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Impacts of Green Landscapes of Urban Freeway on Driver's Visual Perception: An Equilibrium Effect of Greenness and Complexity

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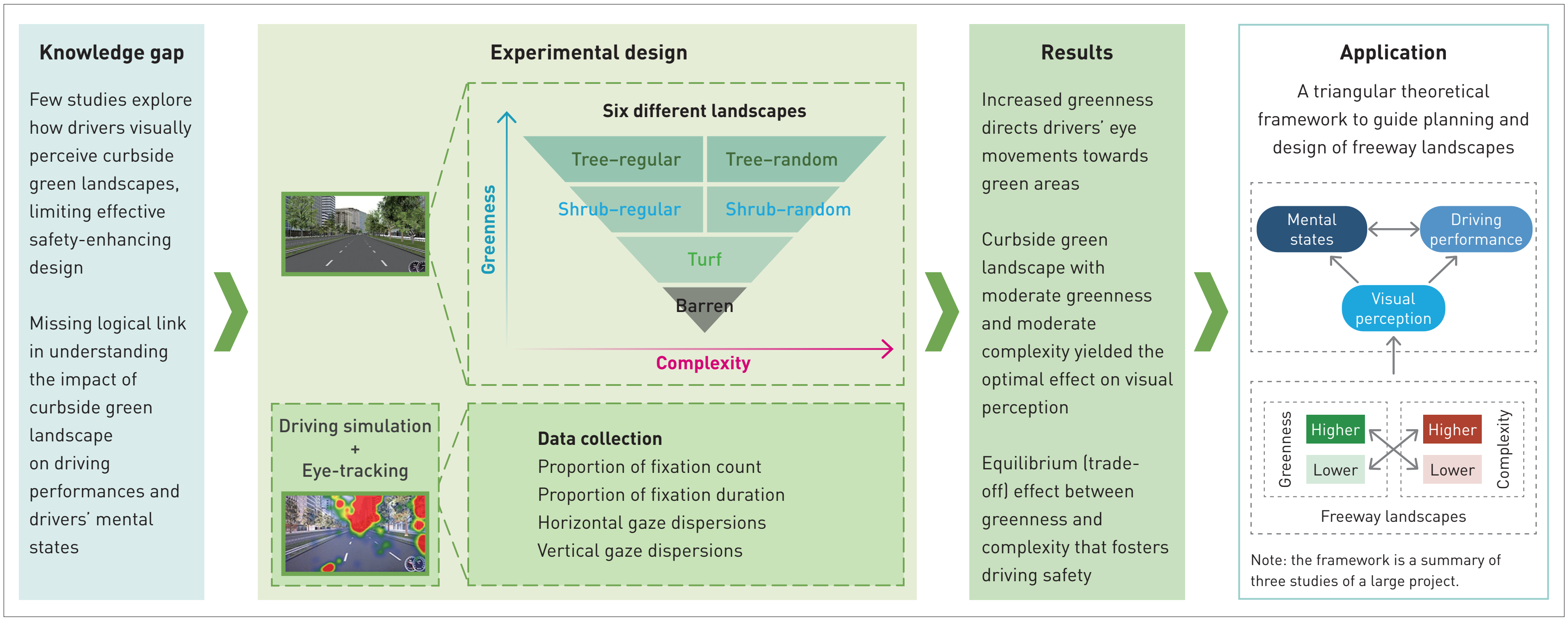
GRAPHICAL ABSTRACT



Knowledge gap

Few studies explore how drivers visually perceive curbside green landscapes, limiting effective safety-enhancing design

Missing logical link in understanding the impact of curbside green landscape on driving performances and drivers' mental states

Experimental design

Data collection

- Proportion of fixation count
- Proportion of fixation duration
- Horizontal gaze dispersions
- Vertical gaze dispersions

Results

Increased greenness directs drivers' eye movements towards green areas

Curbside green landscape with moderate greenness and moderate complexity yielded the optimal effect on visual perception

Equilibrium (trade-off) effect between greenness and complexity that fosters driving safety

Application

A triangular theoretical framework to guide planning and design of freeway landscapes

Note: the framework is a summary of three studies of a large project.

ABSTRACT

While green landscapes are known to influence drivers' visual attention, the optimal configurations for enhancing driving safety and performance remain unclear. This study employed eye-tracking technology to investigate eye fixation and gaze behaviors of 24 drivers during a 90-minute simulated urban highway driving task across six distinct landscape conditions across three primary Areas of Interest (AOIs). Within-subject analysis of variance (ANOVA) comparing barren, turf, and woody landscapes revealed that increased greenness significantly directs drivers' eye movements towards greenery. Comparative analysis of the six landscape conditions suggested that shrub landscape settings achieved the most balanced distribution of visual attention across AOIs, preventing drivers from excessively focusing on either natural or artificial features. Moreover, the ANOVA examining two shrub settings and two tree settings revealed a trade-off effect between landscape greenness and complexity. This study provides crucial empirical evidence for a balanced configuration of greenness and complexity in landscape design, confirming its critical role in achieving optimal visual perception outcomes. Finally, it proposes a triangular theoretical framework linking visual perception, mental states, and driving performance, offering theoretical support and practical reference for future research and design of healthy and safe driving environments.

KEYWORDS

Freeway; Green Space; Curbside Landscape; Visual Perception; Eye Movement; Equilibrium Effect; Driving Simulation

HIGHLIGHTS

- Eye-tracking reveals how landscape greenness and complexity affect drivers' visual perception
- Balanced greenness and complexity of shrub landscapes optimizes drivers' visual attention allocation
- Proposes a triangular theoretical framework of visual perception–mental state–driving performance

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1 Introduction

1.1 Research Background

As the eighth leading cause of mortality among people of all ages, traffic accidents result in over 1.3 million deaths annually[1], highlighting the critical role of road design in improving road safety. To improve driving safety in the long run, cities need to develop a road network that is not only cost-effective but also considers landscape design to promote the wellbeing of drivers and road users[2–3]. With the increasing number of studies on the influencing elements of driving safety suggesting the important role of curbside landscape in affecting drivers' behaviors[4–6], limited studies have investigated how drivers interpret the visual information within the green landscapes on the curbside, making it a crucial aspect for further exploration.

1.2 Existing Evidence and Logical Foundation of the Current Study

1.2.1 Theoretical and Empirical Evidence

Urban and landscape planning is an important approach to promoting citizens' health and wellbeing, a major objective of sustainable development[7]. Prior studies have shown that exposure to green spaces can restore mental fatigue, decrease mental stress, promote cognitive performance, and elicit positive moods[8–11]. Specifically, the attention restoration theory (ART) and stress reduction theory (SRT) explain these benefits from the cognitive and emotional perspective, respectively[12–13]. In general, ART suggests that a mentally demanding task, such as driving, depletes a great deal of individuals' directed attention, leading to mental fatigue and degradation of cognitive functions[12,14]. In contrast, visual contact with green sceneries consumes individuals' undirected attention and could replenish directed attention. Similarly, SRT suggested that urban environments lacking green sceneries can elicit significant mental stress[13,15]. Yet, green sceneries have stress-reducing properties rooted in human evolutionary history: an inherent preference of safe and rich green landscapes for survival and thriving purposes[16]. In urban contexts, the restorative capacity of natural environments also stems from the absence of physical and social stressors, which reduces the risk of emotional problems and cognitive performance impairment.

In summary, as suggested by the ART and SRT, it is plausible to lead to a straightforward conclusion: the higher the level of greenness along the road, the better drivers' mental states and driving performance. Nevertheless, stemming from the previous findings in our series of studies[17–18], this study presents and tests the visual perception aspects of drivers more comprehensively.

1.2.2 An Overview of Our Previous Findings on the Impacts of Green Landscape on Drivers

As part of a larger project expanding from previous knowledge on ART and SRT, we have explored how freeway landscapes impact drivers' mental restoration and the relationship between freeway landscapes and driving performance via simulated high-speed driving environments. Findings from the current project have indicated that freeway landscapes influence driving performance and mental restoration significantly[17–18]. Results suggested that the lowest levels of anxiety, tension, and mental fatigue were observed when a higher level of visible greenness within a landscape was presented[18]. However, the effects were found to be significantly different among freeway landscapes with various levels of greenness and complexity. In other words, a potential trade-off between greenness and complexity was also observed: high visual complexity of the landscape may diminish the potential mentally restorative effect from high greenness under a speedy environment[6,17–20]. Specifically, drivers responded to landscapes with homogeneous plantation layout more positively in comparison to landscapes with diversity and spatial variation of plants. A further study regarding the impact of freeway landscapes on driving performance also confirmed the same trade-off effect between greenness and complexity: a moderate level of greenness with a moderately high level of complexity (i.e., shrubs with random spatial arrangement) yielded the greatest impact on driving performance[17]. Despite the positive impact of green landscapes on drivers' mental restoration and driving performance, how they visually understand the driving environment has yet to be explored.

1.3 A Critical Knowledge Gap: Using Eye-tracking Technology to Connect Visual Perception, Mental Restoration, and Driving Performance

To explore the "black box" of the research—drivers' visual perception of the freeway landscapes while driving—it is essential to first understand drivers' accurate visual perception while navigating various freeway settings, enabling researchers to gain insight into the elements that drivers perceive and interpret in them. The current study aims to examine drivers' area of interest (AOI) in different freeway landscapes to further understand the connection between exposure to green landscape, driving performance, and drivers' mental states via an eye-tracking study in a simulated freeway driving environment, ultimately providing a definitive closure to the entire project. The hypothesis is proposed that freeway landscapes influence drivers' visual perception, reorienting their focus area while driving, which subsequently leads to changes in their mental states and driving performance (Fig. 1).

1.4 Eye-tracking Technology in Assessing Drivers' Visual Perception of Landscapes

Eye-tracking technology has been widely employed in various research domains, such as behavioral psychology, environmental psychology, transportation, and usability studies[21–23]. Research on tracing eye movement was proposed with the assumption that eye movements are associated with mental processing, with nearly 80% of the external information being delivered to brain via the visual pathway[24]. In recent years, researchers begun to use eye-tracking technology to evaluate urban and natural environments[25–26]. Eye movement parameters including fixations, saccades, and smooth pursuits were measured in identifying attention orientation[27]. Particularly, past research has suggested that drivers' fixations or gaze behaviors are effective in revealing their perception, which was also significantly influenced by freeway landscapes and alignments, altering their reaction time for emergency situations[28–29]. By applying eye-tracking tools under a simulated driving environment, it is now possible to better understand how various levels of greenness and complexity within the freeway settings reorient drivers' AOI visually.

1.5 Research Questions

To determine how green landscape is perceived visually by the drivers, this study first investigated how green landscape impacts the overall eye movements, where the nature of driving was understood as a visual task; then, how greenness and complexity of the freeway landscapes impact drivers' eye movements was explored; lastly, the potential connection between freeway landscapes, eye movements, driving performance, and mental states

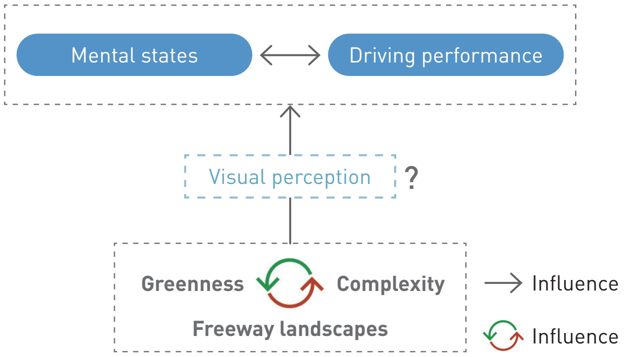

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Fig. 1 An illustration of the hypothesized logical link in understanding the impact of green landscape on driving performances and drivers' mental states.

were discussed.

Three research questions were addressed through the design of six experimental conditions of curbside landscapes, with the barren landscape condition serving as the control condition: 1) To what extent does drivers' eye movement differ among three different fundamental levels of greenness (i.e., barren, turf, and woody) when driving? 2) To what extent does drivers' eye movement differ among six roadside landscape conditions when driving? And 3) how do greenness (shrubs vs trees) and complexity (regular vs random) in different levels affect drivers' eye movements independently and interactively?

2 Materials and Methods

A simulated driving study was conducted to investigate how various levels of greenness and complexity within the freeway landscapes impacts drivers' eye movements, mental states, and driving performance. Eye movements of the participants were recorded during a 90-minute driving task to explore how their eye movements have reoriented by different types of freeway landscapes[30–31]. Three fundamental types of landscapes (i.e., barren, turf, and woody) and two planting patterns (i.e., regular and random) were created, with woody landscapes further divided into two sub-types: shrubs and trees. A total of six freeway landscape conditions (i.e., barren, turf, shrub–regular, shrub–random, tree–regular, and tree–random) were formed and implemented within the driving simulation system[32–33] to record participants' real-time driving performance. The barren landscape condition served as the control condition. All participants completed all six landscape conditions in a randomized order through six separate experimental sections.

2.1 Participants

All participants were recruited utilizing social media platforms (i.e., WhatsApp and WeChat) as well as convenience sampling, which involved putting fliers on and off the university campus. A total of 40 healthy residents aged between 18 to 60 were recruited in Hong Kong, with 33 participants aged between 19 to 51 completing all six experimental sections. All participants reported having normal or corrected-to-normal eyesight, a valid driver's license, and no history of vehicle-related trauma. They also confirmed no caffeine and alcohol intake, eating, or smoking within 60 min before the experiment. A demographic survey inquiring about the basic characteristics and self-reported driving performance history was assigned to all participants to further address the influences of potential confounding variables.

A statistical power analysis was performed using the G*Power 3.1.9.2, a free software for assessing the power of statistical tests[34], which suggested that 24 participants (13 males, and 11 females) were required to reach 90% power for the repeated measures within factors analysis of variance (ANOVA) with an α error probability value of 0.05[35–36]. Upon initial review of the data from 33 participants, data from 6 participants were first excluded due to data loss. Considering the nature of the data, an outlier analysis using the median absolute deviation (MAD) method was conducted[37], in which extreme outliers from 3 participants were detected and therefore excluded. Ultimately, 24 participants were included in the final data analysis (Table 1).

2.2 Experiment Materials and Apparatus

A driving simulator consisting of a Logitech G29 driving set, a play-seat, a 79 inches LG SUPER UHD TV 79UF9500, and a Sony SS-WSB128 speaker system was used in this experiment. The driving simulation was conducted using an open-source OpenDS® system

Table 1: Statistics of demographic characteristics and driving performance history of the participants

	Item	Number of participants	Ratio of participants
Age	18 ~ 25	9	37.5%
	26 ~ 30	10	41.6%
	31 ~ 40	1	4.1%
	41 ~ 50	3	12.5%
	51 ~ 60	1	4.1%
Gender	Male	13	54.2%
	Female	11	45.8%
Education	Elementary school	0	0
	High School	1	4.1%
	Bachelor	13	54.1%
	Master	8	33.3%
	Doctorate	2	8.3%

(Continued)

Table 1: Statistics of demographic characteristics and driving performance history of the participants (Continued)

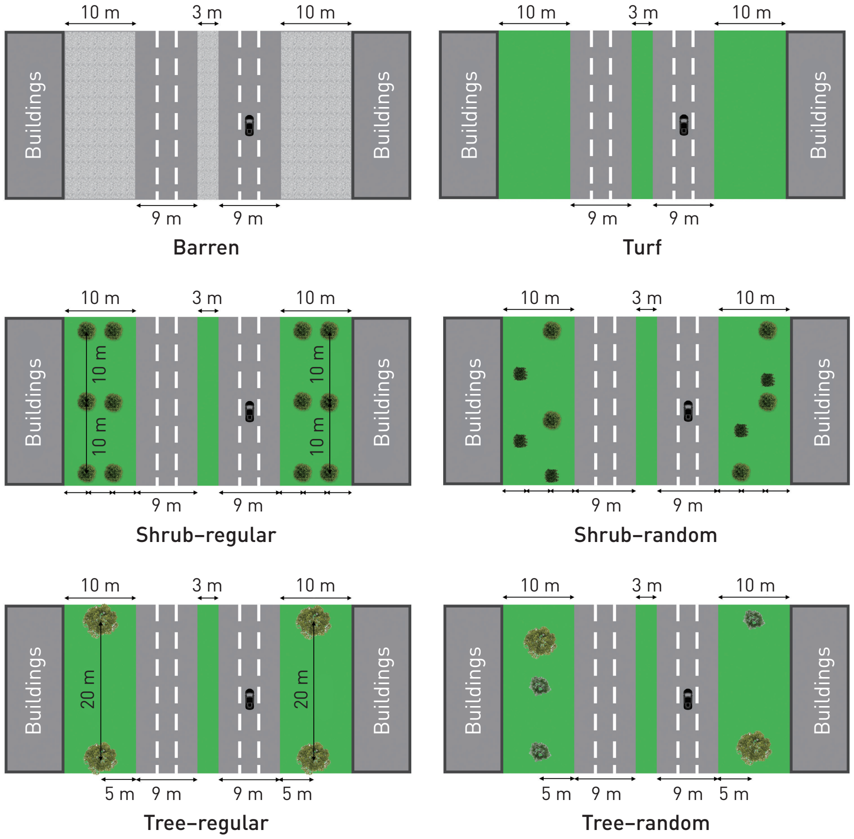
Item		Number of participants	Ratio of participants
Monthly income (HKD)	≤ 5,000	1	4.1%
	5,001 ~ 10,000	3	12.5%
	10,001 ~ 20,000	11	45.8%
	20,001 ~ 30,000	5	20.8%
	30,001 ~ 50,000	3	12.5%
	≥ 50,001	1	4.1%
Marital status	Never married	20	83.3%
	Married/living with a partner	4	16.6%
	Widowed/divorced/separated	0	0
Year(s) holding a driver license	≤ 1	3	12.5%
	2 ~ 5	8	33.3%
	6 ~ 10	7	29.1%
	11 ~ 20	4	16.6%
	21 ~ 30	2	8.3%
Driving over 2,000 miles in the past 3 years	Yes	11	45.8%
	No	13	54.2%
Conviction of driving violation(s) in the past 3 years	Yes	4	16.6%
	No	20	83.3%
Any accident(s) for which a traffic violation conviction was issued	Yes	0	0
	No	24	100%
Any involvement in a vehicle accident while driving within the past 3 years	Yes	0	0
	No	24	100%
Self-reported historical driving performance	Rating scale 1 to 10 (very bad = 0; moderate = 5; very good = 10)	Mean = 6.65, *SD* = 1.24	

(version 4.5) in conjunction with Blender® plugins (version 2.78c).

To create freeway landscapes for the driving simulations, 3D models were built using Esri CityEngine®, with AutoCAD 2016, Rhinoceros 5, and Grasshopper (0.9.0076) as supplementary software. A standardized freeway loop designed with reference to a typical urban freeway in developed cities in a partly cloudy weather, with three lanes on each traffic direction and a total length of 40,500 m, has been applied in all driving simulations.

Six different curbside landscape conditions were designed and merged with the freeway infrastructure model (Figs. 2, 3). Among the three fundamental types—barren, turf, and woody—woody landscapes was designed with a higher level of visible greenness for drivers as they have the vertical volume. In contrast, the turf landscape had a distinctively lower level of visible greenness, and the barren landscape with zero visible greenness. Accordingly, a barren landscape was operationally defined as a freeway landscape without any vegetation. A turf landscape was operationally defined as a freeway landscape with minimal vegetation, meaning that only grassy median was used in the environment. Both shrub–regular and shrub–random landscapes were operationally defined as freeway landscapes with organized and unorganized layouts of

Fig. 2 Layouts of the six freeway landscape conditions.



Barren

Turf

Shrub–regular

Shrub–random

Tree–regular

Tree–random

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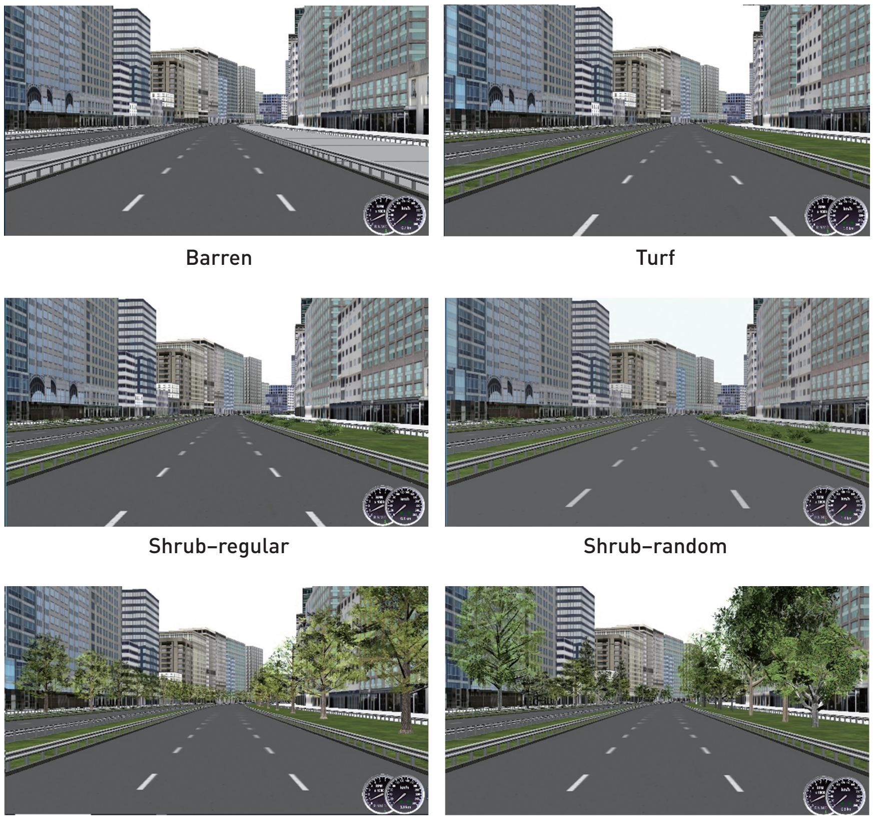

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Fig. 3 Screenshots of the six simulated freeway landscape conditions.

medium-sized perennial woody plants, respectively. Lastly, both tree–regular and tree–random landscapes were operationally defined as freeway landscapes with organized and unorganized layouts of tall perennial plants with a trunk and branches, respectively.

Except for the barren condition which had a concrete central reservation, a grassy median was placed in the 3-meter-wide central reservation for the other five conditions. The landscape zones were located on the two sides of the freeway, with each lane being 10 m wide. A simple grassy median was used for simulating the turf landscape. For the tree–regular and tree–random conditions, a single line of trees was placed in the center of the landscape lanes. For the shrub–regular and shrub–random conditions, two lines of evenly spaced shrub were placed in the center of the landscape lanes (i.e., the distance between two shrubs and each shrub to the edge of the road was 3.3 m). In the tree–regular and shrub–regular conditions, trees and shrubs were placed 20 m and 10 m evenly apart, respectively. To generate these two randomized layouts, the Grasshopper® plugins (0.9.0076) was used to develop randomly configured intervals for planting the vegetation along the freeway.

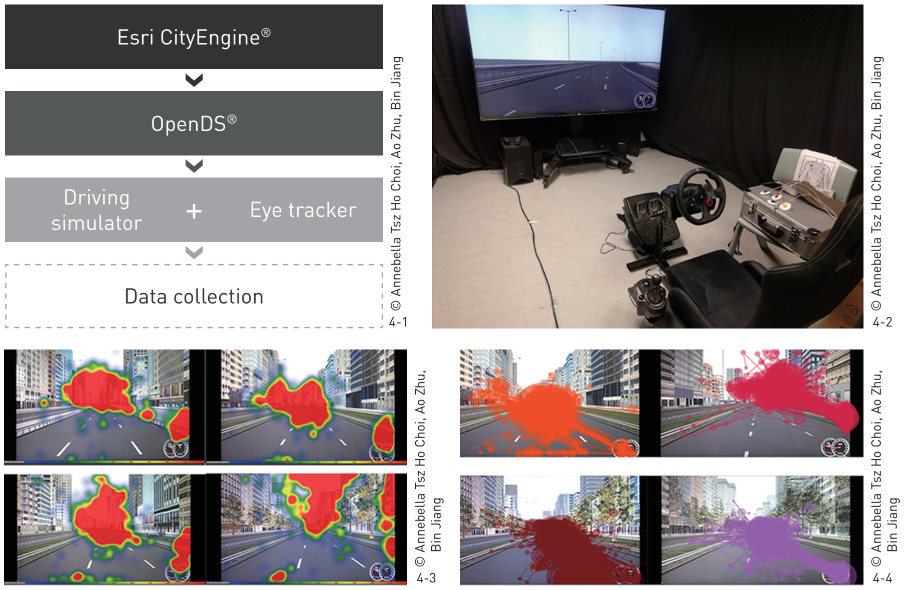
For these settings, 10 prevalent species of trees and 10 common shrubs were chosen based on the street vegetation inventory of major cities in sub-tropical and temperate areas, including New York, Chicago, London, and Hong Kong. To maintain equivalent total green volume for both tree and shrub conditions, the dimensions and quantity of shrubs and trees were configured in Esri CityEngine® for both regular and random layouts. The total green volume was calculated by summing the three-dimensional crown volumes of all vegetation elements in the foundation drawings, ensuring that despite differences in individual plant dimensions, the gross green volume remained equivalent across shrub and tree conditions.

Participants' eye movements were recorded using the SensoMotoric Instruments (SMI) Eye Tracking Glasses, with a sampling rate of 60 Hz or 120 Hz, a scene camera resolution of 1,280 × 960 pixels at 24 fps, and a video resolution of 960 × 720 pixels at 30 fps, with an accuracy of 0.5°. The recorded eye movement data were then exported into the SMI BeGazeTM eye tracking software for the pre-processing for further analysis (Fig. 4).

2.3 Experimental Design

The experiment was set up based on a one-way, six-level, within-subject design, with curbside landscape condition as the sole independent variable. A balanced Latin square (BLS) was used to counterbalance the order effect of the assignment of the six landscape conditions for the participants. The six landscape

Fig. 4 Experiment materials and apparatus of the driving simulation. Fig. 4-1: the process of generating the driving simulation. Fig. 4-2: setup of the driving simulator. Fig. 4-3: sample heatmap visualization of drivers' eye fixation data upon transferring to the eye tracking software. Fig. 4-4: sample scan path visualization of drivers' eye movements upon transferring to the eye tracking software.



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© Annebella Tsz Ho Choi, Ao Zhu, Bin Jiang conditions were further categorized into three fundamental types: barren, turf, and woody (i.e., shrub and tree). The woody landscape had a higher level of visible greenness for drivers as they have the vertical volume. In contrast, the turf landscape only had a green surface with no vertical volume and distinctively lower level of visible greenness. The barren landscape was a concrete paving surface with zero visible greenness. This categorization was designed to address Question 1.

2.4 Procedure

Prior to the experiment, an informed consent form was provided to the participants for their examination and endorsement to affirm their agreement. The experimenter and participants then proceeded to the laboratory, followed by a short briefing section and tour of all procedures and equipment. To confirm that participants' eyesight was normal or corrected to normal, a vision test was next administered. Participants were then instructed to adjust the play-seat to a comfortable position and to keep their heads as still as possible during the driving process.

Participants were given a 10-minute practice to get familiarized with the driving simulator and the operation of the equipment. They were then asked to fill out the first Visual Analog Scale (VAS) questionnaire, which would also be asked after each trial in the experiment, with the assistance by the experimenters. Subsequently, participants began a 90-minute driving task with a regulated speed limit of 120 km/h under one of the six conditions according to the BLS, where each driving task (under one landscape condition) was divided into six 15-minute trials. A 1-minute break was given to the participants upon completion of each trial (Fig. 5). The above procedure was repeated over six different days until the participants completed all six landscape conditions. Seven VAS questionnaires were completed by the end of the each, totaling 42 questionnaires per participant upon full completion of all sections.

2.5 Data Analysis

Eye-tracking data were recorded throughout the driving task, and analyzed to investigate eye fixation behaviors, including the proportion of fixation count on AOI, the proportion of fixation duration, and both the horizontal and vertical gaze dispersions[38–40] (Table 2).

Features in the driving scene were divided into three main regions

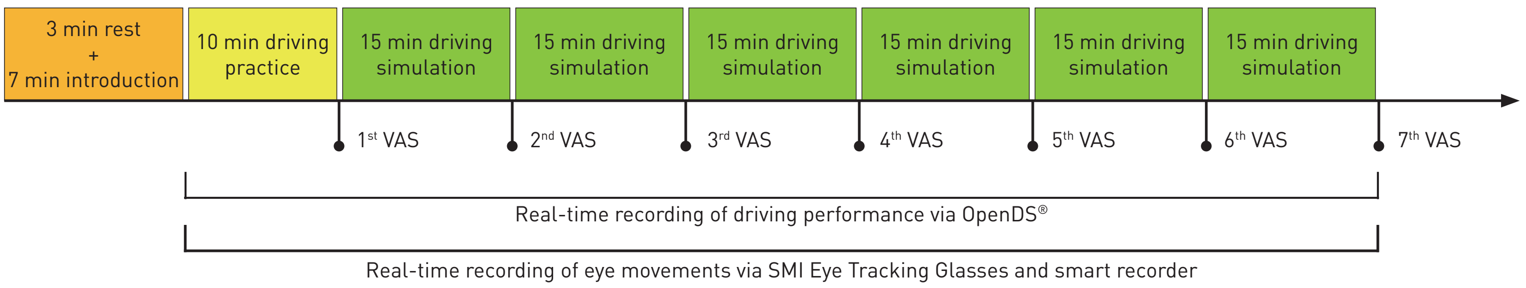

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Fig. 5
Experiment procedure.

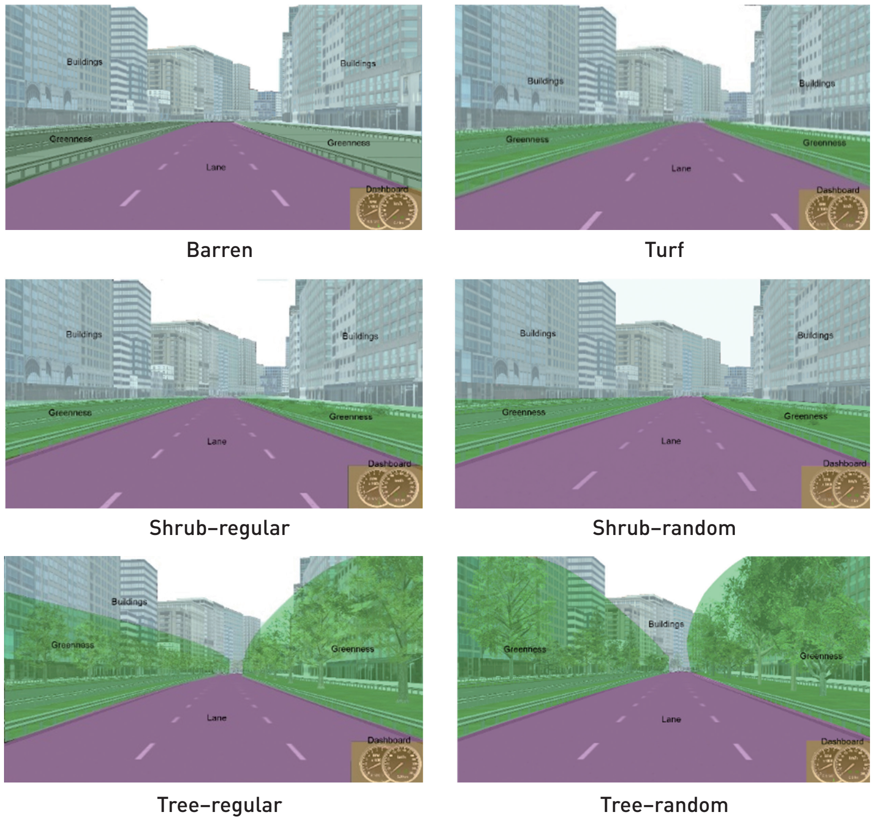
Table 2: Definitions of eye-tracking parameters

Parameter	Definition	Meaning	Reference
Proportion of fixation count	The proportion of total number of fixations on the AOI	A larger proportion indicates a higher number of fixations and greater level of engagement	Refs. [30–31]
Proportion of fixation duration	The proportion of length of time participants spent fixating on the AOI, representing the relative engagement with the object	The value strongly correlated with proportion of fixation count; a larger proportion indicates a longer proportion of time of fixation and greater level of engagement	Ref. [31]
Horizontal gaze dispersion	The standard deviation of gaze positions for horizontal coordinate	A higher value indicates more horizontal scanning by the driver, meaning a lower level of gaze concentration in one area	Ref. [32]
Vertical gaze dispersion	The standard deviation of gaze positions for vertical coordinate	A higher value indicates more vertical scanning by the driver, meaning a lower level of gaze concentration in one area	Ref. [32]

as the target AOIs for analysis: greenery, buildings, and task-related area (Fig. 6). The AOI on greenery consisted of both left and right landscapes with concrete, turf, shrubs or trees, and the central reservation. The AOI on buildings referred to the buildings located on both sides of the freeway and upcoming buildings in front of the visual field that was not blocked by any vegetation. The AOI on task-related area included the dashboard, as well as the lanes of the freeway.

Eye-tracking data of greenery, buildings, and task-related area were being transformed according to the data distribution for normalization. The data was submitted to IBM SPSS 23.0, and normality tests were conducted on all data prior to further statistical analysis with the one-way repeated-measure ANOVA. The normality tests were conducted by first calculating the kurtosis and skewness of the original data—kurtosis measures the distribution's peakedness, and skewness measures a variable's asymmetry in its distribution[41]. Since the sample size of the current study was less than 50, the null hypothesis should be rejected if the absolute Z-score of the skewness or kurtosis is larger than 1.96, and declared that the sample's distribution is not normal (α level 0.05)[41]. Then, with the consideration of the large individual differences in the eye-tracking data, an outlier analysis using the MAD method was performed and resubmitted for normality tests[37,42]. The normalcy transformation was then performed using the square root transformation on all skewed data to achieve a normal distribution before proceeding to the ANOVA[36,43]. Upon completion of the normality tests, the AOI data on green landscapes and buildings were transformed accordingly.

The analyses of the current study included three parts. Firstly, a one-way repeated measures ANOVA of the three fundamental landscape types were conducted to understand the basic nature of driving as a visual task (for Question 1). Then, a one-way repeated-measures ANOVA was used to uncover more features upon the six landscape conditions (for Question 2). Finally, the results from a two-way repeated-measures ANOVA were used to investigate the impact of complexity and greenness levels independently and interactively (for Question 3). All post-hoc tests were conducted using the Fisher's least significant difference (LSD) method.



Barren Turf

Shrub–regular Shrub–random

Tree–regular Tree–random

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Fig. 6 Detailed composition of AOIs of the six different conditions.

3 Results

3.1 Differences in Drivers' Eye Movements Among Three Fundamental Landscape Types

The ANOVA results of the proportions of fixation count and fixation duration on AOIs demonstrated that there were significant within-subject effects among the three landscape types (Tables 3, 4; Fig. 7). In particular, there were significant differences on the greenery

Table 3: ANOVA results of drivers' eye movements among the three fundamental landscape types

Parameter	AOI	Statistic	Barren	Turf	Woody
Proportion of fixation count	Greenery	Mean	0.209	0.232	0.228
		Standard error	0.017	0.022	0.016
		95% confidence interval	0.173, 0.244	0.186, 0.277	0.234, 0.301

(Continued)

Table 3: ANOVA results of drivers' eye movements among the three fundamental landscape types (Continued)

Parameter	AOI	Statistic	Barren	Turf	Woody
Proportion of fixation count	Buildings	Mean	0.530	0.486	0.378
		Standard error	0.045	0.046	0.030
		95% confidence interval	0.437, 0.622	0.390, 0.582	0.316, 0.440
	Task-related area	Mean	0.423	0.437	0.494
		Standard error	0.065	0.067	0.048
		95% confidence interval	0.290, 0.588	0.298, 0.575	0.394, 0.594
Proportion of fixation duration	Greenery	Mean	0.191	0.222	0.248
		Standard error	0.019	0.024	0.017
		95% confidence interval	0.153, 0.230	0.172, 0.272	0.214, 0.283
	Buildings	Mean	0.533	0.486	0.377
		Standard error	0.047	0.049	0.032
		95% confidence interval	0.436, 0.630	0.385, 0.587	0.311, 0.443
	Task-related area	Mean	0.424	0.444	0.507
		Standard error	0.067	0.070	0.051
		95% confidence interval	0.286, 0.562	0.300, 0.589	0.401, 0.612

Table 4: Summary of one-way repeated-measures ANOVA among the three fundamental landscape types

Parameter	AOI	Type III sum of squares	*df*	Mean square	*F*	*p*	η_p^2
Proportion of fixation count	Greenery	0.043	2	0.021	3.708	0.032	0.139
	Error	0.265	46	0.006	—	—	—
	Buildings	0.292	1.551	0.188	5.831	0.011	0.202
	Error	1.152	35.677	0.032	—	—	—
	Task-related area	0.068	1.569	0.043	0.662	0.487	0.028
	Error	2.366	36.077	0.066	—	—	—
Proportion of fixation duration	Greenery	0.039	2	0.019	2.986	0.060	0.115
	Error	0.299	46	0.007	—	—	—
	Buildings	0.308	1.561	0.197	5.413	0.014	0.191
	Error	1.307	35.902	0.036	—	—	—
	Task-related area	0.090	1.555	0.058	0.800	0.428	0.034
	Error	2.579	35.767	0.072	—	—	—

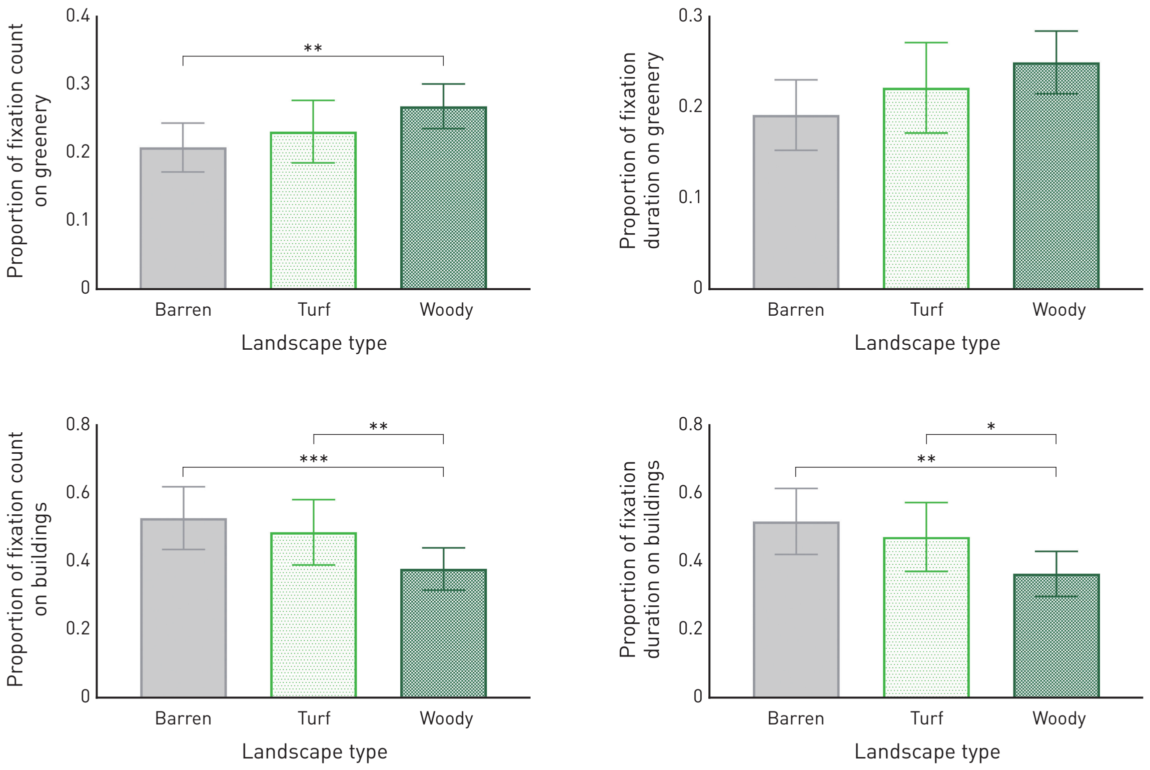

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Fig. 7 Differences in eye movements among the three fundamental landscape types, where error bars stand for 95% confidence interval (***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$).

for the proportion of fixation count, and on the buildings for both the proportions of fixation count and fixation duration. Pairwise analyses demonstrated no significant difference between the barren and turf landscapes for both proportion of fixation count and duration on neither AOIs. However, the proportion of fixation count on the greenery showed a significant result ($p = 0.032$), i.e., the woody conditions displayed a larger proportion than the barren condition. Additionally, both the barren and turf conditions displayed more fixation count and longer fixation duration on the buildings than the woody conditions.

3.2 Differences of Drivers' Eye Movements Among the Six Landscape Conditions

A comparison of the six landscape conditions' distinct impacts on drivers' eye movements was conducted, with the proportions of fixation count and fixation duration on AOIs, and both the horizontal and vertical gaze dispersion analyzed (Table 5).

3.2.1 Proportion of Fixation Count

Through the Greenhouse-Geisser correction (Mauchly's sphericity test, $p = 0.014$), the proportion of fixation count on greenery revealed a significant difference among the landscape conditions ($F(3.328, 76.552) = 8.152$, $p < 0.001$, $\eta_p^2 = 0.262$) (Table 6, Fig. 8). The fixation proportion of greenery under the tree–regular condition was significantly larger than those under the barren ($p = 0.006$), turf ($p = 0.010$), shrub–regular ($p = 0.035$), and shrub–random ($p = 0.004$) conditions, with no significant difference with the tree–random condition ($p = 0.111$). Meanwhile, the fixation proportion under the tree–random condition was significantly larger than those under barren ($p = 0.001$), turf ($p = 0.004$), shrub–regular ($p < 0.001$), and shrub–random ($p < 0.001$) conditions with obvious differences.

The proportion of fixation count on the buildings yielded a significant result ($F(5, 115) = 7.479$, $p < 0.001$, $\eta_p^2 = 0.295$, with $p = 0.442$ for Mauchly's sphericity test). As shown in Fig. 9, the fixation proportion under the tree–regular condition was significantly smaller than the barren ($p < 0.001$), turf ($p < 0.001$), shrub–regular ($p < 0.001$), and shrub–random ($p = 0.026$) conditions, with no significant difference found between the tree–random condition ($p = 0.334$). Furthermore, the fixation proportion was significantly smaller under the tree–random condition than under the barren ($p = 0.001$), turf ($p = 0.003$), and shrub–regular ($p = 0.010$) conditions, but marginally smaller than in the shrub–random condition ($p = 0.083$). Lastly, the fixation proportion under the shrub–random condition was significantly smaller than the barren condition ($p = 0.049$).

AOI result on task-related area was insignificant, $F(5, 115) = 1.355$, $p = 0.247$, with Mauchly's sphericity test yielding $p = 0.201$.

3.2.2 Proportion of Fixation Duration

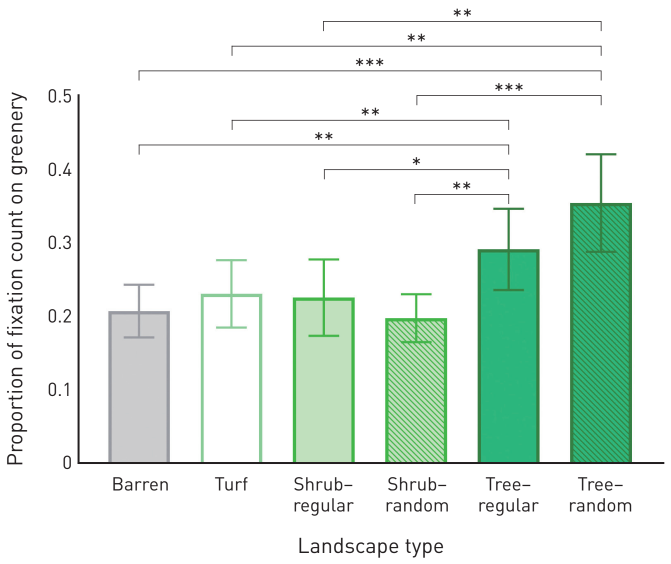
The proportion of fixation duration on greenery yielded a

Table 5: Summary of one-way repeated-measures ANOVA among the six landscape conditions

Parameter	AOI	Type III sum of squares	*df*	Mean square	*F*	*p*	η_p^2
Proportion of fixation count	Greenery	0.434	3.328	0.087	8.152	0.000	0.262
	Error	1.226	76.552	0.016	—	—	—
	Buildings	1.023	5	0.205	7.479	0.000	0.245
	Error	3.145	115	0.027	—	—	—
	Task-related area	0.430	5	0.086	1.355	0.247	0.056
	Error	7.306	115	0.064	—	—	—
Proportion of fixation duration	Greenery	0.417	3.253	0.128	7.365	0.000	0.243
	Error	1.303	74.816	0.017	—	—	—
	Buildings	1.012	5	0.202	6.654	0.000	0.224
	Error	3.497	115	0.030	—	—	—
	Task-related area	0.436	5	0.087	1.240	0.295	0.051
	Error	8.099	115	0.070	—	—	—
Gaze dispersion	Horizontal gaze dispersion	6,651.886	3.840	1,732.107	3.291	0.016	0.125
	Error	46,483.623	115	404.205	—	—	—
	Vertical gaze dispersion	1,828.032	5	365.606	0.985	0.430	0.041
	Error	42,687.507	115	371.196	—	—	—

Table 6: Descriptive statistics of proportion of fixation count among the six landscape conditions

AOI	Statistic	Barren	Turf	Shrub–regular	Shrub–random	Tree–regular	Tree–random
Greenery	Mean	0.201	0.232	0.226	0.198	0.292	0.355
	Standard error	0.017	0.022	0.025	0.016	0.027	0.032
	95% confidence interval	0.173, 0.244	0.186, 0.277	0.174, 0.278	0.166, 0.231	0.236, 0.347	0.289, 0.422
Buildings	Mean	0.530	0.486	0.470	0.417	0.290	0.337
	Standard error	0.045	0.046	0.041	0.043	0.039	0.042
	95% confidence interval	0.437, 0.622	0.390, 0.582	0.386, 0.554	0.328, 0.506	0.211, 0.370	0.250, 0.423
Task-related area	Mean	0.423	0.437	0.419	0.480	0.575	0.500
	Standard error	0.065	0.067	0.058	0.069	0.065	0.069
	95% confidence interval	0.290, 0.588	0.298, 0.575	0.299, 0.575	0.337, 0.623	0.440, 0.710	0.357, 0.643



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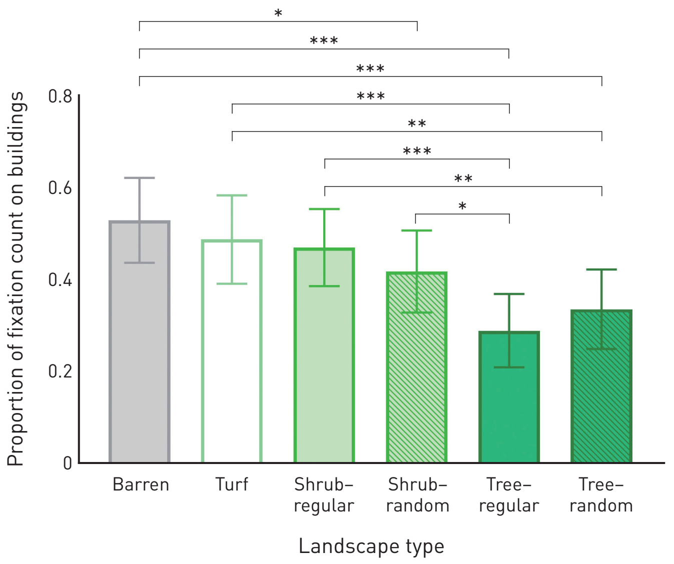

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Fig. 8 Proportion of fixation count on greenery among the six landscape conditions, where error bars stand for 95% confidence interval (***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$).

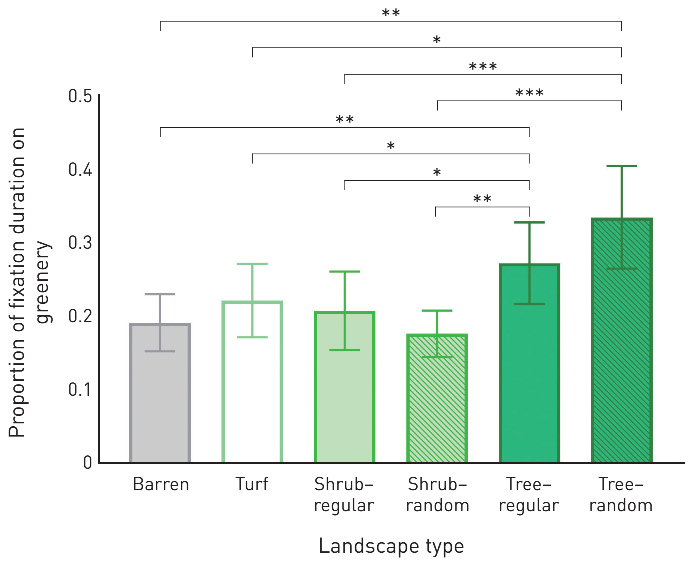
Fig. 9 Proportion of fixation count on buildings among the six landscape conditions, where error bars stand for 95% confidence interval (***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$).

significant result ($F(3.253, 74.816) = 7.365$, $p < 0.001$, $\eta_p^2 = 0.243$, with $p = 0.008$ for Mauchly's sphericity test). As depicted in Table 7 and Fig. 10, the proportions of fixation duration under the tree–regular and tree–random conditions were both significantly smaller than barren ($p = 0.006$, $p = 0.002$), turf ($p = 0.05$, $p = 0.014$), shrub–regular ($p = 0.04$, $p = 0.001$), and shrub–random ($p = 0.003$, $p < 0.001$) conditions. However, no significant difference between the two tree conditions were found. The shrub–random condition showed a marginally smaller result than the turf condition ($p = 0.082$).

The proportion of fixation duration on buildings was significantly different across the six landscape conditions ($F(5, 115) = 6.654$, $p < 0.001$, $\eta_p^2 = 0.224$, with $p = 0.394$ for Mauchly's sphericity test). Figure 11 showed that the proportions of fixation duration were significantly smaller under the tree–regular and tree–random conditions than the barren ($p < 0.001$, $p = 0.001$), turf ($p < 0.001$, $p = 0.006$), and shrub–regular ($p < 0.001$, $p = 0.011$) conditions. Yet, no significant difference was found between the tree–regular, shrub–random, and tree–random conditions. Differed from the proportion of fixation count, the shrub–random condition was significantly smaller than barren ($p = 0.041$) when observing the proportion of fixation duration on buildings.

Table 7: Descriptive statistics of proportion of fixation duration among the six landscape conditions

AOI	Statistic	Barren	Turf	Shrub–regular	Shrub–random	Tree–regular	Tree–random
Greenery	Mean	0.191	0.222	0.209	0.177	0.273	0.334
	Standard error	0.019	0.024	0.026	0.015	0.027	0.034
	95% confidence interval	0.153, 0.230	0.172, 0.272	0.156, 0.262	0.145, 0.209	0.218, 0.329	0.265, 0.404
Buildings	Mean	0.533	0.486	0.470	0.406	0.295	0.338
	Standard error	0.047	0.049	0.042	0.046	0.041	0.044
	95% confidence interval	0.436, 0.630	0.385, 0.587	0.382, 0.558	0.310, 0.501	0.211, 0.379	0.248, 0.428
Task-related area	Mean	0.424	0.444	0.439	0.492	0.584	0.513
	Standard error	0.067	0.070	0.064	0.073	0.068	0.073
	95% confidence interval	0.286, 0.562	0.300, 0.589	0.306, 0.571	0.341, 0.643	0.443, 0.725	0.363, 0.663



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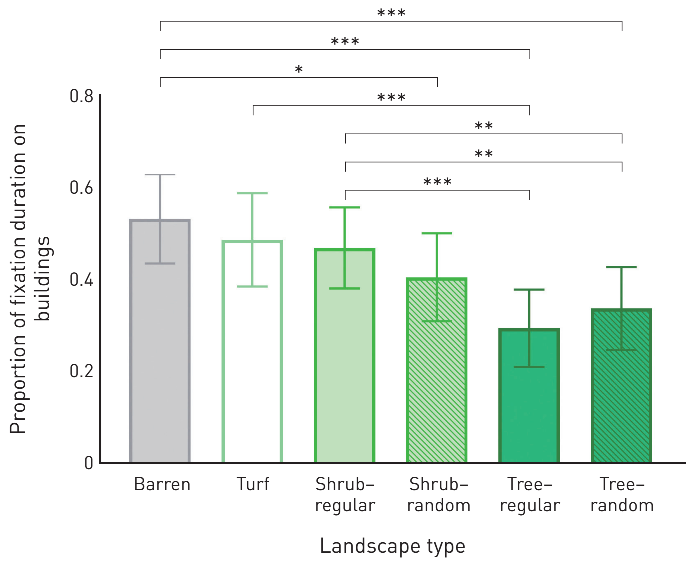

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Fig. 10 Proportion of fixation duration on green landscapes among the six landscape conditions, where error bars stand for 95% confidence interval (***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$).

Fig. 11 Proportion of fixation duration on buildings, where error bars stand for 95% confidence interval (***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$).

AOI on task-related area was also found to be insignificant ($F(5, 115) = 1.240$, $p = 0.295$).

3.2.3 Horizontal and Vertical Gaze Dispersions

To further investigate the impacts of the six different landscape conditions on drivers' cognitive processing, a one-way ANOVA on the horizontal and vertical gaze dispersions was conducted (Table 8).

The results showed that the horizontal gaze dispersion across the six conditions differed significantly ($F(3.840, 88.328) = 3.291$, $p = 0.016$, $\eta_p^2 = 0.125$, with $p = 0.031$ for Mauchly's sphericity test). As illustrated in Fig. 12, the tree conditions evoked the smallest dispersion: the tree–regular condition was significantly smaller than the turf condition ($p = 0.019$), and the tree–random condition was significantly smaller than the barren ($p = 0.001$) and turf ($p = 0.003$) conditions. On the contrary, the turf condition evoked the largest dispersion: not only was it significantly larger than the tree–regular and tree–random conditions as mentioned above, but also the shrub–regular ($p = 0.001$) condition. It is worth noting that there were no significant differences between the shrub–random and other five conditions.

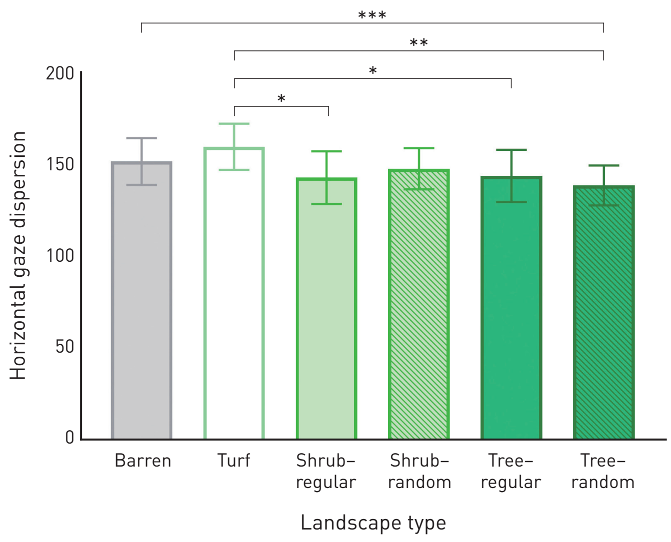
Meanwhile, the result of the vertical gaze dispersion was not found to be significant ($F(5, 115) = 0.985$, $p = 0.430$, $\eta_p^2 = 0.041$).

3.3 Differences of Greenness and Complexity Levels of the Landscape Conditions

A two-way repeated-measures ANOVA was used to examine the

Table 8: Descriptive statistics of the horizontal and vertical gaze dispersions among the six landscape conditions

Parameter	Statistic	Barren	Turf	Shrub–regular	Shrub–random	Tree–regular	Tree–random
Horizontal gaze dispersion	Mean	151.934	159.941	143.218	148.001	144.110	138.963
	Standard error	6.164	6.052	6.913	5.399	6.847	5.240
	95% confidence interval	139.184, 164.684	147.420, 172.461	128.918, 157.519	136.833, 159.169	129.946, 158.273	128.124, 149.802
Vertical gaze dispersion	Mean	89.185	95.706	88.069	85.339	91.562	85.721
	Standard error	5.825	5.860	4.179	3.266	5.327	3.718
	95% confidence interval	77.136, 101.234	83.584, 107.827	79.424, 96.715	78.583, 92.095	80.542, 102.583	78.029, 93.413



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independent and interactive effects of the levels of greenness and complexity, i.e., comparison between the shrub and tree conditions.

3.3.1 Proportion of Fixation Count

For greenery AOIs, the main effect of greenness was significant ($F(1, 23) = 26.556, p < 0.001, \eta_p^2 = 0.536$), with less fixation counts under conditions with lower greenness, while the main effect of complexity was insignificant. A marginally significant interaction effect between greenness and complexity was found ($F(1, 23) = 3.108, p = 0.091, \eta_p^2 = 0.119$) (Fig. 13).

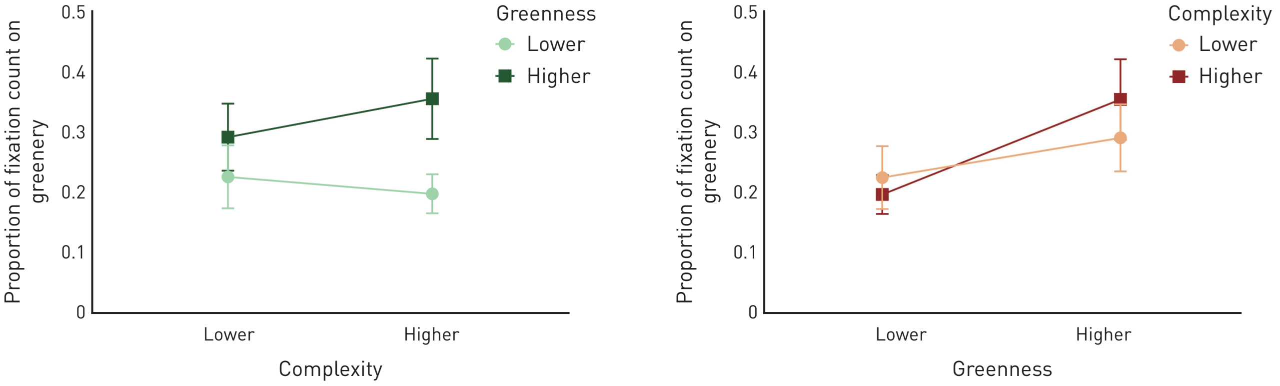
In terms of buildings, the main effect of greenness was found to be significant ($F(1, 23) = 15.031, p = 0.001, \eta_p^2 = 0.395$), with less fixation counts in conditions with higher greenness, but insignificant for the main effect of complexity was found ($F(1, 23) = 0.007, p = 0.934, \eta_p^2 < 0.001$). A marginally significant interaction effect was found ($F(1, 23) = 4.206, p = 0.052, \eta_p^2 = 0.155$) (Fig. 14).

The main effects of greenness and complexity were all insignificant ($F(1, 23) = 2.910, p = 0.101, \eta_p^2 = 0.112$). Similar to the other AOIs, the main effect of the level of complexity was non-significant ($F(1, 23) = 0.014, p = 0.905, \eta_p^2 = 0.001$). The interaction was found to be insignificant ($F(1, 23) = 2.899, p = 0.102, \eta_p^2 = 0.112$).

3.3.2 Proportion of Fixation Duration

For greenery AOIs, the main effect of greenness was significant ($p < 0.001$), with shorter fixation duration in the conditions with lower greenness. Insignificant results were found on the main effect of complexity ($p = 0.496$). A marginally significant interaction effect was found ($p = 0.081$) (Fig. 15).

For buildings, the main effect of greenness was significant ($p = 0.002$), with shorter fixation duration in the higher greenness



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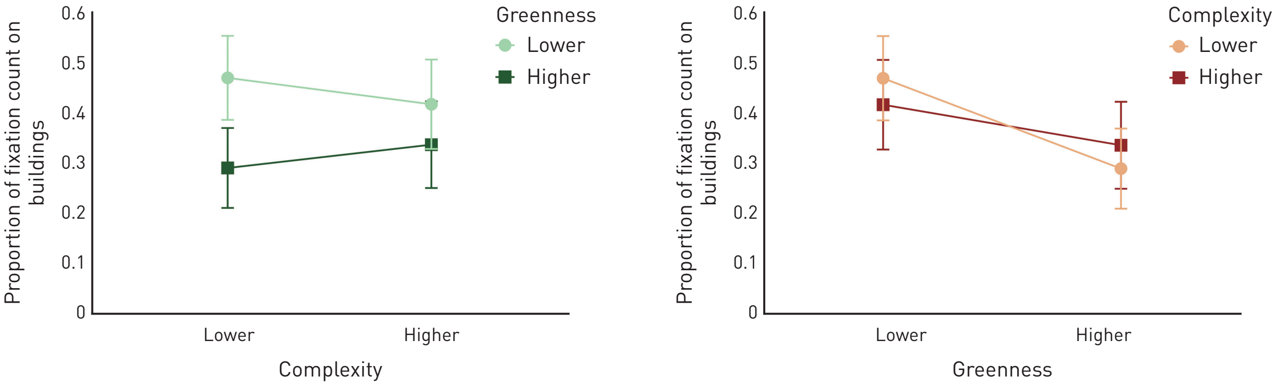

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Fig. 12 Horizontal gaze dispersion among the six landscape conditions, where error bars stand for 95% confidence interval (***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$).

Fig. 13 Two-way ANOVA results between the level of greenness and complexity for proportion of fixation count on greenery, where error bars stand for 95% confidence interval.

Fig. 14 Two-way ANOVA analysis between the level of greenness and complexity for proportion of fixation count on buildings, where error bars stand for 95% confidence interval.

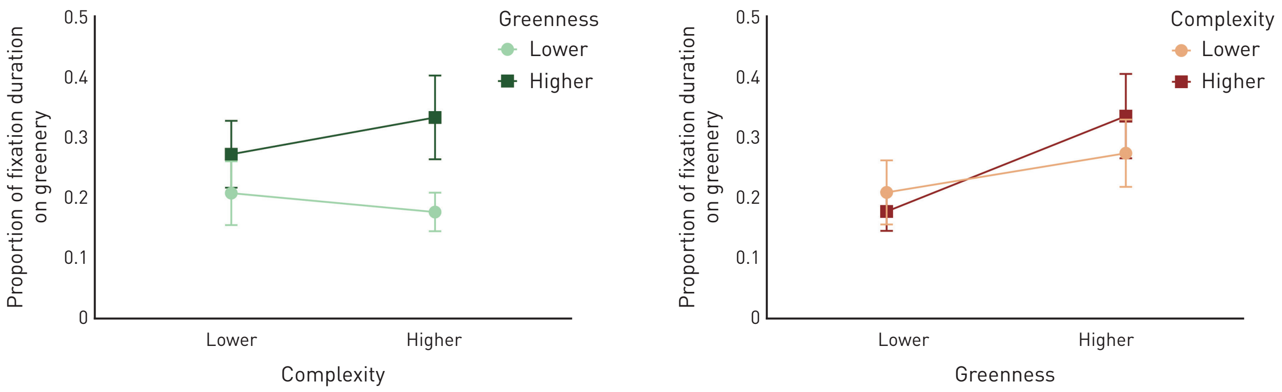

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Fig. 15 Two-way ANOVA results between the level of greenness and complexity for proportion of fixation duration on greenery, where error bars stand for 95% confidence interval.

conditions, but insignificant for the main effect of complexity ($p = 0.790$). A significant interaction was found ($p = 0.049$) (Fig. 16).

Non-significant results were found regarding the main effect of greenness and complexity ($p = 0.129$, $p = 0.888$) on task-related area. The interaction was also found to be insignificant ($F(1, 23) = 1.862$, $p = 0.186$, $\eta_p^2 = 0.075$).

4 Discussion

By measuring and analyzing drivers' eye movements across three main AOIs—greenery, buildings, and task-related area, this study built upon our two previous studies within a larger project, aiming to investigate the implicit impact of freeway landscapes on drivers' visual perception, and how further the findings can be integrated with findings of our two previous studies on impacts of freeway landscapes on drivers' mental states and performance to create a comprehensive framework.

4.1 Interpretations of Key Findings

In terms of the impact of the greenness on drivers' eye movement on barren, turf, and woody landscapes, it was found that the incorporation of higher level of greenness with vertical volume in a freeway landscape reoriented drivers' eye movement towards the AOI of greenery, revealing a clear trend that drivers' eye fixation increased on greenery, which in turn decreased the fixation on buildings. This observed trend can be interpreted through three propositions. First, woody plants that have vertical greenness could act as a visual buffer against drivers' experience of stressors and cognitive burdens in the driving environment[44] (e.g., concrete buildings along the freeway). Second, compared with the barren and turf landscapes, drivers' greater visual engagement to greenery, especially in tree conditions, may partially be explained by drivers' needs to be vigilant for potential physical obstacles to avoid accidents[4,17–18,45]. Last, previous studies in driving and other experimental context suggested that greenery, especially those with a significant vertical volume, could be the key in inducing mental restoration by reducing drivers' mental stress and negative emotions, and by restoring their directed attention[46–47]. In sum, these findings established a solid foundation for our investigation, further emphasizing the consideration of vegetation's volumetric properties and their potential differing impacts on drivers.

Additionally, the findings demonstrated that no significant differences were observed across all conditions regarding the AOIs in the task-related area. This indicates that consistent visual engagement with the speedometer and tachometer is exclusively linked to any potential effects on drivers' mental states and driving

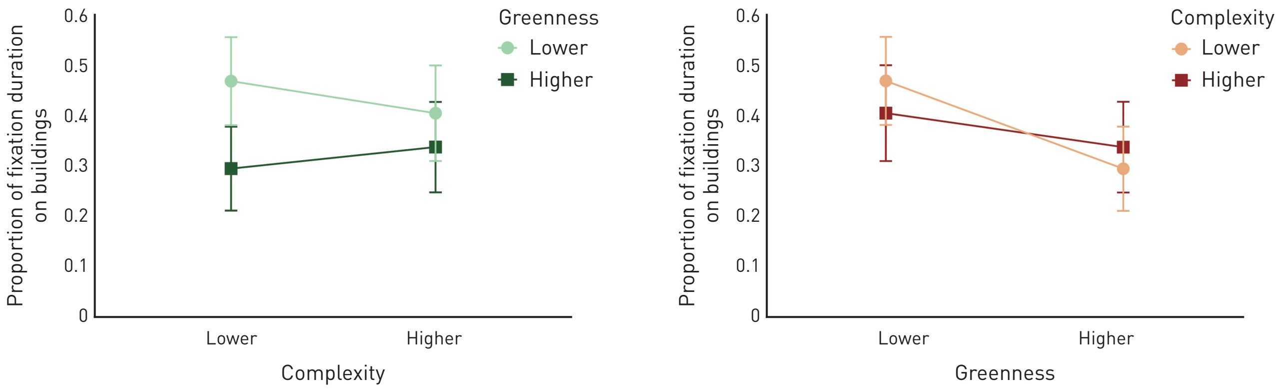

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Fig. 16 Two-way ANOVA results between the level of greenness and complexity for proportion of fixation duration on buildings, where error bars stand for 95% confidence interval.

performance in the varying roadside landscapes. More detailed analyses are discussed as follow.

4.1.1 Moderate Greenness Is Optimal to Balance Eye Movement

When comparing all six landscape conditions, it was discovered that drivers focused on the greenery AOIs for a substantially longer period than that on building AOIs when trees were present. Noting that under the two tree conditions, the plantation of trees blocked a substantial portion of roadside buildings. This may partially explain why a significant difference of both fixation counts and duration were found between the tree landscapes and other conditions for greenery, while other comparisons remained non-significant. However, it is important to stress that a significantly lower fixation proportion of both counts and duration on buildings was only observed under the shrub–random condition, rather than the shrub–regular condition, when compared with the barren condition. The findings are crucial in the debate about striking a balance between greenness and driving performance. With better driving performance being noted under the shrub–random condition in our previous study[17], this visual data is a key to providing further evidence for understanding the underlying relationships between these factors.

Recalling our previous studies, when considering only greenness, shrub conditions were found to elicit mental states with a good balance of relaxation and arousal[17]. Traditional theories such as ART and SRT suggest that visual contact with trees is more mentally restorative than landscapes with little greenness[12–13,15]. This implies that increased visual fixation on trees can facilitate stress reduction, attention restoration, and mood promotion[18]. However, with vehicle–tree collision being one of the major reasons of traffic injuries and deaths[3,48], tree landscape may become a risky feature that drivers must pay "directed attention" to quickly comprehend, calculate, and avoid potential collisions, especially at high speeds[17–18,49]. In other words, the restorative effects of exposure to trees could be compensated when moving at high speeds, highlighting the need to balance restoration with the consumption of directed attention[17].

Supporting this notion, it was observed that while the shrub–random condition did not produce a significant difference when compared with the barren, turf, and shrub–regular conditions for greenery, it did differ significantly from the barren condition for buildings. This may suggest that although drivers fixated on the landscape zone to a similar degree under the barren, turf, and both shrub conditions, the presence of greenness in the shrub–random condition altered drivers' visual fixation on neither greenery nor buildings. Furthermore, results from the horizontal gaze dispersion showed that drivers' gazes were significantly more spread out when driving under the barren and turf conditions, while they were significantly more concentrated under the shrub–regular and both tree conditions. Notably, drivers' gaze was neither too segregated nor too concentrated when navigating the shrub–random condition, indicating a neural level of visual engagement. This finding may help explain the better driving performance observed in the shrub–random condition in our earlier research[17].

Together, these findings suggest that moderate greenness is associated with a balanced drivers' eye movement, reinforcing our previous conclusions that shrub conditions elicited mental states with a good balance of relaxation and arousal, and yielded better driving performance compared with barren, turf, and tree conditions[17–18,50].

4.1.2 The equilibrium Effect of Greenness and Complexity on Drivers' Eye Movement

Analyses were conducted to investigate the main and interactive effects of various levels of greenness and complexity on drivers' eye movements. In either AOI, results revealed a significant main effect on greenness, meaning that drivers were found to be more attracted to greener landscapes, which confirms existing research findings[39]. When comparing the eye movements between conditions with lower (i.e., shrub conditions) or higher (i.e., tree conditions) levels of greenness with the same level of complexity, a higher proportion of fixation count and duration were observed when the drivers were exposed to the tree conditions.

However, the main effect of complexity was not found to be significant in any AOI, suggesting that complexity alone does not directly impact drivers' eye movement. One reason may lie in that human eyes' primary function is to collect and focus light, which is subsequently converted into electrical signals that the brain can interpret[51]. When driving on a freeway, anytime drivers fixate their focal point, the optic flow continues to move away from the focal point. This rapid movement may limit their ability to concentrate on the environment[52]. Therefore, changes of complexity might exert a lower direct impact on drivers' eye movements than the changes of greenness.

Intriguingly, the analysis on the fixation duration on building AOIs showed a significant interaction between greenness and complexity, while other measures showed marginally significant or non-significant interactions. At higher greenness levels, lower levels of complexity were found to be associated with shorter drivers' fixation durations on buildings. Meanwhile, at lower greenness levels, higher levels of complexity were found to be associated with a higher drivers' fixation counts on buildings. Other marginally significant results showed similar patterns. These results echoed with our previous findings on impacts of freeway landscapes on driving performance and mental restoration[17–18].

Regarding mental restoration, drivers' visual access to an environment is associated with individuals' positive (e.g., preference) and negative (e.g., fear) forms of engagement with the environment[53]. For instance, higher visual access of shrub landscapes—characterized by greater exposure to buildings in the shrub–regular condition—may lead to higher degree of engagement with greeneries due to drivers' unconscious shift of preference towards greenness in response to potential stressors (e.g., concrete buildings). On the contrary, lower visual access of tree landscapes—with even less openings in the tree–random landscape—may result in higher degree of engagement with greeneries due to drivers' uncertainty beyond the obstructed surroundings (i.e., potential pedestrians or animals crossing the road). In terms of driving performance, greater visual engagement with a particular landscape might indicate that drivers perceive the landscape as risky (i.e., the presence of trees) and prefer observing to avoid accidents[49,54–55].

Overall, these interactions suggest an equilibrium (trade-off) effect between greenness and complexity, where the objective of visual engagement to various landscapes is to gain a balance between mental restoration and driving performance, shedding light on the relationship between landscapes, mental states, and driving performance.

4.1.3 A Closure to the Multi-study Project

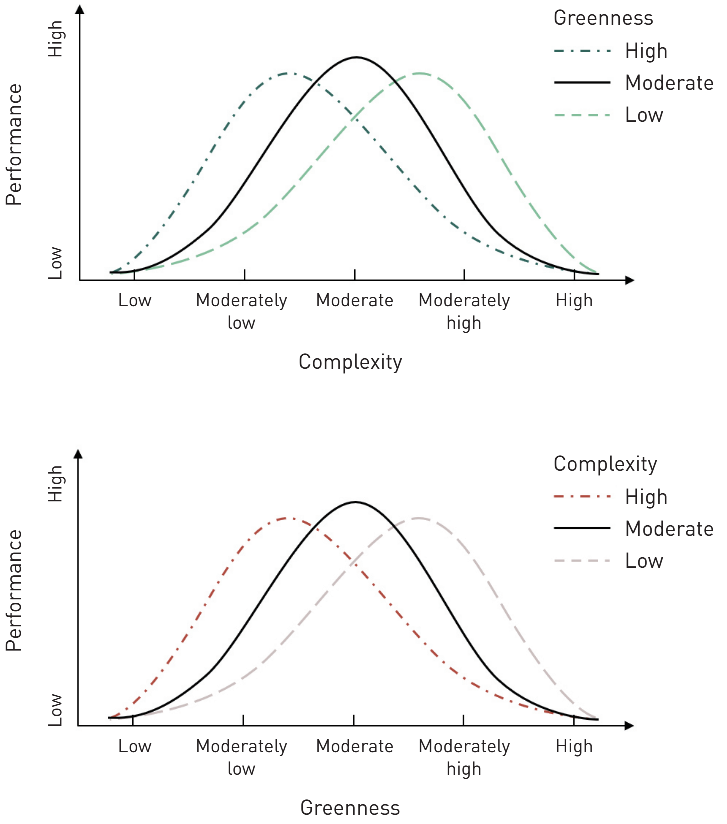
As part of the larger project, the current study's eye-tracking data provided critical evidence supporting the potential equilibrium between relaxation and arousal noted in our previous work, establishing a framework to depict potential links among drivers' visual perception, driving performance, and mental states. This equilibrium, influenced by changes in landscape conditions, likely lead to a balanced benefits on both mental states and driving performance.

In our previous research[18], the landscape with greater greenness and lower complexity (i.e., tree–regular condition) was proved more beneficial to drivers' mental well-being. This finding aligns with the current research results that higher greenness with lower complexity resulted in a reduction of fixation on greenery. This observation may also indicate a successful reorientation of drivers' gaze toward the road ahead[56].

Conversely, our previous research[17] found that the landscape with moderate-level greenness with higher complexity (i.e., shrub–random condition) elicited the best driving performance across all tested conditions, where a balanced level of visual engagement was achieved. This points out that a greater supply of restorative landscapes does not always guarantee better outcomes, which can be supported by the Yerkes-Dodson Law, where the optimal performance is often achieved when the relaxation and arousal reach an equilibrium[18,50,57] (Fig. 17).

In sum, pursuing optimal mental restoration may be seen as a unidimensional effort focused solely on enhancing the mental benefits derived from visual contact with greenery. In contrast, seeking optimal driving performance involves a more nuanced, bipolar approach that requires a balance between achieving mental restoration and maintaining arousal through visual engagement with various landscapes[17]. Thus, the equilibrium effect remains evident, providing scientific evidence for the development of a triangular theoretical framework that links visual perception, mental states, driving performance, and freeway landscapes (Fig. 18). Specially, visual perception, as indicated by eye movement, serves as a solid and crucial connection within

Fig. 17 Considering the results and the Yerkes-Dodson Law, a balance between the level of greenness and complexity is required to maintain a sufficient level of arousal to optimize driving performance.



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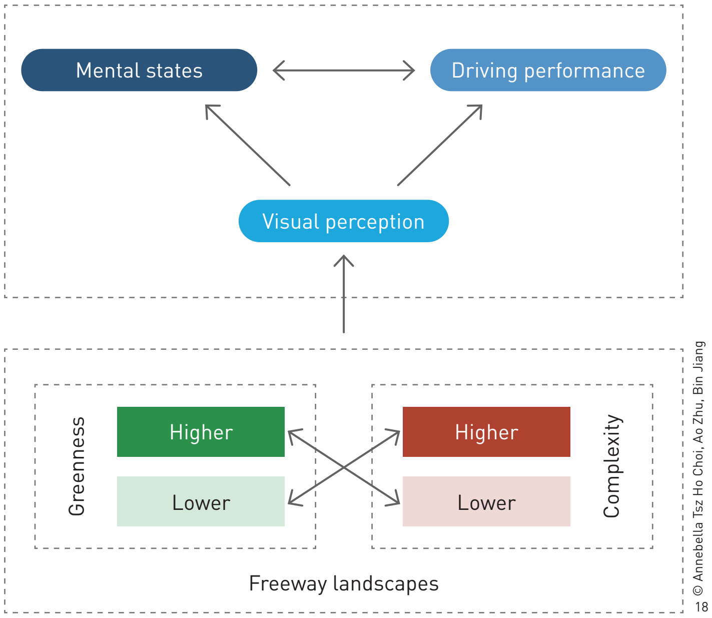

Fig. 18 A proposed framework to describe links based on findings of the whole project: relationship among freeway landscapes, drivers' visual perception measured by eye movement, driving performance, and mental states.

the framework, providing the supplemental piece of information to further affirm the interrelationship.

4.2 Limitations and Potential Directions

Nevertheless, this study has some limitations that warrant attention and may inspire new research ideas on this important topic. First, the present study conducted in a simulated driving environment may not fully represent real-world driving conditions. To enhance ecological validity, future studies should expand the current research in a more realistic and complex simulated environment, incorporating a wider range of landscape features, plant species, and seasonal variations, providing a safe and controlled experimental setting while improving the generalizability of the current findings. Additionally, real-world driving experiments should also be considered to examine the possible effects of natural elements and traffic conditions, such as weather and road congestion, on visual attention and related behavioral changes.

Second, while the six landscape conditions used in the experiment have produced a noteworthy equilibrium effect of greenness and complexity, this represents only a small segment of the broader gradient. Future research is advised to replicate this study with a greater variety of landscape layouts and types, manipulating the range and combination of greenness and complexity. Further analysis could investigate whether different trees uniquely influence drivers' attention and mental states.

Third, although the within-subject design provided significant insights into the effective use of landscape design for enhancing driver safety and well-being, future researchers may benefit from detailed between-subject analyses with a larger sample size to explore interactions between greenness, complexity, and moderating variables like driving experience and age. It would also be beneficial to conduct comprehensive analyses to test and validate the proposed theoretical framework.

Finally, in practice, freeway designs may prioritize mental restoration or aesthetic experience, while other designers may favor maximizing driving performance. Future research should examine these priorities within specific environmental and social context to determine the most feasible landscape design solutions, especially with reference to the proposed framework to consider seeking the equilibrium between all factors.

5 Conclusions

Aiming to explore the impact of freeway landscapes on driving safety, a comprehensive research project was initiated to investigate the effects of greenness and complexity levels on drivers' mental states and driving performance under six landscape conditions. The current study utilizing eye movement observations plays a crucial role in this endeavor by providing evidence for the need to balance greenness and complexity in freeway landscapes to optimize benefits for drivers. Building upon findings from our two previous studies of the same project, this study further proposes the potential connections among freeway landscapes, visual perception, mental states, and driving performance. Future studies are encouraged to incorporate all the elements of the proposed framework in their environmental research and design efforts, creating a more holistic understanding of the dynamics of transportation infrastructure.

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ELECTRONIC SUPPLEMENTARY MATERIAL

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Competing interests | The authors declare that they have no competing interests.

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城市高速公路绿色景观对驾驶员视觉感知的影响：绿化度与复杂度的平衡效应

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摘要

绿色景观对驾驶员视觉注意力具有重要影响，但仍需进一步探索最优的景观构成方案。本研究采用眼动追踪技术开展城市高速公路模拟驾驶实验，记录24名驾驶员在6种不同景观环境下完成90分钟驾驶任务时，在3个主要关注区域（AOIs）的眼部注视和凝视行为。通过对无植物景观、草坪景观和木本植物景观的被试内方差分析发现，绿化度的增加可显著引导驾驶员的眼部运动转向绿色区域。针对6种景观条件的对比分析表明，灌木景观环境能够提供最为平衡的AOI分布，使驾驶员既不过度关注绿色特征，也不过度关注人工特征，实现了视觉注意力的最优分配。此外，通过对2种灌木景观环境和2种乔木景观环境的重复测量双因子方差分析，发现高速公路景观绿化度与复杂性之间存在权衡效应。本研究为景观设计中绿化度与复杂性的平衡配置提供了重要的科学依据，证实了这种平衡对实现最佳视觉感知效果的关键作用。最后，本文提出了“视觉感知－心理状态－驾驶表现”三角理论框架，为未来健康安全驾驶环境的研究和设计提供了理论支持和实践参考。

关键词

高速公路；绿色空间；路缘景观；视觉感知；眼动；平衡效应；驾驶模拟

文章亮点

- 基于眼动追踪技术揭示了景观绿化度与复杂度对驾驶员视觉感知的影响机制
- 发现灌木景观的绿化度和复杂度的平衡配置能够引导最优的视觉注意力分配
- 提出“视觉感知－心理状态－驾驶表现”的三角理论框架，为安全驾驶环境研究提供了新的理论视角

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