Original article

How driving duration influences drivers' visual behaviors and fatigue awareness: A naturalistic truck driving test Study

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Abstract

Background: Commercial truck drivers stay behind the wheel for long hours. Fatigue is thus a major safety concern among such long distance travelling drivers.

Objectives: Primarily, the study explored the effects of driving duration on commercial truck drivers' visual features and fatigue awareness. It also examined the association between visual variables and subjective level of fatigue.

Methods: Participants of the study were 36 commercial truck drivers. During the study, the participants were grouped into nine on the basis of the differences in their age and were made to participate in the naturalistic driving test. In the driving test, the participants were asked to finish 2h, 3h, and 4h continuous driving tasks. Ten visual indicators and self awareness of fatigue level of the drivers were recorded during the driving hours. One-way ANOVA and Pearson product-moment correlation were used to analyze each visual indicator's variation by age groups over time, and its association with subjective level of fatigue.

Results: The statistical analysis revealed that continuous driving duration had a significant effect on changes of visual indicators and self-reported fatigue level. After 2h of driving, both the average closure duration value and average subjective fatigue level changed significantly. After 4h of driving, other than the average number of saccades and average pupil diameter, all of the driver's visual indicators had a significant change. In addition, the change of fatigue level is positively associated with the variation of pupil diameter, fixation duration, blink frequency, blink duration, and closure duration. On the other hand, the change of fatigue level was negatively related to number of fixations, search angle, number of saccade, saccade speed, and saccade amplitude.

Conclusion: Driving duration has a significant effect on driver's visual variation and fatigue level. For commercial truck drivers, traffic laws and regulations should strictly control the amount of their continuous driving time. Moreover, driving fatigue can also be evaluated through the change rate of driver's visual indicators. Awareness of the rate of change in their driving fatigue level alerts drivers to the risk of fatigue and rest moment. [*Ethiop. J. Health Dev.* 2018;32(1):36-45]

Key words: Commercial truck drivers, visual behaviors, fatigue level, Stanford Sleepiness Scale, Pearson correlation

Introduction

Nowadays, fatigue driving is a leading cause of traffic fatalities and injuries throughout the world. In the U.S.A, the National Highway Traffic Safety Administration (NHTSA) estimated that at least 100,000 automobile crashes occurred annually due to drivers' falling asleep while they were driving. This was roughly estimated to result in 1,550 fatalities and 40,000 nonfatal injuries. In the EU 27 countries, about 10-20% of all the road traffic driving fatigue caused crashes. In some cases, as high as 60% of fatal truck crashes were reported to be due to driver's fatigue (source: European Accident Research and Safety Report 2013). According to 'Blue Book of Road Safety in China 2014,' as many as 198,394 road crashes occurred in China in 2013*. This was reported to have caused 58,539 fatalities and 213,724 injuries. About 15% of the crashes were induced by or partially associated with driver's fatigue. Trucks are generally larger than other vehicles and much harder to manoeuvre. It is perhaps because of their recognition of this that many professional truck drivers hold the opinion that, if driving fatigue is allowed to remain unnoticed to drivers, more fatalities and non-fatal injuries are likely to be expected in the future. Commercial truck drivers must remain focused behind the wheel for long hours. No doubt, keeping themselves focused for long hours behind wheels can exhaust, and even make them feel fatigue (1). Driving under fatigue can manifest itself through drivers' an involuntary withdrawal of attention from the road ahead, extended reaction time, slower responses to danger, et al. All of these symptoms give rise to diminished vigilance, and thus, increase the likelihood of crashes (2, 3). Commercial truck driver's hypo-vigilance, that is, driving drowsiness or fatigue, is one of the major factors that lead to traffic crashes (4). Most of these crashes can be avoided, however, if fatigued drivers are alerted on time. Therefore, it is necessary to develop a system to alert commercial drivers at critical moments to prevent them from getting fatigued and avoid crashes (5).

Over the last few years, researchers have been working on how to detect and measure driver's fatigue using different techniques, among which eye movement variables are the most common measures (6). Undoubtedly, drivers under fatigue exhibit certain observable visual changes like small degree of eye

* Accidents that have caused a fatality or a personal injury.

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opening, long blink duration, gazing, yawning, etc., Understanding such visual characteristics can help monitor drivers' fatigue level (7-9). In addition, driver's visual characteristics are often combined with physiological measures (e.g., heart rate, breathing, body temperature, brain waves) or indirect vehicle behaviors (e.g., vehicle's steering wheel movements, time to line crossings, and deviation of lateral position). Understanding these behaviors helps estimate driver's fatigue level (10-12). For example, Bergasa, et al. tracked the following techniques of detecting drivers' fatigue level: percentage of eye closure, eye closure duration, blink and nodding frequency and face position (13). The techniques, however, have not yet been practical due to their technical shortcomings.

Driver's fatigue accumulates gradually with continuous driving for long periods without break (14), and understanding how fatigue progresses over time, is ultimately important for the development of fatigue detection systems. The hypothesis is that high levels of commercial truck driver's self-reported fatigue can be identified through the variation of eye movement variables. Therefore, this study examined commercial truck drivers' visual characteristics after they performed a driving task of some hours. In the study, an attempt was made to associate the driver's visual characteristics with their subjective level of fatigue. To achieve the objective, 36 commercial truck drivers of different age group were recruited to take a naturalistic driving test. During the test, the drivers' visual variations and fatigue level were examined using Smart Eye tracking system and Stanford Sleepiness Scale (SSS). One-way analysis of variance (ANOVA) and Pearson product-moment correlation analysis was used to analyze the collected data.

Methods

Participants: A total of 36 commercial truck drivers (28 male and 8 female) with good physical and mental health from 5 logistics companies in Jinan, China, were the participants of this naturalistic driving test. Each participant held a valid Chinese B1 or B2 driving license for at least 5 years and drove trucks for an annual mileage of 10,000 or more km in the three years prior to their participation in the study.

The participant's average age was 34.7 years for females (SD = 4.5) and 38.2 years for males (SD = 6.4). All the study participants had normal vision. None had any records of major accident. Not any one of the study participants also drank alcohol or took any drugs that could affect their driving performance in the last three days preceding the driving test day. Each of the study participants was paid ¥200 per day or $25 per hour for participation in the test.

Dependent variables: Driver's eye movements mainly included fixation, saccade and blinking. Eye fixations express the focus of driver's visual attention on driving, which is significantly associated with the level of fatigue (Jin et al., 2013). Here, four indicators; namely, average pupil diameter (mm), average number of on-road fixations (times/s), average on-road fixations duration (s), and average deviation of visual search angle were considered (°). As a measure of intensity, the first indicator is defined as the average length of driver's pupil diameter for each age group. This can help examine how driver's attention is attracted by fatigue. The second indicator is the average number of on-road fixations featuring the maintaining number of visual gaze on a specific target in driving. This consisted of at least one gaze. More gaze than just one was, desired in the study. The third indicator represented the average time needed to interpret driving task related information on road. The last indicator was the standard deviation of horizontal visual search angles, which characterizes the visual search breadth from the average fixation position. In general, the larger this number, the wider the variation of the driver's visual search breadth.

Saccades are rapid, simultaneous movement of the eyes between two or more points of fixation in the same direction. Here, three indicators were considered; namely, average number of saccade (times/s), average saccade speed (°/s), and average saccade amplitude (°). The first indicator exhibits the average number of targets to which attention had to be paid by drivers while they were driving. The second is the average ratio of each saccade angle to its duration. This characterizes the speed of interpretation of information associated with significant level of fatigue while they were driving. The third represents the total period of a glance, which increases with the rise of cognitive workload and task complexity.

In addition, three indicators of blinks, including blink frequency (times/s), blink duration (s), and closure duration (s), were collected in the naturalistic driving test to characterize the average amount of blinks per minute, average duration of each blink, and average duration of each single eye closure, respectively. The Stanford Sleepiness Scale (SSS) was used to quantify the driver's subjective judgment of fatigue during driving (15), which was divided into seven refined categories (see Table 1), and scored on each item range from 1 to 7.

Table 1: **The Standford Sleepiness Scale (SSS)**

Level of sleepiness/ fatigue	Scale Rating
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7

Apparatus: In the naturalistic driving test, Smart Eye Pro 6.0 was used to capture driver's eye movement with four cameras mounted in front of windscreen to record each participant's fixation, saccade and blinking at a frequency of 200 HZ. All recorded data could be exported to either a *text* file or a picture (.png, .jpg) for offline analysis. During data processing, each subjective and objective record was analyzed at a 5% significance level using one-way Analysis of Variance (ANOVA).

Test procedure and design: Naturalistic driving test was carried out on three routes (*a*, *b* and *c*, see Figure 1) in Shandong, China. As shown in Figure 1 below, the participants were divided into 9 groups. Each group had 4 participants (I–IV).

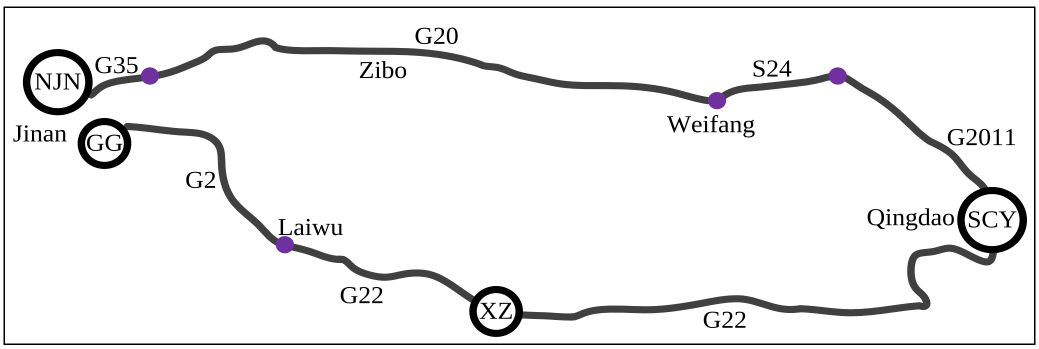

Figure 1: **Route of naturalistic driving test**. **Route a**: 156.6km from Ganggou Interchange (GG) to Xinzhuang Interchange via G2 and G22, 2h driving; ***Route b***: 216.2km from Xizhuang Interchange (XZ) to South Chengyang Interchange via G22, 3h driving; ***Route c***: 333.5km from South Chengyang Interchange (SCY) to North Jinan Interchange (NJN) via G2011, S24, G20 and G35, 4h driving

The tests were conducted in the middle of March 2015. Each of the participants in a group was informed of the purpose, methods, procedures, benefits, and use of eye-tracker and the SSS table prior to taking the test. Each driver's original eye movement variables and personal awareness of fatigue level were collected as baseline data. The driving test started following the calibration of equipments. Participant 1 departed from Jinan at 7:30 p.m. along route *a* and arrived at Yishui after 2h driving, where his/her visual behaviors and subjective level of fatigue were recorded prior to any rest. At 10:00 pm, participant 2 took route *b* and drove to Qingdao. As he/she arrived at South Chengyang Interchange, the driver was asked to finish the visual behavior and subjective level of fatigue test. After some rest, participant 3 drove to Jinan at 3:30 a.m. along route *c*, and ended the 4h continuous driving test after recording the eye movement variables and self awareness of fatigue level. In this round of test, participant 4 helped record the data.

On the three consecutive days following the beginning day of the driving test, participants in each group completed another two driving tasks or helped record the test data. Each group completed four rounds of naturalistic driving test. The driving test ended when all members of each group reported finishing the 2- to 4-h-long driving tasks along their respective routes.

Results

Fixations: As displayed in Table 2, for the drivers aged below 30 years, not all the four fixation indicators showed a significant change after 2h continuous driving compared to the baseline value. After finishing the 3h driving task, drivers' average on-road fixation duration value (F = 13.603, p = 0.003) had significantly increased (26.08%), while the other three fixation indicators did not show any significant change. As shown in Table 2 below, after 4h continuous driving, besides the average on-road fixation duration value (F = 30.523, p < 0.001), the average number of fixations (F = 14.872, p = 0.002) and the average deviation of search angle (F = 25.293, p < 0.001) had an obvious change.

It should be noted that the indicator's change rate of certain driving period represents the amount of increase or decrease of this indicator compared to its value before the driving task.

Similar effects were also found in the '30-40' group (see Table 3). No significant change was found in the four fixation indicators after 2h driving, and only drivers' average on-road fixation duration value ($F = 48.037$, $p < 0.001$) showed obvious change in the three-hour driving test. After the drivers had a four-hour driving test, besides the average on-road fixation duration value ($F = 108.194$, $p < 0.001$), two other indicators changed obviously: average number of fixations on-road ($F = 33.241$, $p < 0.001$), and average deviation of search angle ($F = 66.514$, $p < 0.001$). Not much variation was, however, observed in the drivers' average pupil diameter.

Table 2: **Variance analysis of visual indicators and subjective level of fatigue** (less than 30 years drivers)

Driving duration	Baseline		2h					3h					4h				
	Mean	Std	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*
Fixation																	
Pupil diameter	3.22	0.16	3.33	0.16	1.654	0.223	+3.42	3.48	0.11	12.797	0.004	+8.17	3.56	0.12	19.887	<0.001	+10.48
Number of fixations on-road	5.01	0.80	4.76	0.76	0.353	0.563	-4.96	4.30	0.51	3.910	0.071	-14.16	3.52	0.64	14.872	0.002	-29.78
On-road fixation duration	0.53	0.07	0.58	0.06	2.152	0.168	+9.68	0.67	0.07	13.603	0.003	+26.08	0.75	0.08	30.523	<0.001	+40.59
Deviation of search angles	6.74	0.47	6.33	0.42	3.435	0.089	-6.22	5.83	0.52	13.083	0.004	-13.64	5.36	0.59	25.293	<0.001	-20.54
Saccade																	
Number of saccades	3.68	0.25	3.52	0.29	1.158	0.303	-4.20	3.34	0.25	6.475	0.026	-9.21	3.17	0.26	13.973	0.003	-13.64
Saccade speed	130.91	7.70	120.50	10.60	4.417	0.057	-7.95	109.41	10.20	19.798	<0.001	-16.42	100.26	10.96	36.622	<0.001	-23.41
Saccade amplitude	2.87	0.23	2.75	0.22	0.926	0.355	-4.04	2.61	0.19	4.941	0.046	-8.77	2.50	0.19	10.208	0.008	-12.66
Blink																	
Blink frequency	4.85	0.08	4.91	0.08	2.081	0.175	+1.30	5.26	0.20	25.568	<0.001	+8.58	5.82	0.45	32.311	<0.001	+20.13
Blink duration	0.17	0.01	0.19	0.02	5.205	0.042	+10.00	0.27	0.04	42.293	<0.001	+56.67	0.43	0.03	461.423	<0.001	+150.83
Closure duration	0.87	0.11	1.06	0.10	11.762	0.005	+21.55	1.42	0.21	37.377	<0.001	+63.49	2.25	0.32	119.577	<0.001	+159.05
Subjective level of fatigue																	
SSS value	2.14	0.69	2.83	0.41	3.636	0.086	+32.21	3.83	0.41	22.727	<0.001	+78.88	4.17	0.41	32.727	<0.001	+94.43

Table 3: **Variance analysis of visual indicators and subjective level of fatigue** (30–40 years drivers)

Driving duration	Baseline		2h					3h					4h				
	Mean	Std	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*
Fixation																	
Pupil diameter	3.25	0.09	3.40	0.12	13.948	<0.001	+4.53	3.60	0.19	41.280	<0.001	+10.86	3.68	0.17	69.121	<0.001	+13.33
Number of fixations on-road	4.56	0.76	4.30	0.72	0.822	0.373	-5.57	3.71	0.50	12.120	0.002	-18.48	3.09	0.57	33.241	<0.001	-32.12
On-road fixation duration	0.55	0.06	0.62	0.05	15.083	<0.001	+13.84	0.71	0.07	48.037	<0.001	+30.03	0.80	0.07	108.194	<0.001	+47.00
Deviation of search angles	6.56	0.40	6.05	0.47	9.584	0.005	-7.73	5.61	0.46	33.736	<0.001	-14.39	5.12	0.53	66.514	<0.001	-21.94
Saccade																	
Number of saccades	3.64	0.16	3.46	0.16	8.327	0.008	-4.75	3.21	0.21	36.217	<0.001	-11.65	3.06	0.25	51.569	<0.001	-15.79
Saccade speed	134.27	6.67	117.73	11.49	21.686	<0.001	-12.32	107.83	9.52	72.440	<0.001	-19.69	96.59	11.48	112.748	<0.001	-28.06
Saccade amplitude	2.91	0.18	2.73	0.15	8.154	0.008	-6.17	2.50	0.20	31.448	<0.001	-13.89	2.30	0.17	85.693	<0.001	-20.99
Blink																	
Blink frequency	4.74	0.14	4.85	0.13	4.104	0.053	+2.17	5.28	0.24	55.851	<0.001	+11.43	5.79	0.24	202.860	<0.001	+22.05
Blink duration	0.16	0.02	0.18	0.02	7.591	0.011	+15.21	0.34	0.07	81.591	<0.001	+117.97	0.44	0.07	196.671	<0.001	+184.79
Closure duration	0.78	0.09	1.00	0.10	41.542	<0.001	+29.37	1.56	0.37	59.356	<0.001	+106.08	2.40	0.53	129.204	<0.001	+209.12
Subjective level of fatigue																	
SSS value	1.79	0.70	2.46	0.52	6.621	0.017	+37.83	3.38	0.51	42.105	<0.001	+89.51	4.00	0.41	94.080	<0.001	+123.96

Table 4: **Variance analysis of visual indicators and subjective level of fatigue** (40–50 years drivers)

Driving duration	Baseline		2h					3h					4h				
	Mean	Std	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*
Fixation																	
Pupil diameter	3.30	0.13	3.47	0.15	8.385	0.010	+5.40	3.64	0.14	33.378	<0.001	+10.50	3.77	0.15	56.762	<0.001	+14.38
Number of fixations on-road	5.00	0.53	4.61	0.39	3.411	0.081	-7.71	3.94	0.44	23.464	<0.001	-21.08	3.16	0.31	88.693	<0.001	-36.67
On-road fixation duration	0.48	0.04	0.56	0.06	10.430	0.005	+16.15	0.66	0.08	38.620	<0.001	+36.65	0.77	0.12	48.581	<0.001	+58.80
Deviation of search angles	6.48	0.34	5.87	0.35	15.900	<0.001	-9.53	5.57	0.36	34.317	<0.001	-14.08	4.74	0.42	105.832	<0.001	-26.94
Saccade																	
Number of saccades	3.61	0.19	3.43	0.22	4.175	0.056	-5.23	3.15	0.20	28.264	<0.001	-12.92	2.93	0.30	37.084	<0.001	-18.90
Saccade speed	134.01	8.70	114.87	12.32	16.110	<0.001	-14.29	102.12	9.41	61.882	<0.001	-23.80	89.09	12.54	86.632	<0.001	-33.52
Saccade amplitude	2.89	0.13	2.65	0.13	16.263	<0.001	-8.38	2.47	0.18	35.646	<0.001	-14.54	2.19	0.25	59.720	<0.001	-24.06
Blink																	
Blink frequency	4.82	0.16	4.94	0.17	2.491	0.132	+2.41	5.42	0.22	48.278	<0.001	+12.34	6.00	0.27	138.180	<0.001	+24.45
Blink duration	0.18	0.02	0.22	0.02	13.902	0.002	+17.94	0.44	0.11	56.692	<0.001	+139.13	0.55	0.10	141.816	<0.001	+201.09
Closure duration	0.82	0.09	1.09	0.15	21.901	<0.001	+31.80	1.97	0.34	106.079	<0.001	+138.59	3.01	0.56	149.960	<0.001	+264.93
Subjective level of fatigue																	
SSS value	1.70	0.48	2.56	0.53	13.474	0.002	+50.33	3.56	0.53	60.842	<0.001	+109.15	4.22	0.44	132.250	<0.001	+148.37

Table 5: **Variance analysis of visual indicators and subjective level of fatigue** (more than 50 years drivers)

Driving duration	Baseline		2h					3h					4h				
	Mean	Std	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*	Mean	Std	*F*	*p*	*RC/%*
Fixation																	
Pupil diameter	3.31	0.13	3.51	0.15	5.533	0.047	+6.23	3.71	0.16	19.285	0.002	+12.16	3.88	0.20	27.812	<0.001	+17.24
Number of fixations on-road	4.00	0.41	3.65	0.42	1.803	0.216	-8.80	2.99	0.26	21.753	0.002	-25.31	2.20	0.30	63.321	<0.001	-44.97
On-road fixation duration	0.50	0.04	0.62	0.04	20.306	0.002	+22.62	0.73	0.04	72.264	<0.001	+44.05	0.88	0.05	161.388	<0.001	+74.60
Deviation of search angles	6.15	0.36	5.46	0.31	10.603	0.012	-11.21	4.94	0.27	37.022	<0.001	-19.76	4.20	0.33	81.140	<0.001	-31.75
Saccade																	
Number of saccades	3.52	0.09	3.33	0.09	12.071	0.008	-5.51	3.06	0.05	103.111	<0.001	-13.17	2.88	0.13	85.694	<0.001	-18.12
Saccade speed	132.08	7.19	108.88	6.55	28.426	<0.001	-17.57	95.63	6.90	66.897	<0.001	-27.60	79.64	10.93	80.319	<0.001	-39.70
Saccade amplitude	2.74	0.13	2.46	0.12	12.154	0.008	-10.43	2.26	0.11	37.415	<0.001	-17.51	1.88	0.24	50.388	<0.001	-31.36
Blink																	
Blink frequency	5.02	0.17	5.22	0.17	3.452	0.100	+3.98	5.76	0.19	42.758	<0.001	+14.62	6.44	0.40	52.643	<0.001	+28.16
Blink duration	0.19	0.02	0.24	0.03	6.080	0.039	+23.96	0.53	0.08	78.509	<0.001	+175.00	0.65	0.05	304.920	<0.001	+240.63
Closure duration	0.95	0.05	1.29	0.06	87.341	<0.001	+34.80	2.90	0.22	387.931	<0.001	+204.40	4.10	0.36	379.740	<0.001	+329.56
Subjective level of fatigue																	
SSS value	2.00	0.00	3.25	0.50	25.000	0.003	+62.50	4.50	0.58	75.000	<0.001	+125.00	5.75	0.96	61.364	<0.001	+187.50

For the '40-50' group, not all value indicators changed significantly in the 2h driving test, compared to their baseline values taken before the driving test. It should be noted that the average on-road fixation duration value (F = 20.306, p = 0.002) increased significantly among the drivers aged above 50 years. Considering the 3h test of these two groups, the average on-road fixation duration value ('40-50': F = 38.620, p < 0.001; '>50': F = 72.264, p < 0.001) and average number of fixations on-road ('40-50': F = 23.464, p < 0.001; '>50': F = 21.751, p = 0.002) had varied greatly compared to the baseline data taken before the driving test. In addition to the changes seen in the two indicators of average on-road fixation duration value ('40-50': F = 48.581, p < 0.001; '>50': F = 161.388, p < 0.001) and the number of fixations on-road ('40-50': F = 88.693, p < 0.001; '>50': F = 63.321, p = 0.002), the average deviation of search angle ('40-50': F = 105.832, p < 0.001; '>50': F = 81.140, p < 0.001) also decreased by 26.94% and 31.75%, respectively, after the 4h driving task.

Saccades: For the '< 30' group, not all the three saccade indicators decreased significantly after 2- and 3-h-long driving, as shown in Table 2. However, after four hours of continuous driving, the average saccade speed value decreased greatly (F = 36.622, p < 0.001) by 23.41% although the other two indicators showed no significant decrease. Similar results were also found among the '30-40' group (See Table 3). No significant decrease was found in the three indicators after finishing the 2- and 3-h-long driving tasks. In fact, it should be noted that the average saccade speed value (F = 112.748, p < 0.001) and the average saccade amplitude (F = 85.693, p < 0.001) hindered a significant decrease after the 4h driving. Considering the '40-50' years old group, the average saccade speed value (F = 61.882, p < 0.001) had an obvious decrease (i.e., 23.80%) after 3h driving. Besides this indicator (F = 86.632, p < 0.001), the average saccade amplitude value (F = 59.720, p < 0.001) also decreased greatly after the 4h driving (see Table 4).
As can be understood from Table 5, no saccade indicator showed a significant decrease in the case of the 2h driving of '>50' group, but the average saccade speed value dropped largely. This accounts for 27.60% and 39.70%, respectively. This change happened after 3h (F = 66.897, p < 0.001) and 4h long (F = 80.319, p < 0.001) driving. The average saccade amplitude value also showed an obvious decrease (F = 50.388, p = 0.004) after the 4h driving. The average number of saccades did not show a significant decrease even after the 3h continuous driving.

Blinks: In the 2h driving test, the average eyes' closure duration value of four groups increased significantly (i.e., as much as one-fifth to one-third), compared to the baseline values (See Tables 2–5). Its average value for '< 30' group (F = 11.762, p = 0.005) increased by 21.55%, and expanded to 34.80% for '>50' group (F = 87.341, p < 0.001). The average blink duration value showed obvious increase of 23.96% in the '>50' group (F = 6.080, p = 0.039), but no significant changes were observed among other groups. On the other hand, the value of average blink frequency did not show any significant increase even after 3h driving.

After 3h continuous driving, both eyes' average closure duration value and average blink duration value changed greatly. The indicators for the > 50' group increased by 204.40% (F = 387.931, p < 0.001) and 175.00% (F = 78.509, p < 0.001), respectively. On the other hand, the indicators for the 40-50 years of age group were reported to have increased by 138.59% (F = 106.079, p < 0.001) and 139.13% (F = 56.692, p < 0.001). The other group - '30-40' group – showed an increase of 106.08% (F = 59.356, p < 0.001) and 117.97% (F = 81.591, p < 0.001). The '<30' group, on its part, showed an increase of 63.49% (F = 37.377, p < 0.001) and 56.67% (F = 42.293, p < 0.001). (See Tables 2–5 for the summary data).

In the 4h driving test, the increase in both average closure duration value and average blink duration value extended to more than 150 percent, and specially, the indicators for '>50' group increased by 329.56% (F = 379.74, p < 0.001) and 240.63% (F = 304.92, p < 0.001), respectively. In addition, the average blink frequency value also represented a little increase that ranged between 20.13% for '<30' group (F = 32.311, p < 0.001) and 28.16% for '>50' group (F = 52.643, p < 0.001).

Subjective level of driving fatigue: For the '< 30' group, the average subjective level of driving fatigue was scored as 2.83 (F = 3.636, p = 0.086) after 2h continuous driving. This showed a significant increase, i.e., 32.21%, which was extended by 78.88% and 94.43% to 3.83 (F = 22.727, p < 0.001) and 4.17 (F = 32.727, p < 0.001), respectively, after finishing 3- and 4h-long driving tasks (See Table 2). These changes indicate that the drivers felt just a little fatigue. This, apparently, did not considerably affect their driving performances.
Similar findings were also observed among the '30-40', '40-50' and '>50' groups, but the change rate in the corresponding SSS values increased substantially. For the '>50' group, for example, the average value increased from 3.25 (F = 25.000, p = 0.003) for 2h driving to 5.75 (F = 61.364, p < 0.001) for 4h driving. This accounted for 62.50% and 187.50% increase respectively from the baseline values (See Table 5).

Correlation of variation in visual behavior and subjective fatigue level: Figure 2 presents the Pearson Product-moment correlation coefficient (Pearson correlation coefficient) between change of driver's visual indicator and the SSS value. This indicates that the change of driver's own awareness of fatigue (in term of SSS value) is significantly associated with the increase / decrease of their visual indicators.

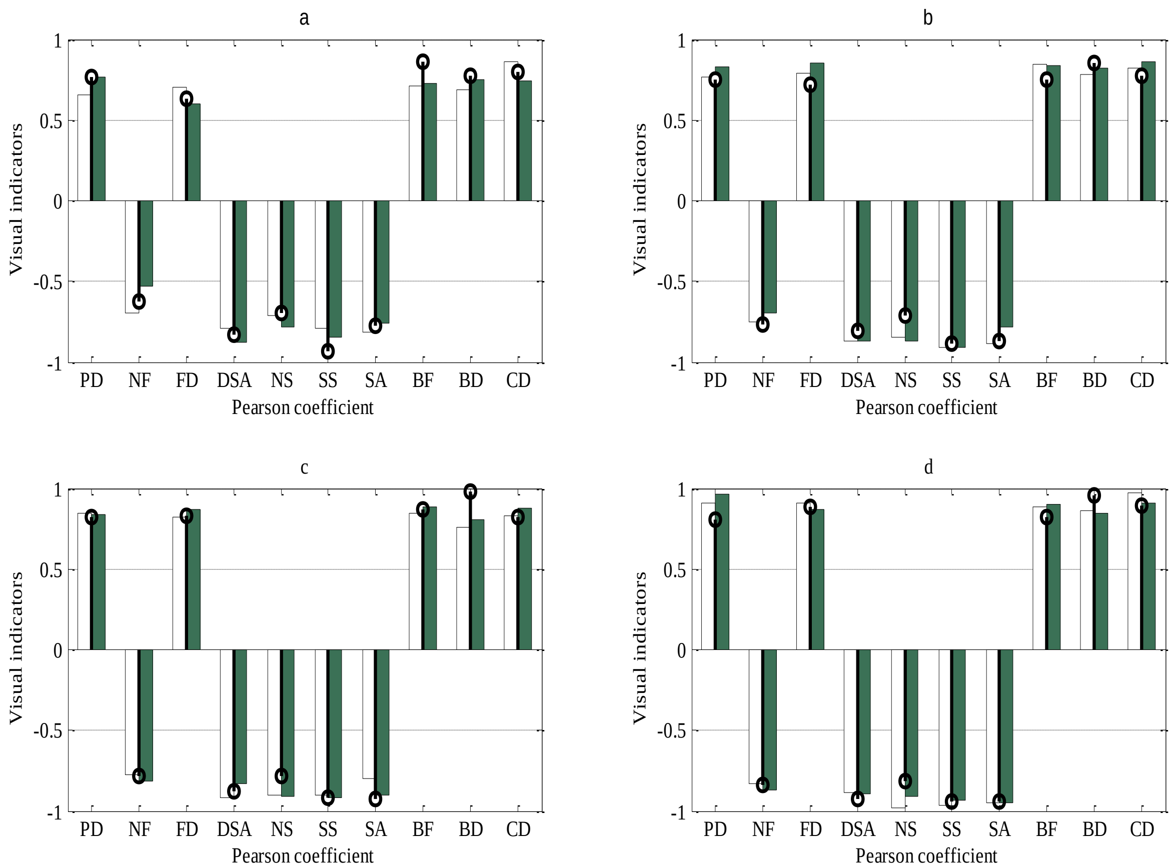

Figure 2: **Pearson coefficient between variation of driver's visual indicators and subjective fatigue level. a. '<30' group; b. '30–40' group; c. '40–50' group; d. '>50' group**

The test results revealed that the average pupil diameter, average on-road fixation duration value, average blink frequency value (BF), average blink duration value (BD), and average closure duration value (CD) negatively correlated with the subjective level of fatigue. On the other hand, the average number of fixations on-road (NF), average deviation of search angle (DSA), average number of saccade (NS) and average saccade amplitude (SA) had a positive correlation with the drivers' self-awareness of fatigue level. Only two visual indicators (i.e., average pupil diameter and average number of saccades), did not show significant change of 20% or more, compared to the baseline value before the driving task, and even after 4h continuous driving. Moreover, drivers' average eye closure duration value, average blink duration value, and average on-road fixation duration value fell in the first three indicators with a greater rate of change.

The stronger the correlation between the changes of driver's visual indicator and SSS value, the closer Pearson correlation *r* will be to either +1 or -1, depending on whether the relationship is positive or negative. (16). Obviously, *r* here varied with driver's age and hours of driving. As presented in Figure 2, *r* fluctuated between two intervals: 0.604 to 0.969, and -0.983 to -0.532. This indicates an obvious positive or negative correlation between the SSS variation and change of driver's visual indicator. In addition, the Pearson correlation became more positive or negative for old drivers engaged in longer driving duration. For the young drivers aged 30 years or below, after 2h driving, the indicator change of eye closure duration had a positive *r*, 0.865, associated with their perception variation of driving fatigue (in term of SSS value). For the drivers aged above 50 years, however, the value *r* increased to 0.969 after their finishing of the same driving task. All these findings showed that the elderly are more easily to fall into fatigue while they are driving.

The level of driving fatigue was found to be more sensitive to the speed of eye's saccadic movement. For the four groups of drivers, for example, the indicator change of saccade speed had a negative *r*, ranging from -0.962 to -0.791, associated with their perception variation of driving fatigue (in term of SSS value), and the average *r* is -0.904. This is a rather strong negative correlation. This means that a decrease in the variation of saccade speed leads to an increase in the subjective level of fatigue. In addition, the number of fixations has the biggest statistical *r* value (-0.873– -0.532), close to 0, and the average value is -0.748. This indicates that the change of this indicator is less negatively and significantly associated with the variation of driver's own awareness of driving fatigue level.

Discussions

As noted in many earlier studies (17, 18), driving fatigue is one of the major potential factors that contribute to fatalities and injuries in road traffic. This makes identifying and monitoring drivers' fatigue important. Once drivers' fatigue is identified and monitored, minimizing vehicle-caused fatalities and injuries could, to a considerable extent, be achieved. In this study, an attempt has been made to investigate the association between the variation of drivers' fixations, saccades, blinks and their subjective level of fatigue while they are performing continuous driving tasks. In other words, the study can be taken as a part of the endeavor needed to be made to detect driver's fatigue level.

The test results showed that the change of SSS value is positively associated with the variation of pupil diameter, fixation duration, blink frequency, blink duration, and closure duration, and negatively related to number of fixations, search angle, number of saccade, saccade speed, and saccade amplitude.

The duration of continuous driving has obvious effects on drivers' variation of individual visual indicator and individual awareness of fatigue. For drivers aged below 30 years, the test results showed that the change rate of average on-road fixation duration increased from +9.68% after two-hour driving to +26.08% after three-hour driving and +40.59% after four-hour driving. The driver's average fatigue level increased from +32.21% to +78.88% and +94.43%, respectively. Thus, it can be stated that a driver's own awareness of his or her fatigue level increases significantly with the extension of continuous driving duration. Hjälmdahl *et al*. (2017) also reported similar findings (19).

The change rate of visual indicators and self-awareness fatigue level varied greatly across drivers aged differently even after the same driving task. Undoubtedly, elderly drivers had poor physical abilities, impaired vision or hearing, divided attention and slow reaction time. Thus, they can get fatigued more quickly in their driving performance than the drivers in the rest of the age groups. Findings of this research showed that the average fatigue level of drivers aged below 30 years rose by about 32.7%, but for drivers aged above 50 years, the increase rate was nearly double the rate for the level of drivers aged below 30 years.

The results of this study revealed the feasibility of measuring driver's fatigue level using visual indicators. This means that fatigue monitoring and warning system (as a potential vehicle-equipped device) can be used to alert drivers of fatigue risk and rest moment (20, 21). The findings of the study tend to suggest the need for strict traffic laws and regulations that govern continuous driving time and drivers' behavior. This carries with itself the need to limit the total number of driving hours per day, especially for long-distance vehicle drivers such as bus or trucks drivers. Mechanisms to ensure drivers' compliance with the rules of continuous driving duration should also be put in place. Evidence in the present study reveals that continuous driving time that generally does not exceed 3 or 4 hours tends to prevent fatigue risk. In addition, drivers should learn to keep themselves aware of symptoms of fatigue driving. Evidence in the present finding suggests that older drivers need to rest longer than their younger counterparts.

This study has some methodological limitations. Firstly, the participants were selected randomly and may not be a representative sample of all the Chinese drivers. They were not selected on the basis of the population percentage of drivers with different socio-demographic features (e.g., gender, age, conditions of driving license). This makes the findings of the study not to be applied to the entire population of drivers in China. Secondly, visual indicators are significantly sensitive to individuals' physiological and psychological conditions, which can be dramatically affected by ambient stimulus. The collected and used visual data may therefore contain inaccuracies due to temporary environmental effects.

Future studies might need to have a method of filtering, identifying and removing noises from the original data. Thirdly, individual's fatigue level acquired through self-reporting may not be reliable due to fault in memory and incorrect judgment. Finally, each participant did not repeat the driving test on each route. To a limited extent, this may affect the reliability and validity of the data used in the study.

Studies that can systematically capture valid driver's eye movement data in a more reliable and conclusive way are recommended. The use of accurate testing techniques (e.g., simulated driving test), among others, can be mentioned as an example. It is also important to consider using a larger sample to ensure the reliability and validity of data to be used in a future similar research. It may also be important to link eye movement metrics to actual driving behaviors such as lane change, acceleration and deceleration, and vehicle following in future studies. This helps to examine how fatigue affects driving behaviors and performance quantitatively over a period of time and how personality conjointly influences this relationship (23). Countermeasures for drivers of different ages should be established. Commercial truck drivers should be the primary focus of such measures to prevent fatigue driving. It is also necessary to combine truck drivers' visual behaviors and driving performances into detecting crash proneness. Evidence obtained from this may help in designing special safety programs which may include education and regulation systems (24).

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Ethics approval and consent to participate

This research was conducted in compliance with the needed research ethics. In addition, consent for participation was obtained from the participants before the beginning of their involvement in the study. All data were recorded and analyzed anonymously.

Competing interests

The authors declared having no competing interests.

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