Cognition, Blinks, Eye-Movements, and Pupillary Movements During Performance of a Running Memory Task

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Introduction: Blinks, saccades, and pupil diameter changes are studied for their application as tools to unobtrusively monitor aspects of performance. ***Methods:*** Subjects performed a running memory task for a 60-min period. To evaluate changes in the relationship of blinks to saccades as a function of time on task, the ratio of blinks occurring with and without saccade was calculated for the second following stimulus termination plus the last 0.2 s of stimulus presentation, and also the second preceding stimulus onset plus the initial 0.2 s of stimulus presentation. Changes in pupil diameter following blinks with and without saccades were measured at the beginning, middle, and late in the experiment. ***Results:*** Blink frequency increased during both periods as a function of time on task ($p < 0.0001$). The ratio of blinks concurrent with saccades during the post-stimulus period increased as a function of time on task ($p < 0.0001$). Pupil diameter increased following blink termination ($p < 0.05$), regardless of time on task, blink duration, or the presence of a saccade during the blink. ***Conclusion:*** Our results suggest that the increase in blinking associated with saccades as a function of time on task, and the pupillary dilation following a blink are associated with aspects of information processing. These results provide a framework for future studies assessing higher-order cognitive function in operational environments based on measurements of blink, pupil, and saccades.

Keywords: blinks, eye movements, pupillary movements, cognition, oculomotor, cognitive performance.

CLARIFYING THE relationship between blinks, eye movements, and pupillary diameter changes as they relate to aspects of information processing is important for the application of oculometrics to monitor and possibly predict components of cognitive function. Many studies have demonstrated that blinks are inhibited during information acquisition, and facilitated following the termination of such processing (1,6,7,9,14,15,19,21), and that blink frequency increases as a function of time on task (19). The basis for this increase is unknown. We suspect that it is attributable to a decrease in the ability to inhibit blinking as a function of variables such as fatigue. There is reasonable evidence in the literature suggesting decay in inhibitory control as a function of time on task. The increase in blinking, increase in extraneous motor activity, and the occurrence of overflow movements as a function of time on task are all evidence for a reduction in such inhibitory control.

Pupil diameter is also affected by information processing. The pupil dilates during information processing (2,4,12), with increasing task difficulty mirrored by increasing pupil dilation. With respect to eye movements, it is obvious that when performing a visual task, the eyes have to move to the target location to acquire relevant information and that variables such as eye movement latency, accuracy, and duration reflect importance of the task for the subject (23).

Blinks, pupil characteristics, and eye movements have generally been evaluated independently. Blinks interfere with the recording of the electroencephalogram (EEG), and also interfere with eye movements and pupillary movements. Thus, subjects are generally instructed to inhibit blinking during task performance (16) in studies where the focus is on eye movements, pupil diameter, and EEG measures. We believe that the results of studies where subjects are instructed to inhibit blinking cannot be directly generalized to the "real world" because in the absence of blinks, reaction times are significantly longer than when the response occurs in the presence of a blink.

Although blink frequency has been shown to increase as a function of time on task (19,21), the time-on-task effect involving the relationship between blinking and eye movements has been minimally investigated. Fogarty and Stern (5) reported that blinks are significantly more likely to occur concurrent with gaze shifts returning the eyes to a central location than when gaze shifts toward a target location to acquire information. In vigilance tasks such as driving an automobile, blinking frequently co-occurs with an eye movement. For example, eye movements returning gaze from a rear-view mirror back to the driving scenario are frequently accompanied by a blink. However, moving the eyes to the mirror is seldom accompanied by a blink (20). The absence of blinks associated with toward-the-mirror

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eye movements may represent an involuntarily suppression of blinks in anticipation of acquisition of critical visual information.

With the increase in blinking associated with time on task, one may ask whether such blinks continue to be associated with "return" saccades, or whether the increase is a reflection of poorer inhibitory control over blinking. In the example given above, this would involve the occurrence of blinks as gaze shifts to the rear-view mirror. Thus, in a vigilance task where the operator has to acquire peripherally presented information and then return gaze to a central location in anticipation of the next peripherally presented stimulus, one would expect most blinks to occur in association with the saccade returning gaze to the central location. Equally important is the inhibition of blinking associated with the occurrence of a temporally predictable stimulus. Decreases in such inhibitory control should be reflected in an increase in blink frequency during the period preceding stimulus presentation, when a stimulus is predicted not to occur. If blink frequencies thus change, this would suggest higher-order central control (that is, either a conscious or unconscious decision) over the occurrence, as well as the inhibition of blinking. The co-occurrence of blinks with saccades makes ecological sense. Saccadic eye movements, as well as blinks, reduce the ability of the operator to take in and process visual information (saccade suppression and blink suppression) (11); therefore, it is reasonable that the two occur concurrently. Since there is an increase in blinking as a function of time on task, we were interested in determining whether the ratio of blinks associated with saccades changed as a function of time on task.

Unpublished research from our laboratory suggested that changes in pupil diameter associated with blinking were surprisingly small, while those associated with momentary blackout of the display for 150 ms or longer produced significant constriction associated with the increase in light falling on the eye (Tanida K, Stern JA. Unpublished communication; 1996). If for a restricted area of a display the number of pixels lighted is not altered, then pupil diameter should not change. When one enacts a saccade under such conditions, pupil diameter should not change because the brightness of the display is not changed. However, blinking changes the amount of light falling on the retina. Since retinal luminance is reduced on closing of the eye and increased following reopening, the pupil should dilate during blinking and then should constrict after blink termination. If the pupil dilates following a blink when it should be constricting immediately after the eye opens and the only determinant is changing light, it is necessary to consider other variables to account for the change. In such a case, we need to compare the pupil diameter changes following a blink associated with information processing to blinks where there are no, or minimal, information processing requirements.

Four research questions are addressed in this manuscript in order to determine the relationships among blinks, eye movements, pupil diameter, and active cognition: 1) Is there a relationship between blinks and saccadic eye movements with regard to time-on-task effects? 2) Is there a relationship between blinks and changes in pupil diameter, and a relationship between blink duration and degree of pupil diameter change? 3) Does the occurrence of a saccade concurrent with a blink significantly affect pupil diameter change? 4) Do pupil diameter changes that occur following a blink differ when the blink is, or is not, temporally close to a stimulus requiring information processing? This last question focuses on the temporal relationship between blinks, pupil changes, and active cognitive processes.

METHODS

Subjects

Eight undergraduate students (four men, four women, mean age: 20 ± 2 yr) from Washington University in St. Louis, MO, participated in the study. All were physically healthy with 20/20 vision, corrected or uncorrected. The study protocol was approved in advance by the Institutional Review Board, Washington University. Each subject provided written informed consent before participating. Subjects were paid for their participation in the study.

Apparatus

The experiment was conducted in a dimly lit room (approximately 200 lx). Participants were tested individually, seated in a chair with the back of the head comfortably cradled. The headrest contacted the head at two points and allowed for rotational head movements. Stimuli were presented on a computer-controlled display located approximately 57 cm in front of the subject. The 57-cm viewing distance provided a full and comfortable view of the stimuli at the focal distance of the camera.

A touch pad was used to record manual responses to the occurrence of specific patterns of characters. The subject was instructed to rest the right index finger on the response pad. A response was made by lifting and then replacing the right index finger as quickly as possible. Reaction time was defined as the time between stimulus onset and finger lift initiation.

Electrooculogram (EOG) was used to measure horizontal eye movements and blinks. Electrodes for EOG recording were applied to the left and right outer canthi to measure horizontal eye position, above and below the right eye to measure vertical eye position and blinks. EOG signals were DC amplified, low-pass filtered at 100 Hz, and notch filtered at 60 Hz. Detailed information about apparatus can be found in Wang and Stern (23).

A video camera located under the CRT display and directed at the subject's right eye recorded eye position, pupil diameter, and pupil occlusion time associated with blinking (LC Technology Eyegaze Development System, Alexandria, VA). The video camera system sampled data at 60 Hz. Eye movements, blinks, pupillary movements, stimulus presentation, and manual responses were digitized at a sampling rate of 1000 Hz using Advanced Technologies Data Acquisition System (AT CODAS, DATAQ Instruments, Inc., Akron, OH). A graphic data reduction system, BBDRS (Bio-Behavior

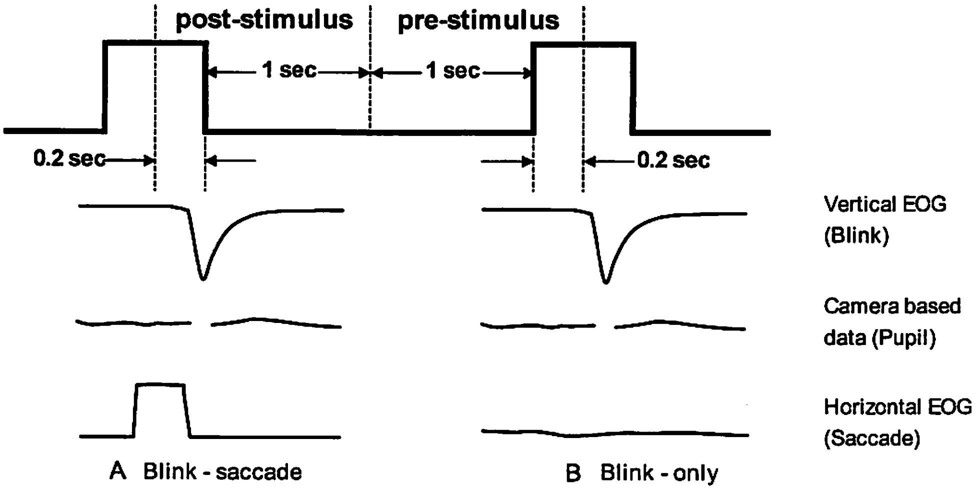

Fig. 1. Identification of A) blink-saccade and B) blink-only events during the post-stimulus and pre-stimulus periods.

Data Reduction System, St. Louis, MO) was used for data analysis (3).

Running Memory Task

Stimuli consisted of a series of 1500 single-digit integers bracketed by Xs (X6X). The central fixation location consisted of three Xs (XXX). Stimuli were presented at eccentricities of 10° to the left and right of center in line with the central fixation stimulus. An integer value between 0 and 9 (zero was defined as an even number) was semi-randomly assigned to each stimulus. Subjects were required to make a manual response following a sequence of two odd integers. A sequence of two odd integers occurred 90 times during the experiment, with 30 presentations of a single odd integer. Thus, only 8% of stimuli were odd integers.

To avoid changes in brightness of the display associated with replacement of stimuli, such changes occurred without either overlap or delay. "XXX" was presented at the central fixation point for 2000 ms (control display). This was followed by a 400-ms presentation of either an odd or an even integer bracketed by Xs, such as "X5X" or "X8X" 10° to the left or right of the fixation area (stimulus display). Following termination of the peripheral stimulus, the central fixation control display reappeared.

When a current integer was even, it was not relevant. When it was odd, the probability that the next integer would also be odd and requiring a response was 0.75. Thus the first odd integer was expected to generate a high level of expectancy that the next stimulus would be an odd integer requiring a response. Subjects were instructed that there would never be a sequence of more than two odd integers.

Procedures

After the participant entered the recording chamber and over a 10-min period, instructions about the task were given, electrodes for EOG were attached, and the EyeGaze system was calibrated. Participants practiced the task for approximately 2 min, until it was performed correctly. After a rest period of up to 2 min, actual duration determined by the subject, the 60-min experiment began. We selected 60 min as the shortest length of time in which statistically significant differences would reliably be found for ocular fatigue effects related to time on task. The same order of stimulus presentation was used for every subject. Interstimulus intervals were 2000 ms and stimulus duration 400 ms throughout the experiment.

Data Processing

Eye movements, blinks, pupillary movements, stimulus timing, and manual responses were simultaneously acquired and analyzed offline. Criteria identified by the experimenter that maximized identification of saccades and minimized identification of noise as saccades were applied. Blinks are defined as total occlusion of the pupil by the eyelid. Blink data were visually screened and those events not achieving these criteria were not included in the data analysis. Data were then entered into the Bio-Behavioral Data Reduction System (BBDRS). Further information about the BBDRS algorithms used to identify and analyze blinks and saccades can be obtained online (3).

The relationship between blinks and saccades: A blink associated with a saccade was identified when the post-blink data in the horizontal EOG differed from the pre-blink data by more than the noise level, and/or the camera-based data identified a shift in gaze position between the points in time where there was signal loss and signal recovery. Blinks without saccades were identified when the A/D (analog/digital) value in the horizontal EOG differed less than the noise level between samples taken immediately preceding and immediately following a blink, and/or there was no change between pre- and post-data loss in the camera-based horizontal gaze position tracing. The pre- and post-blink eye measures were generally in agreement with each other. Blinks collected during the 1 s following stimulus termination and the last 0.2 s of stimulus presentation are identified as post-stimulus blinks, and those occurring during the 1 s preceding stimulus onset and the initial 0.2 s of stimulus presentation are identified as pre-stimulus blinks (**Fig. 1**). The reason for dividing the stimulus presentation period into two equal segments of 0.2 s each and identifying the initial 0.2-s period with the pre-stimulus period was based on the fact that the saccade moving the eyes to the target location occurred approximately 0.2 s after stimulus onset. Thus the pre-stimulus period might equally well be referred to as the rest plus pre-stimulus identification period. Data were grouped into six consecutive 10-min intervals.

The relationship between blink and pupil diameter: Pupil diameter was calculated from an assessment of the vertical dimension of the ellipse that best describes the configuration of the pupil (EyeGaze system algorithm). Blink duration was based on the period of time for which the pupil was occluded. Pupil diameter was sampled every 100 ms starting 300 ms prior to data loss associated with the blink and for 1000 ms following signal recovery. There were 20 blinks sampled at the beginning, middle, and end of the experiment (**Fig. 2**). Pupil diameter, measured at the onset and termination of a blink, were excluded because these two data points do not reliably reflect pupil diameter (10).

RESULTS

Time-on-Task Effects on Blinks Associated with a Saccade

The right-most column in **Table I** shows changes in the average number of blinks as a function of time on task. A 6 (six successive time periods) within subject analysis of variance (ANOVA) for the number of blinks revealed a main effect of time period [F (5,35) = 3.23, $p < 0.05$]. Multiple comparison (MSe = 18.35, $p < 0.05$, LSD = 4.37) demonstrated that blink frequency increased as function of time on task (see also **Fig. 3**).

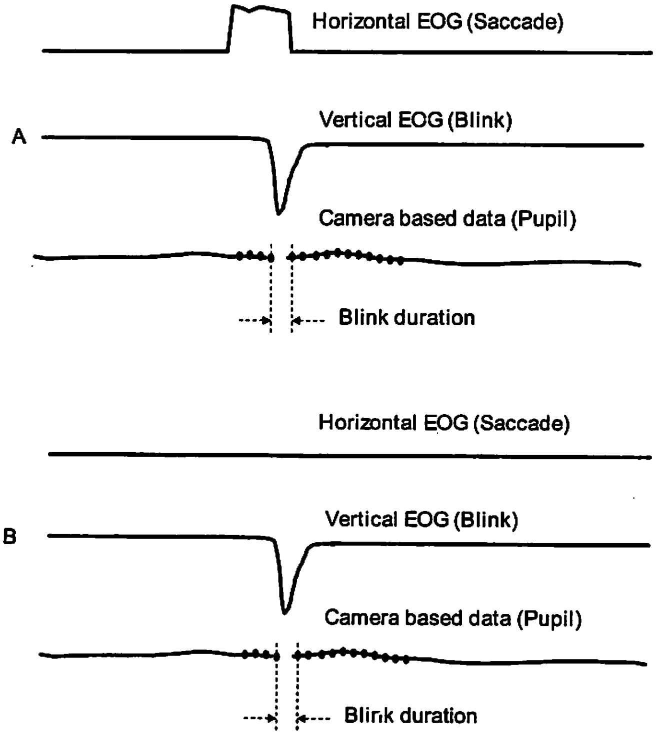

Fig. 2. Identification of pupil data associated with eye blink A) with and B) without saccade. Dots on the pupil line means that pupil data were sampled every 100 ms before and after the blink.

TABLE I. RATIO OF BLINK/SACCADE AND BLINK-ONLY EVENTS.

	Post-stimulus*		Pre-stimulus†		
Time in Minutes	Blink Saccade %	Blink Only %	Blink Saccade %	Blink Only %	Average Number of Blinks
1–10	34.2	51.4	0.7	13.7	253
11–20	46.0	36.9	0.9	16.3	261
21–30	50.8	29.1	2.0	18.2	307
31–40	52.9	26.4	2.6	18.1	300
41–50	54.5	23.8	2.7	19.2	317
51–60	53.4	23.3	4.3	19.1	333
Mean	48.6	31.8	2.2	17.4	295.2

*Post-stimulus—during the 1 s following stimulus termination and the last 0.2 s of stimulus presentation.

†Pre-stimulus—during the 1 s preceding stimulus onset and the initial 0.2 s of stimulus presentation.

A 2 (pre- vs. post-stimulus) × 2 (with vs. without saccade) × 6 (six successive time periods) within subject ANOVA was calculated on the ratio of blinks for each condition. Since a significant three-way interaction [F (5,35) = 9.04, $p < 0.0001$] was found, further analyses were conducted, one each for the post-stimulus, the pre-stimulus, and the blink-saccade vs. blink-only condition.

In the post-stimulus condition, a significant interaction between saccade and a time-on-task effect [F (5,35) = 8.87, $p < 0.0001$] was obtained. Comparing blink-saccades with blink-only events, significant differences were obtained for the last two periods [1–10 min: F (1,7) = 1.04, ns; 11–20 min: F (1,7) < 1, ns; 21–30 min: F (1,7) = 2.81, ns; 31–40 min: F (1,7) = 4.63, $p < 0.1$; 41–50 min: F (1,7) = 10.61, $p < 0.05$; 51–60 min: F (1,7) = 11.96, $p < 0.05$]. A significant time- on-task effect for percent of blink-saccades was obtained [F (5,35) = 6.00, $p < 0.0001$] as well as a significant time-on-task effect for the blink-only [F (5,35) = 11.59, $p < 0.0001$] condition. These results revealed that the difference between the ratios of the blink-saccade and blink-only diverged as a function of time on task with a significant change for the last two periods.

In the pre-stimulus condition, the main effect of saccade was significant [F (1,7) = 20.87, $p < 0.01$] as well as the main effect of time on task [F (5,35) = 7.82, $p < 0.0001$]. Multiple comparison (MSe = 5.32, $p < 0.05$, LSD = 1.69) revealed that both the ratio of blinks-only and blink-saccade increased as a function of time on task. Thus, during this period, relatively few blinks occurred concurrent with a saccade, and the frequency of occurrence of both types of pre-stimulus blinks increased as a function of time on task.

In the blink-saccade condition, a significant interaction between the pre/post effect and time-on-task effect [F (5,35) = 4.13, $p < 0.01$] was obtained. A significant pre-stimulus vs. post-stimulus effect was obtained for all time periods [F (1,7) > 20.35, $p < 0.01$], with a larger percentage of blinks occurring in the post-stimulus period. A significant time-on-task effect in the post-stimulus condition [F (5,35) = 6.00, $p < 0.0001$], and a significant time-on-task effect in the pre-stimulus con-

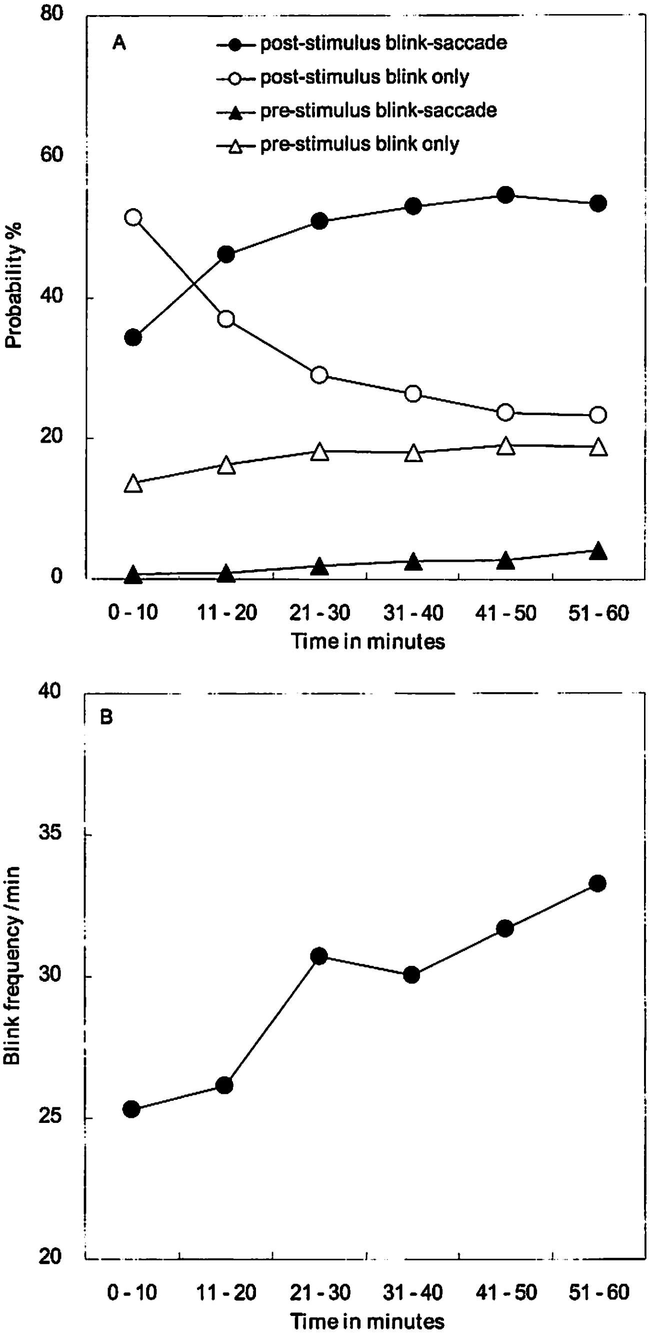

Fig. 3. A) Ratio of blink-saccade and blink-only events during the second following stimulus termination and the last 0.2 s of stimulus presentation (post-stimulus), and during the second preceding stimulus onset and the initial 0.2 s of stimulus presentation (pre-stimulus). B) The average number of blinks in each successive time period for the data shown in Fig. 3A.

dition [F (5,35) = 4.35, $p < 0.01$], were obtained. Multiple comparison (MSe = 78.27, $p < 0.05$, LSD = 9.03 in post-stimulus condition; MSe = 3.09, $p < 0.05$, LSD = 1.79 in pre-stimulus condition) revealed that the ratio of the blink-saccade in both post- and pre-stimulus increased as a function of time on task.

In the blink-only condition, a significant interaction between the pre/post stimulus period and time-on-task effect [F (5,35) = 12.84, $p < 0.0001$] was obtained. A significant pre/post effect was obtained in the time period of 1–10 min only [F (1,7) = 10.13, $p < 0.05$]. A significant time-on-task effect in the pre-stimulus condition [F (5,35) = 3.82, $p < 0.01$] and a significant time-on-task effect in the post-stimulus condition [F (5,35) = 11.59, $p < 0.0001$] was obtained. Multiple comparison (MSe = 9.29, $p < 0.05$, LSD = 3.11 in pre-stimulus condition; MSe = 80.55, $p < 0.05$, LSD = 9.17 in post-stimulus condition) revealed that the difference between the ratio of the blink-only in the pre- and post-stimulus conditions became smaller as a function of time on task. That is, in the post-stimulus period the percent of blinks without saccades decreased over time, while in the pre-stimulus period they increased.

In summary, we find an increase in blinking as a function of time on task. Dividing blinks into those that occur in conjunction with and those occurring independently of saccades, as well as during the time period following and preceding information acquisition and processing, we find:

In the pre-stimulus period:

1. The pattern of percentage of blinks associated with vs. without saccades is the reverse of that seen in the post-stimulus period with a significantly larger percentage of blinks occurring independent of saccades.
2. There is a significant increase in the percent of pre-stimulus blinks as a function of time on task.

In the post-stimulus period:

1. There is a rapid shift in percent of blinks occurring independently of saccades to blinks occurring concurrently with saccades (blink-saccades). In the initial 10 min, more blinks occurred independently of, and following, saccades (51%) as compared with blink-saccades (34%). By the second 10-min period those percentages had shifted to 37% and 46%, respectively.
2. There is a significant increase in percent of blink-saccades as a function of time on task, and a concurrent decrease in percent of blink-only events.

Blink Duration—Camera-Based Data

Blink duration was defined as the time between the camera losing pupil information and reacquiring it under conditions where the vertical EOG signal identified a blink (Fig. 2). A 3 (period in experiment: early, middle, and late) × 2 (with vs. without saccade) within subject ANOVA was calculated on the mean blink duration for each condition. A significant main effect was found for the association with saccade (F (1,7) = 10.76, $p < 0.05$). No significant effects of period (F (2,24) = 2.44, n.s.) or interaction (F (2,24) < 0) were obtained. In the presence of a saccade, blink closure duration was longer than when the blink occurred independently of a saccade (**Table II**).

Pupil Diameter Changes Associated with Blinks

Fig. 4 shows the changes in pupil diameter associated with blinks with and without saccade in early, middle,

TABLE II. MEAN EYE BLINK DURATION.

	Early	Middle	Late
With Saccade	199 ± 61 ms	208 ± 39 ms	207 ± 50 ms
Without Saccade	171 ± 54 ms	192 ± 55 ms	196 ± 43 ms

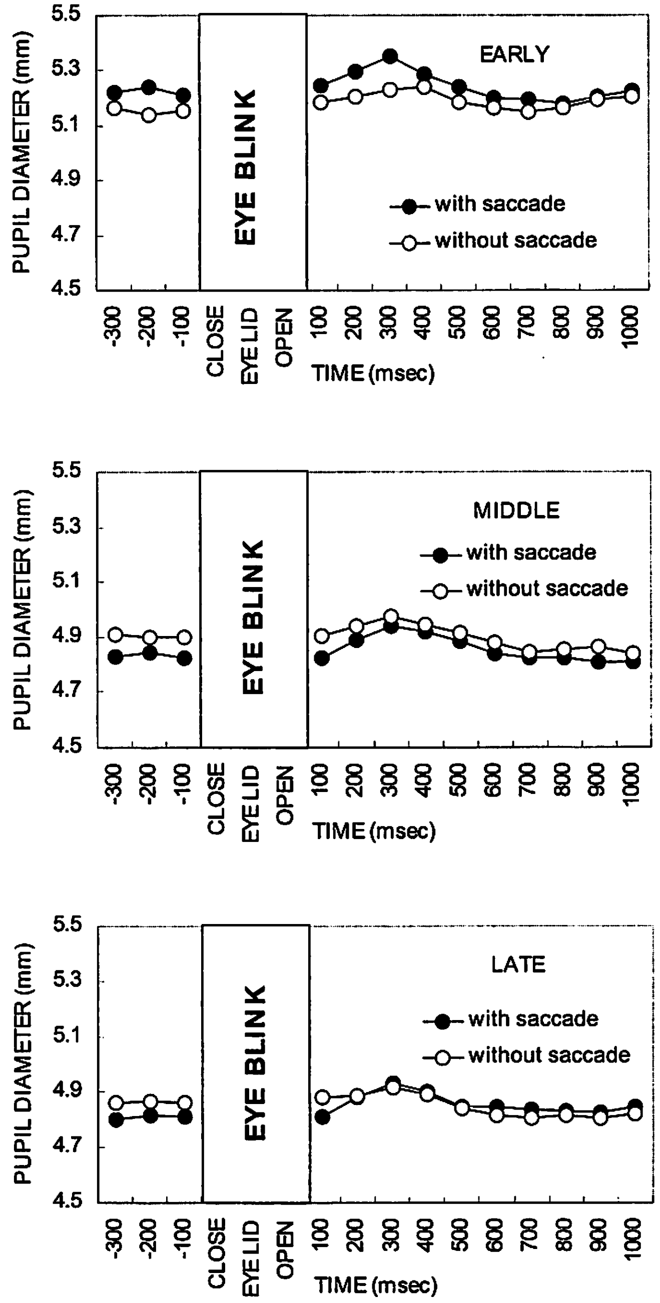

Fig. 4. Changes in pupil diameter with eye blink associated with and without saccade during the early, middle, and late period in the experiment.

and late segments of the experiment. A 3 (period of experiment: early, middle, and late) × 2 (with vs. without saccade) × 13 (time course: from 300 ms before the blink onset to 1000 ms after the blink termination) within subjects ANOVA was calculated on the mean pupillary response for each condition. A significant main effect was obtained for the time course [F (12,84) = 2.38, $p < 0.05$]. There was no significant main time-on-task effect [F (2,14) = 1.14, n.s.] and interaction ($F < 1$) for any other conditions. These results revealed pupil diameter increases following an eye blink, regardless of whether the blink occurred concurrently with a saccade.

The post hoc multiple comparisons (MSe = 0.025, $p < 0.05$, LSD = 0.06) revealed that pupil dilation reached its peak between 200 ms and 400 ms following a blink (**Table III**). Thus, the pupil dilates following blink termination with peak dilation occurring approximately 300 ms following blink termination. No evidence for pupillary constriction following blink termination was observed.

Relationship Between Pupil Diameter and Blink Duration

If the post-blink pupillary measure was affected by the decrease in light falling on the retina during a blink, and if lid closure was accompanied by an increase in pupil diameter, then pupil diameter should have constricted following blink termination. No constriction was observed. Mean blink duration was calculated for each participant. Blink duration longer than the mean was identified as "long," and those shorter than the mean as "short." No difference in the pupil dilation response was obtained between "long" and "short" duration blinks. Pupillary constriction was identified when minimum pupil diameter between 100 ms and 1000 ms after blink termination was smaller than the mean pupil diameter between 100 ms and 300 ms before blink onset. Pupil dilation was identified when a maximum pupil diameter between 100 ms and 1000 ms following blink termination was greater than mean pupil diameter between 100 ms and 300 ms before blink onset. Within subject *t*-tests were calculated for the mean pupil diameter associated with short vs. long duration blinks. No significant effect for either pupil constriction [$t(7) < 1$] or pupil dilation [$t(7) = 2.10$] was obtained. Correlations between blink duration and pupil dilation were calculated for each of eight participants. Five of the eight correlations were negative and smaller than 0.10. Three correlations were relatively large, −0.41, −0.26, and 0.20; with an N of 60 these were statistically significant [$t(58) > 11.84$, $p < 0.001$]. However, removal of two outlier values reduced the −0.41 correlation to −0.20. Both analyses thus lead to the conclusion that blink closure duration has little effect on the observed pupil dilation response.

Pupil Diameter Changes, Blinks, and Information Processing

Comparing the pupil diameter changes incidental to blinks associated with an information processing requirement and blinks not associated with information processing, we categorized the stimuli into two types: those beginning with an odd and those beginning with an even integer. An odd integer could be followed by a second odd integer, or by an even integer. The presentation of an odd integer, independent of what followed, would trigger anticipation of a possible response requirement. An even integer could be followed by an even or odd integer. An even integer would not result in anticipation of a response requirement. Even integers were stimuli that did not have to be remembered.

Of the 60 blinks evaluated for each subject, 15.4% fell into the category "requires stimulus processing" and 84.6% into the non-processed category. Since blinks are generally tightly coupled with saccades when returning

TABLE III. MULTIPLE COMPARISONS OF PUPIL DIAMETER MEASURES OVER TIME.

	−300ms	−200ms	−100ms	100ms	200ms	300ms	400ms	500ms	600ms	700ms	800ms	900ms	1000ms
−300ms		n.s.	n.s.	n.s.	n.s.	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
−200ms			n.s.	n.s.	n.s.	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
−100ms				n.s.	n.s.	$p < 0.05$	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
100ms					n.s.	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
200ms						n.s.	n.s.	n.s.	n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	n.s.
300ms							n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
400ms								n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
500ms									n.s.	n.s.	n.s.	n.s.	n.s.
600ms										n.s.	n.s.	n.s.	n.s.
700ms											n.s.	n.s.	n.s.
800ms												n.s.	n.s.
900ms													n.s.
1000ms													

the eyes to the central location in anticipation of the next peripheral stimulus, we were able to evaluate pupil diameter changes associated with the requirement to retain information (i.e., following presentation of an odd integer) in anticipation of having to make a response (following presentation of a second odd integer), as compared with the situation where no information had to be retained (i.e., following presentation of an even integer) and where no response requirement was likely to occur for at least the next two stimuli. We did not consider the effect of period of experiment (early, middle, and late), because it had no significant effect in the previous analysis.

Fig. 5 shows the change in pupil diameter associated with blinking with and without information processing. A 2 (with vs. without information processing) × 13 (time course: 300 ms before the blink onset to 1000 ms after the blink termination) within subjects ANOVA was calculated on the mean pupillary response. A significant interaction [F (12,84) = 2.51, $p < 0.01$] revealed that the pupil diameter changes associated with blinking following odd integers was larger than those following even integer presentations. Comparing the pupil diameter changes associated with the two conditions (in each of 13 time courses from 300 ms before the blink onset to 1000 ms after the blink termination), significant differences were obtained for all but four time periods (−300 ms and −200 ms before blink onset, and +800 ms and +1000 ms after a blink termination). A subordinate statistical test revealed significant main effects for both conditions [F (12,84) = 2.40, $p < 0.05$ for the minimal information processing condition; F (12,84) = 3.42, $p < 0.001$ for the condition involving information processing]. The post hoc multiple comparisons (MSe = 0.004, $p < 0.05$, LSD = 0.065 for the minimal information processing; MSe = 0.007, $p < 0.05$, LSD = 0.084 for the condition involving information processing) revealed a tonic effect, with the pupil consistently larger under the condition where information had to be retained and expectation of having to respond was present (**Table IV**).

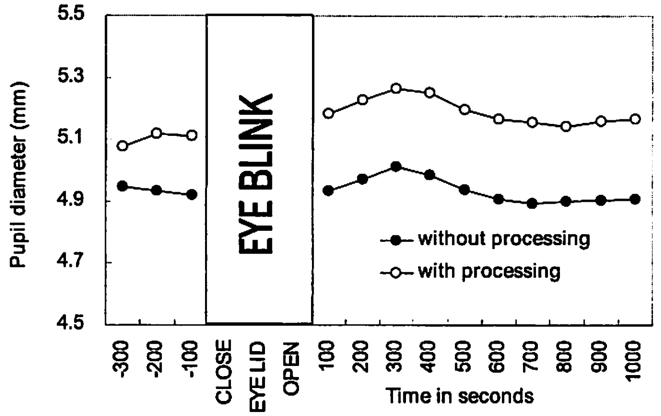

Fig. 5. Changes in pupil diameter with eye blink associated with and without information processing.

Running Memory Task Performance

There was no significant time-on-task effect for response latency [F (5,35) = 1.52, ns]. There was an increase in the number of missed signals and false alarms over time with most such errors occurring between minutes 30 and 50 of task performance. However, because of the small sample size and few misses and false alarms, these effects were not reliable.

Summary

Blinks increased in frequency as a function of time on task. This was true for blinks associated with responding, as well as for blinks occurring in the period preceding stimulus onset. There was no change in blink duration as a function of time on task. Most blinks occurred concurrently with saccades, though in the first 10 min of task performance approximately 50% of blinks occurred independently of saccades. By the second 10 min the percent of blinks occurring concurrently with saccades had been reduced to 37% and that pattern persisted for the remainder of the experiment. Blinks concurrent with saccades were of longer duration than blinks occurring independently of saccades. Blinks occurring during the period preceding stimulus presentation also increased in frequency over the experimental period.

Pupil diameter increases were associated with blinking. The effect, though significant, was modest. Peak dilation occurred approximately 300 ms following eyelid reopening. This dilation was neither affected by blink duration or whether the blink occurred concur-

TABLE IV. MULTIPLE COMPARISONS OF PUPIL DIAMETER MEASURES OVER TIME.

Without Information Processing

	−300 ms	−200 ms	−100 ms	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms	700 ms	800 ms	900 ms	1000 ms
−300 ms		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
−200 ms			n.s.	n.s.	n.s.	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
−100 ms				n.s.	n.s.	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
100 ms					n.s.	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
200 ms						n.s.	n.s.	n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
300 ms							n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
400 ms								n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
500 ms									n.s.	n.s.	n.s.	n.s.	n.s.
600 ms										n.s.	n.s.	n.s.	n.s.
700 ms											n.s.	n.s.	n.s.
800 ms												n.s.	n.s.
900 ms													n.s.
1000 ms													

With Information Processing

	−300 ms	−200 ms	−100 ms	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms	700 ms	800 ms	900 ms	1000 ms
−300 ms		n.s.	n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	n.s.	n.s.	n.s.	$p < 0.05$
−200 ms			n.s.	n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
−100 ms				n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	n.s.	n.s.	n.s.	n.s.	n.s.
100 ms					n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
200 ms						n.s.	n.s.	n.s.	n.s.	n.s.	$p < 0.05$	n.s.	n.s.
300 ms							n.s.	n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
400 ms								n.s.	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
500 ms									n.s.	n.s.	n.s.	n.s.	n.s.
600 ms										n.s.	n.s.	n.s.	n.s.
700 ms											n.s.	n.s.	n.s.
800 ms												n.s.	n.s.
900 ms													n.s.
1000 ms													

rently with, or independently of, a saccade. The effect also was independent of information processing requirements. Pupil diameters associated with stimuli not requiring cognitive processing were smaller than pupil diameters associated with stimuli that required processing.

DISCUSSION

The results of this experiment provided the following answers to the four questions raised in the Introduction. For the first question regarding whether there is a time-on-task effect on blinks and eye movements, we noted that there is a significant increase in blinking as a function of time on task. There is also a significant increase in the number of blinks occurring in the period immediately before stimulus presentation as a function of time on task. The co-occurrence of blinks and saccades increases in the first 10 min of task performance and then becomes asymptotic. Questions two and three dealt with the effects on pupil diameter of blinking and eye movements occurring during a blink. We demonstrated that the pupil dilates, peaking approximately 300 ms following blink termination, and that this effect is independent of both blink duration and the occurrence of a saccade during a blink. The last question asked whether pupil diameter associated with blinking is affected by information processing demands, and we observed that the pupillary response associated with the blink is not affected by information processing. We found, however, a tonic increase in pupil diameter that is associated with information processing.

Blinks and Eye Movements (Saccades)

The most important findings with respect to the relationship between cognition and oculomotor variables were as follows:

1. The majority of blinks occur in conjunction with eye movements returning gaze to the central location, supporting our hypothesis that many (though not all) blinks terminate during a period of information acquisition and processing. These blinks are thus associated with the knowledge that the next stimulus will not occur for some time.
2. Blinks following the presentation and response to a stimulus occur after gaze has returned to the central location early in task performance. However, by minute 10 of task performance, the majority of the blinks following stimulus presentation co-occur with the return of gaze to the central location. We suspect that there is no awareness on the part of the operator of this change in blink/eye-movement pattern. We also suspect that there is no awareness that return gaze shifts are accompanied by a blink, nor is there awareness that saccade duration is adjusting to blink duration.
3. Pupil diameter changes associated with blinks are not affected by time on task nor by whether the blink is associated with, or independent of, information processing activity. Information processing demands are

associated with larger amplitude pupils before as well as following a blink. Anticipating a second odd integer requiring a response leads to an increase in pupil diameter. The effects of information processing requirements on pupil diameter are planned for presentation in a future publication.

The significant difference in blink frequency as a function of time on task found in the present study confirms what has been previously well documented (19). We suspect that the relatively high blink frequency found in this experiment is in part a function of both the frequency with which stimuli were presented and the constant inter-stimulus interval. By knowing when to expect the next stimulus, subjects could time their blinks to a non-stimulus period. To investigate changes in the timing of blinks, the inter-stimulus interval was divided into two segments, each of 1.2 s in length. Again, we suspect that this is not voluntary, and the operator is probably unaware of these relationships. These time periods were selected because we and others have demonstrated that blinks are most likely to occur after termination of information intake and processing than at other points in time (1,6,7,9,14,15,19,21).

Because of the increase in blink frequency as a function of time on task and also to "normalize" the data (because of large individual differences in blink rate), we converted the total number of blinks for each 10-min period into two categories. The first category was based on the timing of blinks (pre- vs. post-stimulus period), and the second on whether a blink was independent of or co-occurred with an eye movement. We predicted (5) and found that most blinks occurred during the post-stimulus period (80.5% vs. 19.5%).

Thus, blinks are inhibited during periods where information is expected, presented, and processed. This inhibition is as true of "real world" situations as laboratory experiments. In a study associated with rear-view mirror gazes where truck drivers drove a truck simulator for extended periods of time, we (20) demonstrated drivers seldom blinked as the eyes moved to the rear view mirror. Most return eye movements to the driving scenario were accompanied by blinks, again suggesting that when information abstraction is important, we inhibit blinking.

We divided blink data into those that co-occurred with and those that occurred independently of saccades. When considering the post-stimulus period, we found that during the initial 10 min of task performance, more blinks occurred independently of saccades than in conjunction with them. Most of these blinks occurred following the saccade returning the eyes to the central location. There were marked individual differences in the speed with which the shift to blinks co-occurring with saccades evolved; by 10 min into the task all subjects were so responding on the majority of trials.

Consistent with our hypothesis that blinks identify the termination of information acquisition and processing, we suggest that early in task performance subjects were still processing aspects of the task while the eyes were returning to the central location in anticipation of the next stimulus. Later in task performance such processing was completed earlier.

Because we seldom saw examples of a blink preceding the return saccade, we believe that initiation of a blink may be a more robust identifier of the termination of information processing than the return of gaze to the central location. The return saccade may index termination of acquisition of the stimulus itself; in this case, numerals. The blink may index the acquisition of additional information about the experiment, such as the predictability of stimulus occurrence, the fixed locations of the stimuli, the requirement to memorize or not abstract information about the integer based on whether it is odd or even, and the preparation of a response.

The relatively high frequency of blinks independent of saccades during both the pre- and post-stimulus periods were, in part, produced by subjects who were "double blinkers"; i.e., they demonstrated a pattern of paired blinks with the first one associated with the gaze shift.

The ratio of blinks independent of saccades and blinks with saccades occurring during the pre-stimulus period showed a pattern opposite to that seen in the post-stimulus period. During the pre-stimulus period, most blinks occurred independently of saccades (17.4% vs. 2.2%). With regard to saccades moving the eyes to the target location, in the present experiment that saccade latency was of the order of 150 ms. These prosaccades, that is, saccades directed toward the target of interest, were not expected to be accompanied by blinks since this is a period of information intake.

The increase in blink-saccades observed as a function of time on task (from 0.7% to 4.3%) is interpreted by us as evidence for a breakdown in the inhibition of blinking normally associated with information intake. Though the increase in all pre-stimulus blinks as a function of time on task is not large (first 10 min 14.4%, last 10 min 23.4%), we believe it to be important. We hypothesize that blinks occurring close in time to an expected stimulus are evidence of a momentary lapse in alertness, suggesting a breakdown in inhibitory control.

Interestingly, we observed a sentinel appearance of micro-blinks in those subjects who shortly thereafter demonstrated blinks occurring closely to an expected stimulus. Micro-blinks, also referred to as lid jerks in the literature, are blinks that do not infringe on the pupil. We would like to suggest that the increase in micro-blinks as a function of time on task may prove to be a sensitive indicator of momentary lapses in attention to task performance. We hope to test this "hypothesis" by the on-line monitoring of such blinks, and by linking a requirement for the performance of a secondary task to the occurrence of a micro-blink. Our prediction is that errors in task performance will be significantly higher under the micro-blink condition than when the secondary task is introduced at random points in time.

Is there a difference in the nature of the blink associated with a saccade as compared with blinks independent of saccades? Blink duration here was measured by identifying the period during which the camera lost the pupil during an EOG identified blink. We found that blink duration was significantly longer in the presence of a saccade, though the difference was small. Reversing the question, we may ask if there are differences in saccades associated with blinks as compared with saccades independent of blink? There is little disagreement that saccades occurring during a blink can be slower than "normal" and frequently mirror blink duration (13). Saccades are not invariably lengthened during a blink, however, and one can identify normal saccades though the vast majority "adapt" to blink duration. It is apparent that the programming of saccades, although remaining an unconscious process, is mediated by higher-level central nervous system mechanisms.

Pupil Activity in Conjunction with Blinks

We controlled for pupil diameter changes associated with stimulus intensity by illuminating approximately the same number of pixels independent of stimulus location. Since there also might be changes in pupil illumination as a function of movements to the right or left of the central location, we assured ourselves that approximately the same number of events were presented at each location. Thus, changes in pupil diameter could not be attributed to display brightness or stimulus location. We obtained a significant change in pupil diameter following blink occurrence. Following a blink pupil diameter increased, reaching its peak somewhere around 300 ms. This dilation effect was independent of blink duration and independent of time on task. No difference in either latency or amplitude of the dilation effect was identified when blinks were partitioned into those below and those above average duration. The amplitude of the post-blink dilation effect was quite constant, although the absolute change in pupil diameter was small, of the order of 0.02 mm. Though there was no difference in the amplitude of these pupil dilation responses as a function of processing requirement, there was a significant difference in tonic pupil diameter between the two conditions, with pupils significantly larger where information processing was required.

Pupil dilation following blink termination was identified in the present study. Obscuring of the retina by a blink produced dilation peaking approximately 300 ms following recapture of the eye by the camera. One might presume that this dilation is associated with the duration for which light falling on the pupil is reduced. If that were the case, one would expect a difference in either or both the amplitude as well as time-to-peak dilation as a function of blink duration. No such effect was observed. Both amplitude and time to peak were comparable for short vs. longer duration blinks. Fractionating the data into blinks in conjunction with a saccade vs. blinks in the absence of a saccade also did not identify any difference in these two parameters. Rather, the pupil dilated after blinking. We thus conclude that changes in light intensity, differences in blink duration, or the presence or absence of a saccade during the blink are not responsible for the pupil dilation response observed immediately following recapture of the pupil following a blink.

Two hypotheses to account for the obtained response are considered. First is lack of awareness on the part of the subject of the blackout of stimulus information during a blink or saccade. One might ask, is awareness of stimulus change a requirement for a pupillary response? Several authors have reported that visual input to the brain, especially the occipital cortex, is inhibited during blinking and saccade occurrence (8,10,17,22). Although this inhibition might account for the lack of constriction following a blink, it does not account for the observed dilation. Second is the finding that the pupil dilates during information processing (2,4,12), and that blinks generally occur following termination of information processing (1,6,7,9,14,15). We suggest that the dilation response observed here is associated with a shift from a brief period of non-processing of information during a blink to a readiness to acquire new visual information.

In addition to its corneal preservation component, blinking may be a mechanism for facilitating synaptic or neuronal cognitive and restorative processes. The blink may assist with modulating the size of the visual information stream. The brief period of darkness may allow for synaptic neuromodulatory processes to ready themselves for a new information stream. Evidence for a relationship between blink rate and cognitive performance exists in the fact that fatigue, extended wakefulness, anxiety, and stress all impact inter-blink intervals. When an individual is well rested and alert, inter-blink intervals are far longer than when the same individual is fatigued or sleepy. When an individual is even moderately sleepy, visual information processing becomes impaired (18). The shortening of the inter-blink interval may positively correlate with an impaired ability to acquire and process new visual information.

The lack of changes in the Running Memory task could be due to the insensitivity of the task and/or the short duration of the task. With regard to task duration, the length of administration was long enough to produce significant changes in eye movement, pupil, and blink variables, so one might speculate that changes in these ocular-related variables could have preceded changes in Running Memory performance, suggesting that ocular variables may be predictive of future task performance impairments.

CONCLUSION

The present experiment suggests that the interactions among blink, pupil dilation, and saccades are related to each other and to information processing. During performance of a vigilance task involving a memory and decision-making component, we demonstrated an adaptive pattern linking blink, pupil, and saccades to task performance. We demonstrated the time-on-task effect of the relationship between eye blink and saccade, and the time-locked pupillary response occurring in conjunction with an eye blink. With respect to the time-on-task effect, a most interesting finding is that blinks occur predominately during the post-stimulus period, and that there is a rapid conjunction of blinking together with the saccade returning gaze to the central location. With respect to the pupillary response associated with an eye blink, we found that the pupil dilated following an eye blink even though experimentally applied (non-blink-related) darkness for similar durations produced pupil constriction. This finding suggests that the pupillary dilation following an eye blink is associated with higher-order aspects of information processing, those that might occur in the fronto-parietal brain regions, rather than purely primary perception, as would be associated with occipital brain regions. The results of the current study contribute to the possibility that pupillary measures, blinks, and eye movements assessed together may be used to track aspects of alertness and active information processing. Currently, progress is being made on the real-time capture of these ocular measures insofar as that they need to be relatively simple, unobtrusive, and transparent to the monitored individual. These findings represent a significant advance in the study of the relationship between oculometrics and cognition, and provide the basis for further study of ocular movements for their potential usefulness as neurophysiologic indicators and predictors of alertness and cognitive performance in operational environments.

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