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RESEARCH ARTICLE

Effects of driving time on microsaccadic dynamics

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Abstract Driver fatigue is a common cause of car accidents. Thus, the objective detection of driver fatigue is a first step toward the effective management of fatigue-related traffic accidents. Here, we investigated the effects of driving time, a common inducer of driver fatigue, on the dynamics of fixational eye movements. Participants drove for 2 h in a virtual driving environment while we recorded their eye movements. Microsaccade velocities decreased with driving time, suggesting a potential effect of fatigue on microsaccades during driving.

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Introduction

Fatigue is a common cause of car accidents (Maycock 1997; Fletcher et al. 2005), and drowsy driving is linked to a fivefold increase in crashes or near-crashes (Klauer et al. 2006). Recent analyses have estimated that the costs of fatigue-related accidents in the US amount to $31.1 billion (Shahly et al. 2012). Yet, many drivers are unaware of, or even deny, an impairment of their abilities due to fatigue (Di Stasi et al. 2012; Dawson 2012).

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Law enforcement agencies and medical departments have attempted to develop fatigue detectors based on eye movement metrics (Citek et al. 2011; Dawson et al. 2013). The validity of these indices remains controversial, however, due to discrepancies in results and inconsistencies in methods and recording techniques across studies (Rubenzer and Stevenson 2010). Further, some of the assessment tools in current use require drivers to interrupt their task to be evaluated (Di Stasi et al. 2013a, for a review). Thus, recent research has aimed to develop non-invasive online tools for the objective and early detection of fatigue (Di Stasi et al. 2012; Ahlstrom et al. 2013), such as on-board devices that monitor a driver's oculomotor dynamics (Balkin et al. 2011; Dawson et al. 2013).

Driving time (DT) is a common inducer of fatigue; thus, professional drivers are usually required to take driving breaks every ~2 h of uninterrupted driving (FMCSA 2000; VOSA 2009). Research has shown that increased DT results in longer and more frequent eye blinks (Schleicher et al. 2008; Benedetto et al. 2011b; McIntire et al. 2014). Because the eyes are closed for longer periods of time, this produces visual information loss and higher likelihood of performance errors (Di Stasi et al. 2012). Thus, an important caveat of monitoring devices that rely on eye blink behavior is that they require eye closure—and thus, visual information loss—beyond a pre-defined interval to set off an alarm.

Assessment tools based on saccade metrics surmount some of the challenges posed by those based on eye blinks, in that they are not dependent on eye closure. Increased DT has been linked to a reduction in the rates (Wertheim 1978; Cerezuela et al. 2004) and velocities (Di Stasi et al. 2013a; Ahlstrom et al. 2013) of large saccades, but no research has addressed the effects of DT on the dynamics of microsaccades (small-magnitude saccades produced during attempted fixation; (Martinez-Conde et al. 2004, 2009, 2013).

Di Stasi et al. (Di Stasi et al. 2013b) recently showed that the dynamics of fixational eye movements, including microsaccades and drifts (curvy slow movements in between microsaccades and saccades), are sensitive to time-on-task within a laboratory environment, but no studies to date have addressed the effects of time-on-task on the dynamics of fixational eye movements during driving, or any other simulated or real-world scenarios.

Here, we investigated the effects of DT on microsaccade dynamics in a simulated driving environment. We found that microsaccade velocities decreased as DT increased, suggesting a possible effect of fatigue. These results may be mediated by arousal-induced variations in the activity of omnipause neurons (OPNs).

Methods

The experiments aimed to determine the effect of DT on eye movement parameters. Data concerning the effects of DT on the metrics of large saccades (>2.5°) were reported previously (Di Stasi et al. 2012).

Ethical approval

We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki) (World Medical Association (WMA 1964). The experiments were approved by the Technische Universität Dresden's Institutional Review Board. Written informed consent was obtained from each participant prior to the study.

Subjects

Ten naive participants (5 men and 5 women, mean age 23.9 year; SD 4.9 year) took part in this experiment. All participants had normal or corrected-to-normal vision and had valid driving licenses (mean 5.6 year; SD 4.4 year). Here, we analyzed data from seven out of ten participants (4 men and 3 women, mean age 24.9 year; SD 5.5 year). We excluded data from three participants because of log-system failures during the recording ($n = 2$) or noise in the data ($n = 1$).

Experimental design, stimuli, and instruments

Participants completed a 2-h driving task without breaks in the PC-based SIRCA driving simulator developed for eye-tracking experiments (see Di Stasi et al. 2010, for more details). This temporal window was chosen to approximate the maximum DT that professional drivers are allowed before a mandated break (FMCSA 2000; VOSA 2009). The road scenario (Fig. 1b) was displayed on a 19-in. screen (36.8 × 27.5 cm; aspect ratio: 4:3) located in front of the driver, who was seated on a comfortable chair. Figure 1b shows a scene from the virtual driving environment's image display: The image included a rearview mirror and a schematic dashboard containing a speedometer. The distance between the driver's eyes and the screen was ~80 cm, resulting in a 25.8° (horizontal) × 19.5° (vertical) field of view. The programmed scenarios traversed curved and straight 2- and 4-lane roads, with moderate surrounding traffic. Road conditions were monotonous and predictable. The task was set to a low level of complexity, consisting of ~75 cars within a radius of 1.5 km of the participant's vehicle. Participants drove around the same simulation circuit 12 times on average (they completed a full circuit in ~10 min, depending on their driving speed).

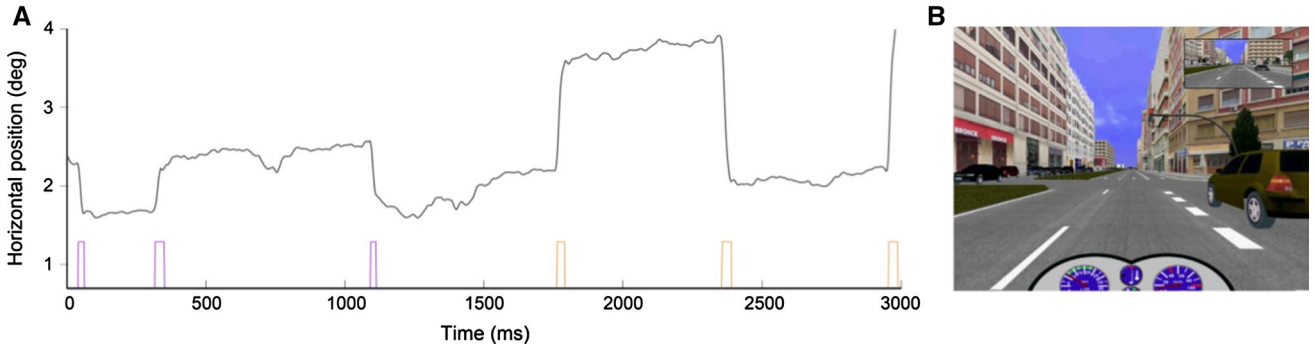

Fig. 1 **a** An example of horizontal gaze position during simulated driving. Data from subject #6 over a 3-second epoch of driving time. The *black line* represents the raw horizontal eye-position signal. Saccades (indicated by the *orange pulses*) and microsaccades (*purple pulses*) were detected using an objective algorithm (Engbert and Kliegl 2003). **b** A screenshot taken from the SIRCA simulator. The rear mirror and the dashboard were displayed during the simulation

Eye movement recordings and analyses

We sampled eye movements monocularly at 500 Hz with the Eyelink 1000 eye-tracking system (SR Research, Ontario, Canada) in its remote configuration. We detected and analyzed (micro)saccades as in (Di Stasi et al. 2013b), except that we imposed no binocular criterion for (micro)saccade detection. Briefly, we first identified and removed blink periods as portions of the raw data where pupil information was missing. We also removed portions of data where very fast decreases and increases in pupil area occurred (>50 units/sample; such periods are probably semi-blinks where the pupil is never fully occluded). We added 200 ms before and after each blink/semi-blink to eliminate the initial and final parts where the pupil was still partially occluded (McCamy et al. 2012, 2014). (Micro)saccades were then identified with a modified version of the algorithm developed by Engbert and Kliegl (Engbert and Kliegl 2003). This algorithm bases (micro)saccade identification on a velocity threshold that adapts to the level of noise in the data (see Engbert and Kliegl 2003 for a detailed description). Here, we used $\lambda = 6$ (to obtain the velocity threshold) and a minimum saccadic duration of 6 ms (see Fig. 1a). To reduce the amount of potential noise, we imposed a minimum intersaccadic interval of 20 ms so that potential overshoot corrections were not categorized as new saccades (Møller et al. 2002). Microsaccades were defined as saccades smaller than 1° of visual angle (°) (Martinez-Conde et al. 2009, 2013). We analyzed data from all fixations, even those occurring outside of the display area (Fig. 1b; see Supplementary Table 1 for further information on fixations directed to the area of the speedometer). The present microsaccadic analyses do not overlap with previous analyses of large saccades (Di Stasi et al. 2012).

Microsaccadic main sequence analyses

The magnitude of microsaccadic eye movements is related to both the velocity and the duration of the movements (Gruart et al. 1995). Thus, we studied the effects of DT on the microsaccadic peak velocity/magnitude, mean velocity/magnitude, and duration/magnitude relationships (Becker and Fuchs 1969; Evinger et al. 1991).

We assumed a linear relationship between microsaccadic magnitude and peak velocity. Thus, to obtain the slope for each peak velocity/magnitude relationship (and the other main sequence relationships), we performed robust linear regressions (using the robust fit function in MATLAB) on the raw data for each subject to obtain the slope for each main sequence relationship. That is, we did a robust linear regression on the raw data, i.e., peak velocity $= m \cdot$magnitude $+ b$; here, b is the y-intercept and m is the slope. To study the effects of DT on microsaccades, we analyzed the slopes of the linear equations for the raw data. To correct the digitization scalloping at the low end of the main sequence plot, and for illustration purposes, we applied a random offset factor chosen randomly from the interval (−0.1 °/s, 0.1 °/s) in peak velocity and from the (−0.06°, 0.06°) in magnitude to each microsaccade.

We categorized the full period of driving into four DT bins, each consisting of 30 min (Di Stasi et al. 2013b). Each of the four temporal bins included approximately three full laps around the simulated circuit; thus, all subjects saw approximately the same visual stimuli during each temporal bin.

Procedure

We asked subjects to drive at ~50 km/h, to follow the usual traffic rules, to not turn off at intersections, and to keep the car mostly in the right lane. The experiment started with the set up and calibration of the eye-tracking system, followed

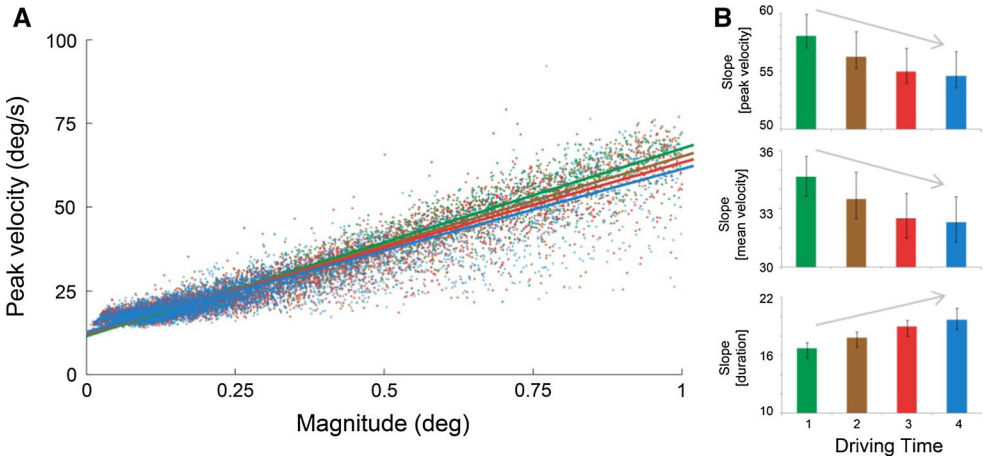

Fig. 2 Effect of driving time (DT) on the microsaccadic main sequences. **a** Microsaccade main sequence (peak velocity/magnitude relationship) for one subject across four consecutive DT bins (1: *green*, 2: *brown*, 3: *red*, 4: *blue*; 30 min per bin). Each *dot* represents a microsaccade. The curves are the linear fits to the data from DT bins. **b** *X*-axis: the four consecutive DT bins. *Y*-axis: main sequence slope mean values for the peak velocity/magnitude (*top*), mean velocity/magnitude (*middle*), and duration/magnitude (*bottom*) relationships. The *arrows* show the linear significant trend of the slopes across DT [from top to bottom: $F(1, 6) = 10.73$, $p = 0.02$; $F(1, 6) = 22.61$, $p = 0.02$; $F(1, 6) = 7.76$, $p = 0.03$]. *Error bars* indicate the S.E.M. across subjects ($n = 7$)

Table 1 Microsaccadic parameters in each driving time (DT) bin. Means and standard deviations were calculated from the (mean) values of each subject ($n = 7$ subjects)

	Driving time (DT)			
	DT 1	DT 2	DT 3	DT 4
Microsaccadic main sequences				
Slope (peak velocity/magnitude)*	58.09 (4.87)	56.30 (5.72)	55.01 (5.40)	54.63 (5.62)
Slope (mean velocity/magnitude)*	34.65 (2.85)	33.50 (3.69)	32.49 (3.47)	32.31 (3.51)
Slope (duration/magnitude)*	16.71 (1.57)	17.83 (1.59)	18.96 (1.82)	19.69 (3.11)
Peak velocity (°/s)*	37.19 (4.51)	34.95 (3.56)	32.56 (3.12)	31.50 (4.57)
Mean velocity (°/s)*	29.06 (3.78)	27.67 (3.40)	26.18 (3.33)	25.53 (4.31)
Duration (s)*	12.92 (1.39)	12.60 (1.16)	12.11 (1.31)	11.99 (0.91)
Magnitude (°)*	0.44 (0.06)	0.41 (0.04)	0.37 (0.03)	0.36 (0.04)
Rate (N/s)	1.15 (0.21)	1.30 (0.30)	1.47 (0.29)	1.58 (0.66)

* denotes differences with statistical significance for the driving time manipulation. All p values < 0.05

by the 2-h driving simulation. The experiment took place in a dimly lit, air-conditioned room (~22 °C), with minimal background noise.

Statistical analysis

We applied separate single-factor repeated-measures ANOVAs to analyze the effect of DT on oculomotor parameters and driving speed with the four DT bins serving as within-subjects factor.

Results

Microsaccadic main sequence

Increased DT was associated with slope decreases for the microsaccadic peak velocity/magnitude [$F(3, 18) = 8.78$, $p < 0.001$, see Fig. 2] and mean velocity/magnitude relationships [$F(3, 18) = 6.98$, $p = 0.002$] and with an slope increase for the microsaccadic duration/magnitude relationship [$F(3, 18) = 6.35$, $p = 0.004$] (Fig. 2b, Table 1). These results provide the first evidence that microsaccadic dynamics may signal operator fatigue during real-world tasks.

Participants fixated the area of the speedometer (see Fig. 1b) on average 3.7 % of the time. Number of fixations, fixation durations, and number of microsaccades in the area of the speedometer remained stable throughout the driving session (Supplementary Table 1). Increased DT resulted in decreased peak velocity/magnitude slopes when we analyzed: (a) data from all fixations (Fig. 2, (b) fixations to speedometer only, and (c) fixations to everywhere but the speedometer (Supplementary Table 2).

Di Stasi et al. (2012), Ahlstrom et al. (2013) previously analyzed the effects of driving time on the peak velocity

Table 2 Blink and saccadic rates in each driving time (DT) bin. Means and standard deviations were calculated from the (mean) values of each subject ($n = 7$ subjects)

	Driving time (DT)			
	DT 1	DT 2	DT 3	DT 4
Saccadic rate (N/s)*	1.28 (0.31)	1.28 (0.36)	1.23 (0.29)	1.08 (0.37)
Blink rate (N/s)*	0.18 (0.09)	0.21 (0.09)	0.25 (0.09)	0.25 (0.08)

* denotes differences with statistical significance for the driving time manipulation. All p values < 0.05

and duration of *large* saccades and found that saccadic velocity decreased and saccadic duration increased with driving time. The present microsaccadic results are consistent with the earlier findings for large saccades during driving and moreover agree with previous reports of the effects of time-on-task on saccades (Hirvonen et al. 2010; Di Stasi et al. 2011, 2012, 2014a, b; Ahlstrom et al. 2013) and microsaccades (Di Stasi et al. 2013b; Siegenthaler et al. 2014) during non-driving tasks.

Blink and saccade rate

Blink rate increases and saccade rate decreases have been associated with subjective fatigue in numerous studies (Morris and Miller 1996; Schleicher et al. 2008). In agreement with earlier reports (Schleicher et al. 2008), here, we also found blink rate [$F(3, 18) = 6.61$, $p = 0.003$] to increase and saccade rate [$F(3, 18) = 5.12$, $p = 0.009$] to decrease (Wertheim 1978; Cerezuela et al. 2004) with DT (Table 2), even though microsaccadic rates (Table 1) did not vary significantly with DT (Benedetto et al. 2011a). This replication lends supports to the notion that the present oculomotor measurements are indicative of driver fatigue effects, consistent with previous investigations.

DT did not affect driving speed ($F < 1$), which remained constant across participants throughout the experiment [average (Km/h): DT1: 53 ± 6; DT2: 53 ± 8; DT3: 54 ± 8; DT4: 53 ± 6]. Participants may have increased their driving efforts to compensate for increasing levels of fatigue (Hockey 1997; Di Stasi et al. 2012). Thus, the observed changes in oculomotor parameters are unlikely to have resulted from changes in optic flow from the simulator's display (which can be affected by driving speed).

Discussion

We analyzed the characteristics of human microsaccades produced during a driving task in a simulated monotonous road environment and found that microsaccade velocities decreased and microsaccade durations increased with increased DT, resulting in lower velocity/magnitude main sequence slopes and steeper duration/magnitude main sequence slopes.

These results are consistent with previous findings for large saccades during driving, as well as with earlier reports of the effects of time-on-task on saccades (Hirvonen et al. 2010; Di Stasi et al. 2011, 2012, 2014a; b; Ahlstrom et al. 2013) and microsaccades (Di Stasi et al. 2013b; Siegenthaler et al. 2014) during non-driving tasks (often conducted in standard laboratory settings).

Changes in the (micro)saccadic main sequence with DT (and more generally, time-on-task) may arise at the level of the excitatory connections from arousal neurons to OPNs (Grossberg and Kuperstein 1986; Moschovakis 1994; Gancarz and Grossberg 1998; Rahafrooz et al. 2008). OPNs, which are critical to encoding saccadic velocity (Gijsman et al. 2002), fire at a relatively constant rate during fixation, but pause during saccades (Everling et al. 1998; Munoz et al. 2000). They also fire less during when arousal is low (Scudder 1988; Fuchs et al. 1985), and they stop firing altogether during sleep (Henn et al. 1984). Therefore, decreased

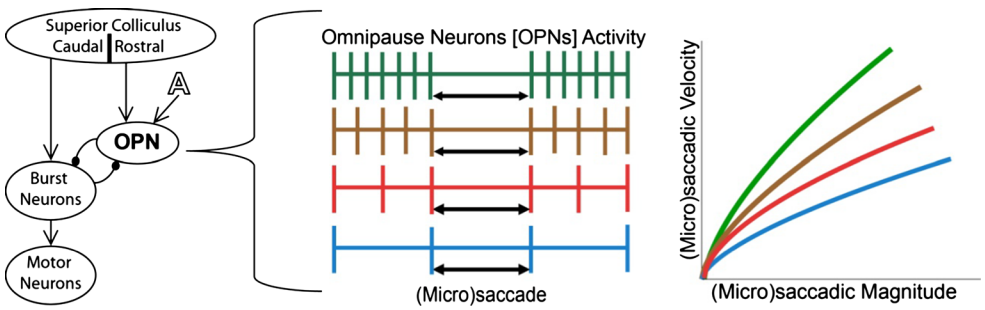

Fig. 3 A possible neurophysiological explanation of the effect of DT on (micro)saccadic velocity. Schematic diagram of the effects of decreased arousal (i.e., due to increased DT) on (micro)saccadic dynamics. Increased levels of fatigue (i.e., reduced levels of arousal) may decrease the activation of arousal neurons [A] and the firing rates of OPNs, leading to slower (micro)saccades. The different colors indicate consecutive DT bins (1: *green*, 2: *brown*, 3: *red*, 4: *blue*; 30 min per bin). Modified from (Di Stasi et al. 2013a)

activation of arousal neurons projecting onto OPNs (Grossberg and Kuperstein 1986; Moschovakis 1994; Gancarz and Grossberg 1998; Rahafrooz et al. 2008)—for example due to increased time-on-task (Di Stasi et al. 2013a)—can result in slowed saccades similar to those observed in the case of fatigue (Grossberg and Kuperstein 1986; Scudder 1988). Thus, the proposal that variations in arousal (i.e., fatigue) can modulate the saccadic main sequence is in line with mechanistic accounts of saccade generation in the oculomotor system (see Fig. 3).

These findings have the potential to reduce the gap between basic and applied neuroscience and to help the development of fatigue-assessment tools that reduce the prevalence of fatigue-related accidents (Di Stasi et al. 2013c).

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