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ORIGINAL ARTICLE

Blinking and Driving: the Influence of Saccades and Cognitive Workload

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ABSTRACT

Purpose: The aim of this study was to investigate the joint influence of cognitive demands and large amplitude saccades on spontaneous blink rate.

Materials and Methods: Twenty healthy volunteers were enrolled in the study and instructed to follow a 60-minute real-life driving circuit while a video camera-recorded ocular movements and blinking. Five different complexity levels were predefined in terms of driving difficulty and traffic intensity, that is, cognitive workload. Five one-minute segments were selected for each complexity level in each driving trial, whereupon spontaneous blink rate and horizontal saccades were monitored. Saccades were classified according to their amplitude and blink-saccade pairs were recorded.

Results: Albeit showing a high inter-subject variability, spontaneous blink rate and saccades were consistent within the same complexity level. At different complexity levels, no statistically significant difference in spontaneous blink rate was encountered, with an average of 20.3 ± 1.6 blinks/minute (mean ± SD). The number of large amplitude gaze shifts increased with the level of complexity ($F = 15.403$; $p < 0.001$). An average of 87.5% of large amplitude saccades were accompanied by a blink, and this percentage was similar for all complexity levels, that is, the number of blink-saccade pairs increased at higher complexity levels ($F = 20.597$; $p < 0.001$).

Conclusions: In a complex, dynamic visual setting, spontaneous blinking accompanying large amplitude saccades may help in counteracting the reduction in blink rate associated with high cognitive demands.

Keywords: Blinking, cognitive demands, driving, saccadic eye movements, spontaneous blink rate

INTRODUCTION

Blinking has been described to occur voluntarily, reflexively or spontaneously.[1,2] While voluntary blinks are associated with emotional expressions such as winking or smiling, reflex blinks are evoked by external stimuli (auditory, flashes of light, mechanical stimulation of the ocular surface or surrounding structures, etc.), or by ocular dryness resulting from the destabilization and rupture of the tear film.[3] Conversely, spontaneous blinks are mainly dependent on cognitive processes, that is, appear to be regulated by a central pacemaker highly sensitive to the attentional demands and cognitive workload of the concurrent visual task.[4,5] In effect, previous authors, albeit noting a considerable inter-subject variability in the frequency of spontaneous blinking,[6] have reported mean ± SD blink rates of 7.9 ± 3.3 blinks/minute while reading, 14.5 ± 3.3 blinks/minute in silent primary gaze and 21.5 ± 6 blinks/minute during a conversation.[4] In addition, a similar reduction in blinking frequency with increasing task complexity has been evidenced in relation to computer use, a field in which spontaneous blinking has been extensively studied in order to understand and alleviate the symptomatology associated with the traditionally known as ‘‘computer vision syndrome’’.[7–11] Interestingly, from a different perspective,

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the increased blink rate observed in studies investigating behavioral indicators of fatigue and drowsiness has been related to a cessation of the attention-driven inhibitor of blinks.[12]

Given the continuous flow of information reaching the visual system, each blink may account for a loss of approximately 400 ms.[13] Consequently, to minimize the loss of potential relevant information, spontaneous blinks have been found to occur during explicit or implicit attentional breaks.[14,15] Indeed, while reading, for example, blinks tend to be timed to occur at the punctuation breaks present within the text.[15]

Similarly to blinks, saccade eye movements are also accompanied by a suppression of visual input, thus explaining the visual stability that persists during ocular movements, despite the corresponding displacement of the image on the retina.[16,17] Recent studies have observed a trend in which saccadic suppression seemed stronger for small gaze shifts (such as in reading) but weaker with increasing saccade amplitude.[18]

Many saccades have been found to be accompanied by a blink,[19] and, even with the eyes closed, neuromuscular contractions associated with blinking tend to occur in relation to large ocular movements.[20] Furthermore, the likelihood of encountering a blink-saccade pair increases with gaze amplitude, particularly when ocular movements are synchronous with head movements.[20,21] These findings have led some authors to speculate whether blink visual suppression may be involved in facilitating visual stability during large gaze shifts, which correspond to the point of weakest saccadic suppression.[18]

With the aim of further exploring the relationship between blinks and saccades, this study evaluated spontaneous blink rate (SBR) and blink-saccade synchronicity while participants drove a vehicle on rural and city roads in real traffic conditions of varying complexity. It was believed that this experimental configuration would be able to provide relevant new information regarding the joint contribution of both cognitive and attentional demands and saccades to blink parameters in a daily-life setting.

MATERIALS AND METHODS

Participants

Twenty young volunteers (age mean ± SD of 37.65 ± 12.31 years; 8 females) agreed to participate in this study. All participants were non-commercial driving license holders and current drivers. Inclusion criteria were binocular visual acuity of 1 (decimal) or better with habitual correction, stereopsis equal or better than 50 arc seconds (measured with the Titmus Wirt test) and normal color vision (evaluated with the Ishihara color test plates). Subjects with binocular vision problems, amblyopia, oculomotor anomalies and eyelid position (such as ptosis) or movement abnormalities were excluded from the study.

All participants provided written informed consent after the nature of the study was explained to them. The study was conducted in accord with the Declaration of Helsinki tenets of 1975 (as revised in Tokyo in 2004) and received the approval of an Institutional Review Board (Universitat Politècnica de Catalunya).

Procedure

Participants were instructed to drive in silence during 60 minutes through an open circuit composed of country and city roads of varying navigational difficulty and traffic intensity. The same predefined circuit was followed in all cases, with the driving sessions taking place at the same hour in the morning to ensure similar traffic intensity. Only sunny days with good visibility were considered suitable for the purposes of this study.

Aiming at exploring the influence of the driving associated cognitive workload on blinks and saccades, five different driving complexity levels were defined in terms of navigational difficulty and traffic intensity (see Table 1). Next, 25 one-minute segments were selected within the 60-minute circuit so as to include five segments from each level of complexity. Each one-minute segment related to a particular event along the route (e.g. entering a roundabout). Small, normal daily variations in traffic intensity were not taken into consideration to redefine the complexity level allocated to a particular segment.

Participants wore their habitual visual correction and were asked to refrain from drinking coffee or alcohol prior to the beginning of the driving trial, as well as to have a good night rest of a minimum of seven hours of sleep. All driving trials were conducted in absolute silence, without ambient music or radio, except for brief instructions to navigate the circuit. Participants were told that their driving performance would not be evaluated and that video recordings were used to assess conjunctival redness.

The same car with manual transmission was employed in all cases. Participants were allowed time to get accustomed to the driving characteristics of the car before starting the trial. They were instructed to adjust the lateral and rear view mirrors to ensure optimal vision. Seat position and steering wheel height were also adjusted to provide the best ergonomically correct position for each driver.

Two different video cameras, fixed to the dashboard of the car, were employed to record the scene, as observed through the windshield (Sony DCR-SR32, 8 MP), and the face of the drivers (Nikon Coolpix S500, 7.1 MP), respectively.

TABLE 1 Driving complexity levels according to navigational difficulty and traffic intensity.

Complexity level	Driving conditions	Traffic intensity
1	Car stopped at a traffic light	–
2	Single carriageway with one traffic lane per direction	Light-moderate
3	Single carriageway with four lanes	Moderate
4	Simple roundabout	Moderate-heavy
5	Roundabout interchange or busy city intersection	Heavy

FIGURE 1 Video stream showing the face of the driver (to assess blinking and saccades) and the scene as observed through the windshield of the car (to determine driving complexity).

Image Analysis

The Pinnacle Studio 15 HD (Pinnacle Systems, Mountain View, CA) was employed to analyze the video recordings of the trial drives. Firstly, the recordings from both cameras were synchronized with the aid of the acoustic signal which marked the start of each driving trial, and fused into a single video stream (Figure 1). Secondly, for each one-minute segment, a frame by frame visual examination of video recordings was conducted to identify blinks and saccades and to determine the corresponding SBR and saccade frequency, as well as the number of blink-saccade pairs occurring within that time segment. Saccades were classified into small (approximately 10° or less) and large (more than 10°) amplitude gaze shifts, and head movements accompanying large amplitude saccades were also noted. Only horizontal or approximately horizontal saccades were taken into consideration.

Data Analysis

Statistical analysis of the data was performed with the IBM SPSS Statistics software 20.0 for Windows (IBM Corp, Armonk, NY). All the variables under study were analyzed for normality using the Kolmogorov–Smirnov test, which disclosed normal distributions in all cases ($p > 0.05$). Therefore, comparisons between the different complexity levels were performed with an analysis of variance (ANOVA) test for repeated measures and, whenever a main effect reached statistical significance, post-hoc pair-wise differences were explored with a Bonferroni analysis. A p value of 0.05 or less was considered to denote statistical significance throughout the study.

RESULTS

Spontaneous blink rate and the probability of observing a blink-saccade pair were found to follow a highly consistent behavior, that is, no statistically significant differences were evidenced between the five measurements corresponding to the same complexity level (ANOVA test for repeated measures, $p > 0.05$).

A summary of the average SBR and blink-saccade pairs per minute for each complexity level is presented in Table 2 and shown in Figure 2. Spontaneous blink rate was found to be similar with independence of the complexity of the driving conditions ($F = 0.591$; $p = 0.670$), with an average SBR while driving of 20.3 blinks/minute.

The amplitude of saccades was found to increase at high complexity levels, with many saccades involving a movement of the head as well. Thus, a similar number of saccades was found at each complexity level (19.5 ± 1.1; $F = 1.955$; $p = 0.108$); the number of large amplitude saccades per minute increased at higher complexity levels ($F = 15.403$; $p < 0.001$) (Table 2 and Figure 2). A post-hoc Bonferroni analysis revealed statistically significant differences between complexity levels 1 and 2 ($p = 0.025$), 3 ($p = 0.009$) and 5 ($p = 0.013$), as well as between 2 and 4 ($p = 0.009$) and 5 ($p < 0.001$), between 3 and 4 ($p = 0.003$) and 5 ($p < 0.001$), and between 4 and 5 ($p = 0.034$). A similar percentage of large amplitude saccades was associated with a head movement at all complexity levels (an average of 59.4% of large amplitude saccades occurred in synchronicity with a head movement).

The probability of encountering a blink-saccade pair was revealed to be dependent on the level of complexity, with an increasing number of blink-saccade pairs per minute at high complexity levels ($F = 20.597$; $p < 0.001$). A *post-hoc* Bonferroni analysis of these findings revealed statistically significant differences

TABLE 2 Blinks and saccade eye movements per minute at each complexity level, with indication of the number of large amplitude saccades, as well as blink-saccade, blink-large amplitude saccade and head movement-large amplitude saccade pairs.

	Complexity level*						
	1	2	3	4	5	Mean ± SD	Differences between complexity levels
Blinks (per minute)	19.6 ± 9.0	19.1 ± 10.2	18.7 ± 9.4	21.9 ± 9.3	22.1 ± 8.9	20.3 ± 1.6	$F = 0.591$ $p = 0.760$
Saccades (per minute)	18.4 ± 3.8	20.3 ± 3.1	18.2 ± 2.8	20.4 ± 3.9	20.2 ± 3.8	19.5 ± 1.1	$F = 1.955$ $p = 0.108$
Blink-saccade pairs (per minute)	11.7 ± 3.8	6.8 ± 2.4	6.4 ± 2.7	11.7 ± 4.2	15.0 ± 4.5	10.3 ± 3.7	$F = 20.597$ $p < 0.001$
Large amplitude saccades (per minute)	7.0 ± 3.3	4.0 ± 2.1	3.7 ± 2.1	7.3 ± 3.5	10.2 ± 3.8	6.4 ± 2.7	$F = 15.403$ $p < 0.001$
Blink-large amplitude saccade pairs (per minute)	5.9 ± 3.3	3.4 ± 1.9	3.6 ± 2.1	5.8 ± 3.5	9.1 ± 3.6	5.6 ± 2.3	$F = 11.705$ $p < 0.001$
Large amplitude saccade-head movement pairs (per minute)	4.2 ± 2.0	2.4 ± 1.3	2.2 ± 1.3	3.8 ± 2.3	6.1 ± 2.3	3.8 ± 1.6	$F = 13.992$ $p < 0.001$

Statistically significant intergroup differences are denoted by a p value of 0.05 or less. All parameters are presented as mean ± SD.
*Complexity levels: 1: Car stopped at a traffic light; 2: Single carriageway with one traffic lane per direction; 3: Single carriageway with four lanes; 4: Simple roundabout; 5: Roundabout interchange or busy city intersection

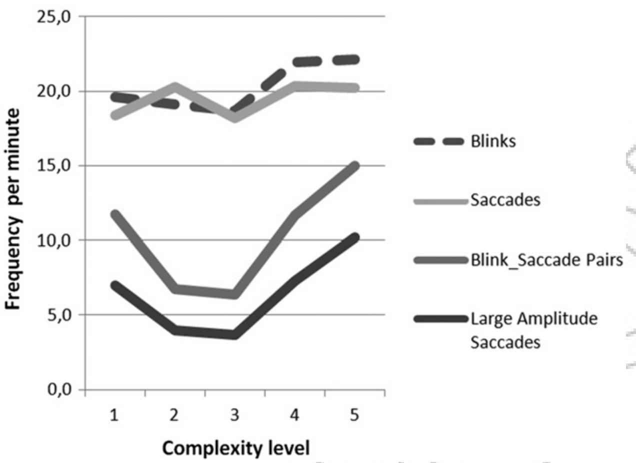

FIGURE 2 Frequency (per minute) of blinks, saccades, blink-saccade pairs and large amplitude saccades.

between complexity levels 1 and 2 ($p < 0.001$) and 3 ($p < 0.001$), between 2 and 4 ($p < 0.001$) and 5 ($p < 0.001$), as well as between 3 and 4 ($p < 0.001$) and 5 ($p < 0.001$), and between 4 and 5 ($p = 0.046$).

Finally, Table 2 also displays the number blinks which occurred in synchronicity with a large amplitude saccade. A statistically significant difference was encountered between complexity levels in the number of blinks associated with large gaze shifts ($F = 11.705$; $p < 0.001$). An average of 87.5% of large amplitude saccades were accompanied by a blink.

DISCUSSION

This study aimed at further investigating the well-documented blink-saccade relationship by assessing SBR, as well as blink-saccade synchronicity, in a real-life driving exercise in which different levels of complexity were defined according to navigation difficulties and traffic intensity. It was our hypothesis that high driving complexity levels, with the subsequent increment in cognitive workload, would be associated with a reduction in SBR, and with large gaze shifts, involving head movements. However, the effect of the apparently contradictory joint contribution of saccades and cognitive demand in determining actual SBR was unclear.

In effect, large amplitude saccades and increasing cognitive workload have been documented to have an opposite influence over the frequency of spontaneous blinks. Thus, on the one hand, increasing cognitive demands have been reported to result in a reduction in SBR, both during computer tasks[7–11] and other activities such as reading or watching a video story.[4,5] On the other hand, blinks tend to be associated with large gaze shifts, rather than saccades of smaller amplitude such as those involved in reading,[20,21] partially contributing to sustaining visual stability through momentary suppression of visual input,[16,17] which is particularly relevant for large gaze shifts, were saccadic suppression is less effective.[18]

The present findings, although evidencing a moderate inter-subject variability, in agreement with previous studies,[6] also revealed a high intra-subject consistency, with participants exhibiting similar blinking and saccade patterns within the same complexity level. Overall, driving was associated with an average SBR of 20.3 ± 1.6. This value may be comparable with that reported by previous authors when examining SBR during tasks of medium cognitive workload such as during a conversation.[4] Interestingly, however, SBR was not found to decrease at higher levels of driving complexity, remaining fairly constant throughout the whole driving trial. To advance an explanation for these findings, it is necessary to refer to our results regarding saccades and the probability of encountering a blink-saccade pair at each complexity level.

The present experimental configuration only allowed for an overall and rather crude classification of saccades in terms of their amplitude. Thus, we differentiated between small and large gaze shifts and we noted the percentage of saccades also involving a head movement. Besides, only horizontal (or approximately horizontal) saccades were taken into consideration, although a preliminary examination of the video recordings showed a limited number of vertical saccades (fixation jumps between the scenery and the instrumentation panel of the vehicle), which was similar at all complexity levels. Similarly, equipment limitations prevented the recording of very small amplitude saccades and, although particular care was employed in the frame-by-frame examination of all video recordings, it may be assumed that an undetermined number of small amplitude saccades could not be identified, thus resulting in an actual underestimation of saccades and an overestimation of blink-saccade pairs.

As was to be expected, high levels of driving complexity and traffic intensity resulted in a statistically significant increase in the predominance of large amplitude saccades, many involving a movement of the head (mainly with the purpose of checking the lateral rear view mirrors). In addition, the majority of large saccades were accompanied by a blink, as opposed to the small amplitude eye movements found at the lowest levels of complexity, many of which occurred without an associated blink. These findings are in agreement with previous publications[20–22] and may give support to the hypothesis that blinking, when associated with large gaze shifts, may help in reorganizing attentional resources by momentarily suppressing attention and transferring it to a different region of the visual stimulus. Recent psychophysics studies investigating perceptual switching when viewing a Necker cube[23] reach a similar conclusion. Therefore, it could be assumed that the reduction in SBR arising from a higher cognitive workload was counteracted, within the same level of complexity, by the increasing occurrence of blink-saccade pairs (gaze-evoked blinks), that is, the presence of large saccades may help in blocking the inhibitory mechanism which inherently decreases SBR during tasks involving high cognitive demands.

It may be noted that at the lowest level of complexity, that is, when the car was stopped at a traffic light, participants tended to perform a number of large amplitude gaze shifts to scan the scenery while waiting for the light to turn green. Many of these saccades were also accompanied by a blink and, therefore, given the low cognitive demand at this level of complexity, it probably should have resulted in an overall larger SBR than at any other complexity level. However, our findings failed to reflect this increase in SBR. Although the reasons behind these results are uncertain and warrant further investigation, it may be speculated that the cognitive demand of drivers, when waiting at a traffic light, was actually not at its lowest.

A good addition to this study would have been to investigate the exact timing of each blink and saccade in terms of the specific information value of the scene observed through the windshield. However, this exploration would require more sophisticated recording and eye tracking instrumentation, not available to us at the moment of the study. It was therefore not possible to determine whether blinks while driving also tend to occur during implicit or explicit attentional breaks, as previously noted.[14,15]

In summary, the present findings give support to recent research describing spontaneous blinking as a complex mechanism regulated by a ''central pacemaker'' which, in turn, is modulated by, among other factors, the cognitive and attentional demands of the visual task at hand and the onset of large amplitude gaze shifts. Our results suggest that, when high cognitive demands are accompanied by an increase in the number of large amplitude saccades, the contribution of the latter is more significant in determining spontaneous blink rate. Therefore, the evaluation of SBR while driving may be considered a useful measure of the joint contribution of environment complexity and cognitive workload, opening possible new avenues of research in driving and blinking.

DECLARATION OF INTERESTS

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper. No financial support was received in support of the study.

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