION BLINK FREQUENCY

Long closure duration blinks again showed consistent changes over the 2-h period, without any suggestion of reaching an asymptote (Fig. 10). These results are again concordant with earlier studies from our laboratory (Stern, Goldstein, and Walrath, 1984). In the present study, subjects were alerted if they missed an infrequently occurring event. Since these events occurred relatively infrequently, and since task duration was considerably longer in the present task, there were many opportunities for the occurrence of long closure duration blinks and closures. The interaction between Gender, TD, and TOT (Fig. 11) suggests a markedly different pattern between males and females as a function of TD of participation in the experiment. If an increase of long closure duration blinks over time is symptomatic of fatigue effects, then males participating in the afternoon developed this effect more strongly than those who participated in the morning. On the other hand, females who participated in the afternoon run showed a low level of LCD blinks and little change in their occurrence over time. Females who participated in the morning showed a pattern similar to that seen in males in the afternoon. What might account for these effects? We know of no literature that ascribes a differential effect in complex task performance to Gender as a function of TD. The literature on circadian rhythms, demonstrating differences in performance between subjects identified as "morning" or "evening" types (on the basis of body temperature changes over the 24-h cycle), does not provide us any clues about the Gender effect.

VI - EYELID CLOSURES

In the present study, eye closure frequency also increased significantly as a function of TOT and D, supporting the idea that motivational (and/or learning) variables, as suggested earlier for the 50 % window measure, may account for the D effect. These results also suggest that there may be a significant correlation between these 2 measures. Are they measuring similar or different effects?

VII - BLINK FLURRY FREQUENCY

The blink flurry measure is a relatively new one for us, though there is precedence to suggest an increase in this variable as a function of TOT. We suspect that flurries may be associated with a "momentary" and marked reduction in blink inhibition. It is our impression that such flurries most frequently occur following the identification of infrequently occurring signals and also prior to, and following, periods of eye closures. These events both appear to be times when attention is likely to lapse. In our review of the literature, we came across 3 comments about flurries. Carpenter (1948) reported that periods of blink inhibition in which subjects appeared to be staring, were sometimes followed by a "burst of blinks." Carpenter did not comment further about this phenomenon. Yamada (1992) reported flurries of blinking following task completion Their observations, thus, are concordant with ours. Frolov (1990) reports as follows:

> In tracking rare random visual signals "volleys of aftereffects" were noticed which were the ER [eye response] at the time when the operator ended the tracking [of a dot moving across the face of the CRT in20 seconds] and was getting ready to wait for new signals. The "volley" indices were computed for minute-long intervals, which followed ends of tracking. These parameters were found sensitive to the complexity of the task for the subject. — p. 74

It is our impression that the "volley of aftereffects" is similar to our measure of blink flurries and that our observations are concordant. Thus, one can identify 3 separate studies, all of which have observed blink flurries and have time-locked them to specific events. As depicted in Fig. 13, the major effect appears between m 10 and 30 and again between m 90 and 110. Between m 30 and 90, there do not appear to be consistent changes in this variable. The 2 significant interactions again suggest that there is greater inhibition of flurries early in task performance, and this effect is most apparent on D 2. Thus, we again see changes over D. The major difference for this variable appears to occur between D 1 and the other 2 Ds.

When the results are broken down further, because of the triple interaction involving TOT x G x D, it appears that the changes over time are principally attributable to the results of the female subject group. Males demonstrate a somewhat random pattern, both with respect to TOTxD effects . Females appear to not only demonstrate more flurries than males, but the pattern of flurry activity discriminates their D 1 from the other 2 Ds of measurement.

Since an initial analysis of similar data had found not only an increase in flurry frequency, but also an increase in the number of blinks constituting a flurry as a function of TOT, we again evaluated this question in the combined data set. As is apparent from comparing Fig. 13 with Figs. 16, 14 with 17, and 15 with 18, these 2 measures reflect the same phenomenon. Thus, we concluded that in the present data set, the TOT effect is restricted to Flurry Frequency. We have no evidence in this data of an increase in the number of blinks constituting a flurry as a function of TOT.

Why is there an increase in flurries as a function of TOT? Do flurries occur at random time points or are they related to other events? It is our impression that flurries do not occur at random time points. Flurries are most likely to be seen after the subject has responded to an infrequently occurring event and are seen (somewhat less frequently) preceding and/or following eye closures. They are also frequently seen when the subject realizes that the experimental procedure has been completed. There is inhibition of blinking during the period of identifying and responding to such events. One possible rationalization for the flurry, but not our favorite one, is that these blinks occur as "catch-up phenomena" to make up for blinks missed while detecting, identifying and responding to an "event". The rationalization we believe to be correct suggests that the flurry of blinks occur because the subject has learned that another "event" will not occur for some time. Thus, the flurry indexes a period of reduced alertness or attention to the task. This latter interpretation is reinforced by the fact that during a flurry, one also sees little saccadic activity in the horizontal plane. Another point in time where flurries are likely to occur is preceding and following an eyelid closure. It appears as if a flurry of blinks is an attempt to ward off an eye closure. We thus suspect that a measure incorporating the concurrence of flurries and long duration fixation pauses may be a useful measure of reduced alertness.

Though not systematically studied by anyone to date we, as well as others (Yamada 1992), have observed flurries of blinking at the end of an experimental run. Yamada (1992), for example, had children perform a number of tasks, ranging from watching a video-animation (Snoopy and Charlie Brown), performing the STROOP test, and playing a video game (Nintendo Super-Mario III). He reports "Subjects' blinking was inhibited just after the initiation of each task. When the given task [was] finished, blinks occurred in bursts" (p. 4).

Results for the blink analyses discussed to this point suggest that: 1) that a number of blink parameters are sensitive to TOT effects; 2) some of these effects wash out over Ds; and 3) that males and females have somewhat different patterns of responding.

IX and X - SACCADE RATE AND SACCADE AMPLITUDE

The second major measure dealt with aspects of eye movements. When we use the term "saccade" here, it should be pointed out that we were liberal in the definition of saccades and included some pursuit eye movements, especially if they were relatively fast. Compensatory eye movements, however, were never identified as saccades. We should point out that pursuit eye movements constituted only a small proportion of these "saccades." The occurrence of saccades (so defined) decreased linearly from the first to the 90-m measurement period, with the final measurement at approximately the same level as the 90-m measure.

Saccade amplitude is affected by TOT. We have identified 2 studies demonstrating significant amplitude changes as a function of TOT. Malmstrom, Randle, and Murphy (1981) obtained a linear decrease in saccade amplitude of 0.29 degrees per m as well as a significant shift in accommodation (0.11 diopters per m) as subjects performed 2 scanning tasks, each for a total of approximately 6.5 m. In the task demonstrating saccade amplitude effects subjects were required to track a sinusoidally moving target (horizontal plane at 0.4 hz, 18 degree amplitude) for 13 consecutive 30-s periods. They obtained a 9% loss of range, with extent of eye movements decreasing from 15.4 to 14.3 degrees over the 6.5 m period. No phase lag changes of eye position with respect to target position were obtained. The authors concluded that the significant change in saccade amplitude cannot be accounted for on the basis of refractoriness of the muscles controlling eye movements and suggest a CNS mediated change. May et al. (1985) recorded eye movements while subjects performed non-visual tone counting tasks differing in complexity. Eye movements were studied under a "free viewing condition," i.e., no restriction on eye movements, and a condition where subjects were required to shift gaze between LEDs 20 degrees apart, with a gaze shift required every 5 s. Spontaneous (non-stimulus triggered) saccades decreased in amplitude as a function of TOT. Of further interest, though not directly relevant here, is their reporting a decrease in saccade amplitude as a function of task difficulty (with no effect on saccade velocity). There was, thus, limited support for evaluating saccade amplitude effects before considering saccade duration or velocity effects.

We should preface discussion of our results with a brief comment on other variables that can contribute to finding changes in saccade amplitude as a function of TOT. The major variable of concern is the head's position relative to the CRT. In the studies identified above, this was controlled by immobilizing the head. If the head is free to move, as is true of our experimental situation, then changes in saccade amplitude may well be secondary to changes in head position. Moving away from the CRT display would decrease the visual angle subtended by the display, and result in decreased saccade amplitude. Moving the head closer to the display would have the opposite effect. The chair on which our subjects sat was not attached to the floor, but subjects were not likely to move it during an experiment. Subjects could, however, shift their position on the chair. They could sit up straight and move their upper body toward the CRT; they could also slouch in the chair, thus moving their eyes further away from the CRT. Such body movements might account for the obtained changes in saccade amplitude as a function of TOT. We suspect, however, that this is not the case. We would consider such movements as unwanted "noise" in our signal analysis, since there is no reason for them to be time-locked to events occurring on the CRT, i.e., we would not expect shifts in body position to occur at specific times, but suspect that they would occur quite randomly, with perhaps an increase in frequency over time.

With a decrease in saccade frequency one might, or might not, expect an increase in saccade amplitude. If one believes that the area searched should decline over time, one might expect not only a decrease in saccade frequency, but in amplitude as well. The current search task, however, did not involve the random presentation of stimuli across the CRT. It will be recalled that the subject's principal task was to monitor aircraft moving along 2 vectors. Thus, as long as subjects are performing this task, one would not expect a decrease in saccade amplitude. One might expect no change, or an increase in saccade amplitude as saccade frequency decreased. The significant changes in saccade amplitude do not relate well to the changes in saccade frequency. While the latter changes is a reasonably linearly fashion as a function of TOT, the saccade amplitude measure shows a sudden shift between the 50- and 70-m samples with decreases in amplitude for other segments. Had we any expectation about this variable, it would have been that it mirrors saccade frequency changes. This is obviously not the case. Why there should be a sudden increase in saccade amplitude between the 50- and 70-m measurement period is a mystery. To evaluate the robustness of this phenomenon, we conducted the following analysis. We tallied the number of times that each of the 25 participants demonstrated an increase or decrease in saccade amplitude from the 10- to the 30-m, the 30- to the 50-m, the 50- to the 70-m, the 70- to the 90-m and the 90- to the 110- m blocks.

These results were compiled for each of the 3 Ds of analysis and are presented in Table 5. The effect is a robust one and was obtained on all 3 Ds. Thus, on D 1, 23 of the 25 subjects showed an increase in average saccade amplitude between the 50- and 70-m time periods. A similar effect is seen for Ds 2 and 3.

We also have no rationale to account for the sustained elevation in saccade amplitude for the last 2 measurement periods. Saccade amplitude increases are most likely to occur when the operator moves closer to the display. Why a majority of subjects should make such a move at about the same time during task performance is equally mysterious.

The Gender by TOT interaction suggests that the slope is steeper for females and that saccade amplitude also discriminates between the sexes. However, we did not attempt to calibrate eye movement amplitudes to allow for a test of the hypothesis that the amplitude differences reflect differences in extent of gaze shift accomplished. It is quite possible that the obtained differences simply reflect differences in variables, such as distance between the eyes, or distance between the CRT and the eyes.

What is nevertheless perplexing is the significant Saccade Amplitude x Gender x TD interaction, where the pattern of saccade amplitude differences as a function of TD cleanly discriminates between the sexes. Female subjects run in the morning hours show the largest amplitude saccades for females, while for males, the largest amplitude saccades were found in those participating in the afternoon. This is a between-subjects effect and since the number of subjects per group was small, could be a fortuitous finding. Future research will have to determine the reality of this effect.

XI and XII - FIXATION DURATION AND FIXATIONS IN 1 SECOND TIME BINS

Fixation Pause

There is a paucity of research dealing with changes in fixation pause duration as a function of TOT. It is clear from the literature that in complex tasks, such as scanning an instrument panel during flight, that neither the search pattern nor the time the eyes dwell at a particular location are random processes (Ellis and Stark, 1968). Statistical dependencies, independent of the placement of specific instruments, are the rule rather than the exception, and most subjects demonstrate specific patterns of search activity while dealing with component aspects of the task of piloting an aircraft (Stoliarov personal communication 1991).

A number of studies have used secondary task technology to evaluate aspects of work load associated with a visual task on scanning performance. The results of such studies, while tangential to the present study, provide some relevant information. Tole et al. (1982), demonstrated, in an aircraft piloting task, that fixation pause durations increase as a function of task difficulty of the secondary task, a verbal loading task. Scanning behavior was also detrimentally affected, with novice pilots showing greater restrictions of scanning behavior than skilled pilots as secondary load increased. Another finding important for us was that, as loading increased, so did dwell time (fixation

TABLE 5

NUMBER OF SUBJECTS DEMONSTRATING AN INCREASE (+) OR A DECREASE (-) IN SACCADE AMPLITUDE BETWEEN SUCCESSIVE DATA BLOCKS.

BLOCK (min)	DAY 1		DAY 2		DAY 3	
	+	-	+	-	+	-
10-30	10	15	12	13	11	14
30-50	9	16	12	13	8	17
50-70	23	2	22	3	22	3
70-90	9	16	4	21	8	17
90-110	9	16	11	14	9	16

duration) on each instrument. The increase, in some cases, was large enough so that these authors referree to the subject "staring" at the display. Stares are defined as dwell times in excess of 5 s. The highest secondary load condition produced increases in stares ranging from 3.7 to 23.4 percent for the 6 subjects for whom data are presented (mean increase of 12.7%, S.D. 7.7).

There is a vast literature dealing with fixation pauses associated with reading. Hoffman (1946) had subjects read without interruption for 4 h. He reported a significant decrease in both the number of fixations and the number of lines read within the first 30 m of reading performance. Variability (SD) of number of fixations per line increased; the increase was significant after 2 h of reading. Average fixation pause duration (interpolated from saccade frequency data, Fig. 4) was 280 ms. at the first sample and 316 ms. at the 4-h completion time sample, approximately a 13% increase (compared to a 6 to 8% increase in our study).

Carmichael and Dearborn (1947) reported (using critical ratio statistics) mean differences in saccade frequency of 3 of 12 comparisons for both of their reading tasks. The general pattern appears to be one of high reading efficiency for the first 5 m of the reading task. There is a marked drop at the 30-m measurement period with relatively asymptotic performance from the second through the sixth h of reading. It should be remembered that reading was interrupted after every 20-25 pages for comprehension checks. Though these authors minimize the importance of the obtained TOT effects, to those looking for such effects, there is abundant suggestive evidence that, had they used more appropriate statistical tools (available at the time), they would have obtained a TOT effect.

The specifically useful references for our evaluation are the Tole et al. studies, which suggest a decrease in saccades and an increase in fixation pause duration, especially long pauses as secondary task demands increase. If we can, instead of invoking secondary task demands (which require the allocation of attentional resources), conceive of TOT effects as requiring greater allocation of attentional resources to the primary task, or the allocation of attentional resources to counteract boredom, fatigue, physical discomfort, daydreaming, and other variables associated with TOT (which can also be conceived of as secondary tasks, albeit not under the control of the experimenter) we would expect both a decrease in saccade frequency and an increase in long duration fixation pauses (Tole's stares).

Two analyses dealing with fixation pause duration were conducted. The first dealt with median fixation pause durations. This was, as one would expect from the saccade frequency results, found to generate significant increases in pause duration as a function of TOT. The next question asked of the data was whether this increase reflected simply an increase in average fixation duration or whether it might be accounted for by a shift in the distribution, i.e., could the increase be accounted for by a shift in only the frequency of occurrence of unusually long fixation pauses, such as might be associated with staring at the display or occasional difficulties in making decisions? For this analysis, we partitioned fixations into 4 time windows, namely fixations less than 1 s in duration, those between 1 and 2, 2 and 3, and longer than 3 s in duration. As might be expected, the greatest percentage of fixations fell into the less than 1 s window (87.8%). Though there is a significant increase in long duration fixations over time, the most dramatic shift appears to be for the decrease in frequency of fixation pauses under 1 s. Though the increase in long fixation pauses as a function of TOT is, on an absolute basis, relatively small, we believe that the occurrence of such long fixation pauses, in general, index periods of non-attention to the task. We say "in general," because there are times during responding to the occurrence of 2 aircraft at the same altitude (one of the infrequently occurring events) that a long fixation pause may be appropriate. After identifying that 2 aircraft are at the same altitude, the observer has to return gaze to the aircraft to determine whether they are flying away from, or toward each other. A 6-s period elapses between displaying 2 aircraft at the same altitude and the next update of the display. Assuming that it took 2 s to identify that 2 aircraft were at the same altitude, and another second to make the required response to the detection of that event, the viewer has 3 s to return and fixate on 1 of the aircraft, and, if he is fortunate, in time to detect direction of motion of the second aircraft during the same sweep. Since such events occurred at most twice during any of the 5-m sampling periods, they cannot account for the TOT effects obtained.

XIII - PERFORMANCE

The finding that all 3 performance measures, namely missed signals, mean response latencies for the first response, and mean latency to second response demonstrated significant D effects, demonstrate that subjects improved in task performance over days, and suggests that they maintained a relatively high and consistent level of motivation to perform the task over the 3 Ds.

The significant TOT effect was limited to the first 2 measures, misses and latency of initial response. In both cases, we see essentially poorer performance over time, with an increase in missed signals and an increase in response latency. The lack of a significant effect for latency of the second response requires explanation. We assume that the level of alertness declines from the start to the end of each session, and that this is reflected in missed signals, as well as longer initial response latencies. However, once 2 aircraft have been identified as being at the same altitude, the subject is alerted that he next has to determine whether the 2 are flying toward, or away from each other. Though not significant, we plotted mean response latencies as a function of TOT for the second response. On D 1, we see a decrease in response latency over TOT, with D 2 and 3 asymptotic at about the same level that characterized the last segment of D 1. This is, thus, the only measure in which there is improvement as a function of TOT. We attribute this improvement to the probability that subjects are learning the location of the keyboard switch that has to be actuated, with alertness at a reasonably constant level, while for the other responses, alertness is decreasing as a function of TOT.

The significant TD effect for the first response latency measure, coupled with the almost significant effect for missed signals, i.e., fewer signals missed by subjects participating in the PM suggests that afternoon participants were generally more alert.

The TD effect was limited to latency of first response, with shorter latencies for the PM, as compared to the AM runs. The TD effect was marginally significant for missed signals, with fewer missed signals for the PM runs. What might account for these significant TD effects? Folkard (1983) summarizes the literature dealing with the effect of TD on aspects of "performance." He points out that the idea that performance on all tasks is equally affected by our "biological clocks" is a mistaken, though popular notion whose history can be traced back to Kleitman's work on biological rhythms (1963). In general, simple visual-motor tasks, i.e., tasks requiring immediate processing and responding, such as simple reaction time, letter cancellation, and card sorting tasks show performance patterns that mirror diurnal variations in body temperature reasonably well. As body temperature increases from 800 to 2000 hours, there is improved performance on such tasks. However, short term memory tasks (reading a short paragraph and responding to questions about the material read) demonstrate a steady decline in immediate recall between those hours. Interestingly, delayed recall is better when material is read in the afternoon. For working memory, some authors report peak performance about mid-day.

No simple (or even complicated) rationale can be invoked for better performance in the PM. The task certainly contains visual-motor, as well as short term or working memory components. As is apparent from Folkard's review these variables would lead to opposing results with respect to TD effects. The fact that PM performance was better than morning performance might suggest that short term memory effects predominated in our task. They certainly are a major component of the task, since subjects had to obtain information about aircraft altitude for up to 8 aircraft on a vector at any one time, then to "forget" that information as the subject started to evaluate altitudes on the second vector. The idea that this task makes greater demands on short term memory is a post-hoc inference not easily subjected to empirical verification.

The results for response latency for the second response (only considered were trials in which the first response was not cued) demonstrated a different pattern. First of all, there was a significant Gender effect with males responding more rapidly than females. The Gender by TD interaction, coupled with the near significant main effect for TD suggests that the greatest difference between the AM and PM performance is attributable to male subjects. Those participating in the afternoon had mean response latencies approximately half the response latencies of those participating in the AM. Females, on the other hand, showed slightly shorter response latencies in the morning. These are intriguing empirical differences with no theoretical reason to account for them.

The finding that TD effect is principally found for male subjects raises another issue that could not be answered by recourse to the literature. Folkard (1983) makes no reference to Gender as a variable contributing to TD effects. Hancock (1983), in a chapter in the same book, deals with the Gender issue. He refers to one study in which an interaction between gender of experimenter and subject was obtained. For male experimenters, same-sex subjects show improvement in performance efficiency, while females tend to perform more poorly with male experimenters. The present experiment did not systematically vary gender of the experimenter. Both male and female experimenters participated.

In summary, our performance measures demonstrated significant improvement over Ds (all 3 measures), significant decrements associated with TOT (2 measures), and suggestive TD and Gender effects. Performance was better in the PM, as compared to AM, and males demonstrated this effect to a greater extent than female participants (1 measure).

GENDER AND TIME OF DAY EFFECTS

There were several oculometric effects involving the Gender variable. The 2 main effects dealt with a higher blink rate and larger saccade amplitude in our group of females. There were 3 significant 2-way interactions. In the first, a Gender x D interaction was obtained for the 50% window duration measure. Females had crisper blinks (shorter 50 % window duration) than males, and the increase in this measure over Ds was smaller for the group of women. The other 2-way interaction dealt with saccade amplitude, in that there was a Gender by TOT (Fig. 21) and a Gender by TD interaction (Fig. 22). The G x TOT is a subtle effect, one most likely accounted for by a greater increase in saccade amplitude between the 50- and 70-m data samples for female subjects and, perhaps, the small differences between the time 10-, 30- and 50-m measures. The Gender by TD interaction is more dramatic and readily seen in Fig. 22. Females who participated in the morning session had larger amplitude saccades, when compared to those participating in the afternoon session, or compared to males in the morning session. The pattern for males was the exact opposite.

There were 4 significant 3-way interactions involving Gender. Three of these were for the Gender x TOT x D interactions. The significant blink amplitude effect is, in part, a function of differences in blink amplitude, with females showing generally larger blink amplitudes than males. The larger blink and saccade amplitudes for females, though not a large effect, is one deserving further attention. We know of no literature suggesting differences in EOG variables as a function of sex. The D component appears to be principally attributable to females, in that the slope of this variable over TOT decreases from D 1 to D 3. In males, if there is a consistent pattern, it is one of a slope increase from D 1 to D 3.

The Gender by TD interaction for saccade amplitude is a surprising one. Why should males and females demonstrate opposing patterns (Fig. 22), and what meaning might be attributed to either pattern? One variable to consider is the time period during which data were collected. All of the AM males, and 4 of the PM females data were collected from July through November 1991; while data for 4 of the 6 males run in the PM, and 6 of the females run in the AM, were collected during approximately the same time span in 1993. Time of year does not appear to be a variable that could account for these results. A second possibility is that the sexes differ in circadian "alertness" rhythms. Initial subject selection was based on the assumption of random sampling. That process generated very few males willing to come to the laboratory in the afternoon hours, and equally few females interested in being tested during the morning hours. If this selection process has anything to do with circadian rhythms, we would expect "morning" types to be more likely to volunteer for morning, and "evening" types for afternoon experiments. One might also expect morning types to perform better in the morning and evening types in the afternoon, though the literature on this point is inconclusive, especially if one utilizes a relatively complex task, as was done here. Evaluating performance, in terms of the number of "unusual" events to which a subject had to be cued because of non-responding in the allotted time, we see little support for a TD effect for male subjects. For females, we see that performance for those participating in the PM session is better than that for those serving in the AM, as well as better than the performance of males, regardless of TD. Because of the small sample size, we believe these results need replication before they can be accepted.

Thus, we have 2 lines of evidence suggesting that female subjects who participated in the PM runs were more alert and able to sustain alertness better, than was true of females participating in the morning. A recent report by Knipling and Wierwille (1993) briefly reviews the literature on automobile accidents in which driving while drowsy was implicated in the Police Accident Report. "Male drivers had an involvement ratio (per km) that was 1.8 times greater and an involvement likelihood (i.e., involvement per registered driver) that was 3.1 times greater than females."(p2) They further point out that male drivers, especially young ones, are over-represented in all automobile accidents. "However, these sex and age differences are much greater for drowsy driver crashes than for crashes in general." Our results would suggest that if TD had been identified in the above accident statistics, that the involvement ratio calculated for the afternoon hours would show an even greater discrepancy between males and females than that calculated for the entire 24-h cycle. This certainly is an area requiring further study.

One 3-way interaction of Gender x TOT x D involving blink amplitude, has already been discussed. The other 2 involved aspects of the blink flurry measure. Since these 2 measures appear to be redundant, we will limit our discussion to the Flurry count measure. Females, on the average, engage in more flurries than males on all days, and show more of an increasing pattern as a function of TOT than is true of males (Fig. 15).

The interactions involving TOT with TD also deserve some special discussion. The 50% closure duration measure shows not only an increase as a function of TOT, but TD as well. We have previously shown that this measure is affected by perceptual task difficulty, with more difficult tasks leading to shorter closure durations. The lengthening of closure durations over days suggests that the task is either becoming easier for the subjects or that they are less well motivated on the third day. We can rule out the latter possibility from the results of the performance analysis. Frequency of occurrence of missed signals decreases significantly over days. If motivation lags, we might expect more missed signals on D 3 than D 1. What we find is that most subjects improve over days, thus the learning hypothesis appears to be a more reasonable one to account for these results.

DAY EFFECTS

Performance data indicated that the number of missed signals and response latencies decreased over days. In line with the improvement in performance, the oculometric measures further suggest that "effort" expended in task performance decreases over days. Blink rate increases significantly over days, blink closing duration becomes longer, the 50% window measure increases, as does the frequency of eyelid closures.

Blink rate is affected by perceptual difficulty with greater inhibition associated with performing more difficult tasks. It is, of course, also affected by TOT, with an increase over time. The observed blink rate increase over Ds may thus indicate that the task is becoming easier for the subject, i.e., that one has to allocate fewer attentional resources to task performance. Similarly, blink "crispness," as measured by the 50% window measure, is associated with task difficulty and expectancy effects. As one approaches a point in time where a stimulus is expected, one sees both a decrease in blink likelihood, as well as a decrease in the 50% window measure (Goldstein, Bauer and Stern 1992). Thus, the changes in closing duration and 50% window suggest that subjects not only improved in their ability to detect unexpected infrequently occurring events, but also learned something about the timing of these events. They apparently learned that the likelihood a second event would occur was small immediately following the occurrence of an "unexpected" event.

The significant increase in eye closures over days is also of interest in this regard. It is our impression that a large percentage of such closures occurred following the making of the manual responses. This is, again, an opportune time to be inattentive to the CRT, since the subject has learned from his D 1 experience, and reinforced by his D 2 experience that the next event requiring action on his part will not occur for a minute or more.

DIAGNOSTICITY OF OCULOMETRIC MEASURES

To further explore the significant TOT results and to determine the diagnosticity of these measures, i.e., how many of the 25 subjects demonstrated the phenomenon, we conducted the following analysis. For each subject for each successive pair of data points (10-30, 30-50, 50-70, 70-90. 90-110 m) we determined whether the second value was larger than the preceding one. Since we had data available for 3 Ds 3 times 5, or 15, such comparisons were made. For each subject we tallied the total number of events so identified. With 15 measures one would expect that on average, 7-1/2 would show an increase, and the same number a decrease between successive values, unless there were consistent trends across subjects (as already demonstrated in the ANOVAs).

Table 6 depicts the results of this analysis for the 12 gaze control measures for which significant TOT results were obtained. It is apparent that 4 of the measures produced splits significantly better than the .02 probability level (using the binomial test). These are: blink rate, closure duration, saccade rate, and frequency of fixations less than 1 s in duration. Two others, though not significant, are worthy of mention, namely 50% window duration and saccade amplitude.

The number of subjects who were appropriately identified by all 6, by 5, 4, 3, and 2 variables is depicted in Table 7. Since the saccade measure had only 1 subject who fell below the median cutoff value, we did a further tally across the remaining 5 variables. These are also depicted in Table 7.

It is apparent that subjects are reasonably consistent across measures, i.e., if they qualify for inclusion on one variable, they are most likely to qualify on the other variables as well. Using the 6 measures, we find 5 subjects fully concordant, 11 concordant on 5, 6 on 4, and 3 on 3 or fewer measures. Conducting the same tally for the 5 variables (excluding the saccade measure), 5 are concordant on all 5, 11 on 4, 6 on 3, and 3 on fewer than 3 variables.

TABLE 6

NUMBER OF SUBJECTS FOR WHOM 7 OR FEWER, OR 8 OR MORE COMPARISONS OF SUCCESSIVE TIME PERIODS (15) SHOWED AN INCREASE OR A DECREASE AS A FUNCTION OF TIME ON TASK.

	=/<7	=/>8
Blink rate	6	19
Closure duration	6	19
50% window	8	17
Blink Amplitude	12	13
LCD blink frequency	13	12
Flurry frequency	11	14
Sum flurry blinks	10	15
Saccade rate	1	24
Saccade amplitude	16	9
Fixation duration	10	15
Frequency fixations <1 sec	3	22

TABLE 7
NUMBER OF SUBJECTS FOR WHOM SPECIFIED NUMBER OF MEASURES DISCRIMINATED

Using all 6 Gaze Measures		Using only 5 Gaze Measures	
No. Measures	No. Subjects	No. Measures	No. Subjects
6	5	5	5
5	11	4	11
4	6	3	6
3	2	2	3
2	1	1	0
1	0	0	0
0	0	25	25

SUMMARY

The present analysis allowed for the partitioning of effects attributable to TOT, TD, and Gender, as well as experience with the task. It also included information about 3 performance measures. From the results of the performance analysis we can infer that motivation to perform the task was maintained at similar levels over the 3 Ds of the experiment. Though subjects demonstrated an increase in missed signals and reaction time as a function of TOT, they demonstrated a reduction in the number of missed events and reaction times over the 3 Ds. Thus, changes in the oculometric variables are not likely to be attributable to a decline in motivation to perform the task over days. Not only is there improvement in performance over days, but blink rate (increases), blink closing duration (increases), 50% window duration (increases) and eyelid closure frequency (increases) all demonstrated changes, suggesting that the task must have become easier to perform over days or that subjects were developing "strategies" to deal with the task. We suspect that one of the strategies involved the realization that "infrequently occurring events," i.e., those requiring a response, did not occur in close contiguity to each other. The interval between any 2 such events ranged between 1.5 and 4 m, with most having an interevent interval of at least 2 m. They, thus, may have learned that lapses in attention were not likely to affect task performance if they occurred shortly after responding to an infrequently occurring event. It was our impression that eyelid closures and blink flurries were most likely to occur in the minute immediately following a response. If these impressions can be substantiated, and the data are available to do this, we would be on more solid ground with respect to this aspect of learning.

Whether the increase in blink rate, closing duration, and 50% window duration also follow this pattern is also of interest. We suspect that the changes in these variables are more likely to reflect the possibility that the task became easier for our subjects as a function of experience.

The observed Gender effect came as somewhat of a surprise. Though the differences are not statistically significant, there was a trend for females to perform better, i.e., miss fewer infrequently occurring events than was true for male subjects. Significant Gender effects included saccade and blink amplitude, with females generally showing larger amplitude responses than males.

Gender effects of greatest interest were those in which Gender interacted with TD. Such interactions were obtained for the Long Closure Duration blink frequency and the saccade amplitude measures. For the LCD Blink measure, the interaction also includes TOT. The results suggest that the TOT effect is greater for PM males and for AM females, with more modest increases in this variable for AM males, and little or no increase for PM females. We interpret these increases in LCD blink frequency as suggestive of "fatigue" effects. It is unclear why females should show such an effect principally for morning participants, while males demonstrate the greatest effect when participating in the afternoon, with modest changes for those participating in the morning. Replicating this gender effect would appear to be highly desirable because of the implication of these results for shift work.

The TOT effects obtained for all variables clearly demonstrates the potential utility of these oculometric measures for defining periods of impaired performance potential. A word of caution is in order, since for some of the variables, the TOT effect was reduced over Ds. Specifically, for the 50% window blink duration measure, the slope becomes shallower over Ds so that by D 3, there appears to be no longer a TOT effect. A similar effect is seen in the blink flurry measure. These, however, were the only measures for which this cautionary comment is applicable.

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