Eur J Appl Physiol (2003) 89: 319–325
DOI 10.1007/s00421-003-0807-5

ORIGINAL ARTICLE

Philipp P. Caffier · Udo Erdmann · Peter Ullsperger

Experimental evaluation of eye-blink parameters as a drowsiness measure

Accepted: 17 January 2003 / Published online: 14 March 2003

Abstract Drowsiness and increased tendency to fall asleep during daytime is still a generally underestimated problem. An increased tendency to fall asleep limits the efficiency at work and substantially increases the risk of accidents. Reduced alertness is difficult to assess, particularly under real life settings. Most of the available measuring procedures are laboratory-oriented and their applicability under field conditions is limited; their validity and sensitivity are often a matter of controversy. The spontaneous eye blink is considered to be a suitable ocular indicator for fatigue diagnostics. To evaluate eye blink parameters as a drowsiness indicator, a contact-free method for the measurement of spontaneous eye blinks was developed. An infrared sensor clipped to an eyeglass frame records eyelid movements continuously. In a series of sessions with 60 healthy adult participants, the validity of spontaneous blink parameters was investigated. The subjective state was determined by means of questionnaires immediately before the recording of eye blinks. The results show that several parameters of the spontaneous eye blink can be used as indicators in fatigue diagnostics. The parameters blink duration and reopening time in particular change reliably with increasing drowsiness. Furthermore, the proportion of long closure duration blinks proves to be an informative parameter. The results demonstrate that the measurement of eye blink parameters provides reliable information about drowsiness/sleepiness, which may also be applied to the continuous monitoring of the tendency to fall asleep.

Keywords Drowsiness · Eye blink · Infrared sensor · Sleepiness

P. P. Caffier · U. Erdmann · P. Ullsperger (✉)
Federal Institute for Occupational Safety and Health,
Noeldnerstr. 40/42, 10317 Berlin, Germany
E-mail: Ullsperger.peter@baua.bund.de
Fax: +49-30-51548171

Introduction

Drowsiness and increased tendency to fall asleep during daytime is still a generally underestimated problem. Epidemiological studies in Germany indicate that about 24 million people suffer from daytime sleepiness (Jordan and Hajak 1997). The increased tendency to fall asleep represents a considerable risk, since it limits the efficiency at work and increases substantially the risk of accidents (e.g., Horne and Reyner 1999; Oginski et al. 2000; Connor et al. 2001). Drowsiness or sleepiness as well as associated problems of reduced alertness are difficult to assess, particularly under real life settings. For assessment mostly questionnaires and sleepiness scales are applied (e.g., Folstein and Luria 1973; Hoddes et al. 1973; Johns 1991) as well as a number of objective procedures such as EEG recording (e.g., Mitler et al. 1982; Carskadon and Dement 1985), vigilance tasks (e.g., Randerath et al. 1997; George 2000), polyphysiographic (e.g., Collet et al. 1999; Wright and McGown 1999) and oculographical measurements (Stern et al. 1996; Yamada 1998). Most of the available measuring procedures are laboratory-oriented and their applicability under field conditions is limited; their validity and sensitivity are often a matter of controversy (Weess et al. 2000).

The spontaneous eye blink is considered to be a suitable ocular indicator for fatigue diagnostics (Stern et al. 1984, 1994). It offers several advantages, since it represents a normal, simply observable and easily accessible phenomenon that reflects the influence of central nervous activation without voluntary manipulation (Blount 1928; Ponder and Kennedy 1928). Endogenous, fast closings and re-openings of the eyelids occur spontaneously, i.e., no external stimuli are needed. Furthermore, the use of contact-free recording procedures such as photo-, video- or reflecting techniques is possible (Doane 1980; Sugiyama et al. 1996; Ogawa 1998; Caffier et al. 1999). Recent studies demonstrate that the analysis of spontaneous blinks may provide substantial information regarding central nervous activation processes and fatigue (Sirevaag and Stern 2000). The parameters blink frequency and duration are especially subject to characteristic modifications with increasing drowsiness or sleepiness. However, validating investigations of larger samples of participants are still required. Moreover, in the majority of previous investigations the eye blink was mostly recorded by procedures requiring the application of electrodes (recording of the electro-oculogram; cf. Oster and Stern 1980).

The present study was carried out within the framework of the doctoral thesis of the first author (Caffier 2002). It was designed to register spontaneous eye blinks by means of a non-intrusive and easy to handle measuring device, namely an infrared sensor that records eyelid movements contact-free and continuously. The goal of the present study was to investigate whether the measuring device provides reliable eye blink parameters reflecting normal variations of alertness as they occur before and after a usual working day.

Methods

Sixty healthy volunteers (34 women, 26 men; mean age 31.9 years, range 16–64 years) participated in this study. Written informed consent was obtained from each of the participants. They took part in two sessions not more than 1 week apart. The eye blinks were recorded at the beginning and end of a working day, once in the morning and once in the evening in their usual home environment. Basically it was assumed that the participants felt more alert in the morning and more drowsy in the evening. Subjective estimation of the personal state served to evaluate the respective individually perceived drowsiness reflecting usual variations and potential additional influences on drowsiness level (e.g., effects of previous night sleep or sleep deprivation) as well.

The participants were seated about 2 m in front of a static neutral landscape picture (25 cm height x 35 cm width). They could choose a picture for each session and were asked to look at this for about 20 min. No further instructions about eye movements or blinks were given.

The portable measuring device (developed by one of the authors U. E.) consists of a contact-free sensor connected via an electronic unit to the printer port of a Laptop-computer. The sensor is fixed at the ear piece of a spectacle frame without disturbing the participant's visual field. The mechanical adjustment is simple by clamping on an empty spectacle frame or for people wearing glasses the sensor can be clipped to their own spectacle frame. The sensor itself is composed of an array of four infrared light emitting diodes,[1] which illuminate through a lens an area of the eye. The reflected light is recorded by an infrared sensitive photo diode included in the sensor. The measurement is based on the different reflection of the emitted infrared light from eyelid and eyeball. The reflected signals are transmitted to the computer after analog-to-digital conversion with a sampling rate of 200 Hz. The signal is stored on hard disk for subsequent off-line analyses. Figure 1 presents an example of the oculographic signal of spontaneous eye blinks recorded by the sensor. To fulfill a requirement for practical application of prospective drowsiness monitoring systems (cf. Wierwille 1999), the infrared sensor-system automatically adjusted the signal amplitude during recording periods to compensate for any changes of the sensor's placement. This procedure, a necessary measure for long-term recording in real-life settings, proved to be insignificant for the duration parameters detected as described below.

For subsequent analyses all eyelid closures were determined in the raw data by peak detection. For each blink a baseline corresponding to the initial state of the completely opened eye was calculated in a time window of 500 ms before the signal amplitude reached 10% of the next following blink. The mean value across this 500-ms time window represents the corresponding baseline value. To determine the blink duration at the baseline level, linear regression lines were fitted to both flanks of the original blink waveform. The intersections of the regression lines with the baseline were determined and the time between both intersections was stored as blink duration. The vertical line from the point of intersection between both regression lines at the peak level divided the blink duration into closing time and reopening time. Additionally, the blink duration was computed at different amplitude levels, e.g., at 90% peak amplitude which corresponds to complete eyelid closure over the pupil (closed time). An example of blink measures is shown in Fig. 2.

For subsequent analyses eyelid closures not fulfilling the following criteria were excluded: blink duration 50–500 ms, closing time < 150 ms. This procedure served to exclude so-called non-blink closures according to the criteria of spontaneous eye blink defined by Stern et al. (1984, 1996). The measures under investigation were blink frequency and the waveform parameters blink duration, closing time, reopening time and closed time. In addition the occurrence of long-closure duration blinks (300–500 ms) were also calculated. The histogram parameters of blink measures obtained in each session were computed.

The subjective estimation of drowsiness or sleepiness was noted immediately before the recording of the eye blinks by means of two different instruments: the personal state scale (EZ; Nitsch 1974) validated for the German population and a standardised morning/evening log containing visual analogue scales (VAS; Bixler et al. 1973; Hoffmann et al. 1997). For EZ participants had to scale how much each of 40 adjectives corresponded to their actual state (hardly ever…entirely). The adjectives represent 14 hierarchical factors including the factor SLEEPINESS (represented by three adjectives "tired", "sleepy", "exhausted"), on which this study mainly concentrated. Besides this verbal estimation different VAS were used, presented as lines anchored by bipolar descriptions. The participants were asked to rate their momentary state by marking the corresponding location with a pencil. Of special interest in the present context was the DROWSINESS dimension which was chosen as the basis for assigning the oculographic data into the categories drowsy and alert according to perceived drowsiness.

Blink measures and subjective data were analysed by multiple analyses of variance or repeated measures ANOVAs. To demonstrate relationships between blink measures and subjective data correlations were computed. All statistical tests were conducted with SPSS, the level of significance was set to $p = 0.05$.

Results

The subjective ratings showed characteristic differences between the morning and evening measurements. Regarding all participants, the repeated measures ANOVAs reached statistical significance ($p < 0.001$) in both subjective scales for the dimensions DROWSINESS (VAS) and the factor SLEEPINESS (EZ). Because both subjective scales correlated significantly among each other (Spearman's rho = 0.83; $p < 0.01$) for the remaining analysis the subjective data obtained by VAS were taken as the basis for computations of the relationship between subjective data and blink measures. Figure 3 shows the VAS values of subjective drowsiness categorised into

[1]The sensor works with invisible chopped infrared light of low intensity far below the permitted threshold of German regulations DIN VDE 0837

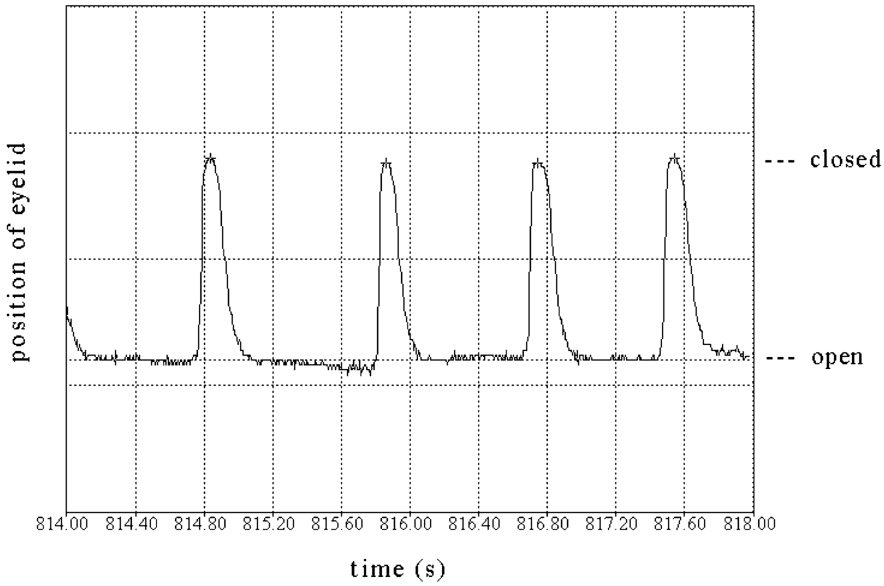


Fig. 1 Oculographic signal of spontaneous eye blinks recorded by the sensor

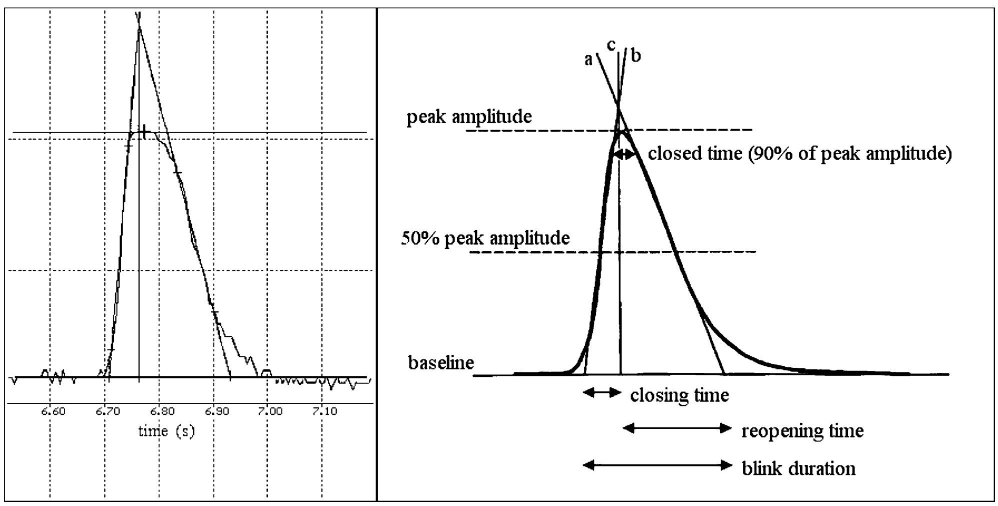


Fig. 2 Example of recorded blink signal (*left*) and schematic indication (*right*) of the waveform parameters blink duration, closing time, reopening time, and closed time. (*a* Regression line computed for the reopening flank, *b* regression line computed for the closing flank, *c* perpendicular line dividing blink duration into closing and reopening epoch)

Table 1 Mean values of eye blink parameters recorded under alert and drowsy conditions. (*s* Level of significance)

Measures	Alert		Drowsy		*s*
	Mean	SE	Mean	SE	
Blinkduration					
Meanvalue (ms)	202.24	6.07	258.57	6.67	$p < 0.001$
Variance	1474.11	96.48	2248.84	148.07	$p < 0.001$
Skewness	0.989	0.10	0.280	0.10	$p < 0.001$
Kurtosis	3.09	0.45	1.13	0.26	$p < 0.001$
Closingtime (ms)	63.00	1.80	71.06	2.01	$p < 0.001$
Reopeningtime (ms)	138.36	5.53	186.61	6.53	$p < 0.001$
Proportionof long closure duration blinks (%)	9.19	2.53	28.78	2.53	$p < 0.001$
Blinkfrequency (min^{-1})	16.33	1.64	15.84	1.79	$p > 0.05$

quartiles, and the corresponding mean values of blink duration.

The eye-blink parameters of the 60 healthy participants showed characteristic differences for the alert and drowsy conditions. Contrary to expectation, three participants felt more drowsy in the morning than in the evening. The mean values presented in Table 1 reveal that, for the drowsy compared to the alert condition, there is a slight decrease of blink frequency and an increase of blink duration, closing time, reopening time and closed time, as well as an increased proportion of long closure duration blinks. By means of repeated

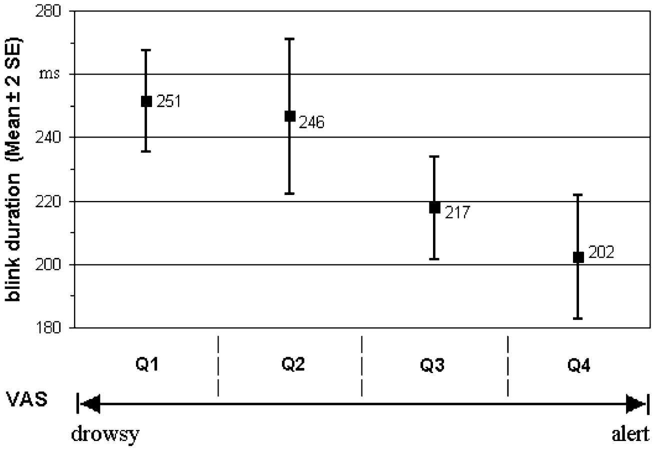
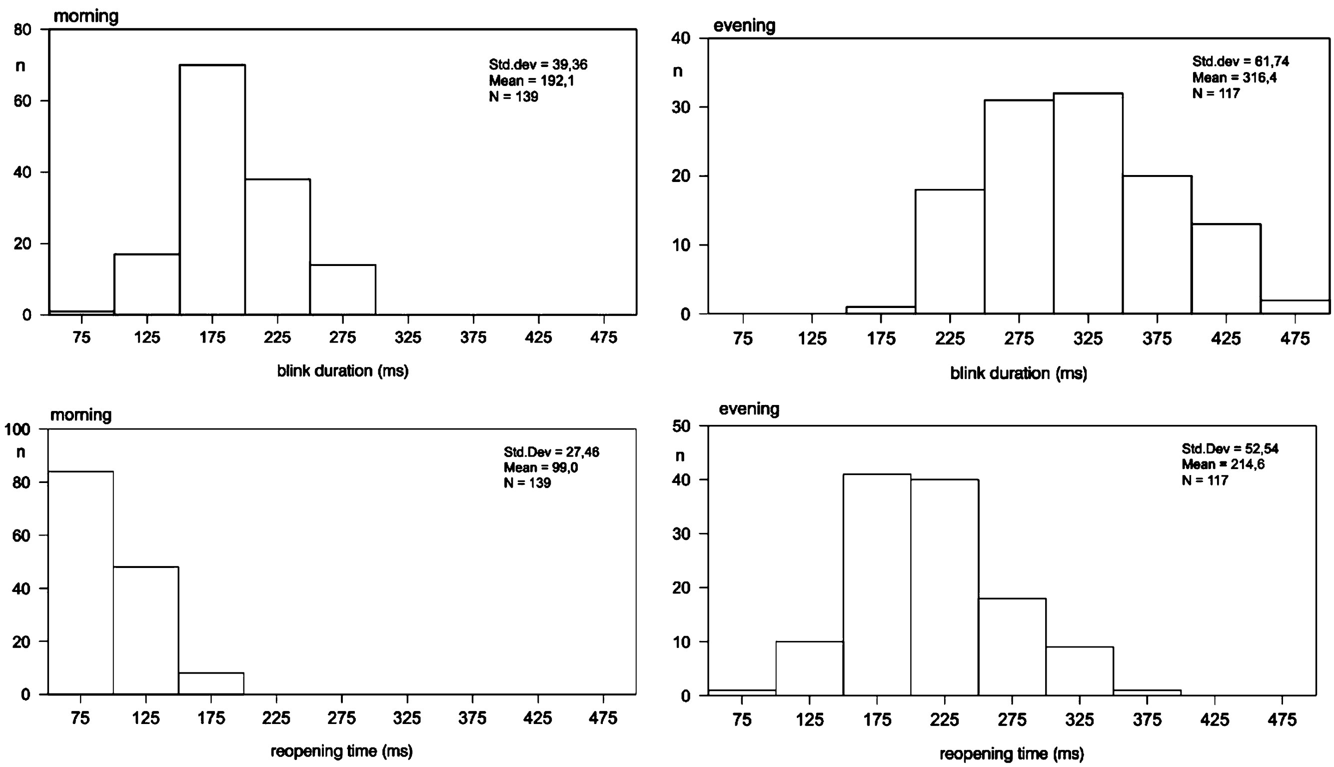


Fig. 3 Mean values and corresponding standard errors of blink duration in dependence on the subjective drowsiness (quartiles Q1–Q4) computed across all measurements of the 60 participants. (*VAS* Visual analogue scales)

measures ANOVAs significant differences between both conditions were proved for the blink measures as shown in Table 1.

Significant correlations between subjective estimation and blink parameters were found for mean values of blink duration (rho = –0.358, $p < 0.01$), reopening time (rho = –0.335, $p < 0.01$), and proportion of long closure duration blinks (rho = –0.369, $p < 0.01$).

Fig. 4 Example of individual histograms of blink duration and reopening time of the morning and evening sessions of one male participant



We compared the histograms of the eye blink parameters obtained in the morning to those obtained in the evening for each individual. This intra-individual comparison confirmed the results of the group comparison and clarified characteristic distribution differences of the blink measures investigated. As an example, the individual histograms of blink duration and reopening time of the morning (alert) and evening (drowsy) measurements of one male participant's blinks are shown in Fig. 4. While the values in the alert status in the morning were distributed closely around the mean, in the evening there was a broader distribution around a clearly higher mean value. In total, 58 participants showed significant differences between the alert and drowsy conditions with the corresponding increase of blink-duration mean values. Two remaining participants indicated that they felt more drowsy in the evening; however, the change in their blink-duration parameters indicated the opposite.

Discussion

The blinks of healthy alert participants, recorded with the infrared sensor presented, occurred with a mean frequency of 16.3 min^{-1}, a value which agrees with other published values [e.g., Davson (1990): 6–30 min^{-1}; Zametkin et al. (1979): 25 (13) min^{-1}]. No significant differences between the alert and drowsy conditions were found: the average value of mean frequency was less for men than for women and tended to decrease in the drowsy condition. Published data concerning alertness-associated influences on the spontaneous blink frequency are different. For example, Barbato et al. (2000) found that spontaneous eye-blink rate significantly increased in the evening (20:30 hours). Numerous studies demonstrate an increase of blink frequency as a function of the time-on-task, as observed during vigilance tasks (Carpenter 1948), reading (Lukiesh 1947; Mourant et al. 1981), driving a car (Haider and Rohmert 1976; Stern et al. 1976) and in aviation (Morris and Miller 1996; Wilson and Lambert 1999), but there are also contrasting results (Brezinova and Kendell 1977; Goldstein et al. 1982). Other investigations showed a rise in blink frequency after a relative decrease, with the reduction occurring in the final phase of extreme sleepiness briefly before falling asleep (Caffier et al. 1999; U.S. Department of Transportation 1999). The different results are probably caused by multiple factors that are hard to control, which influence the blink frequency; for example, environmental factors, burning of eyelids, the requirement for visual information uptake, and emotional factors. In the present investigation no particular load influenced the actual state at the point of measurement. Assuming that the blink frequency does not change in a linear manner with alertness changes (Schandry 1996), one has to consider every potential influence in detail when detecting drowsiness. The considerable inter-individual variability of the spontaneous blink frequency found in this study backs up this view.

Considering the age of the participants, the correlations between age and the different blink parameters were not significant.

The mean blink duration amounted to about 200 ms and, like the other waveform parameters, was typical (Stern et al. 1984, 1996). The blink duration was significantly – about 50 ms –- longer during the drowsy than during the alert condition. That corresponds to an average extension of about one-quarter of the total period. The intra-individual comparison of blink duration showed that, in more than 90% of the participants, there were significant differences between both measurements. Significant correlations were found with the subjective estimation of DROWSINESS, i.e., as a rule the blink durations were longer, the more drowsy or sleepier the participants felt. Published data confirm these significant effects on blink duration under different conditions leading to fatigue (Stern et al. 1976; Satake 1995; Sugiyama et al. 1996). Blink duration has often been measured at 50% peak amplitude, i.e., the time elapsing between the eyelid reaching half of its closing amplitude and returning through the same level during reopening. This period of time is assumed to be nearly equivalent to the duration for which the pupil is covered (Kennard and Glaser 1964). In this study the waveform parameters were determined at the baseline level describing the blink activity more generally.

The increased proportion of long closure duration blinks observed by others (e.g., Stern et al. 1996; Goldstein et al. 1982) was confirmed in this study. The proportion was significantly higher (almost 20%), and in the drowsy condition represented on average more than one-quarter of all spontaneous blinks. The connection between the proportion of long closure duration blinks and blink duration is illustrated in the strong positive correlation between both parameters (rho = 0.958), i.e., longer normal closures of blinks shorter than 300 ms were accompanied by an increased number of unusually long lasting spontaneous blinks (300–500 ms).

In this study the sub-components of blink duration were examined separately; namely, closing time, reopening time and closed time. There are few comparable published results concerning these sub-components of blink duration (e.g., Kennard and Glaser 1964; Kopriva et al. 1970; Stern et al. 1984). As expected, total blink duration correlated positively with the three sub-components; the correlation with closing time was weakest (rho = 0.310), and that with reopening time the strongest (rho = 0.939). The closing time increased significantly in the drowsy condition by about 10% of the mean value when alert. However, the intra-individual comparisons indicated that the differences were only significant for approximately half the participants. The comparison with the subjective measure DROWSINESS resulted in rather weak correlations. The results demonstrate that closing time alone is not suitable for the detection of drowsiness. The reopening time increased significantly when drowsy, on average by almost one-third of the reopening time when alert. Intra-individual comparisons showed that differences were statistically significant for about 80% of the participants. With the subjective dimension of DROWSINESS, the significance of the correlation coefficients was similar to that of the the blink duration data. Obviously the reopening time forms the main part of total blink duration and is the crucial parameter reflecting drowsiness. The closed time was also found to correlate with total blink duration, and its duration was significantly greater during drowsy conditions than during alert conditions. Comparisons of data from individuals showed these differences were significant in 70% of the participants. However, the correlation with the DROWSINESS dimension did not reach significance. Kennard and Glaser (1964) reported an increase of the closed time up to 80 ms duration with progressive fatigue of their participants. Kopriva et al. (1970) observed after the administration of barbiturates an increase of the closed time and a delayed beginning of the period of reopening. These authors suggested that this delay was a useful diagnostic parameter. In contrast, the results of this study show that modifications of the closed time make only a minor contribution to the drowsiness-induced prolongation of blink duration; differences of the measurement techniques may explain this divergence.

This study confirms that drowsiness/sleepiness is associated with characteristic modifications of the waveform of spontaneous blinks. The blink duration, along with its sub-components closing time, reopening time and closed time, increases significantly, as does the proportion of long closure duration blinks. The waveform parameters blink duration and long closure duration blinks are regarded as particularly suitable for predicting the drowsiness accompanying performance loss (Sirevaag and Stern 2000). These authors proposed that blink amplitude is a meaningful parameter, but this was not considered in the present study because of the peculiarity of its measurement system. In conclusion, blink duration was found to be the most informative parameter, and its prolongation when drowsy is based on the simultaneous increase of closing and closed time, but essentially on the prolongation of the reopening time.

References

Barbato G, Ficca G, Muscettola G, Fichele M, Beatrice M, Rinaldi F (2000) Diurnal variation in spontaneous eye-blink rate. Psychiatr Res 93:145–151

Bixler EO, Kales A, Leo LA, Slye T (1973) A comparison of subjective and objective sleep laboratory findings in insomniac patients. Sleep Res 2:143

Blount WP (1928) Studies of the movements of the eyelids of animals: blinking. Q J Exp Physiol 18:111–125

Brezinova V, Kendell RE (1977) Smooth pursuit eye movements of schizophrenics and normal people under stress. Br J Psychiatr 130:59–63

Caffier PP (2002) Spontaner Lidschlag als Ermüdungsindikator bei Registrierung mittels kontaktfreiem Infrarotsensor. Schriftenreihe der Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. Wirtschaftsverlag NW S 69 Dortmund/ Berlin

Caffier PP, Ullsperger U, Erdmann U (1999) Relationship between personal state ratings and eyeblink parameters recorded with contact-free infrared sensor. Psychophysiology 36:S20

Carpenter A (1948) The rate of blinking during prolonged visual search. J Exp Psychol 38:587–591

Carskadon MA, Dement WC (1985) The multiple sleep latency test: What does it measure? Sleep 5:67–72

Collet C, Delhomme G, Dittmar A, Khardi S, Vernet-Maury E (1999) Electrodermal tonic level variations associated with thermo-vascular and cardio-respiratory recordings as reliable indices for the detection of drowsiness in automobile drivers. Psychophysiology 36:S21

Connor J, Whitlock G, Norton R, Jackson R (2001) The role of driver sleepiness in car crashes: a systematic review of epidemiological studies. Accid Anal Prev 33:31–41

Davson H (1990) Blinking. In: Davson H (ed) Physiology of the eye. Pergamon, New York, pp 786–791

Doane MG (1980) Interaction of eyelids and tears in corneal wetting and the dynamics of the normal human eyeblink. Am J Ophthalmol 89:507–516

Folstein MF, Luria R (1973) Reliability, validity and clinical application of the Visual Analogue Mood Scale. Psychol Med 3:479–486

George CF (2000) Vigilance impairment: assessment by driving simulators. Sleep 23 (S4):S115–S118

Goldstein R, Walrath LC, Stern JA (1982) Blink activity as a function of stimulus modality and schedule of presentation in a discrimination task (Tech. Report, U.S. Dept. of the Interior, Bureau of Mines, Contract no. J0205064). Washington University Behavior Research Laboratory, St. Louis, Mo.

Haider E, Rohmert W (1976) Untersuchung zur Lidschlussfrequenz bei vierstündiger simulierter Kraftfahrzeugfahrt. Eur J Appl Psychol 39:137–148

Hoddes E, Dement WC, Zarcone V (1973) The development and use of the Stanford Sleepiness Scale (SSS). Psychophysiology 10:431–436

Hoffmann RM, Müller T, Hajak G, Cassel W (1997) Abend-Morgenprotokolle in Schlafforschung und Schlafmedizin – Ein Standardinstrument für den deutschsprachigen Raum. Somnologie 1:103–109

Horne JA, Reyner LA (1999) Vehicle accidents related to sleep: a review. Occup Environ Med 56 (5):289–294

Johns MW (1991) A new method for measuring daytime sleepiness: the Epworth Sleepiness Scale. Sleep 14 (6):540–545

Jordan W, Hajak G (1997) Gestörter Schlaf – was tun? Arcis, Munich

Kennard DW, Glaser GH (1964) An analysis of eyelid movements. J Nerv Ment Dis 139:31–48

Kopriva K, Horvath M, Stern JA (1970) The effect of pentobarbital on oculomotor activity. [Unpublished manuscript, Czechoslovakia Institute of Physiology, Prague]

Lukiesh M (1947) Reading and the rate of blinking. J Exp Psychol 37:266–288

Mitler MM, Gujavaraty S, Browman CP (1982) Maintenance of wakefulness test: a polysomnographic technique for evaluating treatment efficacy in patients with excessive somnolence. Electroencephalogr Clin Neurophysiol 53:658–661

Morris T, Miller JC (1996) Electrooculographic and performance indices of fatigue during simulated flight. Biol Psychol 42:343–360

Mourant RR, Lakshmanan R, Chantadisai R (1981) Visual fatigue and CRT display terminals. Hum Fact 23:529–540

Nitsch JR (1974) Die hierarchische Struktur des Eigenzustandes – ein Approximationsversuch mit Hilfe der Binärstrukturanalyse (BISTRAN). Diagnostika 20:142–164

Ogawa K (1998) Development of a Drowsiness Detection System. In: Proceedings of Second International Conference on Psychophysiology in Ergonomics (PIE). International Ergonomics Association (IEA), London, pp 122–123

Oginski A, Oginska H, Pokorski J, Kmita W, Gozdziela R (2000) Internal and external factors influencing time-related injury risk in continuous shift work. Int J Occup Saf Ergon 6 (3):405–421

Oster PJ, Stern JA (1980) Measurement of eye movement: electrooculography. In: Martin I (ed) Techniques in psychophysiology. Wiley, Chichester, pp 275–309

Ponder E, Kennedy WP (1928) On the act of blinking. Q J Exp Physiol 18:89–110

Randerath W, Gerdesmeyer C, Ströhlein G, Rühle KH (1997) Messung der Vigilanz mittels Fahrsimulator vor und nach nCPAP – Vergleich zweier Simulationsprogramme mit unterschiedlicher Ereignishäufigkeit. Somnologie 1:110–114

Satake T (1995) A study of evaluation of drowsiness – analysis of blinking duration by facial image. In: Proceedings of 11th Symposium on Human Interface. Human Interface Society, Kyoto/Japan, pp 225–230

Schandry R (1996) Lehrbuch der Psychophysiologie. Psychologie Verlags Union, Munich

Sirevaag EJ, Stern JA (2000) Ocular measures of fatigue and cognitive factors. In: Backs RW (ed) Engineering psychophysiology. Issues and applications. Erlbaum, Mahwah, N.J., pp 269–287

Stern JA, Beideman L, Chen SC (1976) Effect of alcohol on visual search and motor performance during complex task performance. In: Horvath M (ed) Adverse effects of environmental chemicals and psychotropic drugs: neurophysiological and behavioral tests, vol 2. Elsevier, Amsterdam, pp 53–68

Stern JA, Walrath LC, Goldstein R (1984) The endogenous eyeblink. Psychophysiology 21:22–33

Stern JA, Boyer DJ, Schroeder D (1994) Blink rate: a possible measure of fatigue. Hum Fact 36 (2):285–297

Stern JA, Boyer DJ, Schroeder D, Touchstone MR, Stoliarov N (1996) Blinks, saccades, and fixation pauses during vigilance task performance: II. Gender and time-of-day (DOT/FAA/AM/96/9). FAA Office of Aviation Medicine, Washington DC

Sugiyama K, Nakano T, Yamamoto S, Ishihara T, Fujii H, Akutsu E (1996) Method of detecting drowsiness level by utilizing blinking duration. JSAE Rev 17 (2):159–163

U.S. Department of Transportation, Federal Highway Administration (1999) Eye-activity measures of fatigue and napping as a fatigue countermeasure (Final Report, FHWA-MC-99–028). Federal Highway Administration, Washington DC

Weess HG, Sauter C, Geisler P, Böhning W, Wilhelm B, Rotte M, Gresele C, Schneider C, Schulz H, Lund R, Steinberg R (2000) Vigilanz, Einschlafneigung, Daueraufmerksamkeit, Müdigkeit, Schläfrigkeit – Diagnostische Instrumentarien zur Messung müdigkeits- und schläfrigkeitsbezogener Prozesse und deren Gütekriterien. Somnologie 4:20–38

Wierwille WW (1999) Desired attributes of drowsy driver monitoring and candidate Technologies for implementation. In: Ocular measures of driver alertness: technical conference proceedings (FHWA-MC-99–136). Federal Highway Administration, Washington DC, pp 130–143

Wilson GF, Lambert J (1999) Physiological effects of varied mental workload in pilots during flight. Psychophysiology 36:S126

Wright NA, McGown AS (1999) Vigilance on the civil flight deck: incidences of sleepiness and sleep during long-haul flights and associated changes in physiological parameters. Psychophysiology 36:S127

Yamada F (1998) Frontal midline theta rhythm and eyeblinking activity during a VDT task and a video game: useful tools for psychophysiology in ergonomics. Ergonomics 41 (5):678–688

Zametkin AJ, Stevens JR, Pittman R (1979) Ontogeny of spontaneous blinking and habituation of the blink reflex. Ann Neurol 5:452–457