The Endogenous Eyeblink

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ABSTRACT

The endogenous eyeblink is identified as a cortically controlled response event, distinguishable from both reflexive and voluntary lid movements. It has a characteristic rate, form, and temporal distribution. These aspects of endogenous blinks are related to cognitive state variables. Allocation of attentional resources, transition points in information processing flow, and possibly processing mode, are indexed by blink parameters.

DESCRIPTORS: Endogenous eyeblink, Information processing, Attention, Arousal, Cognitive events. Time-on-task.

The eyeblink is a readily observable behavioral phenomenon. The rapid closing and reopening of the eyelid. in the absence of identifiable external stimulation. occurs in most vertebrates and all mammals (Blount, 1928). Neither the immediate physiological needs of the ocular system. such as the necessary lubrication of the exposed eyeball or the inundation of foreign objects in the eye. nor indirect defensive needs, as in the response to startle. nor protection of the eye from potential physical insult. are sufficient to account for the variability in form and frequency of the eyeblink. Although such needs undoubtedly play an important role in blink production, the available evidence suggests that the frequency of occurrence. specific time of production. and mechanics of the involuntary blink reflect the influence of higher nervous processes (Blount, 1928; Ponder & Kennedy. 1927). Illustrative of such higher processes are those invoked by the information processing demands imposed on an individual. The attentional and response requirements of a task are important factors affecting blink production. Additional significant contributions to variability in blinking are such organismic variables as alertness and arousal. fatigue. and anxiety.

The combined effect of factors such as: air quality. defensive responses. higher cognitive processes, and intraindividual factors. determine the frequency of blinking. It should be noted that some. or all, of these factors interact to determine the waveform characteristics of individual blinks. The situational demands and state variables combine to determine not only the overall blink rate but also when blinks are likely to occur. The purpose of this review is to describe and explicate some of the relationships among eyeblink parameters and the state and situational factors relevant to cognitive behavior.

The Behavioral Measure: The Endogenous Eyeblink

The focus of this review is on the "endogenous" blink. It is distinguished from other blinks by the absence of an identifiable eliciting stimulus. We shall argue that this response is sensitive to a broad spectrum of information processing variables including subject variables and both general and momentary task demands and can reflect the effect of these during the performance of a cognitive task. One advantage of the endogenous blink measure is the possibility it offers of baseline assessment. Alterations in the rate, form, or duration of blinks, and temporal distribution of blinks may be evaluated as changes in either direction from a pre-established level. Unfortunately, little experimental work has been done relating blinks to cognitive activity and that which has, is restricted largely to blink rate.

In order to clarify the distinction between the "endogenous" blink and other eye closures, characteristics of the latter will be described briefly.

Eye Closures Other than Endogenous Blinks

Reflex blinks. The stimulus-elicited involuntary (i.e.. reflex) blink is a protective response which

occurs to stimuli potentially injurious to the organism. A loud noise, a tap to the forehead, an electrical shock to the skin, especially in the area close to the eyes, any sudden intense stimulus, a foreign object in the eye, all elicit reflex blinks. Graham and collaborators (Graham, Putnam, & Leavitt, 1975; Silverstein, Graham, & Bohlin, 1981), Hoffman and Ison (1980), and Ison and Ashkenazi (1980) have studied reflexive eyeblinks extensively. Their focus has been on changes in reflex excitability as a function of the interval between a warning signal and a blink-eliciting stimulus, as well as on the allocation of attentional resources during the lead interval. They found, for example, that if the lead time between the warning signal and the imperative signal is short (100–300 ms) blink amplitude is reduced. If the interval extends to several seconds, however, there is facilitation of the blink reflex. Generally, when blink initiation is signaled by a warning stimulus, blink latency is significantly reduced. These studies, as well as eyeblink conditioning studies, continue to make significant contributions to our understanding of the processes by which stimuli are associated or otherwise interact. Nevertheless, we do not believe them to be as well suited a format as studies of endogenous blinks for the investigation of ongoing cognitive processes.

Voluntary blinks. Voluntary blinking has been differentiated from both reflex and endogenous blinking in the literature (e.g. Volkmann, Riggs, Ellicott, & Moore, 1982). Like the reflex blink, the voluntary blink occurs in response to an identifiable stimulus, either self-initiated or at the request of an experimenter. Such blinks have been used to study inhibitory processes in the visual system (Riggs, Volkmann, & Moore, 1981; Volkmann et al., 1982) and will be discussed below in connection with blink-induced visual suppression. Again, however, if our goal is to extract information from an ongoing task, the voluntary blink, even if defined solely in terms of the presence of an eliciting stimulus, is unsatisfactory. Whether the voluntary blink can be differentiated from the reflex and endogenous blinks in terms of amplitude and duration is an unresolved question. It was the position taken by Spence and Taylor (1951) that voluntary blinks were longer in duration and greater in amplitude. This was supported (somewhat informally) by Kennard and Glaser (1964), but this observation is not universal (Gordon, 1951). We might expect the nature of the instructions to be an important factor here: whether the subjects are instructed simply to blink or are told to simulate a reflex or endogenous blink could make a significant difference.

Non-blink closures. The most obvious example of a non-blink closure is that associated with the onset of sleep. Another is the closure associated with periods of microsleep (Williams, Lubin, & Goodnow, 1959) observed in sleep-deprived or otherwise fatigued individuals. Unless eye closure is being used for the purpose of detecting such states, it has little to offer by way of enhancing our understanding of cognitive processing. Fortunately these closures are clearly differentiable from blinks on three dimensions. (a) For blinks, the time from initiation of lid movement to full eye closure is short, taking generally less than 150 ms, whereas for non-blink closures, the time taken to close the eyes is for most subjects generally greater than 250 ms and frequently extends over a period of seconds. (b) The longest period during a blink in which vision is occluded is estimated to be from 270–330 ms (Miles, 1931); for non-blink closures the duration over which the eye remains closed is seldom less than 250 ms and frequently extends for several seconds. Thus, any closure lasting more than one second can be safely assumed to be associated with a phenomenon other than blinking. (c) Reopening time for the blink is relatively long with the full reopening phase lasting from 100–200 ms. The reopening after a closure is generally very rapid, seldom taking as much as 100 ms. Therefore, any eye closure which satisfies these criteria (i.e., time to close greater than 300 ms, closure duration greater than 1 s, time to reopen less than 150 ms) can be excluded from blink analyses without losing essential information.

Although non-blink closures are clearly of interest in the study of attention and alertness, they are equally clearly different in form and function from endogenous blinks. Consequently, they will not be considered further in this review.

Measuring the Eyeblink

A variety of techniques are available to measure the eyeblink. These range from attaching a string to the lid and using a potentiometer to measure closure and opening (the favorite technique of eyeblink conditioners), to the attachment of lever systems (Kennard & Glaser, 1964) and reflecting mirrors (Gordon, 1951) to mechanically or optically transduce eyelid motion. Photoelectric techniques, using scleral reflection or other reflections from the eye, can also be used to index closure. When nothing is reflected the lid is closed. Photographic or video techniques have also been used. Since they require relatively tedious data abstraction procedures their use has been limited. One can also record electromyographic activity (EMG) from the muscles responsible for initiating lid closure, the orbicularis oculi.

Our favorite technique uses electro-oculographic procedures to record the eyeblink. The EOG pre-

sumably records the potential difference between the cornea and the retina or fundus. We say "presumably" since some investigators have been able to record the potential in animals with the retina surgically removed. Because of this it has more recently been referred to as the corneo-fundal potential.

How can the EOG index the eyeblink? We have reviewed the rationale for this procedure (Oster & Stern. 1980, pp. 290–291) and briefly review it here. The upper eyelid moves over the cornea during blinks. closures. and as gaze shifts from the upper to the lower portion of a visual display. The eyelid acts as a sliding resistor, altering the standing potential between the cornea and fundus. The cornea is positively charged with respect to the fundus. Movement of the eyelid over the cornea is associated with increased positivity, retraction with increased negativity (Matsuo, Peters, & Reilly, 1975). This "artifact" is referred to as the "rider artifact." It is an artifact if one is interested in using the EOG to identify eye position in the vertical plane. It is not an artifact to those interested in a simple procedure for recording eyelid movements. The rider artifact makes it impossible to use EOG procedures for locating eye position in the vertical plane, unless one knows what the lid is doing, independent of the movements of the eyeball. Lid position, when the head is restrained, is relatively constant. We say "relatively constant" since, in vigilance and other soporific tasks. one finds the lid closing for reasons other than blinking.

We have assured ourselves that the vertical EOG reasonably faithfully reproduces the position of the eyelid by concurrently videotaping the eye and the polygraph tracing of the vertical EOG. Using a special effects generator, one can concurrently display both pictures on a split screen. Seeing is believing; eyelid closures are clearly associated with potential changes in the vertical EOG.

Blink Waveform

It is desirable to describe the characteristic waveform of an endogenous eyeblink for two reasons. First, blinks must be discriminated from grimaces or other facial activity, from eye movements, and from other lid activity, as indicated in the earlier section on non-blink closures. Second, it is useful to describe components of the typical blink so that potentially meaningful deviations in form can be assessed.

The closing portion. Kennard and Glaser (1964) describe three distinct phases of the closing portion of the blink. The first is a slow phase lasting between 10 and 20 ms during which the lid is accelerating

stant velocity, and the third is a decelerating slow phase lasting from 20–50 ms ending in complete closure. (Kennard and Glaser's suggestion that the initial slow component lasts for 10–20 ms must be taken as an approximation since it is difficult to measure a "slow" component lasting no more than 20 ms using mechanical transduction and strip-chart recording.) Gordon (1951), using an optical recording method. also reports an initial slow upper-lid movement of approximately 1 mm which he attributed to the relaxation of the levator palpebra superiori. This would leave the orbicularis oculi free from its influences (in Gordon's baboon preparation the levator remained inhibited throughout the blink) to effect the rapid phase unimpeded. Although Kennard and Smyth (1963) suggest that the first component of the blink involves a burst of activity from the orbicularis oculi muscle, it appears from their illustratrion (Figure 1) that this activity may, instead, follow, rather than be coincident with, initiation of the lid movement. The gain at which the EMG signal was recorded was too low to make this observation definitive. Whatever the source of the muscular activity, it is clear that blink initiation involves gradual lid acceleration rather than a sharply initiated movement.

The final, decelerating component of the closing portion is apparent in the records of all these authors (Kennard & Glaser, 1964: Kennard & Smyth. 1963: Gordon. 1951), and is also observable in EOG recordings. We have attempted to look at this component of the lid closure by measuring the time from 70% closure to full closure. The duration of this interval ranges from 10 ms to considerably in excess of the 50 ms reported by Kennard and Glaser. Since 70% of full closure does not necessarily coincide with the onset of the final slow phase, however. these measures are not strictly comparable.

To summarize, three phases in the closing portion of the blink can be identified. The first phase persists for 10–20 ms, is associated, perhaps, with inhibition of the levator coupled with or followed by increased activity of the orbicularis oculi muscle. The second, a fast component, persists for 20–50 ms and is due to orbicularis contraction. The third component, another slow component, persists for 20–60 ms. Accordingly, a reasonable estimate for total time taken for lid closure during a blink is from 50 ms for the fastest closure, to 145 ms for the slowest closure.

The reopening portion. Kennard and Glaser (1964) report two phases associated with reopening. An initial rapid return from full closure is followed by progressively slower motion as the lids return to the baseline position) EOG recordings also indi-

and Glaser, does not allow easy resolution of temporal parameters. Onset of the initial opening phase is relatively rapid and, according to those authors, its velocity is positively correlated with blink amplitude. Determining where the first phase ends and where the second begins is difficult; they appear to shade into each other.

Identification of the point where the second phase terminates is especially difficult. It would appear that it should be defined as the point where the lid returns to the position occupied before blink initiation. Several factors militate against this simple solution. As Kennard and Smyth (1963) pointed out, location of the fixation point in the vertical plane is a factor determining eyelid position (the lower the point, the lower the eyelid). Second, changes in vertical eye position following a blink were found to be especially likely. These two facts suggest clearly that return to initial eyelid position (or initial voltage level) can not be used as the termination criterion. The determination of blink completion must therefore be based on final quiescence of the lid rather than on lid-position. Unfortunately, the gradual deceleration of the lid renders precise demarcation difficult.

Although the actual completion of reopening is difficult to specify exactly, there is no question but that reopening, by any criterion, takes longer than closing.

The closed portion. Kennard and Glaser had previously reported that a relatively steady level lasting up to 50 ms may be maintained between termination of the closure portion of the blink and the initiation of reopening. They further report that a few of their subjects appeared to become drowsy during the course of the experiment, and that such drowsiness was associated with increases in the duration of the steady closure level. In two observations, plateaus lasting for up to 80 ms occurred with no change in the nature of either the closing or reopening phase of the blink. In a study of the effects of a short-acting barbiturate (Kopriva, Horvath, & Stern, 1970) it was observed that after drug administration, the EOG record of the eyeblink exhibited a delay at full closure before the reopening phase began. It appears, therefore, that this portion of the blink might prove to be a useful diagnostic tool.

Blink Rate

The last 20 years has seen a paucity of research in which parameters of the endogenous eyeblink have been dependent variables. There is, however, a small and valuable legacy from earlier investigations (ably reviewed by Hall & Cusack, 1972). Most of the early investigators concerned themselves with blink rate. They demonstrated that the

nature of the task to be performed has a significant influence on blink frequency. For example, performance of tasks involving visual activity, such as reading or visual-motor tracking, produces significant decreases in blinking (Ponder & Kennedy, 1927) with more difficult visual tasks leading to greater blink inhibition than less demanding tasks (Drew, 1951). Experimentally induced anger or excitement significantly increases blink rate (Ponder & Kennedy, 1927). Data from field observations indicate that blinking is markedly increased when a person is being cross-examined in a courtroom (Ponder & Kennedy, 1927), or is simply engaged in conversation (Hall, 1945).

Attentional Effects

During a blink, while the eyes are closed, visually presented information obviously cannot be assimilated. In fact, a number of studies (Volkmann, Riggs, & Moore, 1980; Wibbenmeyer, Stern, & Chen, 1983) have gone beyond this, demonstrating that inhibition of information intake actually precedes the blink, a phenomenon similar to presaccade suppression. Saccade suppression refers to the inhibition of visual information processing associated with saccadic eye movement; the general findings (Matin, 1974) are that there is a partial loss of information intake as much as 50 ms prior to saccade initiation. Wibbenmeyer et al. (1983) showed that the processing of information presented to the eye a short time (50 ms) before blink initiation is markedly inferior to the processing of the same information when presented 100 ms before blink initiation. In several recent articles (Riggs et al., 1981; Volkmann et al., 1982; Volkmann et al., 1980) this observation was corroborated utilizing an ingenious procedure. Presentation of the light was through a fiber optic bundle placed against the roof of the mouth. A substantial loss of sensitivity (to light offset) commenced before the blink began and did not fully recover till about 200 ms after blink onset. Note that introducing the light in this manner precluded the inhibition from occurring by direct interference with the visual stimulus. These authors attributed the suppression to an inhibitory efferent signal coinciding with the discharge initiating the blink. The blackout period thus starts before the onset of a blink. This, coupled with a blink which takes not less than 200 ms (and averages over 400 ms), produces a significant period around each blink during which visual input is reduced or not available. The surprising fact is that we do not perceive this gap even though briefer blackouts of room lights are readily perceived (Moses, 1975).

A reduction in blink rate during visual task performance under these circumstances would seem adaptive and the initial report of such reductions

(Ponder & Kennedy, 1927) has found considerable subsequent support (cf. Baumstimler & Parrot, 1971; Poulton & Gregory, 1952). Typically, reduction in blink rate is greater in more demanding visual tasks (Drew, 1951). Specific stimulus parameters, however, may produce periodic changes in the likelihood of blink production. As will be discussed below, in discrete trial procedures, which provide opportunities for intermittent reduced attention, blinks often occur during each such period. The result, consequently, may be a paradoxical increase in blink rate. Therefore, one must be cautious in drawing sweeping generalizations concerning blink rate without detailed task analysis, a theme to which we shall return.

Alterations in blink rate are not unique to visual task performance; they occur during nonvisual tasks as well. Stylus maze performance, even with vision of the maze occluded, results in significant blink reduction (Gregory, 1952). Gregory further reported that performance of an auditory tracking task also led to blink inhibition. Similarly, blink rate decreases were found during mental arithmetic and digit span recall (Holland & Tarlow, 1975). In agreement with Drew's (1951) data on a visual task, more difficult tasks produced a greater reduction in blinking than did easier tasks. The general implication of these data is that attention leads to a reduction in blink frequency, with the magnitude of blink inhibition proportional to attentional demands.

Activation Effects

In apparent contradiction to the studies cited, several investigators have reported *increases* in blink rate while subjects were performing mental arithmetic tasks. In the earliest study reporting this (Telford & Thompson, 1933), blink frequency was observed during the performance of mental arithmetic, reading, and conversation. Mental arithmetic produced the greatest number of blinks, reading the fewest.

The results of a series of studies involving verbalization as a variable may help resolve these conflicting observations. Schuri and von Cramon (1981) compared the blink rate of subjects performing a 1-min mental arithmetic task under two conditions. In the first, they were required to continually verbalize the updated results throughout the minute whereas in the second they verbalized the final result only at the end of the 1-min run. The mental arithmetic task used by these investigators involved serial addition and subtraction. Performing the arithmetic operations silently produced no change in blink rate compared to a resting condition. Under verbalization instructions, however, significant

increases in blink rate were obtained for both addition and subtraction tasks. Other evidence suggests that the facilitating effect of verbalization on endogenous blink production is probably dependent on the motor aspect of the vocalization, rather than on its "verbal" characteristics. In an earlier study, von Cramon and Schuri (1980) had found significant effects of vocalization on blink rate using both verbal and numerical tasks. The tasks, reciting the alphabet slowly or reciting sequential numbers starting with 100, were conducted under both vocalization and silent conditions. Recitation generally produced increases in blink rate (significant only for the counting task). Performing the tasks silently led to significant *decreases* in blink rate for both conditions. Von Cramon (1980) also demonstrated that vocalization led to significant increases in blink rate in both verbal and arithmetic tasks. The verbal task involved providing the subject with two words to be used in the generation of a sentence; the arithmetic task involved multiplying a single digit number with another between 10 and 20. Only when the vocal responses were made, and not during the solving of the problems, were increases in blinking observed.

The work just cited implicates vocalization and the inhibition of vocalization as contributors to the control of endogenous blink production. Meyer (1953) suggested that the activation of cortical motor centers close to those which control the eyes (viz., those that mediate the motor aspect of speech) may lead to an "overflow" of activity into the oculomotor areas resulting in increases in blink rate. A similar argument has been used more recently (Kinsbourne, 1970) to account for the relationship between the direction of lateral eye movements and the hemisphere presumably dominant upon introduction of a particular task. Extending Meyer's view, von Cramon (1980) suggested that the simultaneous activation of the topologically adjacent motor channels for lid and speech movements need not necessarily be in the cortex. It is unclear, in either case, why activation of topologically adjacent motor channels for lid and speech should lead specifically to an increase in endogenous blinking rather than, for example, to eye closure or blink inhibition. Perhaps as an alternative, the increase in blink rate which accompanies vocalization may be attributable, more parsimoniously, to a general activation rather than to a specific cortical (or subcortical) "overflow." Telford and Thompson (1933) suggested, in fact, that the increase in blink rate which they observed during mental arithmetic performance appeared to be a function of "excitement and emotional tension." Other authors, using a combination of task requirements, none requiring vocalization, also have reported increases in

dogenous blink production. Brezinova and Kendell (1977) evaluated blink rate while subjects performed a pendulum tracking task by itself or concurrent with mental arithmetic. The mental arithmetic task involved serial subtraction (while attempting to track the pendulum). Under these conditions mental arithmetic in conjunction with pendulum tracking produced a significant increase in blink rate compared to tracking alone, though EMG activity (superimposed on the EOG) failed to reflect the added tension of the incompatible tasks. There are other data (King & Michels, 1957), however, which indicate directly that/increases in blink rate are associated with induced (by hand dynamometer) muscle tension.

Few investigators have attempted to index arousal in a direct fashion rather than infer it from the task demands\ In one attempt to do this. Gille. Otto. and Ullsperger (1977) recorded blinking as well as heart rate and EEG measures while subjects were performing tasks differing systematically in the nature of the demands made. The tasks ranged in level of difficulty from: 1) relaxing with open eyes in a quiet environment, 2) copying numbers. 3) solving mental arithmetic problems and vocalizing the answers. to 4) solving such problems and vocalizing under time stress. Significant differences in blink rate were obtained between all but the last two levels of task difficulty with the more difficult tasks leading to higher blink rates.\Average blink rates reported were 6.5. 7.5. 13.6. and 15.0/min for tasks in ascending order of difficulty. Since the mental arithmetic tasks required vocalization of responses. already shown to be associated with an increase in blink rate, it is obvious that a number of confounding factors make this study and the generalizations drawn from it less than ideal:'the higher blink rate during arithmetic task performance could be attributed to the requirement for a verbal report. a higher level of arousal. or the cognitive demands of the task'. That the two arithmetic tasks did not differ significantly from each other makes a vocalization hypothesis tenable. However. the viability of other hypotheses illustrates the weakness of this demonstration for present purposes./More pertinent to the issue. however, the authors also related blink rate directly to two measures of arousal: an EEG-based measure of activation level. and subjective assessments of alertness. Blink rates per minute for five levels of EEG-based activation values were 3.9. 2.8. 7.2. 7.7. and 8.3. with higher EEG activation levels associated with higher blink rates.' Blink rates with seven levels of self-judged alertness were 3.3. 4.4. 5.5. 5.5. 6.6. 5.5. 12.1. again with the highest blink rate associated with greatest alertness. Although the implication is that blink rate is associated with level of alertness. the omission of any

statistical treatment of these data requires us to accept them as suggestive rather than definitive on this issue.

Ponder and Kennedy (1927). as mentioned earlier, observed an increase in blink rate during cross examination in a court of law. They attributed the increase to the anxiety engendered by the cross examination. Pertinent to this variable, von Cranach, Schmid, and Vogel (1969) reported that'when subjects look at a person (rather than a light)'there is significant increase in endogenous blinking and further, more blinking occurred in a social situation, where the person at whom the "subject" looked, uttered questions to which the subject had to respond with YES or NO answers.'These results, and those of Ponder and Kennedy. 'must be tempered by the findings that speaking is associated with a significant increase in blink rate as is an increase in muscle tension: These might account for the phenomena. obviating "anxiety" as an explanatory variable. In a study specifically designed to explore this. Brezinova and Kendell (1977) found that although inducing anxiety (by threat of shock) produced significant increases in heart rate and subjective ratings of anxiety. there were no concomitant increases in blink rate. In such a situation we might expect that the anxiety induction would be reflected in greater activation (which it was as indexed by heart rate), and this, according to our present thesis, would result in an increase in blink rate. These unambiguously negative results. however. suggest caution in asserting this argument. One possible alternative is that there exists a subject-by-anxiety level interaction in blink rate. Additional data are necessary to support this speculation.

In summary. increases in arousal are generally associated with increases in endogenous blink production. The data do not clearly explicate the nature of this association. Blink rate increases may be secondary to specific speech and motor activity. or reflect a more generalized activation function. The presumed effect of anxiety on blink rate has not been definitively demonstrated.

Time-on-task and Blink Rate

Although decreased arousal is associated with lowered blink rate in alert. rested subjects, the performance of a single task for long periods is often accompanied by blink rate increases. This is particularly true for repetitive tasks. tasks which lead to boredom and fatigue.'Carpenter (1948) measured blink rate during a 2-hr vigilance task (Mackworth clock test) and found systematic increases in blink rate as a function of time. Although the greatest increase occurred over the first hour (from $\overline{X} = 17.4$ to $\overline{X} = 21.9$ blinks/min). most subjects continued to show additional increases in blink rate with an av-

erage increase of 43% from the first to the last half-hour period.

Similar increases in blink rate as a function of time-on-task, have been reported during reading (Hoffman, 1946; Tinker, 1946; Lukiesh, 1947), and automobile driving (Pfaff, Fruhstorfer, & Peter, 1976). Though initiation of reading produced a significant reduction in blink frequency, these authors all reported increases in blink rate as a function of time. Hoffman's subjects read for 4 hrs; average blink rate was 6.9 blinks/min initially and increased to 11.0/min by the end. This increase was linear across the 4-hr session. Lukiesh had subjects read for 1 hr and observed an increase from 7.2 to 9 blinks/min. Tinker's subjects read for a half hour and increased from 4.8 to 6.6 blinks/min. For automobile driving, Pfaff et al. (1976) report that blink rates increased from an initial 13/min to 40/min at the end of a monotonous driving task. Stern, Beideman, and Chen (1976) also noted increments in blink rate over a half hour of simulated driving.

Other data do not so uniformly support the time-on-task effects described for blink rate. In one study (Goldstein, Walrath & Stern, 1982), a discrimination task in which the effects of modality, visual vs. auditory, and schedule of stimulus presentation, fixed vs. variable, were investigated, no time-on-task effect was suggested nor any interaction involving changes in blink rate over the half-hour test periods. Brezinova and Kendell (1977) also failed to find a time-on-task effect over an hour period during which subjects continuously observed the movements of a pendulum. Finally, to complete the spectrum, are the results of a study of the visual behavior of helicopter pilots in a 50-min test flight (Stern & Bynum, 1970). Novice pilots exhibited a significant decline in blink incidence over that period in contrast to experienced instructors, whose blink frequency remained constant. Thus, we have in the asembled studies, all possible outcomes ranging from an increase through no change to a decrease in blink rate, over time periods that are not radically dissimilar. So many variables differentiate these studies that it should surprise us if these apparent inconsistencies did not occur. Time-on-task effects cannot be viewed as due to some unitary factor. Explanation of a given time-related effect on blink rate will undoubtedly require an understanding of the general effects of activation, effort, fatigue and attention, as well as the particular demands imposed by a task.

Blink Waveform

The effects of cognitive requirements on the waveform of the endogenous eyeblink have been largely ignored, though parameters such as amplitude and duration may be sensitive to the specific sensory requirements of a task. The effects of the subject's state during task performance has received only little more attention.

Stimulus Modality Effects

Blink amplitude. The extent of lid movement during blink execution is highly variable. A large part of this variability depends on lid position at blink initiation. When gaze is directed upward the lids are partially raised and the amplitude of a full blink from the starting position is relatively large. Conversely, when gaze is directed downward the lids are allowed to drop and blink amplitude is attenuated. Most variation in blink amplitude thus reflects vertical eye position at blink initiation and is of relatively little import in the exploration of cognitive processes. With EOG recorded blinks we have a further complication in that eye position and lid position lead to opposite voltage level alterations. Voltage level changes associated with an upward rotation of the eyeball (corneo-fundal potential) are in the same direction as those associated with eyelid closure (rider potential). Thus one cannot identify the exact position of either the eyelid or the eyeball from EOG recordings.

There is a subset of endogenous blinks, which are reduced in amplitude, that may be informative. Kennard and Smyth (1963) commented on such partial blinks emitted while subjects were engaged in a visual tracking task. These partial closures, or "microblinks," are apparently not uncommon (Kennard & Glaser, 1964; Records, 1979). On EOG recordings these appear as small amplitude blinks which, as far as the waveform of the blink is concerned, are not discriminable from regular blinks but which may be differentiated from them by concurrent film or video tape recording.

The relationship of microblinks to cognitive activity is not well-established. Kennard and Smyth (1963) suggested that partial blinks might be interpreted as poorly inhibited blinks and that in a visually demanding task, when overt blinks may be largely inhibited, these miniature blinks may, essentially, serve as surrogates. Unfortunately, they provide no evidence substantiating their observation. A visual and auditory discrimination study by Sirevaag, Stern, Oster, and Walrath (1981) provided little support for Kennard's hypothesis. One would expect the incidence of such microblinks to be greater in visual than in auditory tasks. In that study, however, no differences were found even though significantly fewer full blinks occurred in the visual task, the presumed optimal conditions for demonstrating the effect.

Blink duration. A waveform parameter which the evidence suggests is sensitive to the mode of stimulus presentation, is blink duration. In the study

cited above (Sirevaag et al., 1981), this relationship was examined/blinks were assessed for each subject during a prestimulation baseline period, a self-paced visual-following task (after Wilkinson & Houghton, 1975), and a fixed interval auditory discrimination task. Using either a 50% or an 80% amplitude criterion to define closure duration, blinks were significantly shorter during the visual than during the following auditory task though neither differed significantly from baseline duration which was intermediate to the two tasks/ In a subsequent study (Goldstein et al., 1982) two experimenter-paced duration-discrimination tasks were used which were counterbalanced in order of presentation. In this manner, task type and task order were unconfounded with modality as they had been in the Sirevaag et al. experiment. Task parameters were identical for the two modalities except that the stimulus was a dim light in one, and a pure tone in the other. Again, blink duration was shorter in the visual than in the auditory conditions for either criterion selected (50% or 70% in this case). Apparently the duration as well as the frequency of the endogenous blink is sensitive to the requirement for specific sensory channel monitoring: visual presentation appears to be associated with fewer and briefer closures than is auditory presentation. It should be noted that no effort was made to equate the tasks for difficulty. It is, thus, conceivable that this might account for the modality effect (cf. Drew, 1951).

Time-on-task Effects

In the study just described (Goldstein et al., 1982) subjects completed four variations of the discrimination paradigm spending a total of 128 min on the tasks. From the first to the final 5 min of the first task, mean blink duration (50% criterion) increased significantly (133 to 189 ms) independently of task. This was consistent with the finding that the *proportion* (arc-sine transformed) of unusually long duration blinks (≥ 200 ms, using the 50% criterion) increased with increasing time-on-task. This effect was seen in another study, mentioned earlier, conducted to explore alterations in attention under alcohol. Subjects "drove" two 20-min motion picture scenarios in a Singer LINC simulator (Stern et al., 1976). Both for inebriated and sober subjects there was a reliable change in closure duration from the first to the second film. This study thus demonstrated significant time-on-task effects. The effect again was accompanied by an increase in the proportion of long duration eyeblinks.

Temporal Distribution of Endogenous Blink

The endogenous blink is, by definition, not evoked by external events. Nevertheless, the evidence cited thus far indicates, consistent with the theme of this paper, a relationship between the occurrence of such blinks and ongoing cognitive operations. It is only a quantitative step from this to the expectation that the *momentary* demands of a task: the mode and manner of input, the transition from one to another stage in the sequence of processing, as well as the type of output, might also be reflected in alterations in some parameter of the blink.

The central programming for an opportune time for blink generation appears to be of three different types which will dictate the organization of the present section. (1) Coordination of blinks with eye movements. This coordination could translate into mechanical efficiency in the visual input channel. (2) In relatively unstructured situations, blinks frequently occur in bursts at those points where processing mode is changed. These usually follow a period during which blinks have been inhibited. (3) In structured processing tasks, blinks can be seen to occur in specific temporal relationship to stimulus (and response) events. A blink might thus be interpreted as indicative that a specific point in the processing has been reached and, therefore, the temporal relationship between blink and other events could be used to index the quality and kind of processing taking place.

Coordination of Eye Movements and Endogenous Blinks

Most eyeblink data have been collected in highly artificial settings with subjects placed in an apparatus to restrict head movement and in situations where visual search activity is limited and stimuli sparse. Few saccades occur in such conditions. Thus, little concern and attention has been devoted to eye position changes associated with blinks. In a free viewing situation, on the other hand, it would be reasonable that relatively tight coupling of eyeblinks and eye movements would have considerable utility. It has been demonstrated that visual information intake is impaired before and during saccadic eye movement (Matin, 1974). Since, as mentioned earlier, during and preceding a blink there is also a period of visual inhibition (Riggs et al., 1981; Volkmann et al., 1980; Volkmann et al., 1982; Wibbenmeyer et al., 1983), it would not seem unlikely that these two disparate sets of muscles were coordinated so that saccades and blinks occurred concurrently. In their visual tracking study, Kennard and Smyth (1963) found that vertical eye rotation affects both the frequency and form of blinks such that blinks are integrated into normal eye and lid movements. They observed that blinks were most likely to occur in conjunction with downward eye movements. Horizontal eye movements as well, are

consistently coordinated with the blink: von Cranach et al. (1969) reported an increase in blink incidence associated with large amplitude horizontal eye movements.

In support of the observation that the angular size of the eye movement is related to blink probability are the data of Watanabe, Fujita, and Gyoba (1980) who found, further, that blinks were more probable when the saccades were spontaneous rather than elicited by tracking. Of additional note was the fact that the frequency of saccade-associated blinks was inversely related to the complexity of the visual display. Watanabe et al. (1980) concluded, in part, that the function of saccade-associated blinking was to reduce retinal blur. Under difficult perceptual conditions, however, this need was overridden which, according to those authors, reflects the importance of cognitive load on blinking. This coordination of the eye movement and the blink, and its integration with information processing requirements clearly indicated a level of control that is not merely reflexive.

Endogenous Blinking and Fluctuations in Cognitive Flow

As previously indicated, blinking is reduced during periods of attention to external stimuli. During performance of relatively unstructured cognitive tasks, those blinks that do occur tend to coincide with periods of reduced attentional demand (Hesse. 1970). or with shifts from one aspect of the task to another. Blinks seem to be produced at points in the processing flow where they are least likely to interfere with information intake or performance (cf. Carmichael & Dearborn, 1947; Poulton & Gregory, 1952; Baumstimler & Parrot. 1971). As a result, blinks often occur in bursts, with each burst occurring at predictable points within the task.

During reading, endogenous blinking is normally suppressed. As the reader shifts from one page of text to the next, however, Hall (1945) observed a typical flurry of blink activity. He also noted that short bursts or individual blinks are likely to occur at other natural attentional breaks such as at the end of a sentence or the end of a line. Similarly, in visually tracking tasks blinks occur immediately preceding and following difficult portions of the task (Drew, 1951).

The aperiodic bursting of blink activity is not restricted to visually oriented tasks. Malmstrom, Rachofsky, and Weber (1977) observed decreases in blink rate while subjects listened to a question and during the period of processing prior to answering. Bursts of blinks occurred during the vocalization of the answer. The blinking during vo-

tivation associated with vocalization as suggested earlier.

The temporal relationship between blink occurrence and both stimulus and response events in controlled, discrete trial tasks represents another instance of the general phenomenon relating endogenous blinks to aspects of a cognitive task. Although tightly coupled with stimulus events. it should be pointed out that the blinks to which we refer are not evoked or reflexive, but endogenous: in a context in which there is no call for processing. the same stimuli do not elicit blinks.

Illustrating these points are a series of studies by the authors. In several variations of a visual sequential comparison task (Walrath, Stern. & Rude. 1980), subjects were required to make a finger response indicating whether or not a displayed letter was different from the previous letter on one of a number of dimensions. Upon stimulus offset they were to return their finger as rapidly as possible to the start position. We will ignore the fact that a response followed both stimulus onset and offset and concentrate, for the moment, on the distribution of blinks in this sequence. Although the interstimulus interval averaged 4 s in duration, a significantly greater number of interstimulus blinks were initiated in the first second following stimulus termination than would be expected by chance. Further, of the blinks occurring during the stimulus period (which averaged 2.25 s). a disproportionately greater number were initiated within the second following stimulus onset. Every subject showed this interstimulus and stimulus effect. This stimulus-blink temporal contingency was also observed in the tone discrimination study by Sirevaag et al. (1981) mentioned earlier. In the auditory portion of that experiment, tones of either 200 or 300 ms duration were presented at 2-s intervals (offset to onset). A response was required only for the shorter tone. As in the above study, a significantly greater number of the interstimulus blinks occurred in the first half of that interval. Again, reinforcing the robustness of this effect, among the 18 subjects in that study, there were no exceptions to the overall pattern. These results have since been corroborated (Goldstein et al., 1982) employing visual as well as auditory discrimination tasks in a go/no-go paradigm. Regardless of the underlying mechanisms, it seems clear that the appearance of a blink is closely related to the dynamics of task performance.

In pointing out the stimulus-blink relationships in these studies. no distinctions were made between blinks following those stimuli that called for a response and those that did not. When a motor re-

[requirement in the chronological sequence.] The sequential processing task (Walrath et al., 1980), it will be recalled, used a two-choice procedure in which subjects responded on every trial. This precluded investigation of the effects of response occurrence. In the duration-discrimination task (Goldstein et al., 1982), however, subjects were required to respond only to the short duration stimulus which allowed for the possibility of such analysis. Accordingly, blinks were dichotomized into those occurring on response and non-response trials. On response trials, blinks typically were delayed until after initiation of the motor response. Latency of blink initiation (measured from stimulus offset) averaged 728 ms on response trials and only 406 ms on non-response trials, a significant difference. The average latency between motor response and blink was 275 ms. Two sources of artifact might mitigate this effect. First, if the rate of blinking on response trials exceeded that on non-response trials and blinks were randomly emitted, this would put a positive bias on blink latency. Blink rates on the two trial types, however, were almost identical, which rules out this possibility. A second possible source of this effect lies in the confounding of the response-nonresponse blink latency difference with the difference in duration of the target and non-target stimuli (in this case 200 and 400 ms, respectively). Let us assume, for purposes of argument, that the blink latency is related only to the completion of the processing of the critical stimulus dimension and is unrelated to response occurrence. We may suppose, then, that when a 400-ms stimulus is perceived as exceeding 200 ms, permitting its recognition as a non-target stimulus, the blink sequence would be initiated. Since blink latency is measured from stimulus offset, this would decrease the measured blink latency for non-target stimuli and account for something less than 200 ms of the 322-ms difference. Resolution of this issue awaits a procedure (counterbalanced) wherein target and non-target stimuli of equal durations may be examined. If taken at face value, these data suggest that, in the absence of a motor response, the occurrence of a blink marks the termination of the stimulus evaluation process. When a response is required, however, the blink appears to be delayed to the end of the response selection, or perhaps, the motor programming, process.

If these hypotheses prove correct, the latency of the blink, in such instances, may be a more sensitive indicator of the efficiency or speed with which these response processes are executed than is the motor response. For example, in the Goldstein et al. (1982) study, mean latencies were obtained for each of the four 30-min tasks. Independent of the modality of

the stimulus, auditory or visual, finger reaction time did not vary across the four-task session nor did blink latency on non-response trials. On response trials, however, blink latency decreased significantly (a 150-ms drop) from the initial to the final task. What seems to be suggested by these results is that some component(s) of the stimulus recognition/response selection/response execution sequence had improved with practice. Since non-response stimuli also require recognition time, the origin of the decrease appears to devolve upon some aspect of response programming. Nevertheless, reaction time did not reflect the inferred increase in efficiency. Reconciliation of this conflict awaits additional evidence.

When blinks occur at points in the stimulus sequence, other than in temporal relationship to the stimuli and response, they often represent breakdowns in smooth efficient processing. In the go/no go procedure, discussed above, blinks were randomly distributed within the interstimulus interval on both false alarm and miss trials, in contradistinction to the clear patterning of blink production seen on correct trials. In the four-choice self-paced following task (Wilkinson & Houghton, 1975) used by Sirevaag et al. (1981), stimulus onset was programmed to follow each correct response by 100 msec. In this task, blinks were markedly reduced in frequency from baseline level. Those blinks which did occur were associated with significantly increased latency of the motor response. In these two very different tasks, endogenous blink emission was associated with response inefficiencies or inaccuracies indicative of inadequate processing. Such increases in blink production may, of course, merely reflect momentary reductions in attention to the task, perhaps coupled with momentary increases in activation. In either case, they mark specific points within a task when processing efficiency is reduced.

Summary

The endogenous blink is an ocular response with a characteristic rate and waveform, and is coordinated centrally with cognitive events. Unlike exogenous blinks, it is not evoked by specific stimulus events. Nevertheless, its production is coordinated with stimulus occurrence (if the stimulus is relevant to the task), with motor response production, and with other oculomotor events. Parameters of the endogenous blink are sensitive indicants of cognitive activity. The allocation of attentional resources, the subject's level of activation, and the effects of accumulated time-on-task are all evidenced by variations in endogenous blinking. Within specific tasks the blink may index transition points within the processing flow.

The immediate effect of externally directed attention is a reduction in blink rate. This is so regardless of stimulus modality though visual input appears to result in the greatest suppression of blinks. Visual attention is also associated with blinks of shorter closure duration. During a task, blinks tend to occur during moments of decreased attention, thus marking a temporary cessation of information intake. In fast-paced discrete-trial procedures, the rapid fluctuations in attention may result in an overall increase in blink rate.

In general, higher levels of activation are associated with elevated blink rates. Most evidence for this association is indirect; blink rate is higher when a requirement to vocalize is added to the other requirements of a task. Although the increased blinking may be specific to speech activity, the limited data from both EEG analysis and subjective reports indicate that the effect is more general.

Blink data collected during protracted involvement in a single task presents a picture which at first appears anomolous. Increasing time-on-task has often been associated with increments in blink rate though the data here are far from consistent. Time-on-task effects may be attributable to momentary losses of attention, to compensatory activation in the effort to maintain performance, or to some other, as yet unidentified, factor. A second variable apparently sensitive to time-on-task is blink waveform. Otherwise normal blinks with unusually long durations occur with increasing frequency as the task progresses.

Endogenous blinks are coordinated with oculomotor activity in such a way as to minimize interference with information intake. In relatively unstructured tasks, bursts of blinks mark the transition from one stage of processing to another, and blink rate at any given time reflects the kind of processing going on at that time. In discrete-trial tasks, a blink is likely to occur at the end of the stimulus input phase. If a motor response is required the blink typically follows the initiation of the response.

The endogenous blink has been demonstrated to be a sensitive mirror of general cognitive factors, e.g., attention and activation, and holds promise as an indicator of more specific aspects of information processing.

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