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Physiological and Behavioral Changes of Passive Fatigue on Drivers during On-Road Driving

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Abstract: Driver fatigue can be further categorized into passive fatigue and active fatigue based on the task-induced fatigue perspective, with its categorization necessary from a theoretical basis and practical needs. Passive fatigue is caused by mental underload and inactive task engagement, which is considered more hazardous. To facilitate the construction of the driver monitoring system (DMS), the current study aims to investigate the physiological and behavioral changes of passive fatigue. A total of thirty-six participants completed a 90 min driving task on a monotonous highway, during which subjective fatigue level, eye tracking indicators, and driving dynamics were recorded using the Stanford Sleepiness Scale, Smart Eye Pro, and CAN Bus system. Results showed that drivers reported higher levels of fatigue as driving duration increased. An increase in pupil diameters and gaze dispersions were observed during the task. Drivers gradually reduced the control of the vehicle, in which faster speed and lower speed compliance were witnessed. In addition, a compensatory process was found as passive fatigue increased. Drivers tended to lower their standards to maintain the lateral position but recovered their lateral control when they lost control of the car speed. The current study emphasizes the importance of investigating active and passive fatigue of drivers independently, and the unique physiological and behavioral changes accompanied by passive fatigue should be considered in designing driver monitoring systems.

Keywords: on-road study; driver fatigue; passive fatigue; eye tracking; gaze dispersion; driving dynamic

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1. Introduction

A recent report released in 2021 by the World Health Organization (WHO) showed that about 1.3 million deaths were caused by traffic accidents every year. Traffic injuries have become the major reason for the death of people early in their childhood or adulthood with ages ranging from 5 to 29 years. The cost of traffic accidents takes up 3% of the gross domestic product in most countries [1]. Driver fatigue was estimated to contribute to as much as 22% of all injury-related accidents [2], making fatigue one of the primary causes of traffic accidents.

1.1. Types of Task-Induced Fatigue

The definition of fatigue varies in different disciplines and is usually applied based on a specific task or activity. In transportation research, fatigue-related concepts are consistently embedded with ambiguities, which are deemed to be a barrier to understanding the complex mechanisms of fatigue, hindering the accuracy and specificity of detection systems and mitigation strategies. It is therefore suggested that driver fatigue research should be conducted under a more articulated conceptual framework [3].

The present study adopted a task-induced fatigue perspective [4], from which driver fatigue is suggested to divide into two types: active fatigue versus passive fatigue, based on the characteristics of the tasks that operators engage in. Active fatigue is often caused by continuous tasks which impose a high cognitive workload and require frequent responses to respective circumstances, whereas passive fatigue is induced by prolonged tasks in which operators act as a supervisor of the system with little effort exerted [4]. The former was accompanied by mental overload and distress due to the engagement in intensive tasks, while the latter corresponded to mental underload and inactive task engagement [5].

In the driving scenarios, factors such as dense traffic, poor visibility, and multi-tasking might lead to active fatigue, while passive fatigue might be related to monotonous highways, automated systems, and extended driving duration [6]. Yet, it is more valuable to explore passive fatigue of drivers in modern driving-related research. Firstly, compared with active fatigue, passive fatigue usually causes sleepiness due to its monotonous nature, which is believed to be more hazardous than the depletion of attentional resource without sleepy symptoms [3]. Secondly, with the continuous development of vehicle automation, passive fatigue may occur more frequently in future driving experiences. For instance, the impending conditional automation driving (SAE Level 3) vehicles will be equipped with systems that undertake the primary role during the driving task, where drivers will only be required to provide assistance when take-over requests are raised [7]. In general, with the development of autonomous vehicles, the advanced systems will greatly reduce drivers' workload and potentially relieve the experience of active fatigue; however, it will also create a more monotonous situation, leading to an increase in passive fatigue [8]. As the above, the present study focused on assessing passive fatigue of drivers.

1.2. The Assessment of Driver Fatigue

The assessment of driver fatigue can be categorized into four classes of measurements: subjective, cognitive, physiological, and behavioral. The subjective class usually involves self-rating questionnaires, for example, the Stanford Sleepiness Scale (SSS) [9]. The cognitive measurements include attention tests such as the psychomotor vigilance tasks for identifying whether drivers are undergoing a fatigue status [10].

Regarding the physiological measurements, the eye tracking method is recommended over the others (brain activity signals, heart rate, etc.). The connections between eye movement behaviors and driver fatigue have been well established, including metrics such as the classic PERCLOS index (percentage of eyelid closure over the pupil over time), pupil (e.g., pupil diameter), blinks (e.g., blink duration and blink count), and saccade (e.g., mean velocity of saccade and saccade amplitude) [11]. It is believed that although other neurophysiological methods are reliable, they are still far from daily application; in contrast, the eye tracking equipment has provided a relatively easy and convenient setup with no skin contact for measuring physiological signals [3].

Behaviorally, one of the most widely adopted indicators is vehicle-based behavior. Prior studies have revealed that the manipulation activity of the steering wheel, driving speed compliance, together with the standard deviation of the lateral lane position (SDLP) are highly related to driver fatigue [12]. However, as summarized in Table 1, the associations between fatigue and its physiological and behavioral indicators may demonstrate different tendencies when comparing passive fatigue and active fatigue, which further implies that the assessment of these two types of fatigue should be studied separately.

1.3. Passive Fatigue and Attention Allocation

Physiological and behavioral changes accompanied by passive fatigue are highly related to the allocation of attention [13]. As the capacity model of attention implies, attention allocation is determined by individual's current arousal level, evaluation of demands on capacity, enduring dispositions, as well as momentary intentions when engaging in a specific task [13]. When experiencing passive fatigue, reduced arousal level and low task requirements would decrease individuals' intention to exert effort on the current task, which further leads to a reduction in attention allocation and task performance standards [12] (see Figure 1).

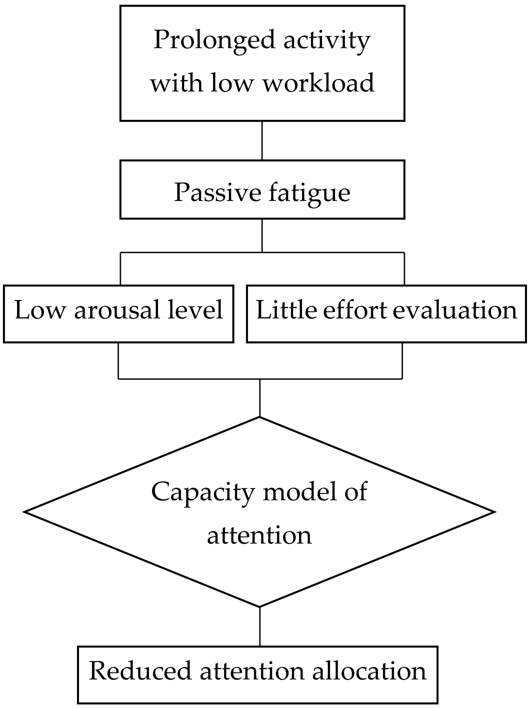


Figure 1. Attention allocation under passive fatigue.

This phenomenon also happens in driving scenarios. When undergoing less-demanding tasks, drivers are likely to experience passive fatigue, where low arousal levels are observed. Additionally, they are likely to be distracted by internal thoughts [14]. According to the capacity model of attention, as a result of the evaluation of demands on capacity, drivers tend to lower their standards and become less motivated, thus leading to impaired driving performance.

Table 1. Comparisons of physiological and behavioral indicators for active fatigue versus passive fatigue.

Indicators	Comparisons between Active Fatigue versus Passive Fatigue
Pupil diameter [15]	Decreased significantly in both conditions of active fatigue and 1 h passive fatigue driving, while no statistically significant change was reported after 90-min passive fatigue driving.
Blink duration [15]	Only increased in active fatigue driving.
Mean velocity of saccade [15]	Only increased in active fatigue driving.
Saccade duration [15]	Increased in active fatigue driving and 1.5-h passive fatigue driving.
Standard deviation of lane position (SDLP) [16]	Lower SDLP in passive fatigue driving.
Response time (RT) [16]	Slower braking and steering RTs in the passive driving.
Collision [16]	More collisions in the passive fatigue driving.

1.4. Research Questions

In summary, considering the different manifestations of driving under states of active fatigue versus passive fatigue, the more hazardous nature of the passive fatigue, and the expected more frequent passive fatigue in the coming autonomous vehicle age, the necessity and urgency to investigate passive fatigue is confirmed after the above literature review of practical needs and theoretical categorization of active versus passive fatigue.

More specifically, the current study aims to address three important research questions: First, what are the changes of eye movement and driving performance during passive fatigue of drivers, especially in a real-world scenario? Second, does there exist any compensatory behavioral strategies to mitigate the risks of passive fatigue? Third, what are the representative indicators for the early versus late stage of fatigue? Answers to this question can inform the parameter selections for the development of a Driver Monitor System (DMS).

To address the above-mentioned research questions, techniques of eye tracking and CAN-bus (measuring driving performance) are implemented. Eye tracking and driving performance have been proven to be highly correlated with fatigue [12] and are more feasible to apply in the real world with no direct body contact with drivers. Real-world driving is emphasized in the current study as previous passive fatigue studies were mostly conducted in driving simulators with highway or autonomous driving settings [16]. Extensive literature search in major databases, including ProQuest, Web of Sciences, etc., only generated a couple of papers on passive fatigue in a real-world scenario. There is only one recent initial attempt to study passive fatigue of drivers in a real-world scenario, signifying the necessity of real-world examination of driving performance. However, it emphasizes use of a motion seat [17], not a full scope examination of the core driving behaviors, that is, eye movement and vehicle manipulations. Personal communications with major recent authors (including Fellow and Dr. Hancock [4] and Dr. Jinfei Ma [18]) on this topic in the United States and China confirmed the lack of studies on passive fatigue in a real-world scenario. However, they confirmed and agreed the necessity to execute such research, although they reminded us the potential technical difficulty and financial costs. Therefore, to maximize the external validity, the current study was carried out in a real highway environment [6].

2. Methods

2.1. Participants

The expected sample size for participants was estimated using the power analysis with the field-standard software of G-power (Version 3.1.9.6) [19]. Thirty-six participants were finally recruited to achieve sufficient power (≥90%). All participants had highway driving experiences, normal or corrected-to-normal vision, and a valid driving license for a minimum of five years. Four participants were not included in the final data analysis due to technical issues and voluntary early termination of participation, resulting in a valid sample size of 32 participants (ensures an 85% power; 26 males, 6 females, mean age = 38.09 ± 7.90 years old). The mean year of driving experience of the sample is 12.44 years, and none of them has experienced a traffic accident within one year. Participants were also strongly required to sleep for a minimum of seven hours in the night prior to participation in the experiment, abstained from coffee or tea within 24 h, and prohibited from nicotine intake 2 h prior to the experiment.

2.2. Materials and Apparatus

To estimate drivers' subjective level of fatigue, the widely used one-item Stanford Sleepiness Scale (SSS) was applied [20]. SSS is a Likert scale with seven points that measures individuals' arousal and drowsiness level, and has been proven valid among Chinese participants [21]. Each point of the scale has a specific description that is used as the reference and definition of the subjective level of fatigue. For example, point 1 means feeling awake and energetic; point 7 means unable to remain awake and can fall asleep soon. This indicates that the higher the SSS score, the higher the level of driver sleepiness. See Appendix A for a complete detailed description of the Stanford Sleepiness Scale (SSS). Rating a score greater than 3 (including 3) represents that the driver is under fatigue status [22]. The mean and standard deviation of the Subjective fatigue level measured using SSS scores at the three stages were 2.34 ± 0.87, 3.06 ± 0.95, and 3.53 ± 0.84, respectively.

This proves that the operation chosen to measure fatigue status for 90 min in this study is valid.

A Baojun RC-6 equipped with the CAN Bus system, a Smart Eye Pro, and a laptop were used in the experiment. The CAN Bus system retrieved vehicle dynamics, and the Smart Eye Pro was fixed above the dashboard to collect eye tracking data. The Dell Precision 3630 laptop was placed at the back seat of the car to monitor the data collection in real-time (see Figure 2). The Smart Eye Pro is a fixed-based remote eye-tracking device, with one infrared sensor on the right side of the camera that enables researchers to accurately track participants' eye and head movements.

Figure 2. Experimental setup.

2.3. Experiment Design

This experiment adopted a one-way repeated measures design, with time serving as the independent variable. Previous studies indicated that drivers became fatigued or reduced task engagement levels after about 30 min of driving [23], and a 90-min driving experiment could induce driver fatigue [24]. Therefore, the current study adopted a 90-min driving task, which was further divided into three segments of 30 min. As the experiment protocol suggested that every fatigue score represented drivers' fatigue status for the past 10 min, all data in the last 10 min of each segment were comprised of the final dataset [25] (see Figure 3). Furthermore, according to Antonson, Mårdh, Wiklund, and Blomqvist (2009), participants driving in the open landscape experienced less stress and did not consume many cognitive resources [26], which was a low workload driving condition and was easy to induce passive fatigue driving experience. Therefore, the present study set the experimental scenario as an open, monotonous highway in order to induce passive fatigue for the participants.

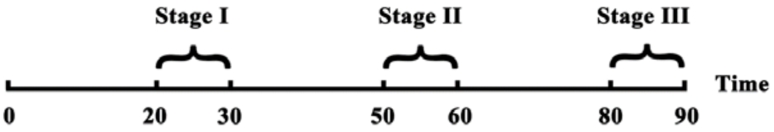


Figure 3. Driving segments.

Upon arrival, the experimenter tested the participants' vision using the Standard Logarithmic Visual Acuity Chart and then asked them to sign the informed consent form. The results of Yoon and Oh (2011) showed that the traffic flow on the highway varied with speed between 9 a.m. and 7 p.m., and the low traffic flow could be maintained when the speed was kept below 90 km/h (55.92 mph) [27]. Therefore, during the experiment, participants were informed to retain their normal driving styles and maintain a driving speed of 80 km/h (49.68 mph). A pair of research assistants counted the number of vehicles per hour by watching the experiment video recordings. According to their statistics, the same-side traffic flow was less than 20 vehicles per hour during the experiment, ensuring that the experiment was conducted under low traffic flow traffic conditions, which was a condition that induced the passive fatigue driving experience. The experimenter recorded the drivers' fatigue score every 30 min by verbal inquiry based on the SSS.

The driving route was a 145 km highway section of the Wuzhou–Liuzhou Highway in Guangxi Province, starting and ending at Liuzhou East Toll Station and Pingnan East Toll Station, respectively (see Figure 4). The experimental section of our study was Wuliu Expressway in Liuzhou City, Guangxi Province, starting and ending at Liuzhou East Toll Station and Pingnan East Toll Station. The technical standards of the Wuliu Expressway were executed in accordance with the provisions of "Technical Standards for Highway Engineering" (JTGB01-2014) issued by the Ministry of Transportation, China, and the specific information was shown in the Table 2. Wuliu Expressway was completed and used since December 2017, and all standards at the time of acceptance were in accordance with the relevant requirements of the "Rules for the Implementation of the Measures for the Completion (Delivery) and Acceptance of Highway Projects" of the Ministry of Transportation, China (Transportation Highway Development [2010] No. 65). According to China's Technical Standards for Highway Engineering (JTG B01-2014), the maximum vertical slope was 3% when the designed speed was 120 km/h; the maximum vertical slope was 4% when the designed speed was 100 km/h; and when the designed speed of 120 km/h and 100 km/h expressway was restricted by terrain conditions or other special circumstances, the maximum vertical slope value could be increased by 1% after technical and economic proof. The turning angle was not required, but the turn radius was specified, with the designed speed of 120 km/h, the minimum radius was in the range of 570–810 m; and with the designed speed of 100 km/h, the minimum radius was in the range of 360–500 m. Therefore, the road condition selected by this experiment will not force the drivers to change their driving speed or steer because of the degree of road tortuosity, or steepness of the road surface.

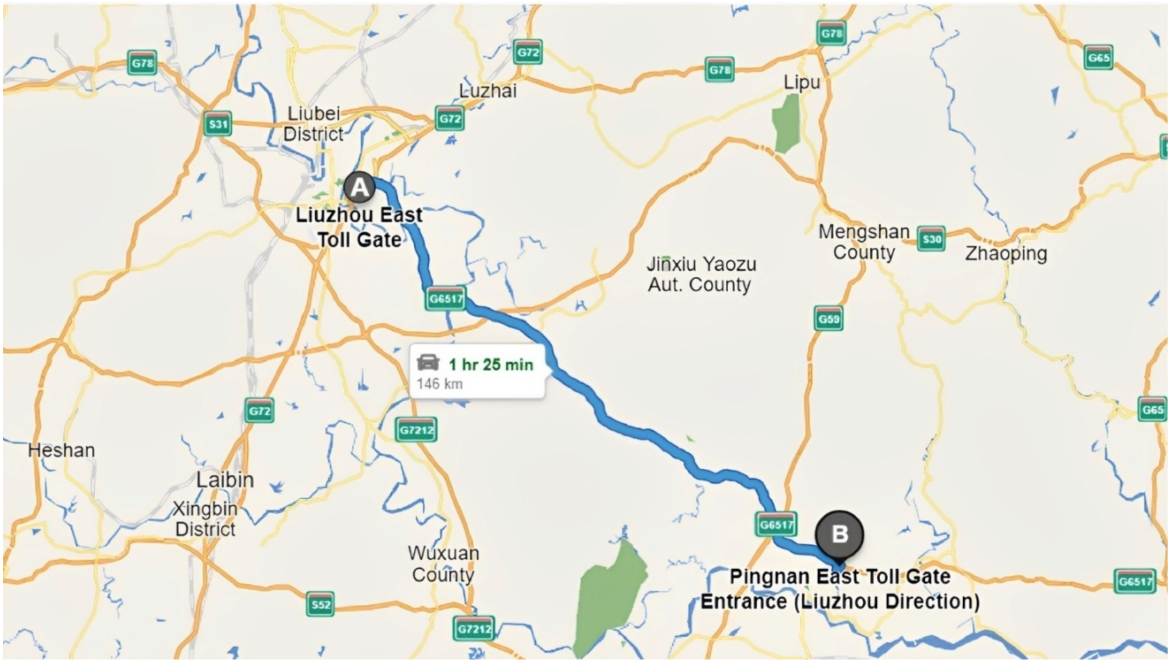


Figure 4. Driving route (Note: Point A represents Liuzhou East Toll Station, and point B represents Pingnan East toll station).

Table 2. Technical Standards of Wuzhou–Liuzhou Highway.

	Technical Information
Highway grade	Expressway
Line mileage	212.55 km
Width of roadbed	Wuzhou–Xiangzhou section: 26 m, Xiangzhou–Liuzhou section: 28 m
Design speed	Wuzhou–Xiangzhou section: 100 km/h, Xiangzhou–Liuzhou section: 120 km/h
Lane scale	Two-way four lanes
Design load	Highway-I
Flood frequency	Special bridge: 1 time/300 years, large, medium, and small bridges, culverts: 1 time/100 years
Seismic grade	IV degree
Number of bridges and tunnels	Special bridge: 4488 m/4, large, medium, and small bridges: 41,371.91 m/213, tunnels: 15,265.5 m/16

All participants completed the experiments under suitable temperature and good meteorological conditions. During the experiment, the maximum temperature was 27 °C and the minimum temperature was 7 °C, and the detailed temperature changes were shown in Figure 5. Previous studies have shown that temperature had little effect on highway traffic accidents when the temperature was 7 °C to 28 °C, and the accident density tended to be homogeneous [28], which indicates that the temperature in our study did not affect the experimental results.

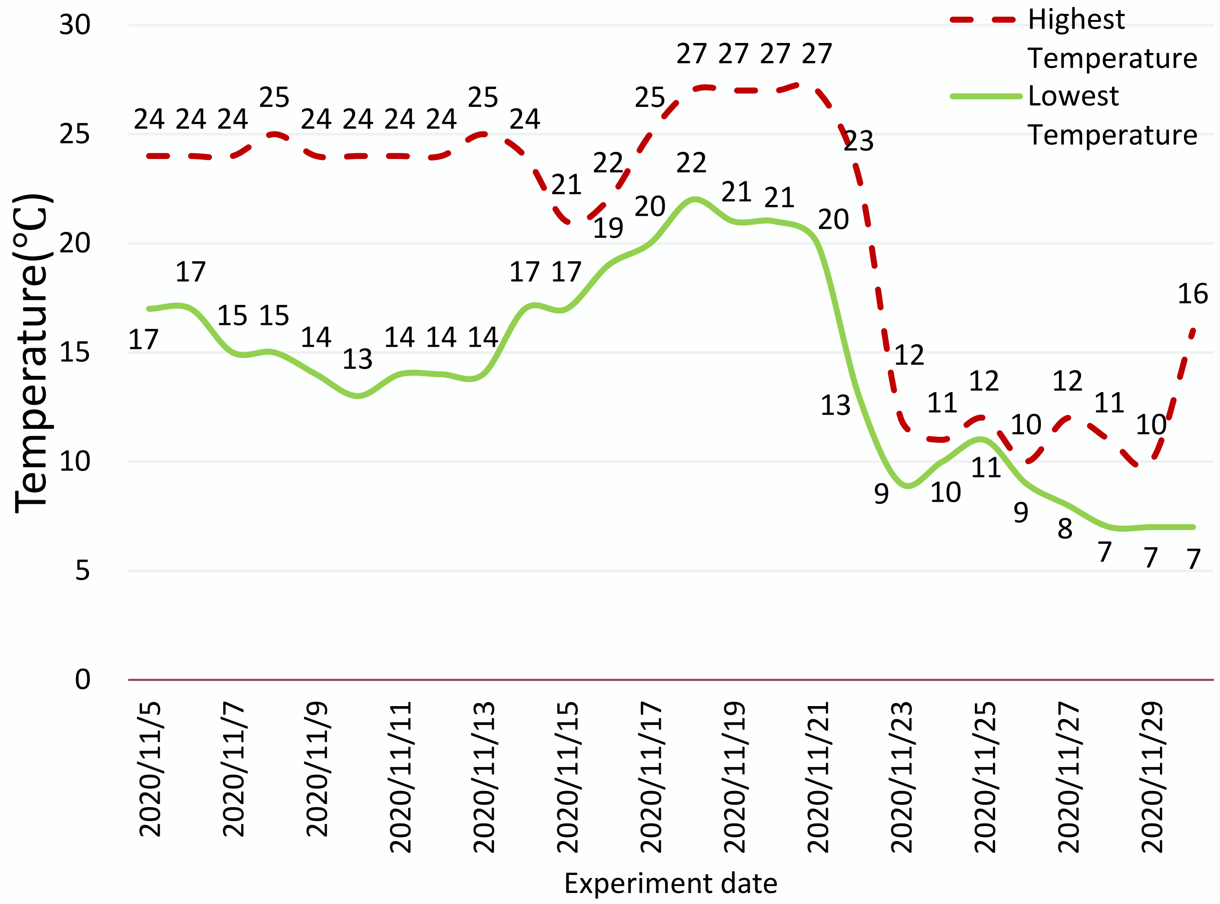
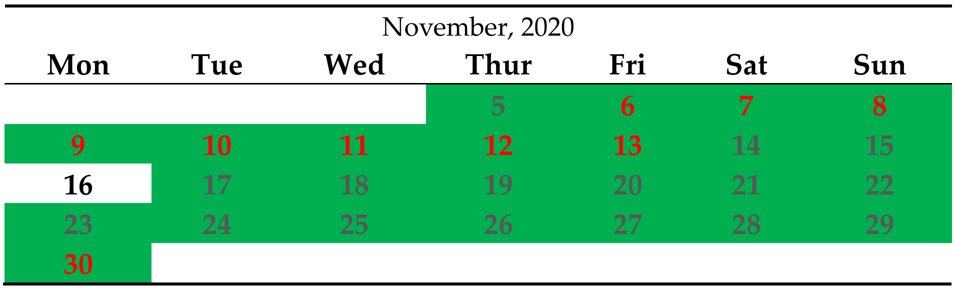


Figure 5. Experimental temperature changes across time. (Note: Red represents the daily highest temperature; green represents the daily lowest temperature).

In addition, none of the experiments in our study were conducted under unfavorable weather conditions such as snowfall, icing, rainfall, fog, and wind, and were able to ensure that the experiments were not influenced by additional variables such as weather. In our 26-day experiment, there were 9 days of sunny weather, 16 days of cloudy weather, and 1 day of rain (See Figure 6). Previous studies have shown that, the number of traffic accidents in rainy and snowy weather was significantly higher than in sunny weather conditions, and the number of highway accidents was two to three times higher per unit time than in normal weather conditions [29,30]. For safety reasons and to avoid the potential contaminating effect of adverse weather conditions on driving performance, our study did not conduct the experiment on 16 November 2020.



November, 2020

Mon	Tue	Wed	Thur	Fri	Sat	Sun
			5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

Figure 6. Experimental weather conditions (Note: Data were collected for 25 days from 5 to 30 November 2020 except 16 November 2020. Among them, red font color represents sunny weather, totaling 9 days; grey font color represents cloudy weather, totaling 16 days; and black font color represents rainy weather, totaling 1 day).

2.4. Indicator Definition and Data Analysis

After data extraction, eye tracking indicators and vehicle dynamics were calculated as Table 3 presents. The Mauchly's test of sphericity, analyses of variance (ANOVA) with repeated measure design, and post hoc analysi0s were executed to examine the changes in subjective fatigue levels, eye movement, and driving behaviors over time. Corrections using either Huynh–Feldt (when $\varepsilon > 0.75$) or Greenhouse–Geisser (when $\varepsilon \leq 0.75$) were adopted when sphericity was violated. Effect sizes were assessed by Cohen's *d*. The criterion for a large effect size is a Cohen's *d* of 0.8, medium size for 0.5, and small size for 0.2 [31]. Data preprocessing and analysis were conducted in Python and SPSS.

Table 3. Description of indicators analyzed in this study.

Indicator (Unit)	Algorithm	Influences on Driving
Horizontal (vertical) gaze dispersion (m) [32]	The mean variance of the x (y) value of the intersection of gaze direction and plain z = 0.9	A larger gaze dispersion indicates drivers look at wider spaces, but might not be alert, which is similar to inattentional blindness.
Pupil diameter (mm)	The mean value of pupil diameter	
Mean speed (km/h)	The mean value of speed	A larger speed might lead to severe accidents.
Standard deviation of speed (km/h)	The standard deviation value of speed	A larger variance of speed indicates worse control to speed.
Speed compliance (%) [33]	The total time of the speed in the range from 75–85 km/h divided by the total time	A smaller speed compliance indicates worse control and less attention allocation to speed.
Standard deviation of steering angle (degree)	The standard deviation value of the steering angle	A larger standard deviation of the steering angle indicates worse control of lane keeping.
Steering hold frequency (Hz) [34]	The frequency in one second that the steering wheel did not turn for more than 400 ms.	A smaller steering hold frequency indicates worse control to the steering wheel.

3. Results

3.1. Subjective Fatigue Level

As shown in Figure 7, the level of subjective fatigue increased over time as the driving task proceeded. The repeated measures using ANOVA and the subsequent post hoc test indicated that there was a significant change among the three driving stages, $F(2, 62) = 33.63$, $p < 0.001$, $\eta_p^2 = 0.52$. The subjective fatigue level was higher in stage III than in stage I ($t(31) = 8.14$, $p < 0.001$, Cohen's $d = 1.44$) and stage II ($t(31) = 3.21$, $p < 0.01$, Cohen's $d = 0.57$), and higher in stage II than in stage I ($t(31) = 4.93$, $p < 0.001$, Cohen's $d = 0.87$). The mean and standard deviation of fatigue levels at each stage are presented in Table 4.

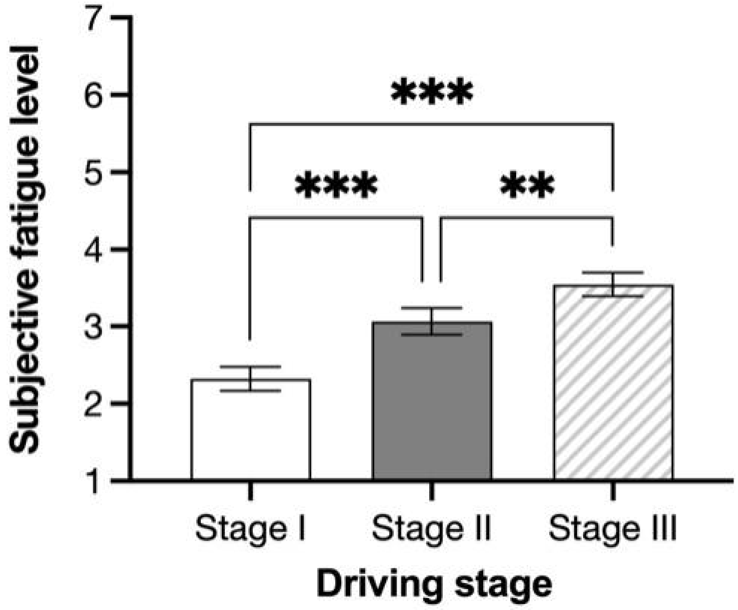


Figure 7. Subjective fatigue level under three stages. (Note: Error bars in this and all following graphs represent standard errors. Two asterisks (**) indicate $p < 0.01$, and three (***) indicate $p < 0.001$).

Table 4. Overview changes of eye movement and driving performance caused by passive fatigue in different driving stages [*M* (*SD*)].

	Indicator (Unit)	Stage I	Stage II	Stage III	Stage I vs. II	Stage II vs. III	Stage I vs. III
Eye movement	Subjective fatigue level measured using SSS	2.34 (0.87)	3.06 (0.95)	3.53 (0.84)	***	**	***
	Horizontal gaze dispersion (m)	0.13 (0.04)	0.14 (0.04)	0.15 (0.05)	n.s.	n.s.	*
	Vertical gaze dispersion (m)	0.14 (0.04)	0.13 (0.03)	0.14 (0.04)	n.s.	*	n.s.
	Pupil diameter (mm)	3.58 (0.91)	3.68 (0.97)	3.73 (1.07)	n.s.	n.s.	*
Driving Performance	Mean speed (km/h)	81.52 (4.42)	79.99 (4.28)	85.68 (5.83)	n.s.	***	***
	Standard deviation of speed (km/h)	4.13 (2.24)	4.75 (2.12)	4.83 (2.62)	n.s.	n.s.	n.s.
	Speed compliance (%)	0.28 (0.19)	0.27 (0.13)	0.16 (0.15)	n.s.	**	**
	Standard deviation of steering angle (degree)	1.01 (0.16)	1.19 (0.16)	1.06 (0.16)	***	**	n.s.
	Steering hold frequency (Hz)	2.68 (0.75)	2.46 (0.73)	2.73 (0.79)	***	***	n.s.

Note: * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$; n.s. indicates not significant.

3.2. Eye Movement Indicators

Analysis of drivers' horizontal gaze dispersion reported a significant main effect of driving stages, $F(2, 62) = 3.97$, $p < 0.05$, $\eta_p^2 = 0.11$ (see Figure 8a). The post hoc test showed that drivers' gazes were considerably more dispersed in the horizontal dimensions in stage III than in stage I, $t(31) = 2.80$, $p < 0.05$, Cohen's $d = 0.50$.

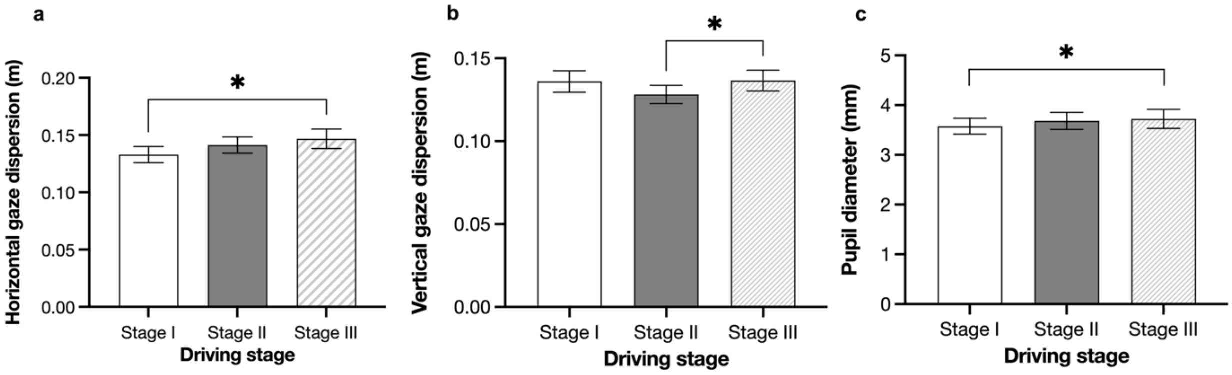


Figure 8. Eye tracking indicators under three driving stages. (Note: (**a**) represented analysis of drivers' horizontal gaze dispersion; (**b**) represented analysis of drivers' vertical gaze dispersion; (**c**) represented analysis of drivers' Pupil diameters. A single asterisk (*) indicates significance at $p < 0.05$).

Significant differences have also been reported in drivers' vertical gaze dispersion, $F(2, 62) = 4.24$, $p < 0.05$, $\eta_p^2 = 0.12$ (see Figure 8b). The post hoc test indicated that a broader vertical gaze dispersion appeared in stage III than in stage II, $t(31) = 2.60$, $p < 0.05$, Cohen's $d = 0.46$. The density contour plots based on the intersection coordinates of three-dimensional gaze direction and vertical plain $z = 0.9$ in Figure 9 further visualize these tendencies.

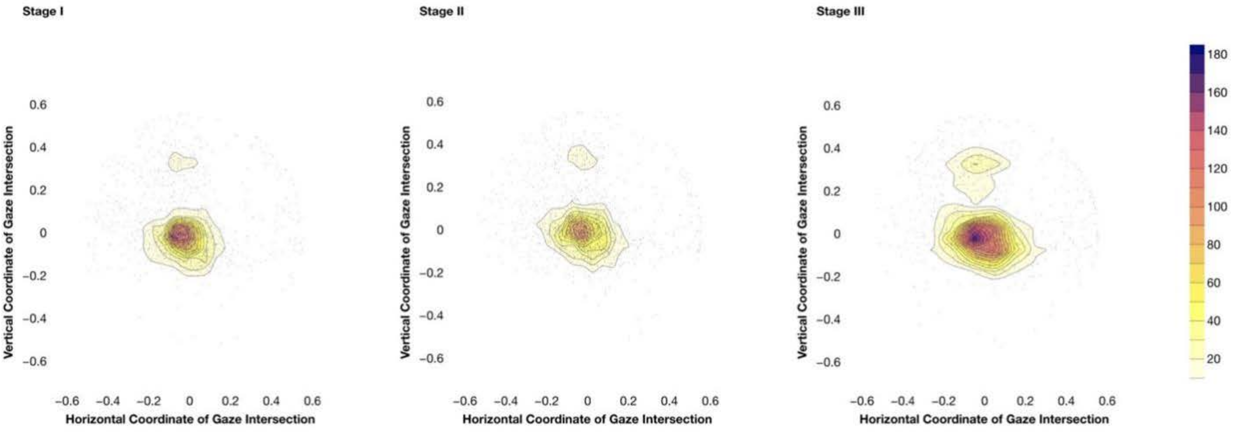


Figure 9. Visualization of horizontal and vertical gaze dispersions under three driving stages.

Pupil diameters of drivers as shown in Table 3 became greater as time went by, $F(2, 62) = 3.44$, $p < 0.05$, $\eta_p^2 = 0.10$ (see Figure 8c). The difference between stage III and stage I has been proven to reach significance, $t(31) = 2.54$, $p < 0.05$, Cohen's $d = 0.45$.

3.3. Driving Performance

Drivers drove faster as the experiment went on (see Figure 10a), $F(1.30, 40.31) = 16.30$, $p < 0.001$, $\eta_p^2 = 0.35$. Stage III had a significantly faster mean speed than in stage I ($t(31) = 4.04$, $p < 0.001$, Cohen's $d = 0.71$), and stage II ($t(31) = 5.52$, $p < 0.001$, Cohen's $d = 0.98$).

For the standard deviation of speed, no significant differences have been found.

Speed compliance was found to be influenced by the length of driving time (see Figure 10b), $F(1.67, 51.77) = 8.17$, $p < 0.001$, $\eta_p^2 = 0.21$. Stage III had substantially lower speed compliance than stage I ($t(31) = 3.62$, $p < 0.01$, Cohen's $d = 0.64$), and stage II ($t(31) = 3.37$, $p < 0.01$, Cohen's $d = 0.60$).

The standard deviation of steering angle varied among the three stages (see Figure 10c), $F(1.68, 52.11) = 10.54$, $p < 0.001$, $\eta_p^2 = 0.25$. The standard deviation was significantly larger in stage II than in either stage I ($t(31) = 4.49$, $p < 0.001$, Cohen's $d = 0.79$), or stage III ($t(31) = 3.09$, $p < 0.01$, Cohen's $d = 0.55$).

Steering hold frequency significantly changed during the drive (see Figure 10d), $F(1.12, 34.82) = 18.14$, $p < 0.001$, $\eta_p^2 = 0.37$. The frequency was lower in stage II than in either stage I ($t(31) = 4.61$, $p < 0.001$, Cohen's $d = 0.82$), or stage III ($t(31) = 5.66$, $p < 0.001$, Cohen's $d = 1.00$).

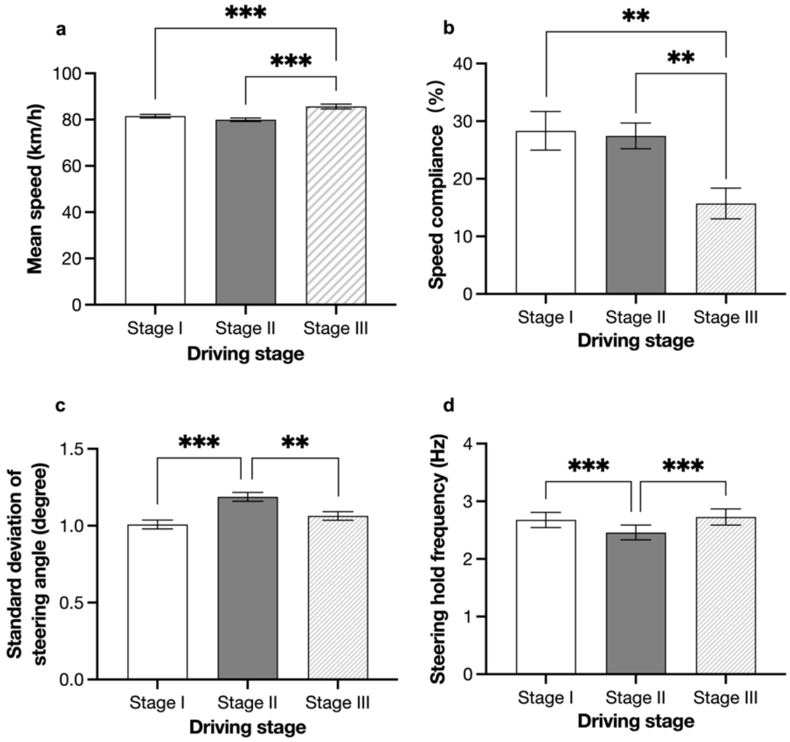


Figure 10. Vehicle dynamics under three driving stages. (Note: (**a**) represented analysis of drivers' mean speed; (**b**) represented analysis of drivers' speed compliance; (**c**) represented analysis of drivers' the standard deviation of steering angle; (**d**) represented analysis of drivers' steering hold frequency. Two asterisks (**) indicate $p < 0.01$, and three (***) indicate $p < 0.001$).

4. Discussion

As emphasized in the introduction, it is important for researchers to differentiate the two types of fatigue, that is, passive fatigue and active fatigue. Road situations and traffic load change diversely in real-world driving scenarios, which are both common exogenous factors that induce either passive fatigue or active fatigue. Since the two categories of driver fatigue are driven by different mechanisms, drivers' performance would be influenced diversely, indicating the significance of developing a more accurate way to assess driver fatigue regarding various kinds of driving scenarios. Furthermore, with the growing number of autonomous vehicles being implemented in the upcoming future, drivers would possibly experience passive fatigue more frequently when driving on a monotonous highway or riding in an autonomous vehicle with a minimum workload.

The following sections address the three research questions as introduced in the Introduction section.

4.1. Research Question 1: Eye Movement Patterns and Driving Performance under Passive Fatigue

The results of eye movement patterns in the current study centered on the eye tracking method. The results found that gaze dispersion grew larger both horizontally and vertically after about 90 min of driving, which echoed with findings from the previous studies focusing on autonomous and sleep-deprived driving situations [35]. When tasks are monotonous and boring, drivers would possibly experience passive fatigue and decrease attention allocation as illustrated in the capacity model of attention [13], leading to driver inattention or a status similar to mind wandering [14].

Moreover, the current study found that pupil diameter increased as the driving task went on. However, the robustness of pupil diameter indicating fatigue level is relatively low [36], with multiple factors influencing the change of pupil diameters, such as workload, alertness, and sleepiness level [3]. A driving scenario that elicits passive fatigue might have a combined influence on pupil diameter.

For driving performance, the current study showed a significantly faster driving speed and declined speed compliance at driving stage III. According to the capacity model of attention, the above observation might be a result of drivers' passive fatigue, leading them to gradually lowering their standard to obey with the research protocol and posted speed requirements (i.e., maintaining a constant driving speed). Regarding steering wheel control, the current study demonstrated that the steering wheel control was impaired more at stage II than stage I (i.e., larger *SD* of steering angles and longer steering hold frequency), but the same trend was not found at stage III.

4.2. Research Question 2: Compensatory Strategies

Do compensatory strategies exist to counteract the increasing risks caused by passive fatigue after a long-time driving? Close examination of eye movement and driving dynamics showed existence of a compensatory process during passive fatigue in two aspects. Reduced attention allocation led to a more limited numbers of tasks that drivers can manage. Thus, in the aspect of eye movement, drivers would need more time to process a piece of visual information if they were not paying full attention [37], thus they compensatively increase visual search span to acquire more visual information, resulting in a more dispersed gaze allocation [38]. In the aspect of driving performance, drivers unconsciously lowered their standard to control lateral position in order to keep a stable driving speed. At driving stage II, most participants remained at a relatively constant speed, while they failed to stabilize their lateral position by controlling the steering wheel. Yet, at stage III, it become harder for participants to control the speed as passive fatigue increased, but they compensatively managed better lateral control.

4.3. Research Question 3: Measurements for Passive Fatigue in Different Stages

The third research question asked about indicator changes for the early versus late stage of passive fatigue. This question is not only important to uncover the theoretical progressive process of passive fatigue, but also comes from urgent industry needs for the development of a Driver Monitor System and the development of machine learning algorithms.

Fatigue detection indicators can be categorized into four types, according to machine learning needs and the pairwise comparisons in the last three columns of Table 4, that is, early indicators and late indicators, or short-period indicators and long- period indicators.

Early indicators are changes observed at early stage of fatigue, often minor levels of fatigue, for example, after relatively short driving time, or when SSS = 3 with a label of "*Awake, but relaxed; responsive but not fully alert*" [21]. Early indicators are operationally defined as changes occurring before the first 60 min, when Stage I vs. II are significant in Table 4. In contrast, late indicators are changes observed at late stage of fatigue with severe levels of fatigue, for example, when SSS = 6 ("Sleepy, woozy, struggling to sleep; prefer to lie down") or 7 ("No longer struggling to sleep"). Late indicators are operationally defined as changes occurring after 60 min, when Stage II vs. III are significant in Table 4. Early indicators should be used if the DMS users are conservative or the losses from fatigue are extremely high, for example, a vehicle carrying explosives. Late indicators are recommended for users who are liberal, or the risks of fatigue are low, or when false alarms of the DMS are bothersome. As summarized in Table 4, steering controls (measured in standard deviation of steering angle and steering hold frequency) are early indicators; vertical gaze dispersion and speed measurements (both mean speed and speed compliance) are late indicators.

The categorization of short-period indicators and long- period indicators is based on the time windows in which data are averaged over. Short-period indicators refer to indicators which are significant when comparing short time windows, but not significant anymore if larger time windows are compared. Short-period indicators are often behaviors occurring less frequently, such as steering control on highway. Long-period indicators are data which are significant when averaged and compared after a large time window. In this study, short-period indicators are operationally defined as indicators which are significantly when comparing either Stage I vs. II or stage II vs. III, but insignificant when comparing Stage I vs. III. According to Table 4, steering controls (measured in standard deviation of steering angle and steering hold frequency) and vertical gaze dispersions are short-period indicators; speed measurements (both mean speed and speed compliance) are long-period indicators.

4.4. Limitations

Nevertheless, as a large on-road driving study, the current study is limited in several aspects. Firstly, the experiment was conducted in the real world in which, naturalistic behaviors were recorded when drivers were driving on the highway. It is, therefore, unable to control elements such as the weather and lighting conditions, leading to fluctuations in the change of pupil diameter in this study. However, the weather conditions throughout the experiment session were similar, suggesting that the pupil-based results of the current study have provided valuable significance and external validity. Secondly, due to safety concerns, the total driving duration was set to be ninety minutes. To further understand the impact induced by severe passive fatigue, future research is suggested to conduct the experiment with a longer duration via driving simulations. Thirdly, the scale used for measuring subjective fatigue level was SSS. Although the concrete definition of each SSS score allows drivers to accurately measure their fatigue level, it is not the scale that specifically differentiates or measures different types and levels of fatigue. In fact, there is currently no scale that measures different types of fatigue, so future research could attempt to develop scales for more accurate measurements of active and passive fatigue. Future studies are also advised to further investigate the compensatory processes of drivers when experiencing both active and passive fatigue.

Regardless of the above limitations, combining the findings on eye tracking indicators and driving dynamics, the current study not only investigated the effect of passive fatigue but also shed light on the complex mechanism of passive fatigue and attention allocation. Moreover, the results of this study provided new options for the design of the driver monitoring system (DMS). To increase the accuracy of driver status detection, researchers, as well as manufacturers should consider adding gaze dispersion into the algorithm of the DMS. More data regarding driving behavior is also needed to improve the efficiency of a DMS.

5. Conclusions

To summarize, first, passive fatigue driving causes a series of eye movement and driving performance changes, including wider horizontal gaze dispersions, larger pupil diameters, quicker speed, lower speed compliance, larger standard deviation of steering angle, and an increased steering hold frequency. Second, drivers do exhibit compensatory behaviors to reduce increasing risks of passive fatigue including wider horizontal gaze dispersions and prioritizing speed manipulation over lateral steering control. Third, strict conservative early detection of fatigue can put more weight on steering control, and late severe fatigue detection can put more weight on mean speed and speed compliance. In addition, adding gaze dispersion into the algorithm of the DMS might be an effective way to further increase the accuracy of driver status detection.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Stanford Sleepiness Scale [39].
Please circle the item which best describes your current sleepiness level.

1 (feeling awake and energetic)
2 (good physical condition, thinking ability, but not optimal; able to concentrate)
3 (awake, relaxed, not optimal responsiveness)
4 (more or less not awake, not in high spirits)
5 (not clear-headed; a little sleepy; slowed thinking)
6 (sleepy, trying to hold on to sleep; wants to lie down)
7 (unable to remain awake, can fall asleep soon; dream-like thinking occurs)

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