Urban Forestry & Urban Greening 58 (2021) 126976

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Moderate is optimal: A simulated driving experiment reveals freeway landscape matters for driving performance

Bin Jiang [a,b,*], Jibo He [c], Jielin Chen [a,d], Linda Larsen [e]

[a] Virtual Reality Lab of Urban Environments and Human Health, HKUrbanlabs, Faculty of Architecture, The University of Hong Kong, Hong Kong
[b] Division of Landscape Architecture, Department of Architecture, The University of Hong Kong, Hong Kong
[c] Department of Psychology, Tsinghua University, China
[d] Department of Architecture, National University of Singapore, Singapore
[e] Smart Energy Design Assistance Center, University of Illinois at Urbana-Champaign, USA

A R T I C L E I N F O

Handling Editor: D Dexter Locke

Keywords:
Driving performance
Freeway landscape
Greenness
Complexity
Mental arousal
Mental restoration

A B S T R A C T

Driving on freeways is a daily activity across the world. Poor driving performance on freeways can cause severe injuries and deaths. However, few studies have examined whether and to what extent different types of freeway landscapes influence driving performance. A simulated driving task was designed to measure the impacts of six types of freeway landscape on 33 participants' driving performance. Each participant completed a driving experiment with six blocks of 90-minute driving sessions in a random sequence. During the experiment, participants' driving performance was measured through eight parameters. A set of repeated-measure one-way ANOVA analyses show that landscapes with three-dimensional branch and foliage (shrub & tree) were generally more beneficial for driving performance than barren (concrete-paved ground) or low green landscape conditions (turf). Furthermore, a repeated-measure two-way ANOVA analysis of four conditions with vertical green foliage (two shrub and two tree conditions) showed moderate levels of greenness and complexity are optimal for driving performance.

1. Introduction

Extensive empirical research has shown that landscapes can significantly impact human cognitive and behavioral performance. One important setting that has rarely been explored is freeway landscapes. Freeways are defined as highways with full control of access and are common infrastructure in many countries (United States Department of Transportation [USDOT] & Federal Highway Administration [FHWA], n.d.; Beria et al., 2015). This setting is especially important because many people drive for long periods of time on freeways every day. A poor freeway landscape setting might contribute to poor driving performance, dangerous driving behaviors and traffic accidents.

This study is part of a larger project in which the authors used simulated driving environments to examine the impacts of six types of freeway landscapes on drivers' psychophysiological and behavioral states. While the current study explores the relationship between freeway landscapes and driving performance, our previous research for this project examined the impact of freeway landscapes on mental restoration (Jiang et al., 2020). The findings of the previous studie provide emprical evidence and logic foundation for this study. Moreover, we compare the results of these two studies in the discussion.

1.1. Background

According to a 2018 World Health Organization (WHO) report, road traffic accidents cause more than 1.25 million deaths each year worldwide and are projected to be the seventh leading cause of death by 2030 (World Health Organization [WHO], 2018). They are also the major cause of death for people ages 15–29. Previous studies have asserted that around 95 % of car accidents are caused by human factors, and human error is identified as the most important factor (Sabey and Taylor, 1980; Ulleberg and Rundmo, 2003). While autonomous vehicles have the potential to greatly reduce human error and traffic accidents, they are still in their infancy and prone to accidents (Demmel et al., 2019).It is unlikely that autonomous driving will replace human driving in the near future (Boudette and Vlasic, 2017; Marx, 2018). It is likely that driving along freeways will continue to be a daily activity for numerous people worldwide in the next few decades. It is therefore

* Corresponding author at: 614 Knowles Building, The University of Hong Kong, Pokfulam Road, Hong Kong Special Administrative Region.
E-mail address: jiangbin@hku.hk (B. Jiang).

https://doi.org/10.1016/j.ufug.2021.126976
Received 9 October 2019; Received in revised form 27 December 2020; Accepted 30 December 2020
Available online 7 January 2021
1618-8667/

imperative to address factors that impact driving performance.

1.2. Existing literature on roadside landscapes and driving performance: knowledge gaps

There are several studies in the fields of transportation and psychology examining the impact of roadside landscapes on driving performance, but the findings are contradictory and inconclusive. On one hand, some studies have found that the presence of green landscapes contributes positively to driving performance. For example, studies have found that roadside elements like trees positively contribute to drivers' perceptions of safety and play a role in controlling driving speed. Both the presence of trees along the roadside and decreased offset distance of trees from the roadside have been shown to be associated with decreased average driving speed (Antonson et al., 2009; Calvi, 2015; Fitzpatrick et al., 2014, 2016; van der Horst and de Ridder, 2007; Wolf, 2006). One study found that drivers perceived tree landscapes along streets to be safer in both urban and suburban settings. In suburban settings, driving speeds were significantly lower in settings with trees (Naderi et al., 2008). In another study, the absence of trees was associated with more frequent grasps of the steering wheel (Antonson et al., 2009), suggesting greater difficulty in controlling the vehicle.

In contrast, other studies have reported negative or neutral associations between roadside landscapes and driving behavior. Decreased clear zone width and spacing between roadside trees was found to arouse drivers' sense of risk and prompt them to move away from the edge of the road (Calvi, 2015; Fitzpatrick et al., 2016). Roadside trees were found to be visual obstacles or distractions for drivers (Calvi, 2015; Van Treese et al., 2018). However, two additional studies reported that roadside vegetation density and height were not significantly associated with decreased speed or deviations in lateral positioning (Fitzpatrick et al., 2016; Parwathaneni, 2016).

There are several significant knowledge gaps in the literature exploring roadside landscapes and driving performance. First, many studies are binary, comparing roads with or without trees, even when different types of trees are involved (e.g., Cassarino et al., 2019). Second, most studies only explore trees, ignoring other types of roadside vegetation such as shrubs, which are not as visible as trees, but not as invisible as mowed turf or concrete pavement (e.g., Naderi et al., 2008). Third, most experimental studies consider only short driving times, although many drivers have long daily commutes (e.g., Alonso et al., 2012; Antonson et al., 2009; Calvi, 2015; Fitzpatrick et al., 2014). Fourth, only a few studies have examined the impact of landscapes on driving performance in the context of freeway driving, where regulations and speeds are considerably different from local roads and streets (e.g., Farahmand and Boroujerdian, 2018; Thiffault and Bergeron, 2003; Wang et al., 2016a).

1.3. Greenness and complexity

Although many differences exist among landscape conditions, a review of theories and scientific evidence suggest two landscape features to be especially significant in the relationship between freeway landscapes and driving performance: greenness and complexity.

1.3.1. Greenness

Greenness is a widely recognized term in the field of Landscape Architecture and Environmental Psychology, referring to the general provision of perceivable green landscape features (trees, shrubs, or grass) in a site or area (e.g., Kaplan, 2001; Kuo and Sullivan, 2001a,b; Ulrich et al., 1991). Attention Restoration Theory (Kaplan, 1995) and Stress Reduction Theory (Ulrich, 1981) argue that the level of greenness in a physical environment is a critical factor that influences mental health and cognitive performance, and these theories are supported by many ground-breaking empirical studies (e.g., Berman et al., 2008; Jiang et al., 2019; Kaplan, 2001; Kuo and Sullivan, 2001a,b; Parsons, 1991; Taylor et al., 2002; Ulrich et al., 1991). These studies and many others have focused on reporting and interpreting the positive relationship between general greenness and mental health, rather than exploring specific characteristics of a landscape (e.g., type of vegetation or design characteristics). It is widely recognized that greenness in urban environments is a major indicator of mental health. Moreover, the overall level of greenness may be more influential for driving performance than type of vegetation because people who are driving at high speed may not visually perceive the type of vegetation or detailed features of plants as much as the overall volume of greenness at eye-level.

According to Attention Restoration Theory (Kaplan, 1995) and Stress Reduction Theory (Ulrich et al., 1991), landscapes with a higher level of greenness are more mentally restorative than landscapes with a lower level of greenness. Greenness is associated with stress reduction and attention restoration. From an evolutionary perspective, mental restoration is critical to humans' survival and prosperity, and so greener landscapes that bring mental restoration are preferred. This general positive association has been confirmed through many empirical studies in various urban environments (Bratman et al., 2015; DeWolfe et al., 2011; Jiang et al., 2016; Hartig et al., 2003; Li and Sullivan, 2016; Pati et al., 2008). Extrapolating this theory to freeway landscapes, greenness may positively influence driving performance because it facilitates attention restoration and stress reduction while barren landscapes do not.

It is unclear, however, whether green landscapes, which enhance mental restoration, will be associated with improved performance for demanding tasks like driving. Do people exposed to green landscapes who feel mentally restored have improved driving performance? Perhaps they do because they may be less stressed and better able to concentrate. However, it is also possible that mentally restorative freeway landscapes make drivers too relaxed or even sleepy, which may have a detrimental effect on driving performance (Cohen, 2011; Teigen, 1994; Yerkes and Dodson, 1908).

The Yerkes and Dodson (1908) may shed light on the possible relationship between greenness and driving performance. This law describes a nonlinear relationship between the level of arousal/restoration and task performance and has been validated through many environmental psychology studies. These studies, which use psychophysiological, neurological, and hormonal indicators of arousal and restoration, report that landscapes with no or low greenness often elicit more arousal than restoration, but landscapes with moderately high or high greenness often elicit more restoration than arousal (Jiang et al., 2014; Li and Sullivan, 2016; Parsons et al., 1998; Pati et al., 2008; Tang et al., 2017; Ulrich et al., 2003).

According to this law, an inverted U-shape model depicts the relationship between the level of arousal and performance of a demanding task. Low arousal (high mental restoration or relaxation) can make a person feel bored, sleepy, unfocused, and lacking motivation while high arousal (over stimulation) can lead a person to feel stressed, burnt out, and anxious, making it difficult to concentrate and make correct decisions. A moderate dose of arousal (not too relaxed, not too stimulated) elicits more optimal performance as the person is able to concentrate on the task, while not being too relaxed. Although some scientists have argued that Yerkes-Dodson's law is too simplistic, the law is widely accepted in the field of psychology and has been verified for the performance of demanding tasks through many experimental studies (e.g., Cohen, 2011; Teigen, 1994).

Applying this law to landscapes, zero or low levels of greenness (such as landscapes with concrete pavement or turf landscape) may be associated with high arousal or low restoration, leading to suboptimal performance while landscapes with a high level of greenness may be associated with low arousal or high restoration, also leading to suboptimal performance. Peak performance for a demanding task like driving at high speed may instead be associated with a moderate level of greenness, which may elicit a moderate level of arousal.

1.3.2. Complexity

Besides greenness, complexity (Ode et al., 2010) is another key landscape element that may influence performance. The complexity of a freeway landscape can be influenced by different factors, including species diversity, maintenance of vegetation, billboards, and many more. In this study, we focus on two elements that can influence structural complexity: diversity of plant species and spatial configuration. Compared to a regular (or named as “formal”) green landscape with little species diversity and evenly spaced same-size plantings, a randomly placed (or named as “naturalistic”) landscape with greater species diversity plantings typically has higher complexity (Jiang et al., 2018; Özgüner and Kendle, 2006; Yang et al., 2013). Based on our interpretation of the Yerkes-Dodson Law, we hypothesize that landscapes with higher complexity will elicit greater arousal as they are more visually stimulating, while those with low complexity will elicit less arousal. It is plausible that landscapes with moderate complexity may be associated with a more optimal driving performance.

While we use the Yerkes-Dodson’s Law to hypothesize that moderate greenness and moderate complexity in freeway landscapes may yield optimal driving performance, this hypothesis has yet to be tested. We also do not understand the interactive impacts of greenness and complexity on driving performance.

1.4. Central research questions

The knowledge gaps described above prevent developers, managers, and designers of transportation infrastructure from making evidence-based decisions on how to allocate public resources to promote driving performance. To fill these knowledge gaps, we ask three layers of research questions to reveal the impacts of freeway landscapes on driving performance. The barren landscape condition is used as a control condition for the first two questions:

Question 1: To what extent does driving performance differ for freeway drivers exposed to three landscape conditions with three distinct levels of greenness (barren, turf, shrub & tree)?

Question 2: To what extent does driving performance differ for freeway drivers exposed to six different roadside conditions (tree random, tree regular, shrub random, shrub regular, turf, and barren)?

Question 3: What are the independent and interactive impacts of greenness and complexity for the four conditions with two distinct levels of greenness and complexity (tree random, tree regular, shrub random, shrub regular)?

2. Methods

We used a simulated driving system to examine the impact of various landscapes on 33 participants’ driving performance during a prolonged driving task (90 min) (Seen et al., 2010; Sung et al., 2005). We used Esri CityEngine 2015® (version 2015; Environmental Systems Research Institute, 2015) to create six freeway landscape conditions (barren, turf, shrub- regular, shrub-random, tree-regular and tree-random), and implemented the OpenDS 4.5® system (Green et al., 2014; Math et al., 2013) to continuously measure each participant’s driving performance. Participants self-reported their driving performance seven times during the 90-minute experiment. The driving experiment is within-subject, meaning that each participant experienced all six freeway landscape conditions.

2.1. Experimental design

2.1.1. Six simulated driving environments and three categorizations

Simulated driving environments have been widely used in psychological and behavioral studies and their validity is well established (e.g., Hock et al., 2018; Antonson et al., 2009; Green et al., 2014; Math et al., 2013; Parsons, 1995). To simulate driving environments, we first constructed the 3D models in Esri CityEngine® (version 2015; Environmental Systems Research Institute, 2015), with the assistance of AutoCAD® (version 2016; Autodesk, 2016), Rhinoceros® (version 5; McNeel and Associates, 2017) and Grasshopper® (version 0.9.0076; Rutten, 2014) plugins. Next, we converted the constructed 3D models into an open-sourced driving simulation software, OpenDS® system (version 4.5; 2018, June) (Green et al., 2014; Math et al., 2013), with the assistance of Blender® (version 2.78c; Roosendaal, 2017) plugins. Each driving environment has a shared identical freeway infrastructure but a distinctive landscape setting.

Six types of landscape conditions were configured into the models: barren, turf, shrub-regular, shrub-random, tree-regular, and tree-random (Fig. 1). We use different categorizations for each of the three research questions proposed in this study. For Question 1, we divided the six conditions into three groups: 1. The barren condition has zero greenness; the curbside areas consist of a concrete-paved surface. 2. The turf condition has a low level of visible greenness; the curbside areas consist of turf. 3. The shrub & tree condition has a higher level of visible greenness because it provides three-dimensional branches and foliage, in addition to the turf. To answer Question 2, we explored the six landscape conditions independently to examine the differences among the six conditions and whether they follow the Yerkes-Dodson Law.

To answer question 3, we categorized the conditions according to two key features: greenness and complexity. Landscapes with trees have a moderately high level of greenness because trees are taller and take up a larger amount of a driver’s vision; landscapes with shrubs have less vertical greenness and therefore take up less of a driver’s field of vision. We consider them to have a moderate level of greenness. For complexity, shrubs or trees with random spatial configurations and multiple species have a moderate level of complexity while shrubs or trees with regular spatial configurations and a single species have a moderately low level of complexity. We therefore examined four landscape conditions: shrub regular, shrub random, tree regular, and tree random. Once again, the barren condition served as the control condition.

2.1.2. Detailed settings of the simulated driving environments

The curvy loop freeway we created has a midline length of 40,500 meters (roughly 132,900 feet), based on the midline length of similar freeways in typical urban districts, with high-rise and multi-story commercial, office, and residential buildings on both sides of the freeway. The freeway is a dual carriageway separated by a 3-meter wide central reservation (9.8 feet). Each carriageway has three lanes that are each 3 meters (9.8 feet) wide. We did not include other traffic, pedestrians, or driving signs to control for these variables. The simulated weather condition for all six conditions was set to partly cloudy. The greenbelts on both sides of the freeway are 10 meters wide (32.8 feet). The configurations of the central reservation and the greenbelts on both sides are the only difference among the six landscape conditions.

A speedometer function was included in the bottom right corner of the simulation screen so users could see their speed. The configuration of the freeway for the six conditions is also illustrated in top-view layout diagrams (Fig. 2).

For the barren scene, the central reservation and greenbelts on both sides are paved with concrete, while for the other five scenes (turf, shrub-regular, shrub-random, tree-regular and tree-random), the central reservation and greenbelts are paved with short and clean green grass.

For the shrub-regular scene, the shrub spacing on both sides of the freeway was set at 10 meters (30 feet) in accordance with the loading capability of the performance software environment. The shrubs were spaced in double rows, with 3.3 meters (10.8 feet) between the two rows and between the rows and the curb. The total number of shrubs was 16,000.

For the tree-regular scene, we reviewed relevant documents on tree spacing in large, international cities. We found that while standard tree

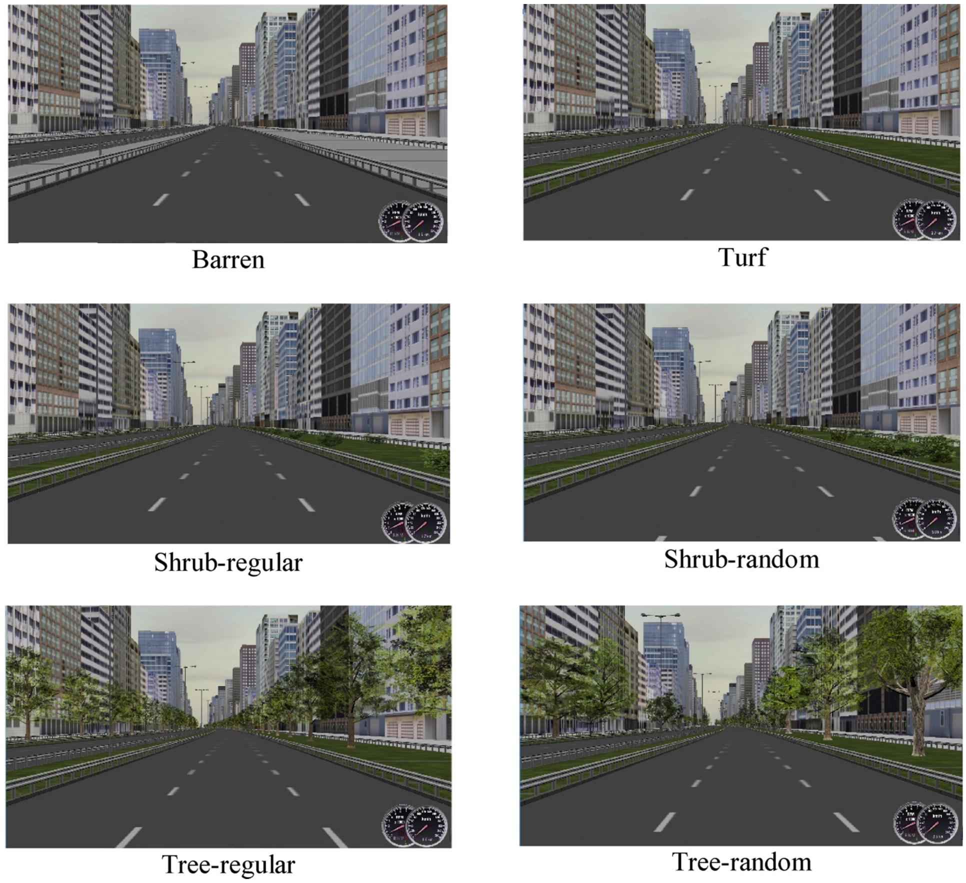

Fig. 1. Six types of landscape condition of a same spot on the freeway. *Note*: the allocation and size of shrubs and trees of random conditions constantly change along the freeway so figures of those conditions presented here might not fully reflect the average level of greenness and complexity.

spacing is not regulated in most international cities, minimum tree spacing is sometimes stipulated. For instance, in New York, the minimum distance between trees (trunk to trunk) is 6–9 meters (20–30 feet), depending upon the tree species and other local conditions (Bloomberg and Benepe, 2008; NYC Parks, 2016). Tree spacings of 15–18 meters (50–60 feet) are commonplace (Gilman, 2015), while for many cities, the minimum tree spacing ranges from 4.5 to 15 meters (15–50 feet) (Macdonald et al., 2006). Hence, for tree-regular scenes, we set the tree spacing in our model at 20 meters (60 feet). The trees were laid out linearly in a single row, 5 meters (16.4 feet) from the curb. The total number of trees allocated on both sides of the road was 4053, with residuals due to the curvy nature of the road.

We selected Buxus hybrids (also known as common boxwood) for the shrub-regular scene and Aesculus hippocastanum (also known as horse chestnut) for the tree-regular scene, because they are widely used street plants in cities of both sub-tropical and temperate climate zones.

We selected ten common shrub and tree species from street plant lists of major international cities in both sub-tropical and temperate zones, and forged mixed lists of shrubs and trees for shrub-random and tree-random scenes accordingly (Biodiversity Information System for Europe [BISE], n.d.; Global Biodiversity Information Facility [GBIF], n. d.; The Morton Arboretum [TMA], n.d.; United States Department of Agriculture [USDA], n.d.; Harris County Extension Horticulturists [HCEH], 2009). Then, we chose the simulation model of plants based on their appearance in Esri CityEngine® (version 2015; Environmental Systems Research Institute, 2015) compared with their corresponding appearance in the real world.

For random scenes, we randomly spaced the shrubs and trees on both sides of the road by using Grasshopper® (version 0.9.0076; Rutten, 2014) plugin, which provides a random number generator to reset the spacing between any two shrubs or trees. The distances between the shrub rows as well as the distance between the rows and the curb remained unchanged. The total number of shrubs and trees in the random scenes were also kept the same (16,000 shrubs and 4053 trees respectively).

The dimensions of shrubs and trees for regular and random scenes were designed in Esri CityEngine® (version 2015; Environmental Systems Research Institute, 2015) to ensure the total green volume in the 3D models for both scenes is identical. Each type of plant in the random scenes had 3 different size settings. The selected plants for simulation and their appearance in Esri CityEngine® (version 2015; Environmental Systems Research Institute, 2015) with respective dimensions are documented in Appendix Tables A & B. The descriptive statistics of the plants in the simulation are also documented in Table 1.

2.2. Participants

We used a convenience sampling method (Etikan et al., 2016) to recruit healthy participants ages 18–60 who were Hong Kong residents. Each participant held a valid driver's license.

To determine an appropriate sample size, we conducted a statistical power calculation with the assistance of G*Power 3.1.9.2 (Buchner et al., 2014; Faul et al., 2009, 2007). Based on the nature of the experiment settings, we implemented the calculation with ANOVA test (repeated measures, within-between interaction) settings with an alpha error probability value of 0.05. The calculation suggested that a sample size of 30 can produce a power value of 0.98 with an effect size of 0.5. We recruited 40 healthy participants and collected 33 sets of complete data: 21 males and 12 females, ages 19–51 (Mean = 28 years, Standard Deviation = 7.97 years), which ultimately produced a power value of

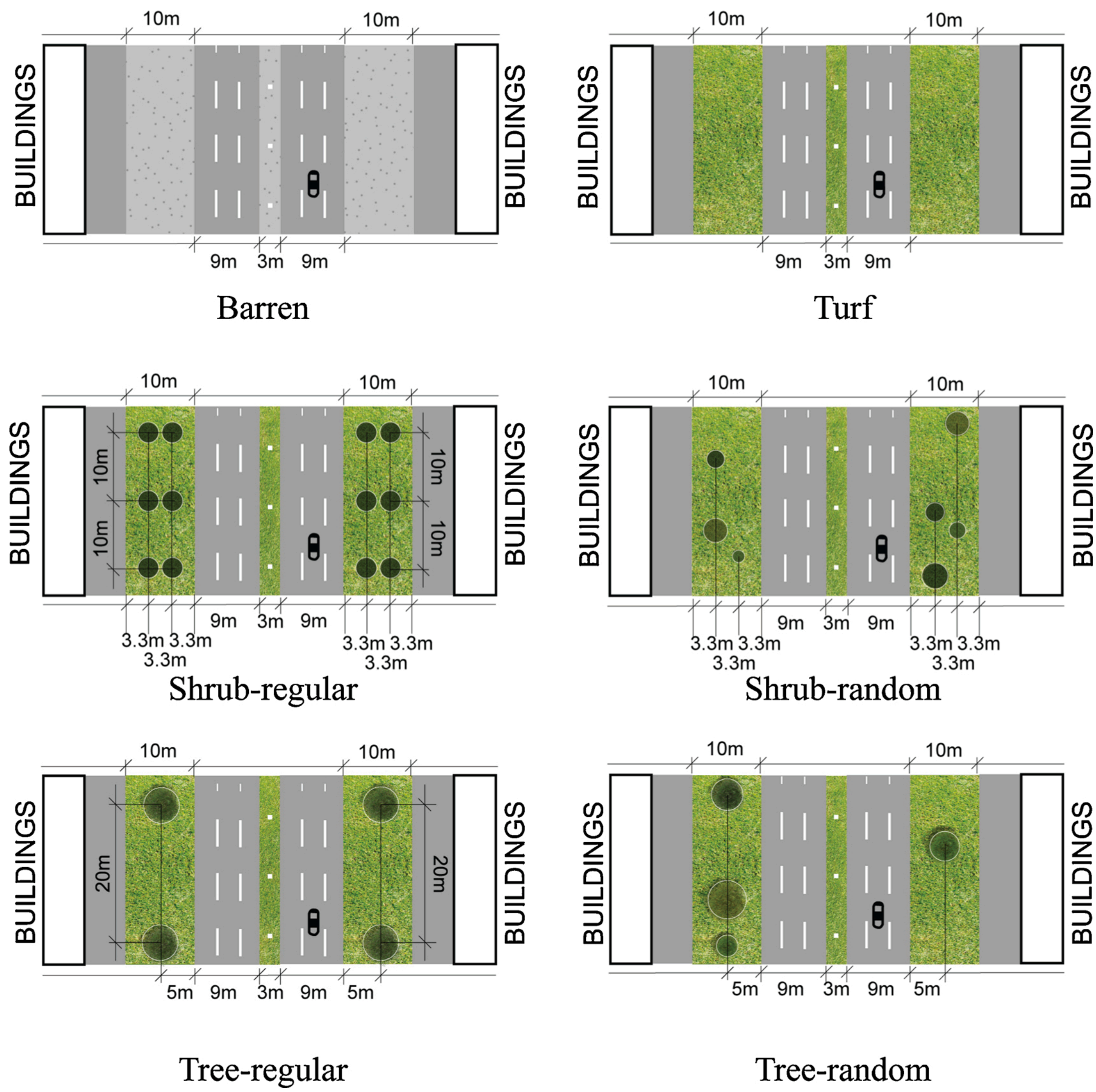

Fig. 2. Standard layouts of the freeway with six different landscape conditions.

Table 1
Descriptive statistics of the plants in simulation.

Conditions	Min (m)		Max (m)		Mean (m)		SD		Total number
	Height	Radius	Height	Radius	Height	Radius	Height	Radius	
Shrub-regular	1.00	0.75	1.00	0.75	1.00	0.75	0.00	0.00	16,000
Shrub-random	0.30	0.30	2.00	2.00	1.20	0.85	0.03	0.03	16,000
Tree-regular	10.00	2.00	10.00	2.00	10.00	2.00	0.00	0.00	4053
Tree-random	5.00	1.00	23.00	5.00	11.90	3.58	0.43	0.09	4053

Note: m stands for meter; SD stands for standard deviation.

0.99.

We placed flyers in multiple locations both on and off campus at a university in Hong Kong and recruited participants through social media platforms including WeChat and WhatsApp. Individuals were required to have a valid driver's license and were not allowed to participate if they were diagnosed with any sort of mental and physical illness or any sort of vehicle accident trauma. Individuals were also not allowed to participate in the study if their visual acuity (after vision correction) is less than 20/20. The participants were asked to refrain from consuming any alcohol or caffeine within 6 hours before the experiment. To avoid external sleep deprivation, they were also asked to have ample sleep the night before the experiment.

Each qualified participant visited the laboratory six times, and each received 1000 Hong Kong dollars as an incentive for participating in the six experiments. All participants finished the six experiments with different landscape conditions in a randomly assigned order. As a result, each condition group had 33 cases. To assign the sequence of the six simulation conditions, Latin Square was implemented to achieve a randomized yet counterbalanced arrangement to avoid practice and order effects (Cochran and Cox, 1950; Jacobson and Matthews, 1996). Participants were randomly assigned into as many subdivisions of equal sizes as the Latin Square requires and each participant experienced the conditions in one of the possible orders. To further address confounding factors, all participants completed a background questionnaire to report their age, gender, education, economic status, marital status, and self-reported historical driving performance. Participants' background information is shown in Table 2.

2.3. Experimental equipment and procedure

The driving operation software environment was set up by Lenovo Think Station P910 running Windows 10 64bit with 64.0 GB RAM and NVIDIA® Quadro® P6000 graphics card, and the simulation was rendered in Open DS, which was also responsible for collecting data for the seven driving parameters (Table 3, item 1–7). The driving hardware environment was configured by Logitech G29 driving set including the steering wheel, pedals (clutch, brake, accelerator) (Eudave and Valencia, 2017) and play-seat. 79" LG SUPER UHD TV 79UF9500 was used for simulation display and Sony SS-WSB128 speaker system was used for car engine sound simulation. A black canvas was used to cover the surrounding walls of the designated lab space for the experiment to avoid external light source interference.

The experiment was conducted from Jul 10th, 2017 to November 6th, 2017 at a university in Hong Kong. All experiments were implemented in the identical laboratory where only the participant and the facilitating research assistants were present. Each time the experiment involved only one participant. Before each experiment, the lab environment was configured in the same way, with identical lighting conditions and temperatures (Fig. 3). The acoustic ambience of the indoor environment with simulated freeway sound effects was set to a constant level of 76 dB

Table 2
Descriptive statistics of socio-demographic information, driving-performance-related background information.

Social-demographic measures	N	%	Driving-experience-related measures	N	%
Age			**Year(s) holding a driving license**		
18–25	15	45.5	<= 1	5	15.2
26–30	12	36.4	2–5	14	42.4
31–40	2	6.1	6–10	8	24.2
41–50	3	9.1	11–20	4	12.1
51–60	1	3.0	21–30	2	6.1
Gender			**Above 2000 miles driving experience during last 3 years**		
Male	21	63.6	Yes	14	42.4
Female	12	36.4	No	19	57.6
Education			**Convicted any moving violation(s) during last 3 years**		
Elementary School	0	0	Yes	5	15.2
High School	1	3.0	No	28	84.8
Bachelor	19	57.6	**Any accident(s) involved in the convicted traffic violation(s) during last 3 years**		
Master	10	30.3	Yes	0	0
Doctorate	3	9.1	No	33	100.0
Monthly income (HK$)			**Being involved in any vehicle accident while driving during last 3 years**		
< = 5,000	4	12.1	Yes	1	3.0
5,001–10,000	4	12.1	No	32	97.0
10,001–20,000	15	45.5		M	SD
20,001–30,000	5	15.2			
30,001–50,000	3	9.1			
> = 50,001	2	6.1			
Marital status			**Self-reported historical driving performance** *Very bad skill = 0; Moderate = 5; Very good skill = 10*		
Never married	28	84.8			
Married/Living with a partner	4	12.1		6.69	1.30
Widowed/Divorce/Separated	1	3.0			

Table 3
Definitions of driving performance measures and their relationships with driving performance.

Measure	Definition	Relationship with freeway driving performance
Mean of lateral acceleration	The average value of vehicle acceleration in the lateral direction, which results in the changes of lane position (Wang et al., 2015).	A higher value indicates a poorer consistency of lane position control, or abrupt changes of steering wheel position.
Standard deviation of lateral acceleration	It indicates the consistency of lateral lane position control, which is calculated using the standard deviation of the acceleration in the lateral position (Wang et al., 2015).	A higher value indicates a poorer consistency of lane position control, or abrupt changes of steering wheel position.
Steering hold frequency	It is the number of times in a second that the steering wheel position has not been changed continuously for at least 400 ms.	A higher value indicates a poorer control of steering position (He et al., 2014).
Mean of speed	It is the average value of vehicle travelling velocity	A higher value often indicates a more radical driving strategy (He et al., 2014).
Standard deviation of speed	It is the standard deviation of vehicle travelling velocity (He et al., 2014).	A higher value indicates poorer control of driving speed (He et al., 2014).
Speed manipulation hold frequency	It is the number of times in a second that both the accelerator pedal and the brake pedal positions have not been changed continuously for at least 400 ms. The speed manipulation holds frequency is also sometimes referred to as throttle hold rate (Ahlström and Kircher, 2010; He et al., 2013).	A higher value indicates a poorer control of speed (He et al., 2013).
Steering reversal rate	Steering reversal is defined as a change of the steering wheel position larger than two degrees within the time that steering wheel velocity left and then returned to the zero-velocity bands (Ranney et al., 2005; Tijerina et al., 1995). The steering reversal rate was then defined as the number of steering reversals per second.	A higher value indicates a better lane keeping performance (MacDonald and Hoffman, 1980).
Self-reported driving performance	It was measured using a Visual Analog Scale (VAS) with a continuous scale ranging from 0 to 10 (0 indicates "Very bad," 5 indicates "Moderate," and 10 indicates "Extremely good" driving performance).	A higher value indicates a better self-reported driving performance.

(Iac Acoustics, 2017). The experiments were administered by three investigators; all three were all to follow an identical procedure (Fig. 4). Investigators were randomly and evenly assigned to run experiments with the six conditions to further avoid bias.

When each participant entered the laboratory, investigators introduced the experiment procedure to the individual. The participant was asked to give consent to engage in the experiment and was asked to review the inclusion criteria to confirm that they were eligible to participate. Then the participant practiced driving for 10 min to make sure they fully understood the operation of the driving equipment. The participant then drove while being exposed to one of the six driving simulations for 90 min with a required speed limit of 120 km/h (75 mph). The 90 min were divided into six 15-min blocks. The participant completed a VAS questionnaire before the first driving block and during

Fig. 3. Lab environment for the driving experiment.

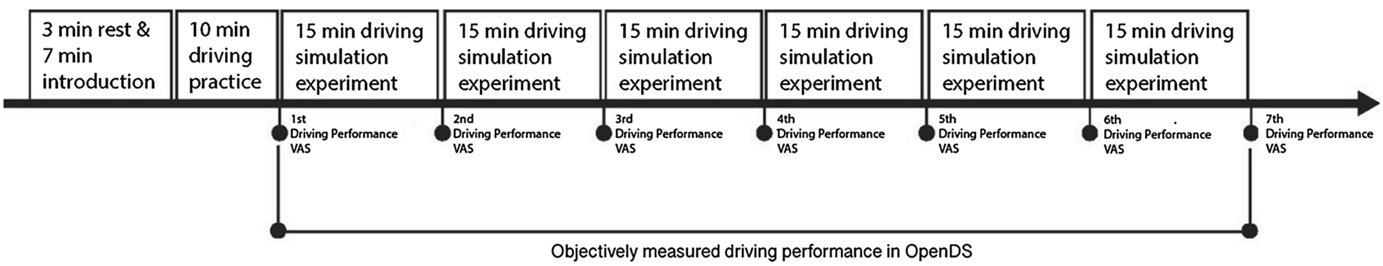

Fig. 4. Experiment procedure.

the brief break after each experimental driving block (Table 3, item 8). Each break lasted around 60 seconds and the participant was asked to remain seated on the driver's seat. No communication was allowed between the participant and investigator besides quickly answering the VAS questionnaire on paper. During the driving simulation, investigators continuously tracked seven driving parameters (Table 3, item 1–7). After the six simulation blocks were finished, the participant was asked to complete a background questionnaire regarding their driving experience for the past 3 years. No food or drink was allowed during the experiment. The whole process took around 110 minutes.

2.4. Dependent variables: indicators of driving performance

To estimate how driving performance is impacted by different roadside landscapes, we continuously recorded the following driving parameters through Open DS software: mean lateral acceleration, standard deviation of lateral acceleration, steering holds frequency, mean speed, standard deviation of speed, speed manipulation holds frequency, and steering reversal rate. Drivers were asked to report their driving performance by answering a Visual Analog Scale (VAS) questionnaire six times during the experiment. Detailed definitions of the

Table 4
Descriptive statistics of driving performance measures for six conditions.

Variables		Barren	Turf	Shrub-regular	Shrub-random	Tree-regular	Tree-random
	M	0.33	0.33	0.32	0.31	0.31	0.32
Mean lateral acceleration (m/s^2)	SD	0.05	0.03	0.07	0.04	0.03	0.03
	95% CI	0.31, 0.35	0.32, 0.34	0.29, 0.34	0.30, 0.33	0.30, 0.32	0.31, 0.33
	M	0.53	0.54	0.51	0.42	0.53	0.50
Standard deviation of lateral acceleration (m/s^2)	SD	0.09	0.07	0.08	0.10	0.08	0.08
	95% CI	0.49, 0.55	0.51, 0.56	0.48, 0.54	0.40, 0.46	0.50, 0.56	0.47, 0.53
	M	0.08	0.09	0.06	0.05	0.08	0.06
Steering holds frequency (Hz)	SD	0.03	0.03	0.03	0.02	0.03	0.02
	95% CI	0.07, 0.09	0.08, 0.10	0.05, 0.07	0.04, 0.06	0.07, 0.09	0.05, 0.07
	M	99.05	100.73	96.06	100.07	98.21	99.40
Mean speed (kph)	SD	16.66	18.15	19.56	21.44	16.90	15.86
	95% CI	93.27, 104.82	94.44,107.02	89.28,102.84	92.65,107.5	92.36,104.07	93.91,104.9
	M	11.88	10.98	12.15	11.40	10.80	10.37
Standard deviation of speed (kph)	SD	6.57	6.05	5.84	7.47	5.96	4.71
	95% CI	9.60,14.15	8.89,13.08	10.12,14.17	8.81,13.99	8.74,12.87	8.74,12
	M	0.08	0.07	0.06	0.04	0.07	0.05
Speed manipulation holds frequency (Hz)	SD	0.03	0.02	0.02	0.02	0.02	0.02
	95% CI	0.07, 0.08	0.06, 0.08	0.05, 0.06	0.03, 0.05	0.06, 0.08	0.05, 0.06
	M	0.01	0.01	0.01	0.02	0.02	0.02
Steering reversal rate (Hz)	SD	0.02	0.03	0.02	0.02	0.06	0.05
	95% CI	0.005,0.019	0.001,0.023	0.005,0.019	0.010,0.025	0.001,0.042	0.006,0.039
	M	5.96	6.47	6.33	6.25	6.48	6.34
Self-reported driving performance (0–10)	SD	1.99	1.54	1.60	1.80	1.77	1.60
	95% CI	5.26, 6.67	5.92, 7.01	5.77, 6.90	5.61, 6.89	5.86, 7.11	5.77, 6.91

Note: M stands for mean; *CI* stands for confidence interval; *SD* stands for standard deviation; *N* stands for sample size.

eight parameters and their relationship with driving performance are presented in Table 4.

3. Results

We used one-way repeated ANOVA to examine differences among the three general landscape conditions (barren, turf, shrub & tree) (Question 1), and to examine differences among the six landscape conditions (Question 2). We used two-way repeated ANOVA to examine differences among the shrub and tree conditions (Question 3). For all ANOVA analysis, we reported results of Greenhouse Geisser analysis when the data could not pass Machy's Test of Sphericityp ($p < 0.05$). IBM SPSS v18.0 was used in the statistical analysis.

3.1. Driving performance differences among three general landscape conditions

In this first layer of analysis, we created a combined shrub & tree condition because shrubs and trees have a much higher level of greenness than the barren and turf conditions. Combining the four random and regular shrub and tree conditions can largely equalize the impact of the two distinct levels of complexity in the analysis.

The results of one-way repeated ANOVA show that there are significant within-subject effects among the three conditions for mean lateral acceleration, standard deviation of lateral acceleration, speed manipulation holds frequency, steering holds frequency, and steering reversal rate. Further, pairwise comparisons for measures with significant within-subject effects show a non-significant difference between barren and turf conditions for all five measures. In contrast, the other pairwise comparisons (barren vs shrub & tree, turf vs shrub & tree) show significant differences for all five measures (Table 5 & Fig. 5).

Table 5
Results of one-way repeated ANOVA and pairwise comparison analysis for three landscape conditions.

	Within-subject Effects	Barren vs Turf	Barren vs Shrub & Tree	Turf vs Shrub & Tree
Mean of lateral acceleration	$F(2, 64) = 36.58$, $p < 0.001$; $\eta^2_p = 0.52$	-0.01^{ns}	0.01^{ns}	0.01*
Standard deviation of lateral acceleration	$F(2, 64) = 6.46$, $p<0.01$; $\eta^2_p = 0.17$	-0.01^{ns}	0.04*	0.05*
Mean of speed	$F(1.69, 54.12) = 0.43$, $p = 0.66$; $\eta^2_p = 0.01$	ns	ns	ns
Standard deviation of speed	$F(2, 64) = 0.40$, $p = 0.67$; $\eta^2_p = 0.01$	ns	ns	ns
Speed manipulation holds frequency	$F(2, 64) = 12.83$, $p<0.001$; $\eta^2_p = 0.29$	0.00^{ns}	0.02***	0.02***
Steering holds frequency	$F(2, 64) = 34.58$, $p<0.001$; $\eta^2_p = 0.52$	-0.01^{ns}	0.02***	0.02***
Steering reversal rate	$F(1.33, 42.51) = 3.90$, $p<0.05$; $\eta^2_p = 0.11$	0.00^{ns}	-0.01^{ns}	−0.01***
Self-reported driving performance	$F(1.62, 51.65) = 3.26$, $p = 0.06$; $\eta^2_p = 0.09$	ns	ns	ns

Note: Pairwise comparison is not necessary when the general within-subject effect is non-significant (when $p \geq 0.05$, marked as "ns"). The number of pair comparison stands for mean difference, which is marked as $^{***}p < 0.001$, $^{*}p < 0.05$, or ^{ns}p = non-significance when $p \geq 0.05$.

3.2. Differences in driving performance among six landscape conditions

3.2.1. Lateral acceleration

Mean lateral acceleration did not differ significantly across the six road conditions, $F(5,160) = 1.98$, $p = 0.09$, $\eta^2_p = 0.06$. Standard deviation of lateral acceleration differed significantly across the six road conditions, $F(3.57, 114.19) = 13.17$, $p < 0.001$, $\eta^2_p = 0.29$ (Table 6). As shown in Fig. 6 and Table 7, pairwise comparisons showed that the value in the barren condition was significantly higher than in the shrub-random condition. The value of the turf condition was significantly higher than in the shrub-regular condition, shrub-random condition, and the tree-random condition. The value of shrub-regular condition was significantly higher than the shrub-random condition. The value of the shrub-random condition was significantly lower than the tree-regular condition and the tree-random condition.

3.2.2. Steering holds frequency

Steering holds frequency differed significantly among the six road conditions, $F(5,160) = 39.78$, $p < 0.001$, $\eta^2_p = 0.55$ (Table 6). As shown in Fig. 7 and Table 8, pairwise comparisons showed that the value in the barren condition was not statistically different than in the turf condition, but significantly larger than in the shrub-regular, shrub-random, and tree-random conditions. The value in the turf condition was significantly higher than in the shrub-regular, shrub-random, tree-regular, and tree-random conditions. The value in the shrub-regular condition was significantly higher than in the shrub-random condition but was significantly smaller than in the tree-regular condition. The value in the shrub-random condition was significantly smaller than in the tree-regular condition and tree-random condition. The value in the tree-regular condition was significantly higher than in the tree-random condition.

3.2.3. Speed manipulation holds frequency

Within-participant analyses of variances (ANOVA): Speed Manipulation Holds Frequency differed significantly among the six road conditions, $F(5,160) = 17.03$, $p < 0.001$, $\eta^2_p = 0.35$ (Table 5). As shown in Fig. 8 and Table 9, pairwise comparisons showed that the value in the barren condition was significantly larger than in the shrub-regular, the shrub-random, and tree-random conditions. The value in the turf condition was significantly larger than in the shrub-regular, the shrub-random, and the tree-random conditions. The value in the shrub-regular condition was significantly higher than in the shrub-random condition but was significantly smaller than in the tree-regular condition. The value in the shrub-random condition was significantly smaller than in the tree-regular, and tree-random conditions. The value in the tree-regular condition was significantly larger than in the tree-random condition.

3.2.4. Other measures

For other measures, the values of performance did not differ significantly among the six landscape conditions (Table 6).

3.3. Two-way repeated measures ANOVA analysis on greenness and complexity

To answer Question 3, a two-way repeated analysis of variance (ANOVA) was conducted to test the independent and interactive impacts of greenness and complexity in the four conditions with vertical green foliage (two shrub and two tree conditions). The ANOVA includes two levels of greenness and two levels of complexity. The two levels of greenness include moderate greenness (the two shrub conditions) and moderately high greenness (the two tree conditions) The two levels of complexity are moderately low complexity (the shrub regular and tree regular conditions) and moderate complexity (the shrub random and tree random conditions). The qualified parameters include lateral acceleration, standard deviation of lateral acceleration, steering holds

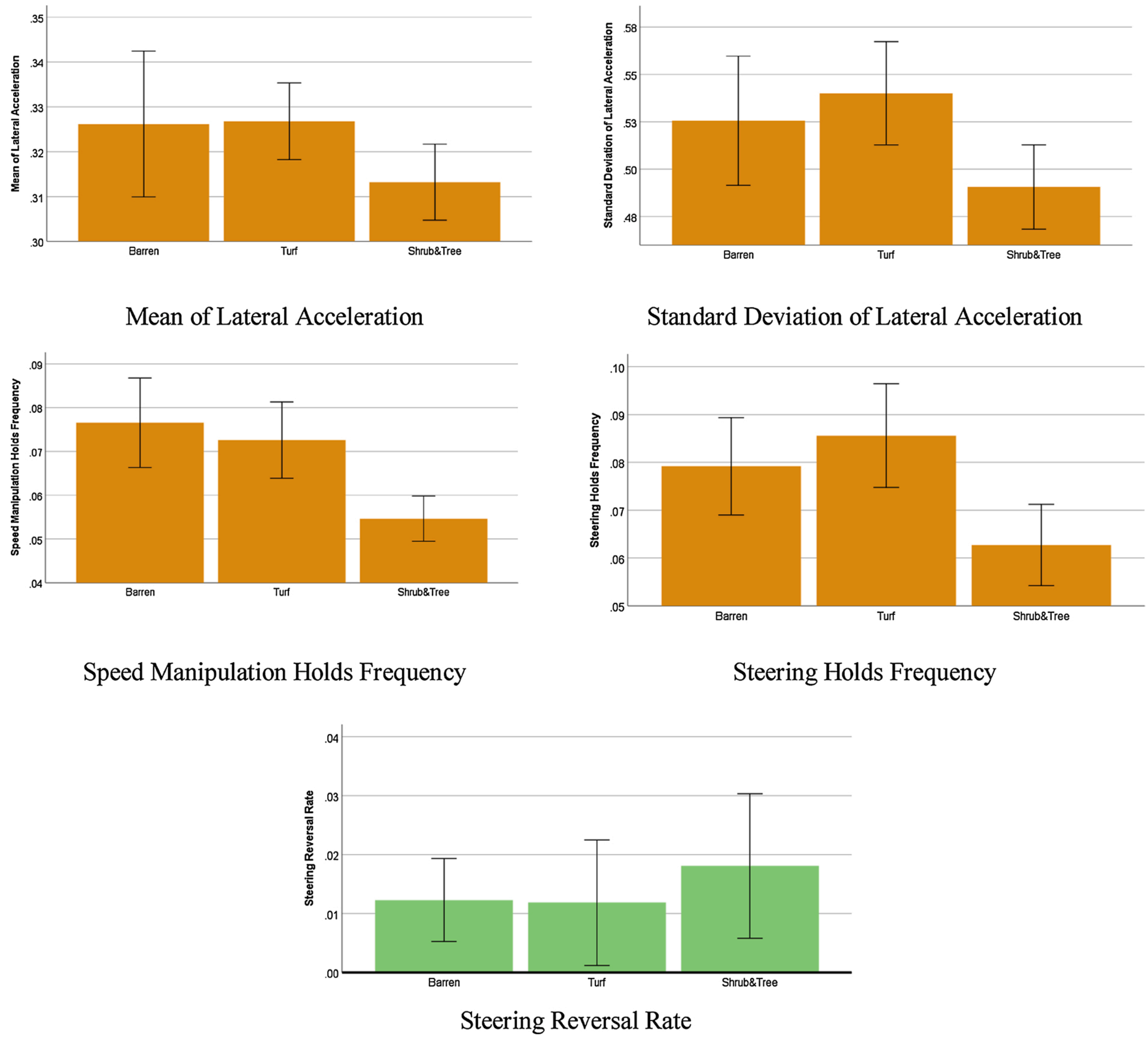

Fig. 5. Five significant measures in three general landscape conditions (Error bars: 95 % CI). The brown (green) color means a higher value of the measure indicates a poorer (better) performance.

Table 6
Within-subject effects of one-way repeated ANOVA analysis for six landscape conditions.

Variables	Within-subject Effects
Mean lateral acceleration	$F_{(5,160)} = 1.98$, $p = .09$; $\eta^2_p = 0.06$.
Standard deviation of lateral acceleration	$F_{(3.57,\ 114.19)} = 13.17$, $p < 0.001$; $\eta^2_p = 0.29$
Steering holds frequency	$F_{(5,160)} = 39.78$, $p < 0.001$; $\eta^2_p = 0.55$
Mean speed	$F_{(5,160)} = 0.36$, $p = 0.88$; $\eta^2_p = 0.01$
Standard deviation of speed	$F_{(5,160)} = 0.91$, $p = 0.48$; $\eta^2_p = 0.03$
Speed manipulation holds frequency	$F_{(5,160)} = 17.03$, $p < 0.001$; $\eta^2_p = 0.35$
Steering reversal rate	$F_{(5,160)} = 1.67$, $p = 0.14$; $\eta^2_p = 0.05$.
Self-reported driving performance	$F_{(3.75,\ 120.11)} = 1.25$, $p = 0.30$, $\eta^2_p = 0.04$

frequency, and speed manipulation holds frequency.

3.3.1. *Lateral acceleration and standard deviation of lateral acceleration*

For the lateral acceleration, none of the interaction effects or main effects were significant and all p values were greater than 0.1. For the standard deviation of lateral acceleration, the interaction effect was significant, $F\,(1,32) = 16.51$, $p < 0.001$, $\eta^2_p = 0.34$. The main effect of greenness level was significant, $F\,(1,32) = 26.03$, $p < 0.001$, $\eta^2_p = 0.45$, with smaller values in lower greenness conditions than the higher greenness conditions. The main effect of complexity was also significant, $F\,(1,32) = 8.52$, $p = 0.006$, $\eta^2_p = 0.35$, with smaller values in the random distribution conditions than the regular distribution conditions (Fig. 9).

3.3.2. *Steering holds frequency*

The main effect of greenness level was significant, $F\,(1,32) = 27.13$, $p < 0.001$, $\eta^2_p = 0.46$, with smaller values in the lower greenness conditions than the higher greenness conditions. The main effect of complexity was also significant, $F\,(1,\ 32) = 62.51$, $p < 0.001$, $\eta^2_p = 0.661$, with values in the random distribution conditions than the regular distribution conditions. The interaction effect was non-significant, $F\,(1,32) = 0.73$, $p = 0.40$, $\eta^2_p = 0.02$ (Fig. 10).

3.3.3. *Speed manipulation holds frequency*

The main effect of greenness level was significant, $F\,(1,32) = 14.21$, $p < 0.001$, $\eta^2_p = 0.31$, with smaller values in the lower greenness conditions than the higher greenness conditions. The main effect of complexity was also significant, $F\,(1,32) = 34.24$, $p < 0.001$, $\eta^2_p = 0.52$, with smaller values in the higher complexity conditions than the lower complexity conditions. The interaction effect was non-significant, $F\,(1,32) = 0.55$, $p = 0.47$, $\eta^2_p = 0.02$ (Fig. 11).

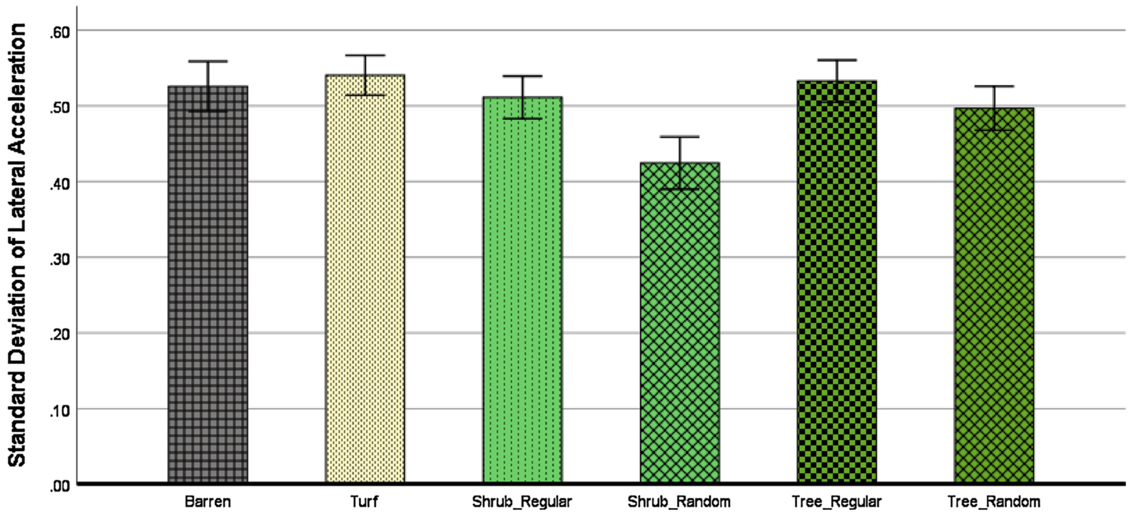

Fig. 6. Standard deviation of lateral acceleration by six landscape conditions (Error bars: 95 % CI).

Table 7
Pair comparison of six conditions in standard deviation of lateral acceleration.

	Barren	Turf	Shrub-regular	Shrub-random	Tree-regular	Tree-random
Barren	–					
Turf	ns	–				
Shrub-regular	ns	0.03*	–			
Shrub-random	0.10***	0.12***	0.09***	–		
Tree-regular	ns	ns	ns	−0.11***	–	
Tree-random	ns	0.04*	ns	−0.07***	0.04*	–

Note: The numbers are mean differences (column-row); ***p <0.001, *p <0.05, ns$p$=non-significance. when $p \geq 0.05$.

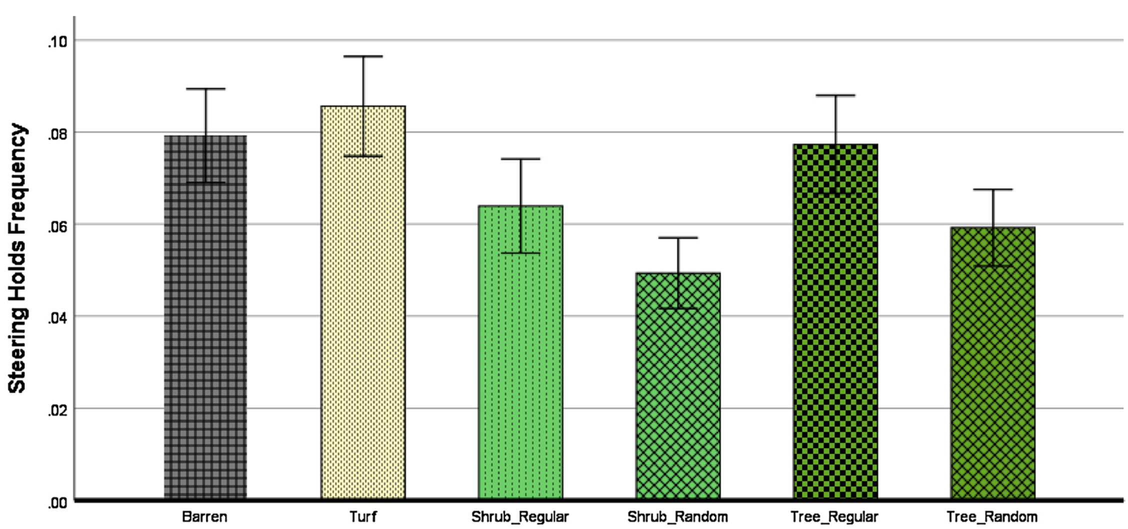

Fig. 7. Steering holds frequency by six landscape conditions (Error bars: 95 % CI).

Table 8
Pair comparison of six conditions in steering holds frequency.

	Barren	Turf	Shrub-regular	Shrub-random	Tree-regular	Tree-random
Barren	–					
Turf	ns	–				
Shrub-regular	0.02***	0.02***	–			
Shrub-random	0.03***	0.04***	0.02***	–		
Tree-regular	ns	0.01*	−0.01***	−0.03***	–	
Tree-random	0.02***	0.03***	ns	−0.01**	0.02***	–

Note: The numbers are mean differences (column-row); ***p <0.001, **p <0.01, *p <0.05, *p <0.1, ns$p$ = non-significance when $p \geq 0.05$.

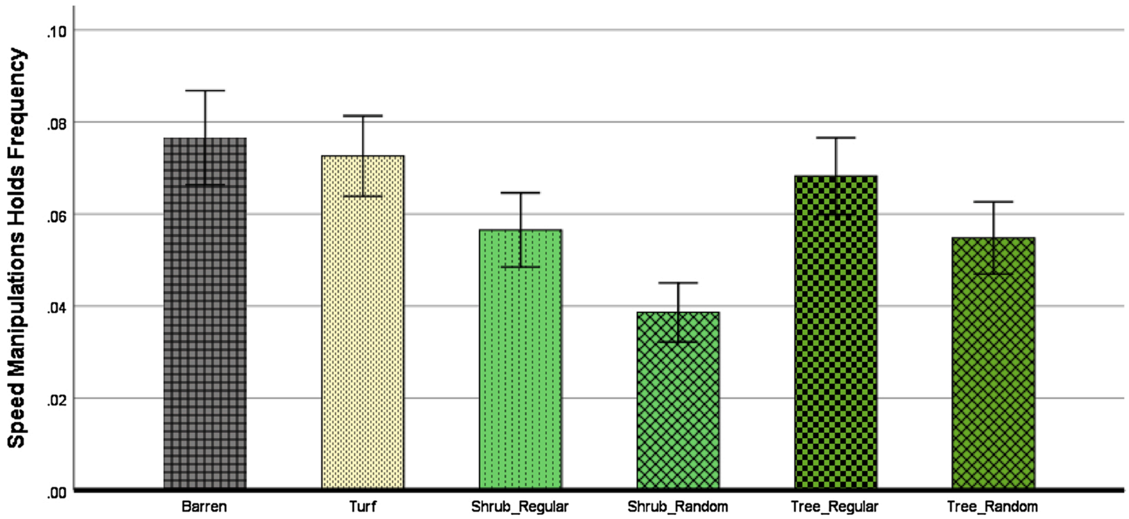

Fig. 8. Speed Manipulation Holds Frequency by six conditions (Error bars: 95 % CI).

Table 9
Pair comparison of six conditions in speed manipulation holds frequency.

	Barren	Turf	Shrub-regular	Shrub-random	Tree-regular	Tree-random
Barren	–					
Turf	ns	–				
Shrub-regular	0.02**	0.02**	–			
Shrub-random	0.04***	0.03***	0.02***	–		
Tree-regular	ns	ns	−0.01*	−0.03***	–	
Tree-random	0.02***	0.02**	ns	−0.16**	0.01**	–

Note: The numbers are mean differences (column-row); *** p <0.001, ** p <0.01, * p <0.05, * p <0.1, ^{ns}p = non-significance when $p \geq 0.05$.

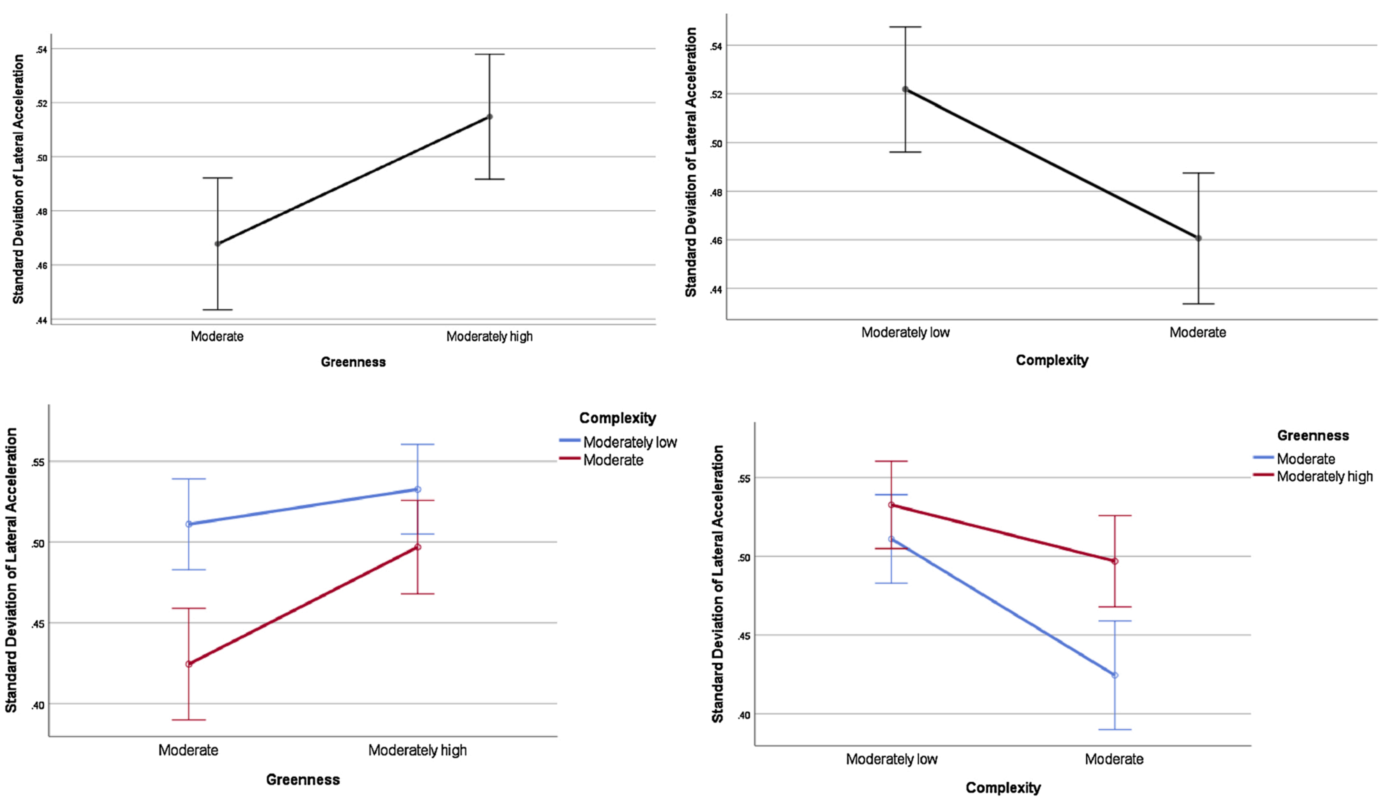

Fig. 9. Two (greenness) × Two (complexity) ANOVA analysis for the *Standard Deviation of Lateral Acceleration* (Error bars: 95% CI).

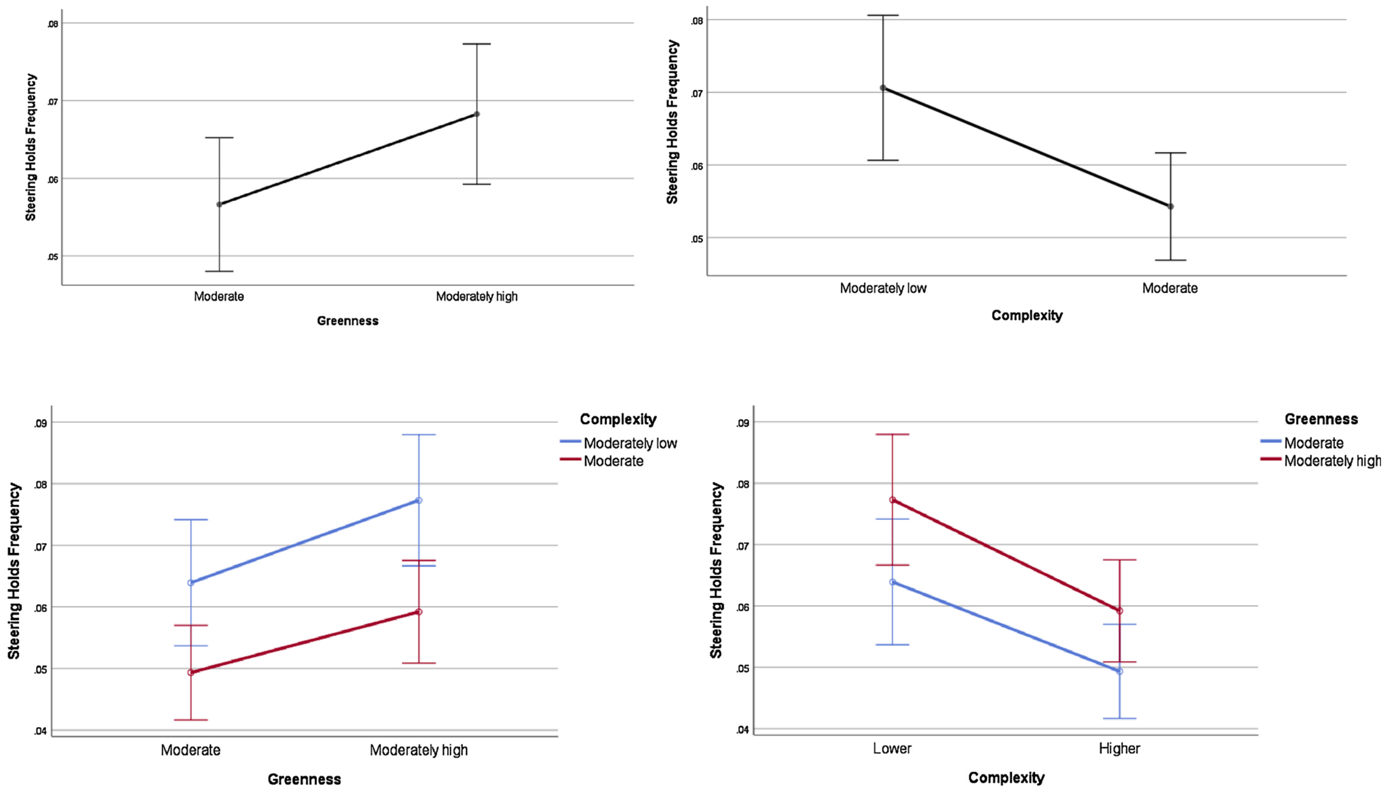

Fig. 10. Two (greenness) × Two (complexity) ANOVA analysis for the *Steering Holds Frequency* (Error bars: 95% CI).

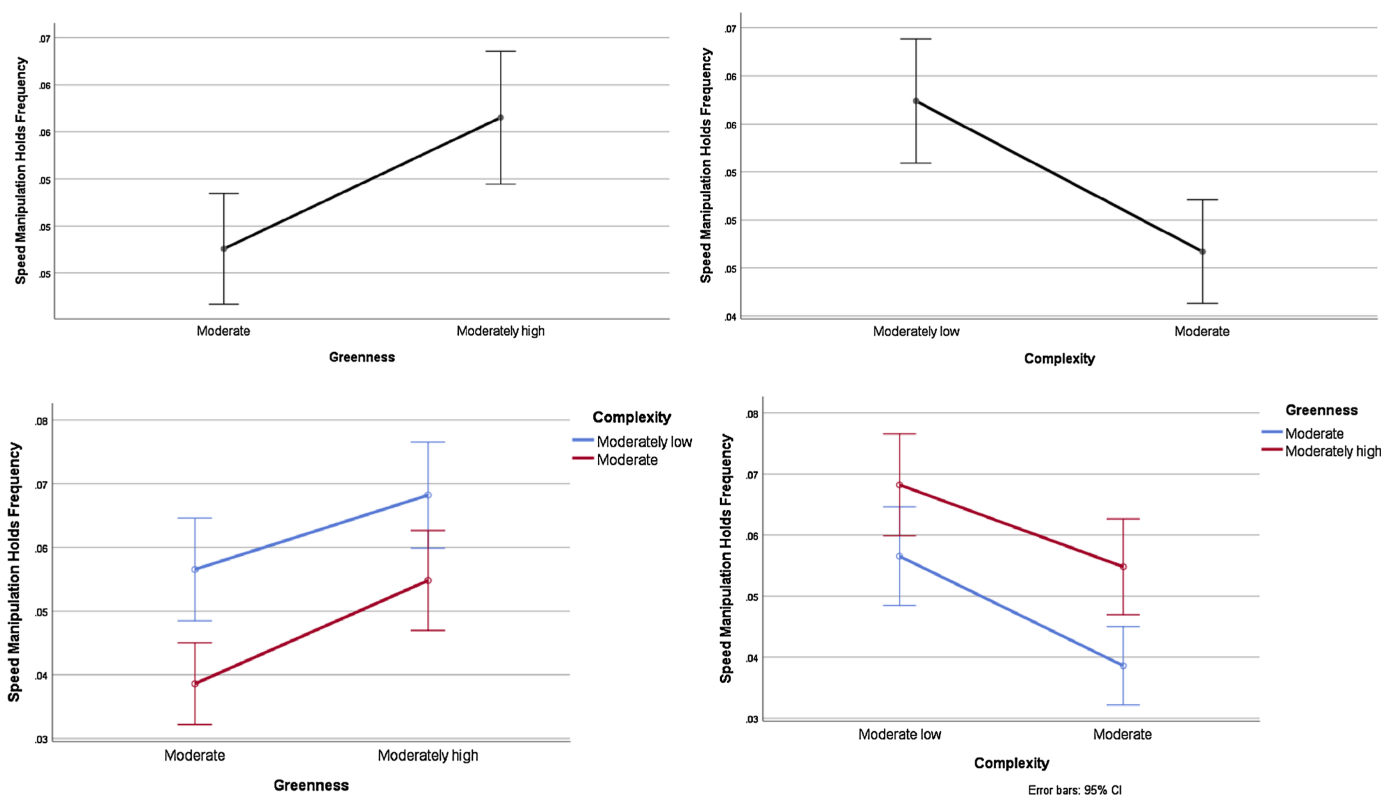

Fig. 11. Two (greenness) × Two (complexity) ANOVA analysis for the *Speed Manipulation Holds Frequency* (Error bars: 95% CI).

4. Discussion

4.1. Summary of major findings

This study used a driving simulator to examine the impacts of different freeway landscapes on driving performance.

First, we investigated to what extent driving performance differs for freeway drivers exposed to three general conditions. In general, green landscape settings more positively affect driving performance: The shrub & tree condition has a significantly more positive impact on driving performance than the turf and barren conditions, while the turf and barren conditions have a similar impact on driving performance. This result was further confirmed through the analysis of the six different roadside conditions.

Next, we examined the differences among the six landscape conditions. The results suggest an inverted U- shape pattern to explain the impact on driving performance of the six conditions with varying levels of greenness. In general, the conditions with the highest greenness (trees) or lowest greenness (barren or turf) yielded lower driving performance compared to the conditions with moderate greenness (the turf conditions).

Last, we explored the independent and interactive impacts of greenness and complexity for four shrub and tree conditions. The findings of repeated measure two-way ANOVA analyses showed that a moderate level of greenness and complexity is optimal for performance. Among the four conditions, the shrub-random condition yielded the best driving performance.

4.2. Interpretation of main findings

4.2.1. Different restorative effects of landscape conditions

In a previous study associated with the authors' project on freeway landscapes (Jiang et al., 2020), we used the same six landscape conditions to explore the relationships among these landscape conditions and mental restoration. We found that landscape conditions with greater greenness had a more positive impact on drivers' mental restoration. The barren and tree landscape conditions elicited the least and greatest restoration effects, respectively. The current study's findings exploring the relationships among the landscape conditions and driving performance shed new light on the findings of our previous study, which we discuss below.

4.2.2. Why do green landscape settings more positively affect driving performance?

This finding supports our previous findings, as well as other theories and studies in the field of environmental psychology. First, driving is a demanding task that consumes a great deal of directed attention (Kaplan, 1995; Sullivan, 2015). When directed attention fatigues, this can lower driving performance (Oron-Gilad and Ronen, 2007; Seen et al., 2010). The visual contact with green landscapes consumes our involuntary attention so that directed attention can be restored, according to Attention Restoration Theory. On the other hand, environments with zero or little greenness in highly urbanized areas consume a good deal of our directed attention (Chang et al., 2008; Hartig et al., 2003; Roe and Aspinall, 2011; Wang et al., 2016b). Therefore, green landscapes might partially contribute to a better driving performance by restoring our directed attention.

Stress Reduction Theory might also partially explain why exposure to vertical green landscapes with more visible greenness had a positive impact on driving performance, compared to barren or turf landscapes. Stress Reduction Theory suggests that exposure to green landscapes has a significant effect on reducing acute mental stress (Ulrich et al., 1991). Many studies have found that green environments elicit greater stress reduction than barren environments (e.g., Hunter et al., 2019; Jiang et al., 2015; Li and Sullivan, 2016). Researchers have also reported that green landscapes can facilitate greater stress reduction and safer driving behaviors (Antonson et al., 2009; Parsons et al., 1998).

4.2.3. Why do the shrub conditions yield a better performance than the other conditions?

Although we found green landscapes generally are more beneficial for driving performance, the shrub conditions yielded slightly better driving performance than the other conditions, including the tree conditions. This result contrasts to our findings from the previous study that the tree conditions were more positively associated with mental restoration than the shrub conditions. We propose two possible reasons for this difference.

One reason is that the restoration effect of greenness may not be linearly associated with driving performance, in comparison with our results from our previous study, which suggest a more linear relationship between greenness and mental restoration for drivers. According to the Yerkes and Dodson Law, both low and high levels of arousal may elicit less than optimal performance while a moderate level of arousal elicits optimal performance (Cohen, 2011; Yerkes and Dodson, 1908). Landscapes with zero or little greenness, such as the barren or turf conditions do not promote optimal driving performance because they are associated with low restoration and high arousal, which makes drivers more vulnerable to mental fatigue, stress, and other negative moods, such as boredom, anger, and frustration (Groenewegen et al., 2006; Kuo and Sullivan, 2001a,b). Many studies have reported that these negative mental states are detrimental to cognitive performance (Kweon et al., 2017; Li and Sullivan, 2016). However, landscapes with moderately high or high levels of greenness, such as the tree condition, may also not elicit the optimal driving performance because they may make drivers more relaxed and less vigilant (Chang et al., 2021; Diamond et al., 2007; Mateo, 2008), or the trees may be distracting for driving performance (Jiang et al., 2020). In contrast, the shrub conditions with moderate greenness likely elicit an equilibrium of restoration and arousal and are thus more likely to elicit optimal driving performance compared to the other landscape conditions.

These results suggest an inverted U-shaped association between landscape conditions' restoration (arousal) effect and driving performance, which might partially explain why shrub conditions yielded better driving performance than the other four conditions.

There are other possible reasons why the shrub conditions yielded better performance than the other conditions. Past studies have suggested that a low greenness has a negative impact on controlling driving speed and steering, thus leading to poorer driving performance (Antonson et al., 2009). Without curbside objects to view, drivers may have a weaker sense of space and time, which may make drivers less focused and aware (Antonson et al., 2009). The shrubs provide important visual stimuli to help drivers focus.

Other researchers found that trees may create problems caused by significant visual occupancy by the tree landscapes that can lead to poor driving performance: a strong sense of oppressiveness, distraction (Van Treese et al., 2018), and visual obstacles (Calvi, 2015). Vehicle accidents involving trees, especially large trees, are common, leading to severe injuries or even death (Wolf, 2006).

In sum, these results hint at an inverted U-shaped dose-response curve describing the relationship between the level of greenness and performance of demanding tasks, such as driving on freeways (see Fig. 12). When the level of greenness is low, an increase in greenness will elicit an increase in performance. The rate of growth will continue to be positive until the greenness arrives a certain moderate level (optimal performance). Then, as greenness continues to increase, the performance will gradually drop. This study is an initial investigation into the relationship; subsequent studies with a greater range of greenness, especially high greenness, are needed to more accurately describe this curve.

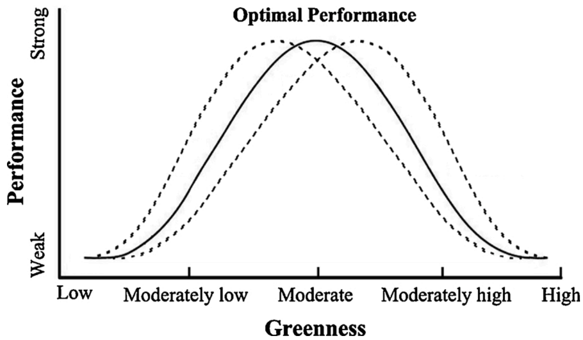

Fig. 12. We propose to use this inverted-U curve to interpret the relationship between greenness and performance of a demanding task, such as driving on a freeway. *Note*: the curves in dash lines suggest the curve is not necessarily symmetric.

4.2.4. Why did the shrub-random condition yield better performance than the shrub-regular condition?

According to the Yerkes-Dodson Law, landscape complexity may also have an inverted U- shaped association with performance (Cohen, 2011; Yerkes and Dodson, 1908) (Fig. 13) (Fig. 13). That is, when complexity is extremely low, the landscape is associated with a small dose of stimulus, which leads to low arousal and thus low performance (Farahmand et al., 2018; Thiffault and Bergeron, 2003). When complexity is high, the landscape is associated with a large dose of stimulus, which might lead to a high arousal and thus also a low performance (Teigen, 1994). In contrast, moderate complexity is more likely to yield optimal performance. More studies with a greater range of complexity, especially those with moderately high and high complexity, are needed to better describe this curve.

An interaction effect between greenness and complexity existed for only one of the three significant measures of driving performance. For that measure, the combined greenness and complexity elicited a greater effect on driving performance than the sum of the independent effects of greenness and complexity. The interaction effect might provide an additional reason why shrub-random yielded better driving performance than the other conditions. Future research should explore the complex interaction between greenness and complexity for a full range of landscape conditions.

4.2.5. Why does turf yield a similar negative effect as the barren condition?

Turf, which is widely used for roadway and freeway landscapes in many countries, had a similar association with driving performance as the barren condition. This result can be explained by the characteristics of turf landscapes. In many studies, compared to trees or shrubs, turf has a non-significant or even negative influence on people's place preference, mental status, or performance (e.g., Jiang et al., 2015; Kweon et al., 2017; Lottrup et al., 2015). One possible reason is that mowed turf presents only flat greenness and is less visible for drivers than green landscapes with three-dimensional branches and foliage above the ground, like shrubs and trees. Turf may therefore produce a smaller restorative effect (Jiang et al., 2015). In addition, the turf landscape is featureless and monotonous, which may elicit drivers' sense of boredom, thus contributing to worse driving performance (Farahmand and Boroujerdian, 2018; Thiffault and Bergeron, 2003)

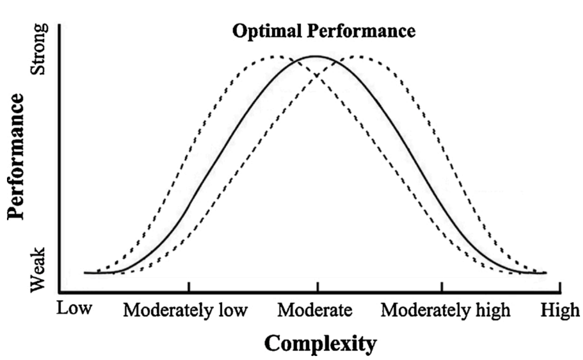

Fig. 13. We propose to use this inverted-U curve to interpret the relationship between complexity and performance of a demanding task, such as driving on a freeway. *Note*: the curves in dash lines suggest the curve is not necessarily symmetric.

4.3. Implications

There are three key implications of this study. First, freeway landscapes matter for driving performance: different types of landscape significantly influence driving performance in positive or negative ways. The lack of research on this topic has led to a misconception among many policy makers, engineers, and planners that freeway landscapes are unessential, a last-step decoration after the design and construction of all other aspects are complete. Our findings dispel these notions: freeway landscapes significantly impact driving performance and should be regarded as a critical part of transportation infrastructure.

Second, we found barren and turf landscapes yield significantly poorer driving performance than shrub and tree conditions, which suggests that barren (concrete, asphalt, stone) or featureless landscapes (such as turf or soybean fields) should be avoided while green landscapes with trees or shrubs should be provided along freeways.

Last and most importantly, we found that moderate levels of greenness and complexity likely elicit optimal driving performance. It is critical for designers to regard greenness and complexity as two key characteristics of landscapes because both significantly impact driving performance. The impacts happen simultaneously and sometimes interactively. We argue that the shrub-random condition yielded the highest performance because exposure to moderate levels of greenness and complexity may elicit a balance of mental restoration and arousal.

In general, we suggest moderate levels greenness and complexity in freeway landscapes are more likely to elicit optimal performance while barren freeway should be avoided.

4.4. Limitations and future research opportunities

This is an initial exploration of complex relationship between freeway landscapes and driving performance. We find there are several limitations existing in the present study. However, we would also recommend those limitations as opportunities for future search.

First, we used two terms, including greenness and complexity, to categorize the six landscape conditions in this study. The terms depict major differences among the six conditions but cannot depict all measurable differences. Thus, to some extent, we have sacrificed the completeness of measures to clarify the analysis and interpretation. We would admit that inaccuracy of terms is an issue, and future studies should adopt a more comprehensive set of measures to address the limitation for this type of research. For example, future studies may control for many other characteristics of freeway landscapes, including type, texture, color, shape, size, form, and health condition of plants. Future studies should also acknowledge that driving speed may influence people's perceptions and responses to these different factors.

Second, a naturalistic landscape is mainly featured by high levels of diversity of plant species and spatial configurations, but it may also contain certain levels of repeating species and spatial patterns (Verberk, 2012). Thus, the random landscape conditions adopted by this study might be satisfactory but not full simulations of naturalistic landscape conditions. Future research may adopt computer models to simulate naturalistic landscapes along the freeway by following landscape ecology principles with a comprehensive consideration of anthropological, environmental, and biological factors, such as climate zone, soil condition, biodiversity, and environmental stress and interference caused by transportation and other land uses (Yu, 1996; Zhang and DeAngelis, 2020).

Third, we tested six types of landscape that are often seen along freeways in many cities. However, most freeways include many landscape types. Moreover, these landscapes often have greater variances in levels of greenness and complexity. Future studies should examine many other types of freeway landscapes and many combinations of different landscape conditions.

Fourth, there is no gold standard to identify high, moderate, or low levels of greenness and complexity. If such a standard can be established, future research should use this standard to improve study design and analysis. Moreover, we suggest that movement and speed may influence the visual perception of greenness and complexity, as well as the relationship between landscapes and task performance. Thus, we recommend that future research duplicate this study for other types of movement and speed.

Fifth, when comparing this study to our previous study on freeway landscapes and mental restoration, we see clear connections and differences. One important difference is the optimal effects are not associated with the same level of greenness and complexity. We strongly suggest studies to explore landscape conditions that can achieve a good balance between promoting driving performance and mental restoration under different circumstances. The balance does not necessarily mean the two effects should be equally prioritized. It is possible that driving performance should prioritized for some conditions while mental restoration should be prioritized in others. No matter which effect is prioritized, it is important to aim for a positive impact for both (baseline levels of performance and restoration).

Lastly, the simulated driving task did not include complex conditions, such as car following, aggressive driving, traffic accidents, and changes in typography making it less challenging than a real freeway drive (He et al., 2014; He et al., 2015). To enhance the generalizability and validity of these findings, future studies should simulate more realistic and complex driving conditions.

5. Conclusion

This study is an initial attempt to quantify and compare the impact of a variety of freeway landscapes on driving performance. In this study, we adopted a 90-minute simulated driving experiment for six different types of freeway landscape settings. The OpenDS driving simulator enabled us to continuously measure the objective driving performance. The within-subject experiment enabled us to largely control bias caused by different individuals' socio-economic, behavioral, and cognitive characteristics.

We found that different freeway landscapes elicit significantly different impacts on driving performance, suggesting that landscapes should be regarded as essential freeway infrastructure, not a dispensable decoration. In general, landscapes with more greenness in three dimensions were more positively associated with driving performance, and a moderate level of greenness and complexity led to the optimal driving performance. We expect these findings to shed light on future research and practice related to landscape design and driving performance.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgements

The project was fully supported by the General Research Fund (GRF) managed by the Research Grants Council (RGC) of the Hong Kong Government. The project number is 27609816. Thanks for Huaqing Wang at the Texas A&M University for her contribution to construction of simulated driving environment. Thanks for edition work by Lan Luo, Xueming Liu, and Wenyan Xu from the University of Hong Kong. Thanks for suggestions from Prof. William C. Sullivan at the University of Illinois at Urbana Champaign and Prof. Chun-Yen Chang at the National Taiwan University. Thanks for enormous support by Prof. Chris Webster and Prof. Jiangping Zhou of the Faculty of Architecture and Prof. Matthew Pryor of the Division of Landscape Architecture at the University of Hong Kong.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2021.126976.

References

Alonso, M., Vega, M.H., Martín, O., 2012. Driving simulation study for the analysis of distraction effects in longitudinal driving behaviour. Cogn. Technol. Work. 14 (4), 283–297.

Antonson, H., Mårdh, S., Wiklund, M., Blomqvist, G., 2009. Effect of surrounding landscape on driving behaviour: a driving simulator study. J. Environ. Psychol. 29 (4), 493–502.

Beria, P., Ramella, F., Laurino, A., 2015. Motorways economic regulation: a worldwide survey. Transp. Policy 41, 23–32.

Berman, M.G., Jonides, J., Kaplan, S., 2008. The cognitive benefits of interacting with nature. Psychol. Sci. 19 (12), 1207–1212.

Bloomberg, M.R., Benepe, A., 2008. Tree Planting Standards. New York. http://www.nyc.gov/html/artcom/downloads/pdf/tree_planting_standards_2009.pdf.

Boudette, N.E., Vlasic, B., 2017. Tesla Self-driving System Faulted by Safety Agency in Crash. September 12. The New York Times. https://www.nytimes.com/2017/09/12/business/self-driving-cars.html.

Bratman, G.N., Daily, G.C., Levy, B.J., Gross, J.J., 2015. The benefits of nature experience: improved affect and cognition. Landsc. Urban Plan. 138, 41–50.

Buchner, A., Erdfelder, E., Faul, F., Lang, A.-G., 2014. Universität Düsseldorf: G*Power. http://www.gpower.hhu.de/.

Calvi, A., 2015. Does roadside vegetation affect driving performance?: Driving simulator study on the effects of trees on drivers' speed and lateral position. Transp. Res. Rec. 2518 (1), 1–8.

Cassarino, M., Maisto, M., Esposito, Y., Guerrero, D., Chan, J.S., Setti, A., 2019. Testing attention restoration in a virtual reality driving simulator. Front. Psychol. 10, 250.

Chang, C.Y., Hammitt, W.E., Chen, P.K., Machnik, L., Su, W.C., 2008. Psychophysiological responses and restorative values of natural environments in Taiwan. Landsc. Urban Plan. 85 (2), 79–84.

Chang, D.H.F., Jiang, B., Wong, N.H.L., Wong, J.J., Webster, C., Lee, T.M.C., 2021. The human posterior cingulate and the stress-response benefits of viewing green urban landscapes. NeuroImage 226, 117555.

Cochran, W.G., Cox, G.M., 1950. Experimental Design John. Wiley, New York.

Cohen, R.A., 2011. Yerkes-Dodson Law. In: Kreutzer, J.S., DeLuca, J., Caplan, B. (Eds.), Encyclopedia of Clinical Neuropsychology.

Demmel, S., Gruyer, D., Burkhardt, J.M., Glaser, S., Larue, G., Orfila, O., Rakotonirainy, A., 2019. Global risk assessment in an autonomous driving context: impact on both the car and the driver. IFAC-PapersOnLine 51 (34), 390–395.

DeWolfe, J., Waliczek, T.M., Zajicek, J.M., 2011. The relationship between levels of greenery and landscaping at track and field sites, anxiety, and sports performance of collegiate track and field athletes. HortTechnology 21 (3), 329–335.

Diamond, D.M., Campbell, A.M., Park, C.R., Halonen, J., Zoladz, P.R., 2007. The temporal dynamics model of emotional memory processing: a synthesis on the neurobiological basis of stress-induced amnesia, flashbulb and traumatic memories, and the Yerkes-Dodson law. Neural Plast. 2007.

Etikan, I., Musa, S.A., Alkassim, R.S., 2016. Comparison of convenience sampling and purposive sampling. Am. J. Theor. Appl. Stat. 5 (1), 1–4.

Eudave, L., Valencia, M., 2017. Physiological response while driving in an immersive virtual environment. May 2017 IEEE 14th International Conference on Wearable and Implantable Body Sensor Networks (BSN) 145–148.

Farahmand, B., Boroujerdian, A.M., 2018. Effect of road geometry on driver fatigue in monotonous environments: a simulator study. Transp. Res. Part F Traffic Psychol. Behav. 58, 640–651.

Faul, F., Erdfelder, E., Lang, A.G., Buchner, A., 2007. G* Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39 (2), 175–191.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.G., 2009. Statistical power analyses using G* Power 3.1: tests for correlation and regression analyses. Behav. Res. Methods 41 (4), 1149–1160.

Fitzpatrick, C.D., Harrington, C.P., Knodler Jr., M.A., Romoser, M.R., 2014. The influence of clear zone size and roadside vegetation on driver behavior. J. Saf. Res. 49, 97–e1.

Fitzpatrick, C.D., Samuel, S., Knodler Jr., M.A., 2016. Evaluating the effect of vegetation and clear zone width on driver behavior using a driving simulator. Transp. Res. Part F Traffic Psychol. Behav. 42, 80–89.

Gilman, E.F., 2015. Spacing Between Trees. University of Florida. http://hort.ifas.ufl.edu/woody/spacing.shtml.

Green, P.A., Jeong, H., Kang, T.P., 2014. Using an OpenDS driving simulator for car following: a first attempt. September Adjunct Proceedings of the 6th International

Conference on Automotive User Interfaces and Interactive Vehicular Applications 1–6.
Groenewegen, P.P., Van den Berg, A.E., De Vries, S., Verheij, R.A., 2006. Vitamin G: effects of green space on health, well-being, and social safety. BMC Public Health 6 (1), 1–9.
Hartig, T., Evans, G.W., Jamner, L.D., Davis, D.S., Gärling, T., 2003. Tracking restoration in natural and urban field settings. J. Environ. Psychol. 23 (2), 109–123.
He, J., Chaparro, A., Nguyen, B., Burge, R.J., Crandall, J., Chaparro, B., et al., 2014. Texting while driving: Is speech-based text entry less risky than handheld text entry? Accid. Anal. Prev. 72, 287–295.
He, J., Choi, W., McCarley, J.S., Chaparro, B.S., Wang, C., 2015. Texting while driving using Google GlassTM: promising but not distraction-free. Accid. Anal. Prev. 81, 218–229.
Hock, P., Kraus, J., Babel, F., Walch, M., Rukzio, E., Baumann, M., 2018. How to design valid simulator studies for investigating user experience in automated driving: review and hands-on considerations. September Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications 105–117.
Hunter, M.R., Gillespie, B.W., Chen, S.Y.P., 2019. Urban nature experiences reduce stress in the context of daily life based on salivary biomarkers. Front. Psychol. 10, 722.
Iac Acoustics, 2017. Comparative Examples of Noise Levels. https://www.iacacoustics.com/blog-full/comparative-examples-of-noise-levels.html.
Jacobson, M.T., Matthews, P., 1996. Generating uniformly distributed random Latin squares. J. Comb. Des. 4 (6), 405–437.
Jiang, B., Chang, C.Y., Sullivan, W.C., 2014. A dose of nature: tree cover, stress reduction, and gender differences. Landsc. Urban Plan. 132, 26–36.
Jiang, B., Larsen, L., Deal, B., Sullivan, W.C., 2015. A dose–response curve describing the relationship between tree cover density and landscape preference. Landsc. Urban Plan. 139, 16–25.
Jiang, B., Li, D., Larsen, L., Sullivan, W.C., 2016. A dose-response curve describing the relationship between urban tree cover density and self-reported stress recovery. Environ. Behav. 48 (4), 607–629.
Jiang, B., Mak, C.N.S., Zhong, H., Larsen, L., Webster, C.J., 2018. From broken windows to perceived routine activities: examining impacts of environmental interventions on perceived safety of urban alleys. Front. Psychol. 9, 2450.
Jiang, B., Schmillen, R., Sullivan, W.C., 2019. How to waste a break: using portable electronic devices substantially counteracts attention enhancement effects of green spaces. Environ. Behav. 51 (9-10), 1133–1160.
Jiang, B., He, J., Chen, J., Larsen, L., Wang, H., 2020. Perceived green at speed: a simulated driving experiment raises new questions for attention restoration theory and stress reduction theory. Environ. Behav. 0013916520947111.
Kaplan, S., 1995. The restorative benefits of nature: toward an integrative framework. J. Environ. Psychol. 15 (3), 169–182.
Kaplan, R., 2001. The nature of the view from home: psychological benefits. Environ. Behav. 33 (4), 507–542.
Kuo, F.E., Sullivan, W.C., 2001a. Aggression and violence in the inner city: effects of environment via mental fatigue. Environ. Behav. 33 (4), 543–571.
Kuo, F.E., Sullivan, W.C., 2001b. Environment and crime in the inner city: Does vegetation reduce crime? Environ. Behav. 33 (3), 343–367.
Kweon, B.S., Ellis, C.D., Lee, J., Jacobs, K., 2017. The link between school environments and student academic performance. Urban For. Urban Green. 23, 35–43.
Li, D., Sullivan, W.C., 2016. Impact of views to school landscapes on recovery from stress and mental fatigue. Landsc. Urban Plan. 148, 149–158.
Lottrup, L., Stigsdotter, U.K., Meilby, H., Claudi, A.G., 2015. The workplace window view: a determinant of office workers' work ability and job satisfaction. Landsc. Res. 40 (1), 57–75.
Macdonald, E., Harper, A., Williams, J., Hayter, J.A., 2006. Street Trees and Intersection Safety. Retrieved from. Institute of Urban and Regional Development, UC Berkeley. https://escholarship.org/uc/item/9t6465vq.
Marx, P., 2018. The Driverless Revolution Isn't Coming Anytime Soon. January 12. https://medium.com/@parismarx/the-driverless-revolution-isnt-coming-anytime-soon-fdf569cd6c6f.
Mateo, J.M., 2008. Inverted-U shape relationship between cortisol and learning in ground squirrels. Neurobiol. Learn. Mem. 89 (4), 582–590.
Math, R., Mahr, A., Moniri, M.M., Müller, C., 2013. OpenDS: a new open-source driving simulator for research. GMM-Fachberichht-AmE 2013, 2.
Naderi, J.R., Kweon, B.S., Maghelal, P., 2008. The street tree effect and driver safety. ITE J. Web 78 (2), 69–73.
NYC Parks, 2016. Street Tree Planting Standards for New York City. https://www.nycgovparks.org/pagefiles/53/Tree-Planting-Standards.pdf.
Ode, Å., Hagerhall, C.M., Sang, N., 2010. Analysing visual landscape complexity: theory and application. Landsc. Res. 35 (1), 111–131.
Oron-Gilad, T., Ronen, A., 2007. Road characteristics and driver fatigue: a simulator study. Traffic Inj. Prev. 8 (3), 281–289.
Özgüner, H., Kendle, A.D., 2006. Public attitudes towards naturalistic versus designed landscapes in the city of Sheffield (UK). Landsc. Urban Plan. 74 (2), 139–157.
Parsons, R., 1995. Conflict between ecological sustainability and environmental aesthetics: conundrum, canärd or curiosity. Landsc. Urban Plan. 32 (3), 227–244.
Parsons, R., Tassinary, L.G., Ulrich, R.S., Hebl, M.R., Grossman-Alexander, M., 1998. The view from the road: implications for stress recovery and immunization. J. Environ. Psychol. 18 (2), 113–140.
Parwathaneni, R., 2016. Effect of Roadside Vegetation on Driver Behavior. Doctoral dissertation. Cleveland State University.
Pati, D., Harvey Jr., T.E., Barach, P., 2008. Relationships between exterior views and nurse stress: an exploratory examination. Herd Health Environ. Res. Des. J. 1 (2), 27–38.
Ranney, T.A., Harbluk, J.L., Noy, Y.I., 2005. Effects of voice technology on test track driving performance: implications for driver distraction. Hum. Factors 47 (2), 439–454.
Roe, J., Aspinall, P., 2011. The restorative outcomes of forest school and conventional school in young people with good and poor behaviour. Urban For. Urban Green. 10 (3), 205–212.
Sabey, B.E., Taylor, H., 1980. The known risks we run: the highway. In: Schwing, R.C., Albers, W.A. (Eds.), Societal Risk Assessment: How Safe Is Safe Enough? Springer US, pp. 43–70. https://doi.org/10.1007/978-1-4899-0445-4_3.
Sullivan, W.C., 2015. In search of a clear head. In: Basu, R.K.A. (Ed.), Fostering Reasonableness: Supportive Environments for Bringing Out Our Best. University of Michigan Press, pp. 54–69.
Sung, E.J., Min, B.C., Kim, S.C., Kim, C.J., 2005. Effects of oxygen concentrations on driver fatigue during simulated driving. Appl. Ergon. 36 (1), 25–31.
Tang, I.C., Tsai, Y.-P., Lin, Y.-J., Chen, J.-H., Hsieh, C.-H., Hung, S.-H., Sullivan, W.C., Tang, H.-F., Chang, C.-Y., 2017. Using functional Magnetic Resonance Imaging (fMRI) to analyze brain region activity when viewing landscapes. Landsc. Urban Plan. 162, 137–144. https://doi.org/10.1016/j.landurbplan.2017.02.007.
Taylor, A.F., Kuo, F.E., Sullivan, W.C., 2002. Views of nature and self-discipline: evidence from inner city children. J. Environ. Psychol. 22 (1–2), 49–63.
Teigen, K.H., 1994. Yerkes-Dodson: a law for all seasons. Theory Psychol. 4 (4), 525–547.
Thiffault, P., Bergeron, J., 2003. Monotony of road environment and driver fatigue: a simulator study. Accid. Anal. Prev. 35 (3), 381–391.
Tijerina, L., Kiger, S.M., Rockwell, T.H., Tornow, C., 1995. Workload assessment of in-cab text message system and cellular phone use by heavy vehicle drivers on the road. In: SAGE PublicationsProceedings of the Human Factors and Ergonomics Society Annual Meeting, 39, pp. 1117–1121. October 17.
U.S. Department of Transportation & Federal Highway Administration, 2021. Manual on Uniform Traffic Control Devices (MUTCD): Section 1A.13 Definitions of Words and Phrases in This Manual. n.d. https://mutcd.fhwa.dot.gov/HTM/2003r1/part1/part1a.htm#section1A13.
Ulleberg, P., Rundmo, T., 2003. Personality, attitudes and risk perception as predictors of risky driving behaviour among young drivers. Saf. Sci. 41 (5), 427–443.
Ulrich, R.S., 1981. Natural versus urban scenes: some psychophysiological effects. Environ. Behav. 13 (5), 523–556.
Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A., Zelson, M., 1991. Stress recovery during exposure to natural and urban environments. J. Environ. Psychol. 11 (3), 201–230.
Ulrich, R.S., Simons, R.F., Miles, M.A., 2003. Effects of environmental simulations and television on blood donor stress. J. Archit. Plann. Res. 38–47.
van der Horst, R., de Ridder, S., 2007. Influence of roadside infrastructure on driving behavior: driving simulator study. Transp. Res. Rec. 2018 (1), 36–44. https://doi.org/10.3141/2018-06.
Van Treese, J., Koeser, A.K., Fitzpatrick, G.E., Olexa, M.T., Allen, E.J., 2018. Drivers' risk perception of roadside trees. Arboric. J. 40 (3), 153–161.
Verberk, W., 2012. Explaining general patterns in species abundance and distributions. Nat. Educ. Knowl. 3, 38.
Wang, L., Bie, Y., Li, S., 2016a. The impact of roadside landscape colors on driver's mean heart rate considering driving time. Transp. Res. Part F Traffic Psychol. Behav. 42, 151–161.
Wang, X., Rodiek, S., Wu, C., Chen, Y., Li, Y., 2016b. Stress recovery and restorative effects of viewing different urban park scenes in Shanghai, China. Urban Forest. Urban Green. 15, 112–122.
Wolf, K.L., 2006. Urban trees and traffic safety: considering the US roadside policy and crash data. Arboric. Urban For. 32 (4), 170–179, 32(4), 170-179.
World Health Organization, 2018. Road traffic injuries. World Health Organization. Retrieved July 22nd, 2019 from. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries.
Yang, B., Li, S., Elder, B.R., Wang, Z., 2013. Community-planning approaches and residents' perceived safety: a landscape analysis of park design in the woodlands, Texas. J. Archit. Plann. Res. 311–327.
Yerkes, R.M., Dodson, J.D., 1908. The relation of strength of stimulus to rapidity of habit-formation. Punishment: Issues and Experiments, pp. 27–41.
Yu, K., 1996. Security patterns and surface model in landscape ecological planning. Landsc. Urban Plan. 36 (1), 1–17.
Zhang, B., DeAngelis, D.L., 2020. An overview of agent-based models in plant biology and ecology. Ann. Bot. 126 (4), 539–557.