Transportation Research Part F: Psychology and Behaviour 103 (2024) 273–289

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

Not just more, but more diverse: Green landscapes along urban roads may significantly reduce drivers' psychophysiological fatigue

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ARTICLE INFO

Keywords:
Driving fatigue
Urban transportation
Green infrastructure
On-site experiment
Quantity and diversity
Deep learning technology

ABSTRACT

The impact of roadside greenness on driving fatigue in real urban settings has been insufficiently investigated, presenting a critical knowledge gap for researchers, policymakers, professionals, and the public. In this onsite driving experiment, 34 urban residents completed seven driving tasks on different urban road routes in a randomized order with one-day intervals. A total of 238 tasks were conducted, each lasting an hour, assessing psychophysiological, visual, and muscular fatigue. A cardiovascular activity monitor (BioHarness) continuously measured the driver's heart rate, with lower rates indicating reduced psychophysiological fatigue. Visual and muscular fatigue were self-reported using a Visual Analog Scale questionnaire administered before, at the midpoint, and after completing the driving task. Deep transfer learning semantic segmentation analyzed road landscape characteristics and traffic conditions recorded from the drivers' view. Statistical analysis demonstrated that higher mean and variation in greenness significantly predicted lower psychophysiological fatigue after adjusting for multiple covariates. These results indicate that enhancing both the quantity and diversity of green landscapes along urban roads is vital for reducing driver's psychophysiological fatigue. This study reveals that roadside landscapes in urban settings are not trivial decorations, and they should be considered an essential component of transportation infrastructure.

1. Introduction

Traffic accidents lead to approximately 1.35 million deaths globally each year, with an estimated 3 % loss in GDP in many countries (World Health Organization, 2022). Particularly, driving fatigue has been identified as a significant contributing factor to road traffic risks (Lal & Craig, 2001; Phillips, 2015; Yang, Lin, & Bhattacharya, 2010), leading to severe consequences, and accounted for as many as one in five fatal crashes (Tefft, 2014; Wang, Bie, & Li, 2016). A recent study revealed that driving fatigue was responsible for up to 20 % of driving accidents and up to 25 % of fatal and serious car crashes (Royal Society for the Prevention of Accident, 2020). This highlights the importance of intervention in relieving drivers' sense of fatigue on the road in promote driving safety.

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https://doi.org/10.1016/j.trf.2024.04.009
Received 18 July 2023; Received in revised form 6 April 2024; Accepted 13 April 2024
Available online 25 April 2024
1369-8478/

Driving fatigue can impair performance on a range of cognitive and psychomotor tasks (Dalziel & Job, 1997; Du, Zhao, Zhang, Zhang, & Rong, 2015; Merat & Jamson, 2013; Wijesuriya, Tran, & Craig, 2007; Williamson, Feyer, & Friswell, 1996), prolonging the driving reaction time and increasing the risk of injuries and fatalities in car accidents (Philip et al., 2005). Yet, drivers' performance could possibly be preserved by relieving the level of fatigue or arousing their alertness through the driving environment. Existing literatures suggested that driving fatigue could be countered by restorative effects of natural landscapes on freeways (Chiang, Ke, Li, & Weng, 2022; Jiang, He, Chen, Larsen, & Wang, 2020), or by the alerting effect of a more stimulating environment (Ahlström, Anund, Fors, & Åkerstedt, 2018; Horne & Reyner, 1999); Wang and colleagues (2016) suggested that road designers, landscape architects, and traffic engineers could incorporate landscaping as a mean of providing intriguing scenery for drivers to combat driving fatigue. However, the extent of the effects on reducing fatigue level in the urban driving settings, and the effectiveness of relevant landscape characteristics, have yet to be confirmed. Therefore, in this study, we investigated the impact of roadside greenness on driving fatigue to serve as a reference for future road landscaping design.

1.1. Types and measures of driving fatigue

The field of transportation research often faces challenges in understanding fatigue-related concepts, which hinders the development of accurate detection systems and effective strategies to mitigate fatigue. To address this issue, it is recommended that future research on driving fatigue be conducted within a more conceptual framework, particularly with the incorporation of types and measurements of driving fatigue (He, Li, Ma, Sun, & Ma, 2023; Hu & Lodewijks, 2020).

We focus on discussing the measurements for three typical driving-related fatigue types: psychophysiological fatigue, visual fatigue, and muscular fatigue. In this study, psychophysiological fatigue encompasses psychological fatigue reflected by physiological responses. Psychophysiological fatigue is a neural and physiological activity accompanied by weak biological signals (Rather, Sofi, & Mukhtar, 2021). These biological signals, such as electrocardiogram (ECG), are considered to be reliable features, as they are generally independent of consciousness (Rather et al., 2021). The mean heart rate calculated from ECG signals has been widely used for the objective measurement of driving-induced fatigue, with lower heart rates indicating lower levels of psychophysiological driving fatigue (e.g., Chua et al., 2012; Du et al., 2022; Fu & Wang, 2014; Patel, Lal, Kavanagh, & Rossiter, 2011; Wang et al., 2016). On the other hand, visual fatigue, frequently reported in transportation studies (e.g., Grandjean, 1979; Lal & Craig, 2001; Sikander & Anwar, 2018), occurs when specific eye muscles tighten during visually intensive tasks (Lambooij, IJsselsteijn, Fortuin, & Heynderickx, 2009). Sullivan (2008) suggested that a potential cause of visual fatigue in driving could be the result of constant focal point changes between nearby and distant object viewing. In contrast, muscular fatigue is the phenomenon of reduced performance in a muscle after stress and is characterized by decreased muscular power and movement (Grandjean, 1979; Lal & Craig, 2001). Visual and muscular fatigue resulting from driving reflect more on drivers' physical fatigue and can lead to impaired coordination, increasing the chances of human errors and accidents (Campagne, Pebayle, & Muzet, 2004; Grandjean, 1979; Jamroz & Smolarek, 2013; Lal & Craig, 2001).

1.2. Impacts of roadside greenness on driving fatigue

Previous studies in environmental psychology have indicated that natural environments or features are positively associated with emotions (Hartig et al., 2003; Ulrich et al., 1991), affecting attention restoration, stress reduction, and physiological health (Hartig et al., 1991; Jiang, Chang, & Sullivan, 2014; Lai et al., 2020; Taylor et al., 2015). These positive responses could potentially benefit the driving fatigue, as driving is a mentally and physically demanding activity that can easily arouse drivers' attention and induce stress and mental fatigue (Cantin, Lavallière, Simoneau, & Teasdale, 2009). We thus hypothesize that different roads with diverse landscape features and pattern changes of the landscape may alter driving fatigue, especially psychophysiological fatigue (Wang et al., 2016). Specifically, urban trees can provide benefits to drivers in terms of enhancing environmental aesthetics and regulating microclimates (Nowak et al., 2013). The foliage and branches of these trees effectively obstruct direct sunlight, adding visual diversity to the otherwise monotonous urban street landscapes (Soares et al., 2011). Moreover, street trees can serve as natural shades for both vehicles and pedestrians, alleviating driver eye strain (Song et al., 2018). Collectively, these findings suggest that the presence of street trees has the potential to mitigate drivers' fatigue resulting from urban driving.

In addition, some studies in transportation and health imply that greenness has a positive influence on drivers' fatigue levels, particularly its impact on psychophysiological fatigue, drivers' attention, and driving safety (e.g., Chiang et al., 2022; Jiang et al., 2020; Van Treese, Koeser, Fitzpatrick, Olexa, & Allen, 2018). For example, a recent study showed that routes with higher green view index scores were associated with a more comfortable driving experience (Wu et al., 2020). Moreover, a simulated driving experiment found that freeway landscapes with high greenness elicited a greater positive impact on drivers' mental states than those landscapes with less greenness (Jiang et al., 2020). Furthermore, evidence suggests that roadside trees improve drivers' perceptions of safety and have a positive impact on controlling driving speed (Van Treese et al., 2018). A study pointed out that positive effects of roadside trees on drivers' mental states may be attributed in part to trees' ability to facilitate drivers' sense of the edge of the road (Naderi et al., 2006).

In summary, although some findings can be deduced from previous studies, the evidence on the relationships between roadside greenness and driving fatigue remains inconclusive. Furthermore, while few studies have been completed regarding this topic, they have been conducted in simulated environment settings, where many factors that influence driver fatigue in real-world driving environments have yet to be considered.

1.3. Other factors that may affect driving fatigue

While driving fatigue is commonly associated with prolonged driving in monotonous environments (i.e., freeways; Brown, 1994; Horne & Reyner, 1999; Thiffault & Bergeron, 2003), there are also other contributing factors to types of driving fatigue. In particular, internal factors such as drivers' personality (Wijesuriya et al., 2007), socio-economic and demographic factors (Chiang et al., 2022), sleep disorders (Dinges et al., 1997), and driving physiological time (Monk, Moline, & Graeber, 1988) can hinder one's driving performance. A considerable amount of literature examining the associations between drivers' personal characteristics and driving fatigue suggests that drivers' age and gender are highly associated with both physical and psychophysiological fatigue (Chiang et al., 2022; Di Milia et al., 2011). Specifically, older drivers are more susceptible to muscular (physical) fatigue than younger drivers (Di Milia et al., 2011; Jamroz & Smolarek, 2013), as aging often leads to a gradual deterioration of the mechanisms that support physiological, circadian, and sleep systems. However, young drivers aged 18–22 can also be at higher risk due to their lack of experience and knowledge in managing physical fatigue, as well as their tendency to underestimate driving challenges or overestimate their abilities (Jamroz & Smolarek, 2013; Philip et al., 2005). Specifically, drivers with less experience consume a tremendous amount of energy and become fatigued within a short period of time (Li, Liu, Yuan, & Liu, 2010; Ren, Jin, & Kang, 2007), whereas experienced professional drivers are found to handle sleep restrictions better than other road users (Jamroz & Smolarek, 2013). Gender also plays a role, with female drivers being less susceptible to psychophysiological and physical fatigue, but this can be influenced by factors unrelated to work (Jamroz & Smolarek, 2013). As for socio-economic status, factors including educational attainment, occupational status, income, and marital status also impact drivers' fatigue (Di Milia et al., 2011; Zhang, Yau, Zhang, & Li, 2016).

For external factors, monotony of road environments (Thiffault & Bergeron, 2003), road infrastructure and elements (Ahlström et al., 2018; Choi, Byun, Kim, & Kim, 2020; Wang et al., 2016), and driving tasks (Baulk, Biggs, Reid, van den Heuvel, & Dawson, 2008) can affect drivers' fatigue levels and driving performance in various ways (Meng, Wong, Yan, Li, & Yang, 2019; Merat & Jamson, 2013; Ting, Hwang, Doong, & Jeng, 2008). Monotonous environments generally feature minimal variation of road landscapes in driving (Thiffault & Bergeron, 2003), implying greater fatigue and vigilance decrements in comparison to changeable environments that contain disparate visual elements (Thiffault & Bergeron, 2003). These monotonous driving experiences also generate psychophysiological and psychological statuses that exacerbate driver fatigue (May & Baldwin, 2009).

Despite the negative impacts that a monotonous driving environment brings, it is important to note that complex, changeable road environments can also induce driving fatigue, which has the most negative impact on driving behavior and visual distance estimation (Liu & Wu, 2009). Specifically, roadside built infrastructures have been found to increase fatigue, with evidence showing that urban roads generate higher levels of mental fatigue than rural roads (Zhang et al., 2016). Moreover, artificial landscapes (e.g., buildings and moving objects on roads) and traffic conditions (mainly determined by the number of cars, buses, riders, pedestrians, traffic signs, and lights, etc.) have been proven to influence drivers' visibility on urban roads, affecting drivers' mental state and driving performance (Choi et al., 2020; Hu & Chen, 2019; Lyu, Xie, Wu, Fu, & Deng, 2017; Tanaka et al., 2012). For example, studies have revealed that cognitive workload is related to the amount of information conveyed by traffic signs and lights, and excessive information often induces cognitive fatigue, leading to psychophysiological fatigue and riskier driving behaviors (Lyu et al., 2017; Tanaka et al., 2012). In addition, a study found that mixed traffic flow conditions with various vehicles and pedestrians negatively influence city bus drivers' focus on driving tasks, and increasingly complicated mixed traffic flow conditions increase the risk of attentional errors, psychophysiological, and physical fatigue (Hu & Chen, 2019). On the contrary, a comparative study of driving on rural and suburban roads suggested that driver fatigue should be countered by exposure to a more stimulating visual environment, which is likely due to the increased task demand in high traffic density rather than richer visual sceneries (Ahlström et al., 2018). Overall, while most studies believe that urban traffic conditions contribute to driving fatigue, the opposite view exists.

1.4. Critical knowledge gaps

Although many previous studies have investigated the potential impacts of roadside greenness on driving fatigue, particularly psychophysiological fatigue, most studies were conducted in a virtual driving environment simulated by computers. However, compared with simulated environments, the physical features of real urban roads are much more complex, with a mix of buildings, traffic lights, various traffic vehicles, pedestrians, etc. Whether the findings of previous studies can be applied to urban roads or not, to our best knowledge, has yet to be confirmed. In addition, the greenness in simulated road landscapes lacks a high level of ecological validity—a measure of how test performance predicts behaviors in real-world settings (Alameda-Pineda, Ricci, & Sebe, 2018). It is therefore crucial for the current study to address these problems—whether and to what extent does roadside greenness affect the three types of driving fatigue when driving on urban roads in the real world? This study aims to answer this question by conducting a series of driving experiments on real urban roads in a modern city.

2. Methods

In this study, real-world urban driving experiments were employed to examine the impact of roadside greenness on driving fatigue. A within-subject experimental design was applied by assigning each participant to seven urban road routes, with each driving task lasting one hour. Driving fatigue was measured from three aspects, including psychophysiological fatigue, visual fatigue, and muscular fatigue. During a driving task, the road environment was continuously recorded as a video and analyzed by segmenting instant images abstracted from the video using deep transfer learning methods. Then, the associations between greenness and driving fatigue were analyzed. Finally, interpretations of the main findings and discussion of potential implications were conducted. This section of methods can be presented in four parts: participants, materials and apparatus, procedures, and statistical analysis.

2.1. Participants

Forty-one healthy adult residents of a modern city in China were recruited to participate in the experiment through a public job search website and a social media platform. All participants were required to meet the following criteria: (1) possess a valid driving license for two or more years, (2) be aged between 18 and 60 years old, (3) have no diagnosis of cardiovascular diseases or mental disorders, (4) have no physical disability, (5) have no history of traumatic vehicle accidents, (6) have eyesight greater than 5.0 after visual correction, (7) abstain from alcohol or caffeine intake within six hours of the experiment, (8) have at least seven hours of sleep the night prior to the experiment, and (9) not be professional drivers, such as truck drivers, taxi drivers, or ride-hailing drivers.

2.2. Materials and apparatus

2.2.1. Site city and driving routes

Liuzhou city, located in southern China, was chosen as the study site. Liuzhou is a medium-density modern city with an ordinary and modern streetscape and roadside greenness. The city lies in the subtropical climate zone, ensuring that the roadside landscapes remain stable in appearance throughout the year. The city features urban ring roads, arterial roads, and branch roads, constituting a common traffic network that can be observed in many cities. These characteristics of the study site enable the findings of this research

Fig. 1. Sample photos of urban road environments of seven routes captured during driving.

to be relevant to many other modern cities worldwide. After a two-month site investigation, seven driving routes located in urban areas were planned and drawn using Gaode Map (https://m.amap.com/; similar to Google Map), which provides information on traffic volume and real-time location tracking. Each route was shaped by joining a selected starting point, an ending point, and one or more passing points. These routes were chosen randomly across urban areas, following four criteria: (1) no or limited construction and heavy dust pollution, (2) no severe traffic jams throughout the day, (3) exclusion of roads that are too wide or too narrow, and (4) no sighting of obvious historical and cultural features or dramatically visible waterscapes. Fig. 1 shows sampled photos of road environments of the seven routes.

2.2.2. Measurement of three types of driving fatigue

Psychophysiological fatigue, visual fatigue, and muscular fatigue were measured as dependent variables using various devices or instruments. The mean heart rate, calculated from ECG signals, was used to indicate psychophysiological fatigue, while visual and muscular fatigue were measured by self-reported questionnaires.

2.2.2.1. Measurement of psychophysiological fatigue. During a driving task, the participant's heart rate was continuously recorded in real-time using the Zephyr BioHarness 3, a chest-strap style heart rate monitor designed for performance monitoring in athletic settings (Gancitano et al., 2021). The instrument has been proven to be an effective measurement of physiologically consistent heart rate signals in multiple driving studies (Kuo, Koppel, Charlton, & Rudin-Brown, 2015; Zhou et al., 2020). The device comprises a 45 mm × 10 mm circular electronic component fitted to a neoprene chest and shoulder strap, recording participants' heart rate via ECG signal detection through the conductive pads on the chest strap. The BioHarness can derive a heart rate measurement between 0 and 240 beats per minute (BPM), which was recorded on the device and downloaded after it was removed from the body. Fig. 2 illustrates the components of the Zephyr BioHarness 3, which can be found at https://www.zephyranywhere.com/.

2.2.2.2. Measurement of visual and muscular fatigue. Visual and muscular fatigue were measured using a Visual Analogue Scale (VAS) questionnaire, wherein participants rated each item on a continuous scale ranging from 0 (*Not at all*) to 10 (*Extremely*). These measurements were taken at three points: immediately before, during, and immediately after each driving task.

2.2.3. Measurement of environmental features

2.2.3.1. Image data. The camera was placed at eye-level with the drivers seated in the car to record external environmental conditions, using the back camera of an Oppo Reno 2. A one-hour continuous video was recorded at a fixed angle, in color, at 30 frames per second, and with a high resolution (1920 × 1080 pixels). To decrease data processing time while ensuring the accuracy of image data, a frame in Portable Network Graphics (PNG) format was selected every three seconds using Python 3.8.8. This approach covered image data at a rate of approximately one frame per 20-meter drive (Chen, Lu, Ye, Xiao, & Yang, 2022).

2.2.3.2. Deep transfer learning-based semantic segmentation. Many studies have employed street view images and machine learning to audit street-level environmental features (e.g., Chen et al., 2022; Ma et al., 2021; Zhang et al., 2018). To obtain detailed environmental features during the one-hour drive, semantic segmentation analysis using the DeepLab (Version 3 + with the Xception_65 backbone) approach was applied. The mean proportion of each environmental feature within the driving scene (i.e., the mean of each feature within the environment of a one-hour drive) and the proportion of changes of each feature (i.e., the variation of each feature within the

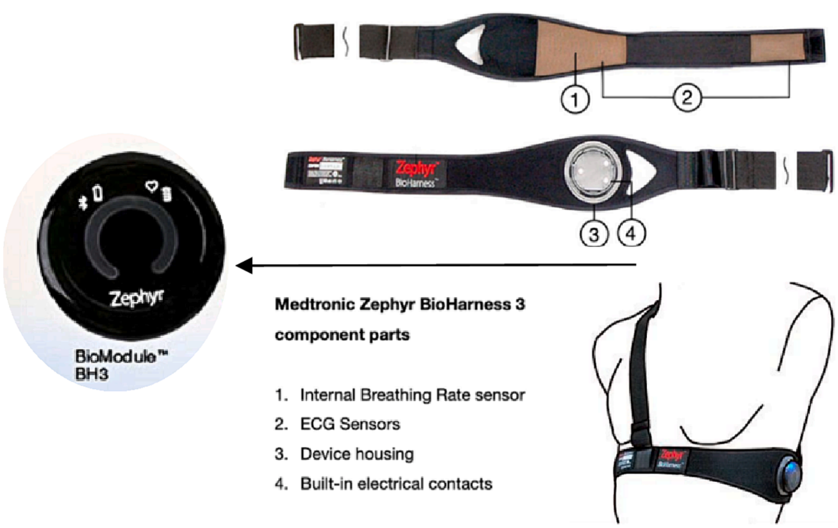

Fig. 2. Zephyr BioHarness 3 Module attached to chest strap with optional shoulder straps (Gancitano et al., 2021).

environment of a one-hour drive) were considered as independent variables.

DeepLab is effective in producing high-quality results on scene parsing tasks and can achieve state-of-the-art pixel-level prediction performance on diverse datasets, including Cityscapes (Li, Xue, Wu, & Yeh, 2022; Xue et al., 2021). Through deep transfer learning, we utilized a pre-trained Cityscapes model to classify every pixel in an input image into a semantic view label, resulting in the segmentation of each photo into 19 categories of ground objects. To determine the proportion of each object in the image, we calculated the ratio of the number of pixels representing the object to the total number of pixels in the image. We selected greenness (vegetation + terrain), sky, buildings, roads (road + sidewalk), traffic lights, traffic signs, traffic vehicles (car + truck + bus + train + motorcycle + bicycle), and pedestrians (person + rider) to represent road environmental or traffic features (see Fig. 3). The computer used for data collection and processing was a Windows 10 workstation with dual Intel Xeon E5-2690 v4 (2.6 GHz, 28 cores), an Nvidia Quadro P5000 GPU, and 64 GB of memory (Xue et al., 2021).

2.3. Procedure

Potential participants were invited to meet the experimenter at a hotel parking lot to be briefed about the objective and procedure of the one-hour driving experiment. They were required to sign a consent form if they decided to participate. Investigators tested the participants' vision using the Standard Logarithmic Visual Acuity Chart. The BioHarness 3.0 sensor was then attached to the participants' chest, and they were instructed to drive to the departure location. Before the driving experiment began, each participant was instructed to familiarize themselves with the planned route by completing a 60-min back and forth driving practice, followed by a 3-min rest.

In the experimental phase, participants were informed that they would be guided by the AutoNavi Voice Navigation during the 60-minute forth and back trip on the assigned planned route. We also emphasized that it was not compulsory to finish all planned routes to ensure participants could drive as usual without potential stress from time constraints, limiting the possible increase of mental burden. A questionnaire was assigned to measure visual and muscular fatigue before the drive, 30 min into the drive, and 60 min into the drive upon returning to the starting point. A camera was set up to record the external environments from the drivers' perspective throughout the experiment. The entire experiment concluded upon completion of the socio-demographic questionnaire after the 60-minute driving task. Each experiment and driving task took approximately 78 min (Fig. 4).

During the 60-minute driving task, participants were asked to adhere to six rules: (1) Follow the planned routes and adjust the departure location only if it cannot be reached, e.g., due to road closures for repairs or traffic accidents, (2) drive in the right lane and avoid following cars too closely, changing lanes, or overtaking cars unless necessary, (3) keep the windows closed and set the temperature at 26 degrees Celsius, (4) refrain from listening to music, making telephone calls, engaging in conversations, or creating other noises, (5) abstain from eating food, drinking alcohol, or consuming caffeine, and (6) obey all traffic regulations and laws, including speed limits. Furthermore, common commuting times (8:40–12:00 and 13:30–17:00) were selected for the experiment. Extreme weather conditions, such as heavy rain or typhoons, were excluded from the experiment. The formal experiments were conducted from November 25th, 2020, to January 26th, 2021. This study received ethical approval from Tsinghua University.

Fig. 3. Two examples of extracted images and semantic segmentation result.

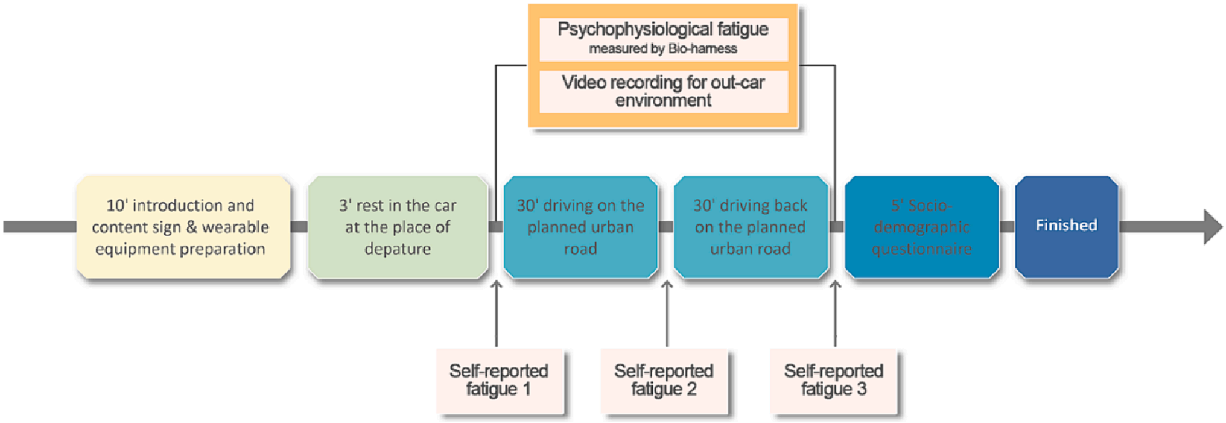

Fig. 4. Procedure of experiment.

2.4. *Statistical analysis*

Results of socio-economic demographic characteristics, drivers' fatigue, and environmental features were first presented using descriptive statistics. Bivariate correlation analysis between greenness and other environmental features was conducted. Next, the impact of greenness on drivers' psychophysiological fatigue was examined in two steps: (1) modeling the association of the mean greenness with psychophysiological fatigue, as measured by the mean heart rate during one hour of driving, and (2) modeling the association of variation in greenness with psychophysiological fatigue. Each step included three hierarchical linear regression models and controlled for other confounding factors. The first model (Model 1) included only socio-economic demographic factors, the second model (Model 2) included all factors of Model 1 as well as the environmental features, and the last model (Model 3) included roadside greenness and all factors of Model 2. The inclusive variables for all models were refined with the variance inflation factor criterion (VIF) $\geq$ 4 to remove multicollinearity from the regression (O'Brien, 2007). Finally, hierarchical linear regression models were also used to examine the associations between drivers' visual and muscular fatigue (measured as the mean value across three time periods) and roadside greenness.

3. Results

The results are presented in four parts. First, the descriptive statistics of drivers' socio-demographic backgrounds are reported. Second, the descriptive statistics of drivers' fatigue and the environmental characteristics of driving routes are reported. Third, the impacts of environmental features on drivers' psychophysiological fatigue are reported. Finally, the impacts of environmental features on drivers' visual and muscular fatigue are reported.

3.1. *Descriptive statistics of participants' socio-economic and demographic characteristics*

Out of the 41 recruited participants, 82.3 % (n = 34) successfully completed all driving tasks, resulting in 34 complete data sets for the final analysis. The participant pool exhibited a balanced gender distribution, with 47.06 % females and 52.94 % males. All participants reported holding a driver's license for at least two years, and 64.71 % indicated they had at least six years of driving experience. A considerable percentage of participants drove multiple times per day (79.41 %), drove for more than 20 min each day (88.24 %), and covered over 5000 km in the past year (91.18 %). Only one participant (97.06 %) reported a history of poor driving performance, with additional details provided in Table 1.

3.2. *Descriptive statistics of three types of driving fatigue, greenness, and other environmental features*

3.2.1. *Psychophysiological fatigue, visual fatigue, and muscular fatigue*

Overall, drivers' psychophysiological fatigue, as indicated by heart rate, increased with driving time, and demonstrated several distinct trends among seven driving routes. Both visual and muscular fatigue levels displayed significant increases after 30 and 60 min of driving when compared to baseline fatigue levels.

3.2.2. *Mean and variation of proportion of greenness and other environmental features in the driving environment*

Green landscapes (greenness) represent a substantial portion of urban road scenes (M = 32.49 %, SD = 5.82 %), with a range of 19.79 % to 46.28 %, signifying a moderately low to moderately high percentage of greenness. Among other environmental features, the sky occupies the largest percentage of urban road scenes (M = 33.33 %, SD = 9.72 %), followed by road surfaces (M = 13.10 %, SD = 6.09 %) and buildings (M = 9.87 %, SD = 4.29 %). Other environmental features comprise a considerably smaller proportion of

Table 1
Descriptive statistics of socio-economic and demographic characteristics.

Measures	N	%	Measures	N	%
Sex			**Marital status**		
Male	18	52.94 %	Divorced/ Separate/ Widowed	5	14.71 %
Female	16	47.06 %	Married/ Cohabitation	20	58.82 %
			Never married	9	26.47 %
Age			**Family member**		
25–30	9	26.47 %	1	2	5.88 %
31–35	8	23.53 %	2	2	5.88 %
36–40	12	35.29 %	3	10	29.41 %
41–45	4	11.76 %	4	10	29.41 %
46–50	1	2.94 %	5	8	23.53 %
			6	1	2.94 %
			≥7	1	2.94 %
Education level			**Monthly household income** (Chinese Yuan)		
Primary School and below	1	2.94 %	<5000	5	14.71 %
Junior	1	2.94 %	5000–9999	13	38.24 %
Secondary School	8	23.53 %	10,000–14,999	10	29.41 %
Diploma	6	17.65 %	15,000–19,999	3	8.82 %
≥Three-year college	18	52.94 %	20,000–24,999	1	2.94 %
			≥25,000	2	5.88 %
Year (s) holding a driver license (driving experience)			**How often have you been convicted of any moving violations (e.g., violations of parking or traffic lights)?**		
2–5	8	23.53 %			
6–10	13	38.24 %	0 time	15	44.12 %
11–15	7	20.59 %	1–5 times	18	52.94 %
15–20	5	14.71 %	6–10 times	1	2.94 %
>20	1	2.94 %			
Year (s) driving actually			**How often have you involved accidents in your traffic violation?**		
1–5	12	35.29 %			
6–10	10	29.41 %	0 time	30	88.24 %
11–15	9	26.47 %	1–2 times	4	11.76 %
16–20	3	8.82 %			
>20	0	0.00 %			
How often do you drive every day? (Frequency)			**Self-reported historical driving performance**		
Less than once a day	7	20.59 %			
1–2 times	17	50.00 %	bad	1	2.94 %
3–4 times	4	11.76 %	Moderate	10	29.41 %
5–6 times	2	5.88 %	good	8	23.53 %
7–8 times	1	2.94 %	Very good	13	38.24 %
More than 8 times	3	8.82 %	Extremely good	2	5.88 %
How long time do you spend on each drive on average?			**What extent of familiarity do you have to Liuzhou city roads?**		
<20 min	4	11.76 %	Very unfamiliar	3	8.82 %
20–40 min	19	55.88 %	Unfamiliar	14	41.18 %
41–60 min	8	23.53 %	Moderate familiar	11	32.35 %
61–80 min	3	8.82 %	Familiar	4	11.76 %
>80 min	0	0.00 %	Very familiar	2	5.88 %
How long have you driven in the last year?					
0–5000 km	3	8.82 %			
5001–10,000 km	9	26.47 %			
10,001–15,000 km	10	29.41 %			
15,001–20,000 km	1	2.94 %			
20,001–25,000 km	0	0.00 %			
>25,000 km	9	26.47 %			

Note: 1 United States Dollar = 6.45 Chinese Yuan in 2021.

Table 2
Statistical descriptions for mean proportions for greenness and other environmental features across seven driving routes.

	Minimum	Maximum	Mean	Std. Deviation
Greenness	19.79 %	46.28 %	32.49 %	5.82 %
Buildings	3.65 %	22.96 %	9.87 %	4.29 %
Traffic lights	0.04 %	0.16 %	0.09 %	0.02 %
Traffic signs	0.33 %	0.89 %	0.52 %	0.10 %
Sky	12.45 %	55.24 %	33.33 %	9.72 %
Roads	1.16 %	23.68 %	13.10 %	6.09 %
Traffic vehicles	3.49 %	14.55 %	7.35 %	1.99 %
Pedestrians	0.08 %	1.55 %	0.53 %	0.36 %

urban road scenes (Table 2).

Greenness exhibited the highest variation in road environments ($M = 18.66$ %, $SD = 2.61$ %), followed by the sky ($M = 14.62$ %, $SD = 2.43$ %), vehicles ($M = 11.68$ %, $SD = 2.79$ %), buildings ($M = 10.32$ %, $SD = 2.36$ %), and roads ($M = 5.48$ %, $SD = 1.67$ %). Variations in other environmental features were considerably smaller (Table 3).

3.2.3. Correlation analysis between greenness and other environmental features

The bivariate correlation analysis was performed and is illustrated in Fig. 5. Most correlations between greenness and other environmental features were either low (0.30–0.50) or moderate (0.50–0.70), indicating a minimal risk of collinearity issues. Similar low or moderate correlations were observed among other environmental features. A strong correlation existed between the mean and variation of greenness, which is reasonable as a higher mean level of greenness is likely associated with increased diversity in plant species, sizes, and spatial configurations. However, it is not valid to assert that the mean of greenness is more important than its variation or vice versa. In other words, dismissing the potential for both to significantly impact psychophysiological fatigue is not justifiable. Consequently, the analysis and discussion will be conducted for both greenness variables.

3.3. Impacts of greenness on drivers' psychophysiological fatigue

3.3.1. The relationship between mean proportion for greenness and drivers' psychophysiological fatigue

By employing three hierarchical regression models, we identified three layers of pertinent associations (Table 4). After incorporating mean proportion of greenness into the hierarchical model (model 3), the results indicated that a higher level of greenness was significantly associated with reduced driving fatigue ($\beta = -3.24$, $p < 0.01$, adjusted $R^2 = 0.22$; Fig. 6). This result demonstrated that driving-irrelevant greenness significantly contributed to the model fit, suggesting that greenness plays a vital role in alleviating driver fatigue after controlling for impacts of other environmental features, socio-economic factors, demographic factors, and other background factors.

3.3.2. The relationship between variation proportion for greenness and drivers' psychophysiological fatigue

Which and to what extent did variation proportion for greenness influence drivers' psychophysiological fatigue was investigated by adopting the same set of hierarchical regression analysis. The result of model 3 in Table 5 showed that variation of greenness played a significant role in reducing drivers' psychophysiological fatigue ($\beta = -2.77$, $p < 0.05$, adjusted $R^2 = 0.25$; Fig. 7) after controlling for impacts of other environmental features, socio-economic factors, demographic factors, and other background factors.

3.4. Impacts of greenness on drivers' visual and muscular fatigue

Whether and to what extent did roadside greenness impact visual and muscular fatigue? After fitting greenness into Model 3, the result showed that greenness was non-significantly associated with visual and muscular fatigue (Appendix Table A and Table B).

4. Discussion

In this study, we obtained three key findings: (1) a higher mean level of roadside greenness resulted in a lower level of psychophysiological fatigue, (2) a greater variation of roadside greenness resulted in a decreased level of psychophysiological fatigue, and (3) neither the mean nor the variation of roadside greenness demonstrated a significant association with visual and muscular fatigue. In the following section, we analyze and interpret these findings and offer recommendations for road landscape planning and design. Lastly, we address the study's limitations and provide insights for future research.

It is crucial to note that our interpretations and discussions of the findings are relevant to a moderate range of mean and variation in greenness, which may represent the greenness of urban roads in a great number of contemporary cities worldwide. Consequently, these insights may not apply to urban roads with extremely low or high levels of mean and variation in greenness.

4.1. Why a higher level of mean proportion of greenness may reduce psychophysiological fatigue?

A major finding of this study is that a higher level of greenery significantly reduces driver psychophysiological fatigue. However, a

Table 3
Statistical descriptions of variation proportion for greenness and other environmental features across seven driving routes.

	Minimum	Maximum	Mean	Std. Deviation
Greenness	13.75 %	27.27 %	18.66 %	2.61 %
Buildings	5.74 %	20.96 %	10.32 %	2.36 %
Traffic lights	0.10 %	0.41 %	0.20 %	0.06 %
Traffic signs	0.62 %	1.62 %	0.92 %	0.17 %
Sky	9.66 %	23.44 %	14.62 %	2.43 %
Roads	1.23 %	9.33 %	5.48 %	1.67 %
Pedestrians	0.25 %	2.87 %	1.03 %	0.48 %
Vehicles	5.38 %	25.25 %	11.68 %	2.79 %

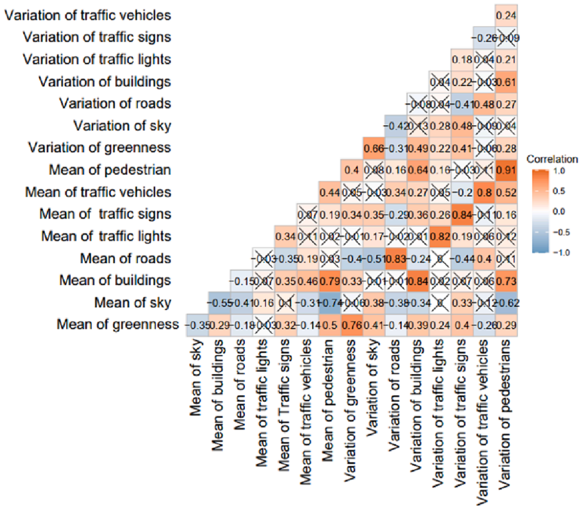

Fig. 5. Correlation analysis between variables of greenness and other environmental features. The X indicates non-significant correlation ($p \geq 0.05$).

concern with simulated driving experiments is that they may induce lower arousal compared to real-world urban roads, which are characterized by complex and confounding factors. Consequently, researchers suggested that findings of simulated driving experiment cannot fully represent the impacts of greenness on the drivers' mental and physical conditions in real urban roads (Jiang et al., 2020). The present study corroborates and extends previous findings from simulated driving experiments, supporting the positive impact of greenery on driver psychophysiological fatigue, as also observed in on-site driving experiments (Fitzpatrick, Samuel, & Knodler, 2016; Van Treese et al., 2018).

What is the specific mechanism that can explain the psychological fatigue relief effect of urban roadside greenness? Driving on urban roads is an activity that necessitates drivers to analyze environmental information rapidly and accurately to constantly make quick and rational decisions. This process demands continuous directed attention, which could easily trigger drivers' psychophysiological fatigue. Numerous previous studies in environmental psychology have consistently discussed the effects of exposure to greenness or natural environments on alleviating psychophysiological fatigue (e.g., Jiang, Larsen, Deal, & Sullivan, 2015; Jiang, Schmillen, & Sullivan, 2019; Kaplan, 1995). Specifically, Attention Restoration Theory (ART) posits that green landscapes, with their rich and captivating stimuli, facilitate the restoration of directed attention by mainly consuming invulnerable attention. In contrast, urban elements, characterized by artificial stimuli, can significantly deplete directed attention thus inducing psychophysiological fatigue.

Consequently, urban roadside greenery has the potential to harness the restorative power of nature in mitigating psychophysiological fatigue (Berman, Jonides, & Kaplan, 2008; Kaplan, 1995). This finding not only supports Attention Restoration Theory, but also indicates that the positive effects of landscape greenness on human psychophysiological fatigue can be realized even while individuals are engaged in demanding tasks, such as driving on urban roads.

4.2. Why a higher level of variation proportion of greenness may reduce psychophysiological fatigue?

Another major finding of this study suggests that a higher level of variation in greenness along urban roads can lead to a decrease in drivers' psychophysiological fatigue. In comparison to monotonous green landscapes, those with a higher level of variation are often preferred due to their resemblance to more naturalistic settings (Herzog & Kropscott, 2004; Kaplan & Kaplan, 1989). A more naturalistic landscape typically comprises various plants with a greater diversity of species, sizes, ages, and spatial configurations. Numerous studies propose that more naturalistic greenspaces can elicit enhanced relief of psychophysiological fatigue (e.g., Chang et al., 2023; Dean, van Dooren, & Weinstein, 2011; Fuller, Irvine, Devine-Wright, Warren, & Gaston, 2007). Consequently, it is reasonable to suggest that a higher level of variation in greenness may facilitate greater alleviation of psychophysiological fatigue.

The habituation process and the orienting response from the field of psychophysiological science can also help explain this finding (Mackworth, 1969). The central nervous system tends to habituate its reactions to repetitive and homogeneous environmental stimulation. The desynchronization of brain activity tends to diminish and eventually disappear after repeated presentation of the same stimuli, as demonstrated by Sharpless and Jasper (1956, see Davies & Parasuraman, 1982). The repetitive nature of sensory stimulation under monotonous conditions habituates the neural response and thereby explains the progressive decline in detection rate found over time during vigilance tasks (Thiffault & Bergeron, 2003). In contrast, a change in the presentation of the stimulation leads to dishabituation, or the immediate restoration of the response (Mackworth, 1969). Thus, the ability to maintain sustained attention on a road environment with unchanged greenness over a prolonged period tends to decrease with activation and increase with fatigue (O'Hanlon & Kelley, 1977; Xu & Zhao, 2023). Conversely, greater variation in greenness can lead to temporary increases in arousal and attention, indicated by a lower level of psychophysiological fatigue.

Table 4
The hierarchical linear regression analysis for psychophysiological fatigue (mean proportion of greenness and other environment features as independent variables).

Model Predictors	Model 1					Model 2					Model 3				
	β	Std. Error	t value	p value		β	Std. Error	t value	p value		β	Std. Error	t value	p value	
Intercept	79.28	0.88	89.68	<2e-16	***	79.25	0.89	88.97	<2e-16	***	79.16	0.88	90.13	<2e-16	***
Sex	−3.83	1.17	−3.26	0.001	**	−3.75	1.19	−3.15	0.002	**	−3.73	1.17	−3.18	0.002	**
Age	2.76	1.59	1.74	0.084		3.02	1.64	1.84	0.067		3.27	1.62	2.02	0.045	*
Marital Status	2.98	1.15	2.59	0.010	*	3.42	1.19	2.88	0.004	**	3.20	1.17	2.73	0.007	**
Family Member	0.26	1.14	0.23	0.821		−0.66	1.27	−0.52	0.602		−0.12	1.27	−0.10	0.922	
Monthly household income	−1.09	1.01	−1.08	0.283		−0.59	1.05	−0.56	0.577		−1.02	1.05	−0.98	0.330	
Driver license	−4.94	1.49	−3.32	0.001	**	−4.94	1.52	−3.26	0.001	**	−5.23	1.50	−3.49	0.001	***
Frequency Day	−1.82	1.20	−1.52	0.131		−1.39	1.25	−1.12	0.265		−1.81	1.24	−1.46	0.146	
Drive Time	−4.74	1.31	−3.63	0.000	***	−3.84	1.44	−2.67	0.008	**	−4.75	1.46	−3.26	0.001	**
Distance A Year	−0.32	1.34	−0.24	0.809		−1.36	1.52	−0.90	0.370		−0.81	1.51	−0.54	0.594	
Violations	1.52	1.21	1.25	0.211		0.11	1.48	0.07	0.941		1.28	1.53	0.84	0.405	
Accidents in Violation	2.95	1.07	2.75	0.006	**	3.58	1.15	3.12	0.002	**	3.31	1.14	2.91	0.004	**
Performance Year	0.95	1.19	0.80	0.428		0.84	1.20	0.70	0.486		1.16	1.19	0.98	0.329	
Familiarity	1.03	1.23	0.84	0.402		1.45	1.25	1.16	0.249		1.26	1.24	1.02	0.309	
Smoking	4.23	1.29	3.27	0.001	**	3.71	1.33	2.78	0.006	**	4.43	1.34	3.30	0.001	**
Drinking	−0.05	1.21	−0.04	0.970		0.74	1.30	0.57	0.570		0.06	1.31	0.05	0.963	
Mean of sky						0.47	1.55	0.30	0.762		−2.07	1.81	−1.15	0.253	
Mean of roads						−2.13	1.44	−1.48	0.141		−2.66	1.44	−1.85	0.065	
Mean of buildings						−0.87	1.65	−0.53	0.600		−1.33	1.64	−0.81	0.417	
Mean of traffic vehicles						1.04	1.11	0.94	0.350		0.19	1.15	0.16	0.872	
Mean of traffic signs						0.41	1.14	0.36	0.717		1.36	1.18	1.16	0.248	
Mean of traffic lights						−0.42	1.02	−0.41	0.682		−0.38	1.00	−0.38	0.706	
Mean of greenness											−3.24	1.23	−2.63	0.009	**
Multiple R-square/Adjusted R-square	**0.25/0.20**					**0.27/0.19**					**0.30 /0.22**				

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

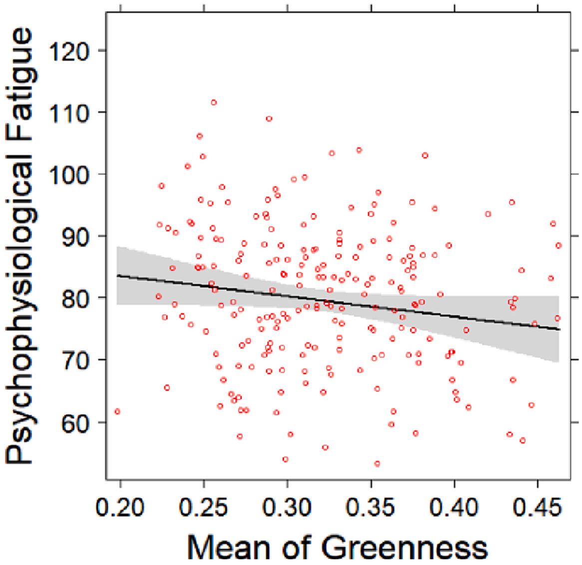

Fig. 6. The plot illustrates the significant relationship between the mean proportion of greenness and psychophysiological fatigue after controlling for covariates ($\beta = -3.24$, $p < 0.01$).

4.3. Greenness in relation to visual and muscular fatigue

The third major finding indicates that both the mean and variation of greenness exhibit nonsignificant impacts on visual and muscular fatigue. There are two possible explanations for these results.

The first possible explanation is that visual fatigue and muscular fatigue might be less easily influenced by roadside greenness. Previous studies suggest that drivers' visual and muscular fatigue are heavily influenced by the act of driving itself, but much less so by the environment outside the lanes (Campagne et al., 2004; Grandjean, 1979; Lal & Craig, 2001). Specifically, drivers' actions or responses are primarily affected by traffic lights, signs, pedestrians, and other vehicles within the lanes, rather than roadside greenness (Mandal, Li, Wang, & Lin, 2016). Thus, two possibilities arise here and should be further investigated in future studies: First, it is possible that roadside greenness may not have a significant impact on visual and muscular fatigue, regardless of how much and how diverse greenness provided. Second, and perhaps more plausible, higher levels of mean and variation in greenness that exceed the maximum values tested in this study may be necessary to significantly alleviate visual and muscular fatigue.

Another possible reason for the nonsignificant effects of greenness on visual and muscular fatigue may be attributed to the inherent limitations of self-reported measures. Numerous studies have reported that perceived health benefits of greenness often mismatch the objectively measured health benefits of greenness (e.g., Chang et al., 2021; Di Milia et al., 2011; Jiang et al., 2014; Jiang, Li, Larsen, & Sullivan, 2016; Reece, Bornioli, Bray, & Alford, 2022). Researchers suggest that self-reported well-being is primarily influenced by the objects on which the observer focuses, while psychophysiological measures are related to both attended and unattended objects (Reece et al., 2022). Furthermore, researchers propose that self-reported fatigue may be biased by differences in gender, social self-esteem, and socio-economic status. For instance, compared to females, males are less likely to report negative mental or physical health status (Jiang et al., 2014). Consequently, future studies should scrutinize and address these potential biases by adopting objective measures of visual and muscular fatigue.

4.4. Familiarity of road environments and its potential impacts on the results

Moreover, some may argue that this experiment, involving two-way driving tasks, could increase familiarity during the return journey, potentially biasing the findings. In addition, drivers may have different levels of familiarity for different routes.

Researchers suggest that individuals experience elevated cognitive workload and fatigue when engaging in novel tasks or situations (Sweller, 1988); however, as familiarity increases, cognitive workload typically decreases. This process may impact the relationships between roadside landscapes and fatigue. Familiarity may reduce physiological arousal and heart rate by alleviating concerns over route uncertainty and frequent lane changes (Harms, Burdett, & Charlton, 2021), while unfamiliarity with road conditions can increase anxiety, risk perceptions, and the need for frequent lane changes, resulting in greater physical exertion and elevated heart rates (Brookhuis & de Waard, 2010).

Nonetheless, we contend that the issue of familiarity has been adequately considered and controlled in the present study thus the bias caused by that issue may be minor. First, participants were local residents who frequently drove in the site city and the city only have a small number of main urban roads, thus they may have sufficient familiarity of the roadside environments tested in this study (Charlton & Starkey, 2011). Second, as urban residents in other modern cities, urban residents in the site city typically engaged in two-way driving between home and work or other destinations, making this a familiar task for them (Williamson, Gold, Stiles, & Brooks,

Table 5
The hierarchical linear regression analysis for psychophysiological fatigue (variation proportion of greenness and other environment features as independent variables).

Model Predictors	Model 1					Model 2					Model 3				
	β	Std. Error	t value	p value		β	Std. Error	t value	p value		β	Std. Error	t value	p value	
Intercept	79.28	0.88	89.68	<2e-16	***	79.22	0.87	91.43	<2e-16	***	79.17	0.86	92.00	<2e-16	***
Sex	−3.83	1.17	−3.26	0.001	**	−3.67	1.15	−3.19	0.002	**	−3.70	1.14	−3.25	0.001	**
Age	2.76	1.59	1.74	0.084		3.23	1.59	2.04	0.043	*	3.20	1.58	2.03	0.044	*
Marital Status	2.98	1.15	2.59	0.010	*	2.98	1.14	2.62	0.010	**	2.95	1.13	2.61	0.010	**
Family Member	0.26	1.14	0.23	0.821		0.38	1.24	0.31	0.756		0.27	1.23	0.22	0.829	
Monthly household income	−1.09	1.01	−1.08	0.283		−1.19	1.03	−1.16	0.249		−1.25	1.02	−1.23	0.221	
Driver license	−4.94	1.49	−3.32	0.001	**	−5.20	1.48	−3.52	0.001	***	−5.12	1.47	−3.50	0.001	***
Frequency Day	−1.82	1.20	−1.52	0.131		−1.81	1.22	−1.48	0.141		−1.99	1.22	−1.63	0.104	
Drive Time	−4.74	1.31	−3.63	0.000	***	−5.42	1.41	−3.84	0.000	***	−5.38	1.40	−3.84	0.000	***
Distance A Year	−0.32	1.34	−0.24	0.809		−0.55	1.47	−0.38	0.706		−0.66	1.46	−0.45	0.653	
Violations	1.52	1.21	1.25	0.211		1.79	1.38	1.29	0.198		1.88	1.37	1.37	0.173	
Accidents in Violation	2.95	1.07	2.75	0.006	**	3.43	1.10	3.12	0.002	**	3.43	1.09	3.14	0.002	**
Performance Year	0.95	1.19	0.80	0.428		1.32	1.18	1.12	0.265		1.36	1.17	1.16	0.249	
Familiarity	1.03	1.23	0.84	0.402		1.03	1.24	0.83	0.407		1.13	1.23	0.92	0.357	
Smoking	4.23	1.29	3.27	0.001	**	4.83	1.30	3.72	0.000	***	4.75	1.29	3.68	0.000	***
Drinking	−0.05	1.21	−0.04	0.970		−0.09	1.27	−0.07	0.942		−0.20	1.26	−0.16	0.875	
Variation of sky						−1.47	1.23	−1.20	0.232		0.08	1.45	0.06	0.955	
Variation of roads						−3.59	1.25	−2.87	0.005	**	−3.74	1.24	−3.00	0.003	**
Variation of buildings						−3.63	1.33	−2.74	0.007	**	−2.50	1.44	−1.74	0.084	
Variation of traffic lights						−1.68	0.97	−1.73	0.085		−1.53	0.97	−1.58	0.115	
Variation of traffic signs						1.21	1.17	1.03	0.303		1.29	1.16	1.11	0.268	
Variation of traffic vehicles						0.94	1.03	0.92	0.360		0.99	1.02	0.97	0.334	
Variation of pedestrians						3.46	1.35	2.56	0.011	*	3.54	1.34	2.64	0.009	**
Variation of greenness											−2.77	1.40	−1.98	0.049	*
Multiple R-square/	**0.25/**					**0.31/**					**0.33/**				
Adjusted R-square	**0.20**					**0.24**					**0.25**				

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

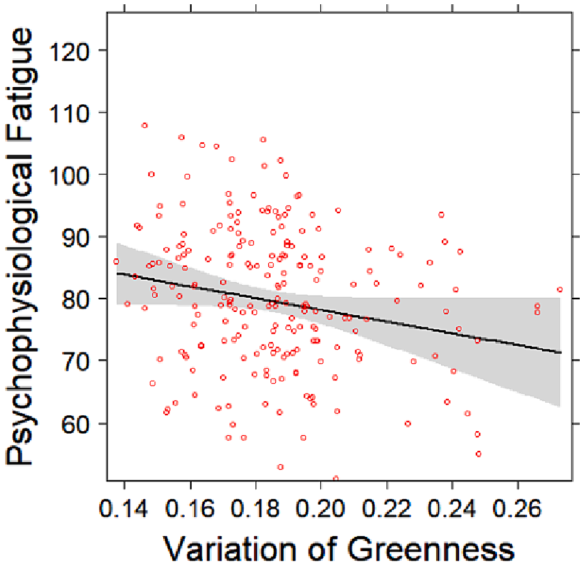

Fig. 7. The plot illustrates the significant relationship between the variation proportion of greenness and psychophysiological fatigue after controlling for covariates ($\beta = -2.77$, $p < 0.05$).

2011). Third, this study adopted a within-subject experimental design, in which every participant completed tasks for all routes in a random manner, effectively mitigating biases caused by learning effects and familiarity levels of road environments. Fourth, the self-reported familiarity level of road environments was controlled in the hierarchical regression analysis, and its effects were found to be non-significant. Lastly, the three types of fatigue did not exhibit a consistent plateau or decrease between the first and second halves of the task, suggesting that changes in familiarity between these halves did not significantly bias the results.

4.5. Suggestions for landscape planning and design of urban road

Driving on urban roads often induces significant psychophysiological fatigue. Except for regulations that prohibit fatigued driving, transportation departments should also engage in forming and building healthy driving environments to mitigate psychophysiological fatigue, therefore improving driving safety. Three main suggestions of landscape planning and design of urban roads are presented as follows.

First, policymakers, transportation planners, and designers should be aware that roadside green landscapes may significantly relieve psychophysiological fatigue while driving on urban roads. Thus, focusing solely on artificial infrastructure, such as road and other transportation facilities, is insufficient to create a safe and healthy transportation system for numerous citizens. Roadside green landscapes should also be considered as an essential part of the transportation infrastructure, but not a trivial decoration (Jiang et al., 2020).

More visual greenness along a roadside provides a visual and psychological buffer to the artificially built environment and evokes significantly lower levels of psychophysiological driving fatigue (Chen, Chen, & Du, 2022). This shows that a higher level of greenness helps to promote drivers' health and traffic safety, since negative mental states can lead to mental and physical illness, as well as a higher risk of accidents and fatalities (Antonson, Mårdh, Wiklund, & Blomqvist, 2009; Chiang et al., 2022; Healey & Picard, 2005). Therefore, urban greenness should be seen by drivers as much as possible in promoting drivers' health and traffic safety.

Finally, the configuration, size, and biodiversity of roadside greenness are also of great importance, because a higher variation of roadside greenness can elicit a greater relief of psychophysiological fatigue. This suggests that installation of trees and other vegetations in a naturalistic manner can generate a greater positive effect on relieving fatigue than planting in a regular and homogenous manner. Moreover, green landscapes along the urban roads should be regarded as a living and dynamic system, so long-term monitoring and management of their life cycle and form is critical (Chen & Webster, 2022).

4.6. Limitations and future studies

This study is among the first to investigate the impacts of roadside greenness on driver's fatigue in real urban roads. Five major limitations need to be clearly outlined here, and they may serve as recommendations for future research.

First, the depletion of drivers' directed attention largely depends on the duration of the driving task (Li, Chen, Peng, & Wu, 2017; Philip et al., 2005; Zhao, Zhao, Liu, & Zheng, 2012), indicating that different durations of driving along urban roads may have varying impacts on the three types of fatigue. The present study adopted a one-hour duration because it is close to a common driving time for urban residents' daily life (Feng, Dijst, Prillwitz, & Wissink, 2013; Fraine, Smith, Zinkiewicz, Chapman, & Sheehan, 2007). However, to gain a more comprehensive understanding, future research should explore the effects of shorter or longer driving durations on driver fatigue.

Second, the present study adopted heart rate as the measure of psychophysiological fatigue. Although heart rate has been proven as a reliable indicator of that type of fatigue, many other measures can be used in future study to further enhance the validity of findings. We suggest that more objective measures of multiple types of fatigue can be used in future studies, such as cognitive tests (Jiang et al., 2018), eye blink rates (Yin, Liu, Hao, Yang, & Feng, 2022), electroencephalograms (Chang & Chen, 2005), and electromyography (Vøllestad, 1997). Moreover, this study objectively measured psychophysiological fatigue by an advanced device but measured visual and muscular fatigue by self-reported items in a questionnaire. The difference of these measurements may induce a methodological bias to the findings. Therefore, we suggest future studies use both subjective and objective measures for all three types of driving fatigue to mitigate possible biases.

Third, although this study controlled the influence of socio-economic and demographic characteristics on the results to yield generalized findings for the public, future studies may further consider comparing the impacts of roadside landscape on driving fatigue by dividing drivers into different groups according to gender, age, or driving experience (Chen & Chen, 2011; Lam, 2002; Sun, Liu, Chen, & He, 2019). In addition, it is advised to recruit more drivers with a greater diversity of socio-economic and demographic characteristics to increase the validity and reliability of the findings.

Fourth, although we have considered the interactive effects between roadside greenness and other road environment factors, there may be additional mediating or complex pathways that contribute to driving fatigue (Anciaes, 2023). Further investigations and the application of advanced methods in future studies are necessary to gain a better understanding of the specific mechanisms and interactions involved (Antonson et al., 2009; Lovell, Wheeler, Higgins, Irvine, & Depledge, 2014). These efforts will provide valuable insights into the underlying factors contributing to driving fatigue and inform the development of targeted interventions and strategies for promoting driver alertness and reducing fatigue-related risks.

Lastly, the roads in this study feature a moderate range of the mean and variation in greenness. Although this range may provide a reasonable representation of greenness for urban roads in many contemporary cities worldwide, it suggests that the findings of linear associations and interpretations may not be applicable for urban roads with significantly lower or higher greenness. We recommend that future studies investigate a broader range of greenness to further improve our understanding of its effects on driving fatigue in the context of urban roads.

5. Conclusion

This on-site experimental study reveals that a higher level of the mean and variation of urban roadside greenness has a greater effect on reducing drivers' psychophysiological fatigue. The findings encourage governments, professionals, and citizens as a whole to change their mindset: Green landscapes along urban roads do not merely possess aesthetic value; they also have significant impacts on drivers' health and safety. In other words, roadside greenness should not be regarded as a trivial decoration but as an essential element of transportation infrastructure (Jiang, Zhang & Sullivan, 2015; Jiang, He, Chen, Larsen, & Wang, 2020).

CRediT authorship contribution statement

Wenyan Xu: Visualization, Validation, Investigation, Formal analysis, Data curation, Writing – review & editing, Writing – original draft. **Jibo He:** Methodology, Resources, Funding acquisition. **Bin Jiang:** Conceptualization, Investigation, Formal analysis, Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2024.04.009.

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