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Characterizing the driving cognition within spiral tunnels based on SER principle

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ABSTRACT

Spiral tunnels, increasingly used in mountainous expressways to traverse significant elevation differences, are frequently associated with traffic safety concerns due to their extended, continuous turns, which can impair driving cognition. Guided by the self-explaining road (SER) principle (Theeuwes, 2021) – which advocates environmental design that enables adequate and swift perception – this study examined both the cognitive characteristics of driving in spiral tunnels and the influence of environment on driving cognition. We first investigated the cognitive significance of tunnel environmental elements through a questionnaire survey, then conducted curvature perception experiments with 20 drivers using real-world driving videos to test fixation duration, fixation number, degree of curvature illusion, and reaction time, and finally analyzed the relations of these indicators. Results showed that compared to ordinary curved tunnels, spiral tunnels induced shorter fixation durations, lower curvature estimation (3.69 %) and prolonged reaction time (39.8 s). Entrance section triggered the longest reaction time (29.9 s) due to attention dispersion, while exit zones exhibited the most serious curvature illusion (28 %). Although the orientation of roadway (OR) was considered the most critical element, environmental elements have complex relationship with visual attention in spiral tunnels. Additionally, fixation duration and number exhibit a negative correlation with curvature illusion reaction time, suggesting adequate environmental information may improve curvature perception. The results reveal that driving cognition in spiral tunnels faces more unfavorable conditions, especially in the entrance and exit sections. Moderate supplementation of environmental information may optimize driving cognition. This study provides stakeholders with cognition-informed optimization strategies for traffic safety in geometrically constrained environments.

1. Introduction

1.1. Background

Construction of roadways in mountainous region frequently encounters significant challenges, especially in dealing with complex terrain features. Tunnels serve as a crucial solution for overcoming geographical obstacles, playing a vital role in the development of road network in such areas. Recently, spiral tunnels have emerged as an effective strategy in China recently, benefited from the development of engineering technology. Representative projects include the Midicun Spiral Tunnel (Zhang et al., 2020), the Jinjiazhuang Tunnel (Jiang et al., 2023), and the dual spiral tunnels at the Yaxi Expressway. Spiral tunnels are specialized by continuous curves of uniform direction inside the mountain (Zhao et al., 2007), solving the problem of crossing significant elevation differences within a constrained space effectively (Chen et al., 2011; Zhang et al., 2020). These tunnels offer considerable advantages in adapting to terrain.

On the contrary, the growth of spiral tunnels is a double-edged sword. As a unique type of curved tunnel, the spiral tunnel features both significant curvature and considerable length, posing challenges to driving cognition and resulting in a heightened likelihood of traffic accidents with potentially more severe consequences. Due to the "psychological rotation effect" associated within spiral tunnels, complicates drivers' recognition of traffic information and environmental cues (Du et al., 2023). Specifically, higher curvatures in spiral tunnels restricts the driver's sight distance, thereby requiring a heightened allocation of attentional resources to compensate for driving (Xing et al., 2024), which exhibit a higher accident rate (Chao et al., 2012). Furthermore, curved tunnels experience considerably severer fires consequences than

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straight tunnels as length increases (Wan et al., 2023). Hence, enhancing traffic safety in spiral tunnels by studying the cognitive mechanism is of paramount importance.

1.2. Literature review

1.2.1. SER principles and applications

The theory of SER was initially proposed by Theeuwes and Godthelp in 1995, building upon coupling between the environment and behavior. Its core premise is that the road environment should proactively guide drivers' anticipated behaviors through "endogenous design features", rather than relying on additional reasoning. There exists a close relationship between the road environment and drivers, with the road's self-explaining performance directly or indirectly influencing driving behavior through drivers' perceptions (Walker et al., 2013).

Self-explaining roads (SER) are considered to be an effective way to reduce traffic accidents and achieve tunnel traffic safety. For instance, the European Transport Safety Council (ETSC) has redefined SER as "the synergistic design of road geometry, visual cues, and operational feedback to enable drivers to automatically adopt safe driving strategies at a subconscious level" (ETSC, 2014). Xiang et al. (2020) conducted a simulated driving experiment, using 75 km/h and 85 km/h as critical thresholds, and integrated the concept of self-explaining roads to calculate recommended radius ranges for spiral tunnels under various conditions. Jiao et al. (2022) investigated the impact of tunnel environments on drivers' speed perception and control, exploring the self-explaining performance of visual guidance facilities in urban underwater tunnels. Their findings revealed that vertically spaced facilities exhibited better self-explaining performance. Yan et al. (2024) also examined the influence of tunnel environments on drivers but further incorporated drivers' visual comprehension, quantifying self-explaining performance using situational awareness. Their results demonstrated that colored road surfaces and light-colored interior wall decorations could enhance the self-explaining performance of tunnels. Herein, the presence of environmental elements is essential for guiding drivers' safety behaviors in an effective way (Theeuwes et al., 2024; F. Wang et al., 2020).

1.2.2. Environmental elements and traffic safety

In the research on environmental elements and traffic safety, it has been found that appropriately designed road elements can guide drivers' perception of the environment, thereby enhancing traffic safety levels (Theeuwes, 2021). Environmental psychology research has shown that before designing or retrofitting, it is crucial to understand how people perceive their environments (Steg et al., 2018). Clues, as elements in the environment that convey important information or trigger perceptual responses, serve as a significant means through which the environment influences behavior (Lindenberg, 2018). Vos et al. (2021) conducted a questionnaire survey to investigate which curve characteristics and environmental elements highway drivers rely on when selecting their operating speed through curves, and analyzed how these factors influence driver behavior. The results suggest that visibility, lane count, and environmental elements should be considered comprehensively when designing curves to guide drivers in selecting appropriate speeds. Similarly, Theeuwes et al. (2024) argued that the presence of road elements generates specific expectations about road types and appropriate driving behaviors, and used a picture-based questionnaire to investigate the impact of different environmental element designs on drivers' speed selection and response times. The results validate the effectiveness of the SER concept and provide targeted recommendations for urban road design.

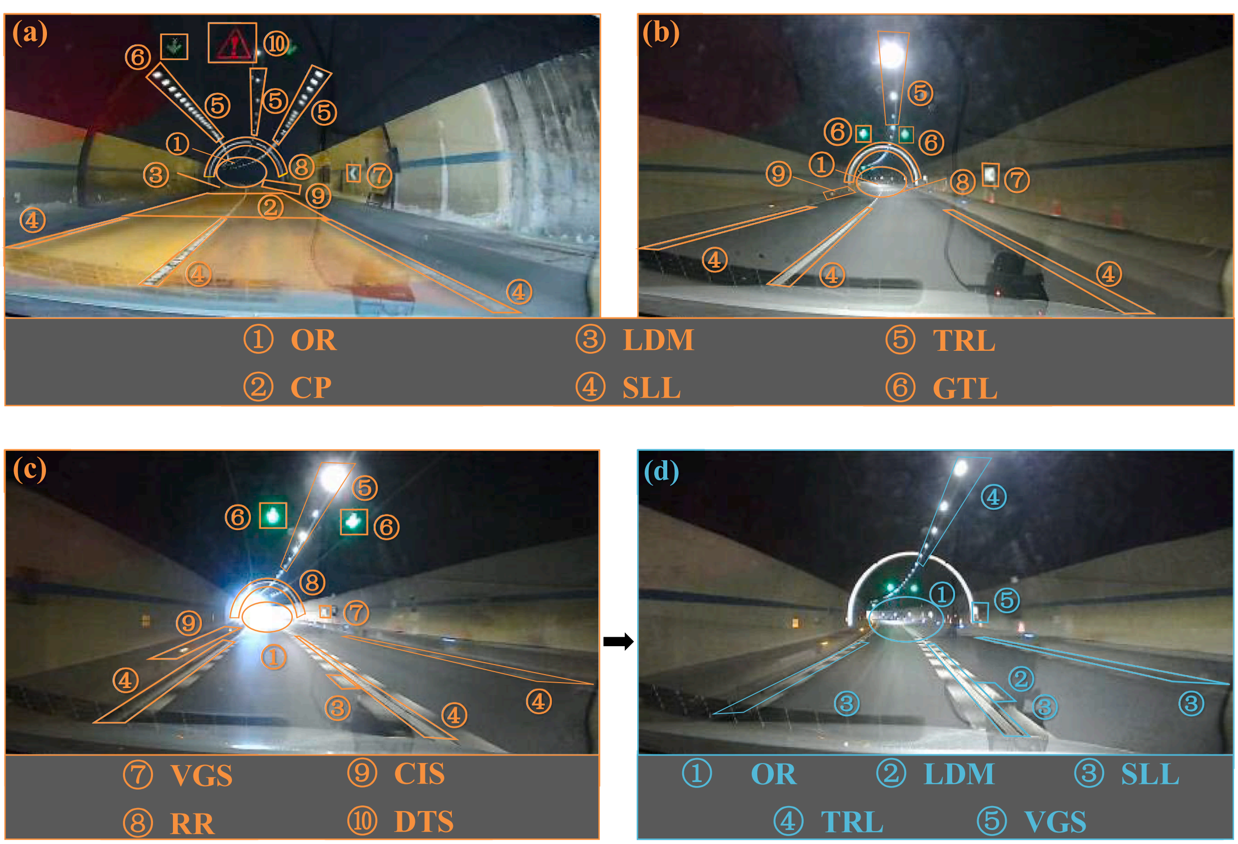

Fig. 1. Tunnel elements in the first and second rounds of survey: (a) Scenario 1: entrance section, (b) Scenario 2: internal section, (c) Scenario 3: exit section, and (d) Road elements in the second round.

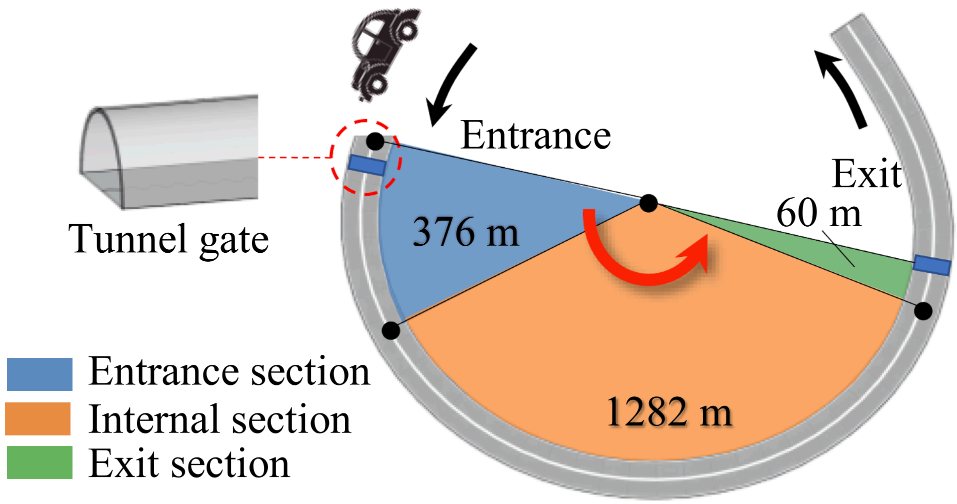

Fig. 2. Diagram of tunnel section division.

Table 1
Specific information in both rounds of survey.

Round	Time	Scenarios	N_e	Sample	Requirements
First	2024.9.19–2024.9.21	a. Entrance; b. Internal; c. Exit; d. Testing.	9–10	27	Elements can be selected without all.
Second	2024.9.25–2024.9.27	a. Entrance; b. Internal; c. Exit.	5	235	All elements must be selected.

Note: the N_e equals 10 in Scenarios a and d because CP only occurred at the entrance section, which had been excluded in the second round of survey.

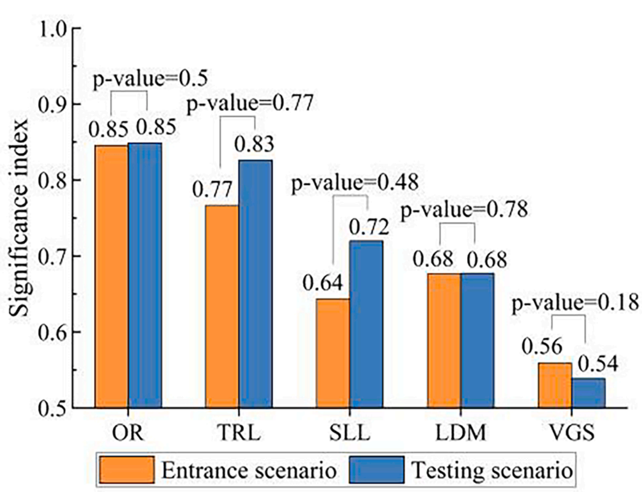

Fig. 3. Test result of road elements (retained) of entrance and testing scenarios.

1.2.3. *Curvature perception and traffic safety*

According to the Attentional Resources Theory, driving cognition relies on the allocation of limited visual attention to critical environmental cues, with a top-down information processing mechanism (attention driven by knowledge and experience) (Wickens, 2015). They have established the specific theoretical connections between elements and vision, as well as between vision and perception, within the framework of SER theory. The Feature Integration Theory proposed by Treisman (1980) (Treisman and Gelade, 1980) suggests that the salience of environmental cues influences perceptual efficiency by modulating the "focus-sustain" process of attention. The continuous curves in spiral tunnels may lead to an overload of visual attentional resources, thereby affecting perception.

Curvature, as an essential part of tunnel environment, has earned significant attention from scholars (Bassan, 2015; Cvahte Ojsteršek and Topolšek, 2019; Jiao et al., 2023). Similar to the speed perception, drivers' accurate and rapid perception of curvature can guide safe driving behavior, thereby enhancing tunnel traffic safety. However, wrong perception of curvatures could cause drivers' misunderstanding of road environment, thereby increasing the risk of collisions (Colonna et al., 2020; Hummer et al., 2010). This issue is related to geometric design (Colonna et al., 2020; Wang and Easa, 2009) and facilities design (Zheng et al., 2017). Reportedly, a smaller radius of curve correlates with an increased likelihood of driver misperception (Hassan and Sarhan, 2012). Thus, given that spiral tunnels typically feature reduced radius, drivers are particularly susceptible to misjudging the curvature, which can result in severe consequences. The validation of "perceptual curvature" posted a practical approach (Bidulka et al., 2002; Hassan et al., 2002), enabling the optimization of tunnel curvatures and facilities in accordance with driving cognition directly (Du et al., 2021).

1.3. *Aim of study*

Despite numerous studies indicating that effective SER design can improve traffic safety within tunnels, they have not studied the cognitive features of spiral tunnel itself. While prevailing SER research prioritizes speed perception in driving cognition, this study argues that curvature perception holds equal, if not greater, significance in spiral tunnels. Moreover, previous literature has examined the influence of environmental elements and curvature perception on traffic safety and proposed some effective improvement methods. However, previous studies lack explicit characterization of the acquisition process of environmental information, or the linkages between it and driving cognition. The substantial impact of tunnel environments on safe navigation within spiral tunnels motivates this study to characterize the self-explaining performance of environmental elements in relation to curvature perception, with the aim of guiding safe driving behavior. Herein, this

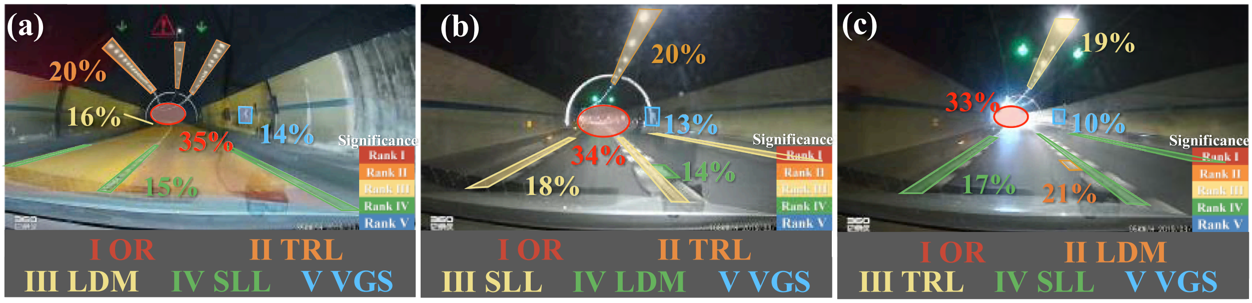

Fig. 4. Percentages and orders of elements significance: (a) Scenario 1: entrance section, (b) Scenario 2: internal section, and (c) Scenario 3: exit section.

study investigates the environmental elements that are crucial in driving cognition and delineates cognitive performance metrics specific to curvature perception in spiral tunnels based on SER principles, ultimately establishing linkages between element significance and cognitive metrics. And several questions were addressed: (i). What is the distinctive driving cognitive characteristics in spiral tunnels compared to ordinary curved tunnels? (ii). How do specific tunnel sections and turning directions impact driving cognition, and what are the specific cognitive problems? (iii). How do environmental elements influence driving cognition in spiral tunnels, and how can the curvature perception in spiral tunnels be optimized by improving environmental elements?

This paper is organized as follows: Section 2 describes a survey for constituent elements within tunnel environment, Section 3 describes the method of our experiment for curvature perception, Section 4 shows the experimental results, Section 5 further discusses the results, while Section 6 presents our conclusions and limitations.

2. Survey of constituent elements

2.1. Survey methodology

This section explains what and how tunnel elements constitute the self-explaining environment of spiral tunnel. By analyzing the properties of these elements in different sections, more specific measures can be used to enhance tunnel's self-explaining design. Since drivers' perspectives were taken into account, these elements were determined based on their significance to driving cognition through the methodology of questionnaire. The elements, namely orientation of roadway (OR), solid lane lines (SLL), tunnel roof lights (TRL), green signal lights (GSL), visual guidance signs (VGS), reflective rings (RR), contour induction signs (CIS), dynamic traffic signs (DTS), colored pavement (CP), and longitudinal deceleration markings (LDM) are shown in Fig. 1 (a)(b)(c).

Spiral tunnels represent a special category of curved tunnels characterized by their continuous and equidirectional curvature. Participants were instructed to watch driving videos of tunnel sections entirely and then rank tunnel elements through their contributions to driving (Xu and Wu, 2023). It should be noted that the final format of questions used were selected in consultation with tunnel safety officers and academics with relevant experience.

A driving video was recorded in a spiral tunnel on an expressway in western China and was used as scenarios in the questionnaire. Guided by the SER principles of "functionality, homogeneity, and predictability"

Table 2
Diffs in gender.

Element	VGS (Entrance)
p	0.001***
Male	0.247
Female	0.368

Table 3
Diffs in driving experience in tunnels.

Elements	VGS (Internal)	VGS (Exit)	SLL (Internal)
p	0.001***	0.002**	0.007**
Have driven in tunnel	0.206	0.15	0.394
Have not driven in tunnel	0.325	0.248	0.314

(Charlton et al., 2010), drivers exhibit consistent behavioral patterns when navigating road segments of the same environmental type. Consequently, three distinct sections within spiral tunnel were divided based on comprehensive environmental design characteristics (Ministry of Transport of the People's Republic of China, 2014). The lengths of each section— entrance, internal, and exit— were determined according to the aforementioned specification, as shown in Fig. 2.

The questionnaire survey was conducted in two rounds, through going online via social networks. The first round of questionnaires focused on survey process, question wording, and option setting, aiming to gather experience for revising and optimizing the second-round questionnaire to ensure clarity and effectiveness. This helped in planning a cost-effective yet reliable sample size for the second round, which will yield the main survey findings. While the second round of questionnaires provided details of significance features of the elements. The comparison of specific information from both rounds is presented in Table 1. The entrance scenario was repeated as the testing scenario at the end of the first round of survey.

For the needs of survey, two prerequisites for respondents to participate were that they must declare they hold a driving license and have the subjective willingness to complete the questionnaire. The final questionnaire used for this investigation was attached to the Appendix A. To facilitate a clear expression of ranking results, a significance index was utilized, as shown in Eq. (1). In this way, higher importance of an element could be represented by a higher significance index.

$$Significanceindex = (N_e - N_R)/N_e \tag{1}$$

Where the N_e denotes the number of elements in each round; N_R denotes the significant ranking of these elements.

2.2. First round of survey

The results are presented in Fig. 3. Here, a hypothesis is proposed (Xu and Wu, 2023) that the questionnaire methodology is considered reliable if there is no significant difference between participants' answers to two identical scenarios (entrance and testing scenarios) presented at the beginning and end of the questionnaire, respectively. To verify the existence of any difference, a non-parametric paired test, specifically the Wilcoxon signed-rank test, was conducted in Matlab. And the result shows that there was no significant difference (p-value > 0.01) in N_R between entrance and testing scenarios at a 99 % confidence level. Thus, the questionnaire format was proved to be relatively stable and subsequently utilized in the second round of survey.

Regardless of the scenarios considered, the five road elements— CP, GSS, RR, CIS, and DTS— were, on average, deemed the least important. Although they provided drivers with specific road information, this information was considered secondary for driving cognition. Therefore, the remaining five elements— OR, LDM, SLL, TRL, and VGS— were retained as primary elements in the second round of survey, as shown in Fig. 1(d).

2.3. Second round of survey

Before the second round of survey, the sample size was determined based on the anticipated confidence level and margin of error for the ranking results (Su et al., 2023). Characteristics of the first-round sample data were taken into account: high recall rate and fewer outliers. Thus, a more conventional and conservative parameter taking method was adopted to estimate the sample size of the second-round questionnaire. The target confidence level for the second-round survey was set to exceed 85 %, and the minimum required sample size was determined to be 208, as calculated through Eq. (2). Ultimately, 239 records were collected, following the exclusion of invalid questionnaires, 235 valid responses were retained for analysis.

$$N = Z^2 p(1-p)/E^2 \tag{2}$$

Where, N represents the required sample size, while Z corresponds to the desired confidence level; for an 85 % confidence level, the Z value is approximately 1.4395, as calculated in Matlab; additionally, p refers to the expected proportion, which is estimated conservatively at 0.5. E signifies the error margin, and for the 85 % confidence level, the E value is set at 0.15.

To determine whether a universally acknowledged ordering of element importance can be deduced from all participants' answers, implying a degree of regularity rather than chaos in their preferences. The Friedman non-parametric test method was employed, revealing significant differences in the ranking of elements at the 99 % confidence level, thereby effectively distinguishing the relative importance of various tunnel elements according to the participants' cognition.

Fig. 4. shows the calculation results of the element significance index in different tunnel sections. Wherever it was, OR which always obtained the highest significance (35 %, 34 %, 33 %), while VGS consistently gained the least attention (14 %, 13 %, 10 %). At the entrance section, TRL (20 %) prompted drivers to enter the tunnel, while LDM (16 %) not only encouraged road users to slow down, but also enhanced the visual reference function of SLL (15 %). At the internal section, the drivers gradually adapted to the dim optical conditions. Here, TRL (20 %) provided essential linear guidance cues. Although SLL at 18 % primarily served to delineate lanes, it contributed to references in perceiving curvature in the low-visibility environment. At the exit section, the pronounced white hole effect hindered the driver's ability to observe OR, so the other tunnel elements— LDM (21 %), SLL (17 %) and TRL (19 %) played an essential role in gathering information about the tunnel curvature.

2.4. Examination of driver heterogeneity

Previous research has identified the characteristics— namely gender (Magaña et al., 2021), driving experience (Padilla et al., 2020), and the experience of driving in tunnels (Lee et al., 2022)— as having a substantial effect on driving cognition. To address concerns about the potential influence of driver heterogeneity on the results, we also collected these characteristics of individuals. Driver heterogeneity examination is completed with two steps by Matlab. First, the Kolmogorov-Smirnov Test is adopted to examine whether the significance ranking of elements is of normal distribution (Öztuna et al., 2006) against driver characteristics. If the data not of normal distribution, the method of independent samples T-test is selected for hypotheses test when data is nonpaired, otherwise paired T-test is selected for paired data (Sawilowsky and Hillman, 1992; Kim, 2015). Next, an independent samples T-test was conducted because the driver data did not exhibit a complete normal distribution. The results, presented in Tables 2 and 3, indicated that driver heterogeneity impacts ranking outcomes to a very limited degree. Nevertheless, drivers' gender and tunnel driving experience still need to be valued in the following experiment.

By analyzing the properties of these elements in different sections, more specific measures can be used to enhance tunnel's self-explaining ability. Although drivers, as mentioned above, always prioritize elements with a visual reference function over others, their perception of elements in different tunnel sections varies due to environmental changes. To further evaluate how driver perception aligns with these environmental features, this study subsequently investigated the cognitive changes of drivers in spiral tunnels.

3. Experimental method

Based on the principle of SER— "roads should be easily recognizable and interpretable." (Theeuwes, 2021). The questionnaire subjectively gave the significance of single environmental elements. This section will further investigate the impact of the environment composed of these elements on driving cognition processes and outcomes.

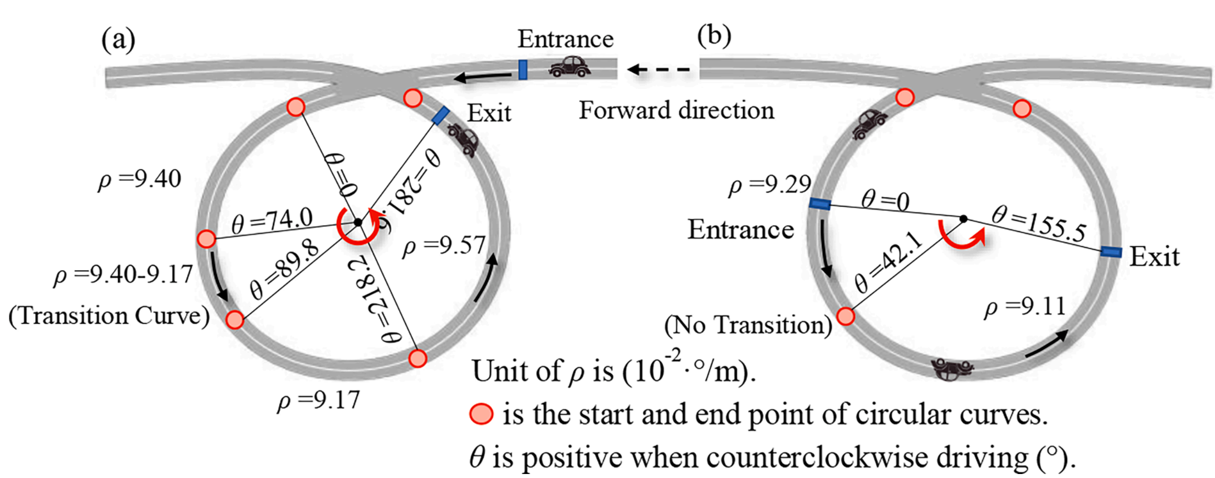

Fig. 5. The dual spiral tunnel in a mountainous expressway of western China: (a) the 2nd spiral tunnel, and (b) the 1st spiral tunnel.

Table 4
Curvatures of the control scenes.

Num.	1	2	3	4	5	6	7	8	9	10	11	12
ρ(10^{-2}·°/m)	9.57	9.40	9.29	9.17	9.11	7.74	7.62	7.17	6.82	6.65	6.36	5.96

Table 5
Information on the scenes in Trial 1.

Direction	Num.	ρ	Tunnel type	ρ-value (10^{-2}·°/m)	θ-value (°)
Clockwise	1	ρ_1	ordinary	7.74	32.89
	2	ρ_2	ordinary	7.17	53.10
	3	ρ_3	spiral	9.57	63.42
	4	ρ_4	spiral	9.17	128.62
Counterclockwise	5	ρ_1	ordinary	7.74	32.89
	6	ρ_2	ordinary	7.17	53.10
	7	ρ_3	spiral	9.57	63.42
	8	ρ_4	spiral	9.17	128.62

3.1. Overview of curvature perception experiment

A curvature perception method was employed to quantitatively assess the driving cognition within spiral tunnels. In this experiment, participants were asked to judge the curvature of trial scenes via a group of control scenes for reference (Bidulka et al., 2002; Hassan et al., 2002). This study draws upon these two theories to examine driving behavior, hypothesizing that environmental elements in spiral tunnels influence drivers' visual allocation of limited attention to critical cues, thereby affecting perceptual accuracy and decision-making efficiency. This includes reducing fixation duration and fixation number, thereby indirectly improving the accuracy and speed of perception.

A series of equidirectional curves with consecutive curvatures creates a spiral line characterized by a curvature angle of not less than 2π rad. In this context, the radius of the circular curves exhibits discontinuity; however, the curvature remains continuous due to the implementation of transition curves that facilitate the connection between adjacent circular curves. Additionally, the variation in curvature results in significant variances in the mileages of different spirals, which complicates the description of travel positions. Consequently, to address the need for continuity in curvature changes and consistency in mileage descriptions, this study employs curvature ρ and angle of curvature $\Delta\theta$ parameters, as outlined in the following Eq. (3).

$$\Delta\theta = \int \rho ds \tag{3}$$

Where angles are given in degrees (°), with 1 degree equal to π radians ($\pi = 3.14$); $\Delta\theta$ denotes the traveling angle passed along the curvature (°), and ρ (°/m) denotes the curvature of each integral curve ds(m).

3.2. Experimental design

3.2.1. Data collection

(1) Fixation characteristics

The spatial distribution of fixation points reflects the visual search

Table 6
Information on the scenes in Trial 2.

Part	Clockwise			Counterclockwise		
	ρ-value (10^{-2}·°/m)	$\Delta\theta$-value (°)	θ-value (°)	ρ-value (10^{-2}·°/m)	$\Delta\theta$-value (°)	θ-value (°)
1	9.11	16.5	16.5	9.29	17.3	17.3
2	9.11	16.5	33.1	9.29	17.3	34.6
3	9.11	16.5	49.6	9.29	9.10	43.7
4	9.11	16.5	66.1	9.11	18.0	61.7
5	9.11	16.5	82.7	9.11	18.0	79.7
6	9.11	16.5	99.2	9.11	18.0	97.7
7	9.11	16.8	116.0	9.11	18.0	115.7
8	9.29	17.0	133.0	9.11	17.0	132.7
9	9.29	17.0	150.0	9.11	17.3	150.0
10	9.29	5.50	155.5	9.11	5.50	155.5

Table 7
Basic information of participants.

Variable	Gender		Driving age		Tunnel driving experience	
Description	Females	Males	4 or below	5 or more	Yes	No
Frequency	7	13	14	6	10	10

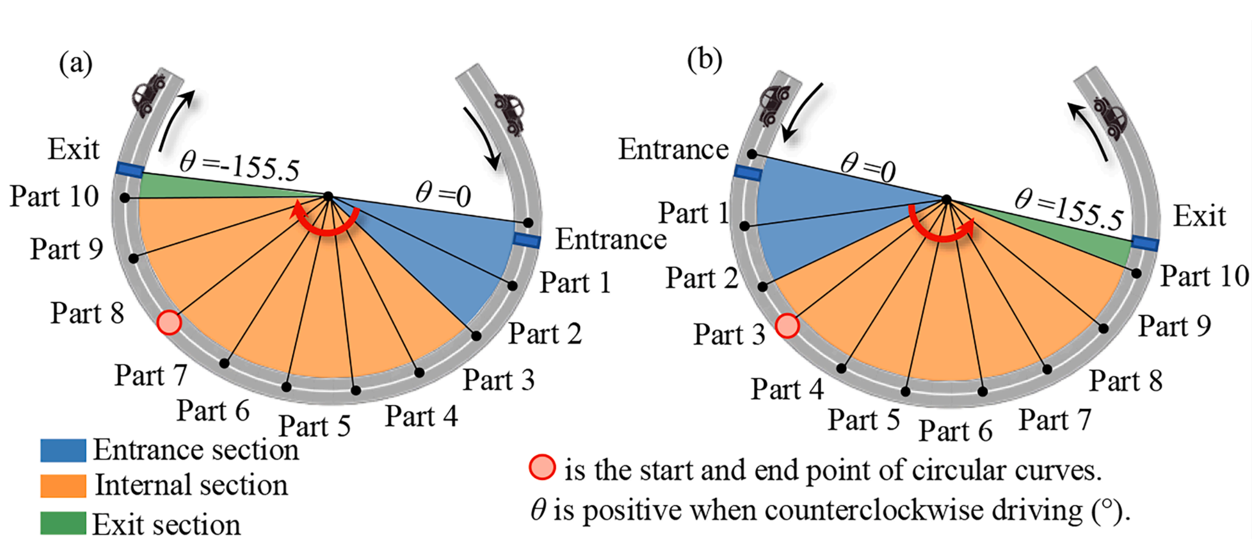

Fig. 6. Illustration of division in 1st spiral tunnel: (a) the clockwise driving condition, and (b) the counterclockwise driving condition.

patterns of drivers for environmental information. Fixation duration and number reflect the complexity and volume of road environment information perceived by drivers. Higher fixation durations and number indicate more complex and abundant environmental information (He et al., 2017; Reimer, 2009).

According to the core concept of SER— "drivers should perceive the road environment efficiently, adequately and swiftly." (Theeuwes, 2021), the degree of curvature illusion and the reaction time were adopted as indicators to evaluate driver's perception. The former represents the adequacy, while the reaction time indicates speed (Du et al., 2021). The degree of curvature illusion is calculated by Eq. (4), and the reaction time is recorded as the duration for driver to make curvature judgement. Higher values of these indicators correspond to poorer cognitive performance.

$$G = \left(\rho/\rho_p - 1\right) \times 100\% \tag{4}$$

Where G denotes the degree of curvature illusion (%); ρ denotes the actual curvature (°/m); and ρ_p denotes the perceptual curvature (°/m). Of note, G is positive when underestimating the curvature (i.e., overestimating the radius) but negative when overestimating the curvature (i.e., underestimating the radius).

3.2.2. *Experimental scenes*

To acquire a sufficient dataset of tunnel scene samples, this research was conducted on an expressway in a mountainous region of western China, where tunnel driving videos were recorded by the car camera. Before video recording, the driver was instructed to maintain a consistent driving speed and adhere to the left-hand lane. The expressway features a total of 26 tunnels, including a dual spiral tunnel, which implies that the facilities and lighting conditions are consistent across all tunnels. The dual spiral tunnel is comprised of 2 individual spirals, as shown in Fig. 5. The 1st spiral is an ordinary long tunnel, while the 2nd spiral comprises a group of tunnels.

The control scene, which served as a reference for assessing the curvature of the trial scenes, consisted a sequence of 12 driving clips with diverse curvatures. To maintain uniformity among the clips and to prevent excessively lengthy videos from hindering the participants' selection process, brief videos ranging from 3 to 4 s in duration were extracted as control scenes. The curvature and corresponding numbering of these control scenes are shown in Table 4.

Spiral tunnels are differentiated from ordinary curved tunnels by their continuous equidirectional curvature, which is the focus of Trial 1 in examining its impact on curvature perception. Given the generally small curvature of spiral tunnels, multiple comparisons are conducted between ordinary curved tunnels with large curvature and spiral tunnels. To mitigate the effects of entrance and exit optics, ordinary tunnels with small radius— where the curved segments are entirely situated within the internal tunnel— were employed for comparison with the 2nd spiral tunnel. Table 5 presents the information of the scenes in the first trial.

Trial 2 focused on analyzing different angles when traveling along the curvature. To mitigate the interference of group tunnels, the scenario was derived from the 1st spiral. According to JTG/T D70/2–01-2014 Guidelines for Design of Lighting of Highway Tunnels (Ministry of Transport of the People's Republic of China, 2014), the environmental scenery outside the tunnel becomes imperceptible at the adaptive distance d before entering the tunnel, which has served as the start of traveling angle θ. From Eq. (5), the start point of the first scene was determined to be located at the 26 m before the tunnel portal. For the purpose of segmentation, the 1st spiral tunnel was divided into 10 parts as uniformly as possible, considering the various sections and curvatures, as shown in Fig. 6. The details of segmentation are presented in Table 6.

$$d = (h - 1.5)/tan10^{\circ} \tag{5}$$

Where, d denotes the adaptation distance (m); and h denotes the height of portal, which is specified as 6 m.

3.2.3. *Participants*

In this study, 20 participants were enrolled, with different genders selected to reflect the gender distribution among Chinese drivers (Xinhua News Agency, 2022).

Participants were required to have at least one year of driving experience and have normal or corrected-to-normal vision. Basic participant information is presented in Table 7. It is important to note that none of the participants were informed of the experiment's purpose in advance. All participants were paid for their involvement.

In driving simulation studies, sample size selection is often constrained by experimental conditions, costs, and time limitations. Yang et al. (2020), through a comprehensive literature review of current practices, demonstrated that sample sizes in driving simulation studies typically remain below 25 participants, which is widely recognized as a feasible approach within the field. This experiment methodology has been consistently adopted in comparable studies (Du et al., 2021; Hassan & Sarhan, 2012), where sample sizes ranged between 10 and 20 participants, thereby validating the adequacy of such sample sizes for similar research. To ascertain the adequacy of the participant count in this research from a statistical standpoint, a two-sample t-test for efficacy was conducted using Matlab software. The findings indicate that,

Fig. 7. Photo of the testing environment.

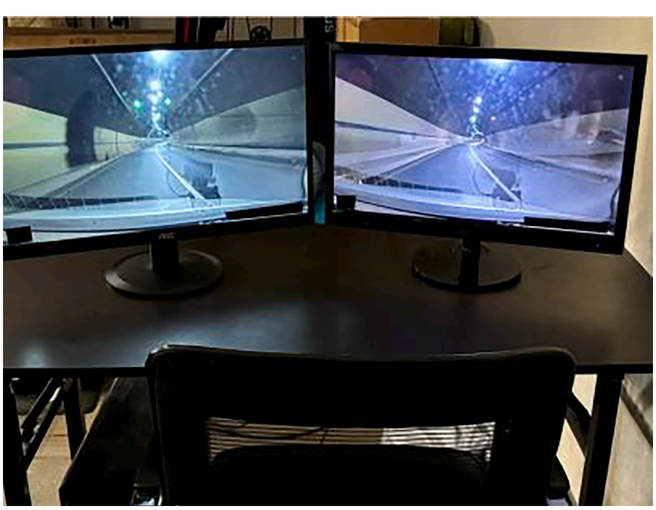

Fig. 8. The experimental video screen as observed by testers.

with 85 % confidence level, the sample size possesses a statistical power of 0.86, surpassing the threshold of 0.80. Consequently, the number of subjects enlisted in this experiment's design is deemed sufficient to yield dependable responses to the inquiries at hand.

3.3. Experimental procedures

In this study, data were collected using an eye tracker (Dikablis Glasses 3.0, Geretsried, Germany). The D-Lab 3.55 was used for fixation data collection and post-processing. Eye movement record ings were conducted on a Lenovo laptop. It is noted that experimental procedures were conducted within the same indoor facility. The trial scenes and the control scenes were played on two screens separately. Photos of testing environment and screens are shown in Figs. 7 and 8.

Participants were presented with two perceptual judgment conditions. If they perceived that the curvature of the trial scene was equal to that of any scene from the control group, they should indicate this, and the actual curvature of the corresponding control scene would be recorded as perceptual curvatures associated with the trial scene. However, given the limitation of human vision in differentiating curvatures of similar magnitudes, participants should specify the upper and lower limits of their judgments from the control group. In such case, the mean of actual value from the mentioned control scenes would be recorded. The duration taken by participants to make curvature judgments after viewing the whole trial video was recorded as reaction time.

The procedures are shown in Fig. 9. To avoid the habitual errors, the control scene videos had been played into two sequences (Du et al., 2021). Firstly, we explained the experimental rules to participants and provided a practice video of a curved tunnel to familiarize them with the task. Subsequently, before initiating each trial video, participants were invited to share their opinions to ensure their readiness and comfort. Finally, upon completion of the tests, invalid data were systematically removed, and the key indicators were evaluated for further analysis.

4. Results

4.1. Trial 1

4.1.1. Fixation characteristics

Tests results about the fixation characteristics, as shown in Table 8. Specifically, fixation durations are significantly shorter in spiral tunnels (clockwise: 1.5 s vs 2.2 s; counterclockwise: 1.2 s vs 1.6 s). In contrast, fixation numbers are markedly higher in spiral tunnels (clockwise: 30.5 vs 19.8; counterclockwise: 42.5 vs 21.2). Furthermore, counterclockwise driving amplifies fixation differences, with spiral tunnels showing both the large fixation number increment (+21.3) and duration reduction (−0.457 s).

4.1.2. Curvature perception characteristics

Tests results about the degree of curvature illusion, as shown in Fig. 10, indicate distinct characteristics for ordinary curved and spiral tunnels. Specifically, the degree of curvature illusion is more pronounced in ordinary curved tunnels, where a higher curvature being perceived (−10.26 % in average). In contrast, the degree of curvature illusion is less pronounced in spiral tunnels, where a lower curvature being perceived (3.69 % in average). Furthermore, when driving in a clockwise direction, more severe curvature illusions are observed in both ordinary and spiral tunnels under the same curvature conditions. In variance analysis, a higher degree of dispersion is observed in spiral

Table 8
Fixation characteristics in different driving orientations in Trial 1.

	Fixation duration (s)		Fixation number	
Tunnel type	Ordinary	Spiral	Ordinary	Spiral
Clockwise	2.2	1.5	19.8	30.5
Counterclockwise	1.6	1.2	21.2	42.5

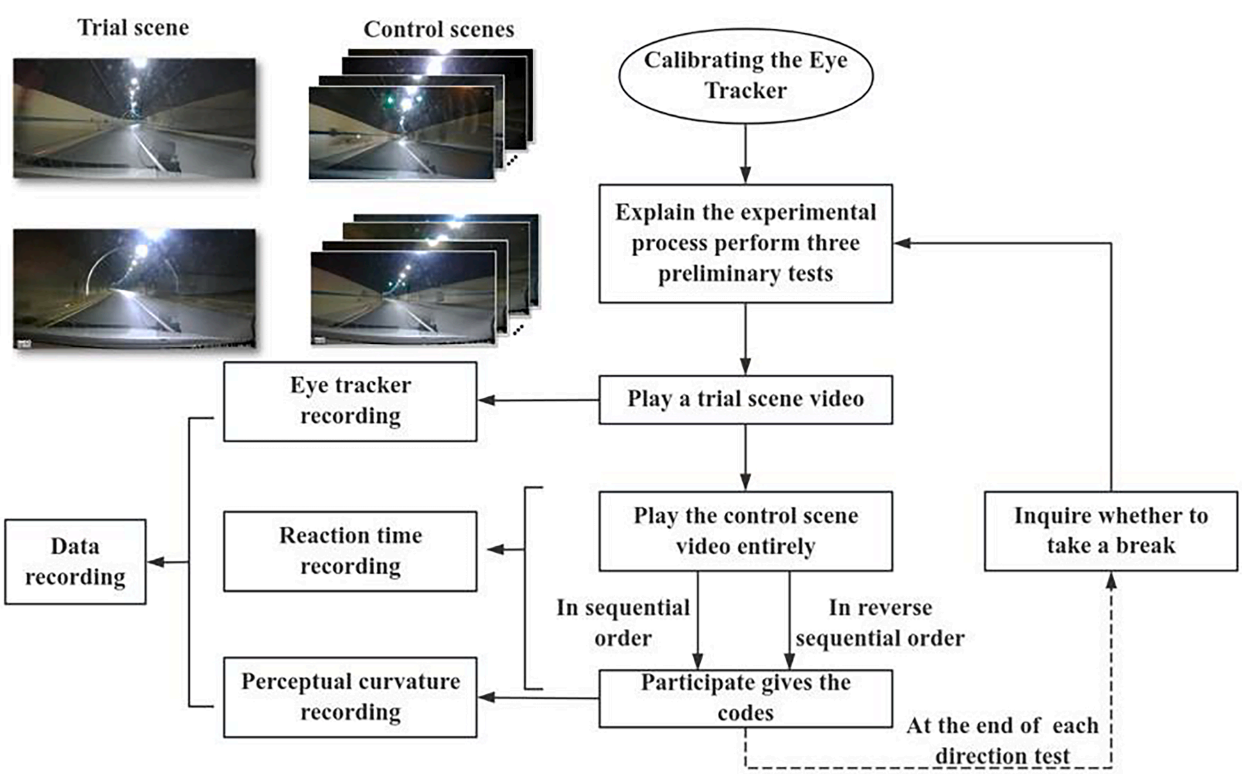

Fig. 9. Procedures of curvature perception experiment.

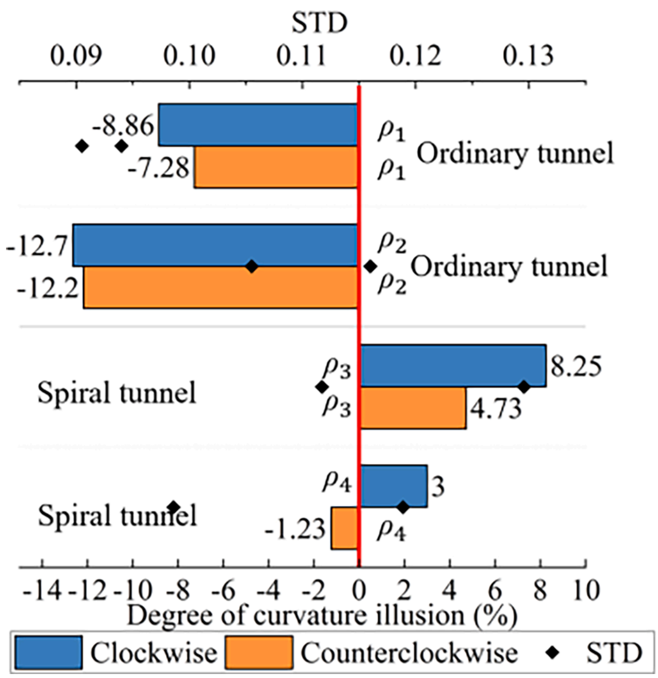

Fig. 10. Degree of curvature illusion in different driving directions in Trial 1.

tunnels, suggesting that the curvature perception here is more significantly influenced by individual factors.

Tests results about the reaction time, as shown in Fig. 11, indicate that the reaction time observed in spiral tunnels are marginally longer (39.8 s in average) than that observed in ordinary tunnels (34.2 s in average). This finding suggests that the curvatures perceived in spiral tunnel are at a slower speed. Furthermore, the data reveals that the reaction time for counterclockwise driving consistently is 15.6 s longer than those for clockwise driving in average, implying that participants usually need more time to interpret the tunnel environment when traveling counterclockwise. Consistent with the preceding finding, a higher degree of dispersion is observed in spiral tunnels, further indicating that individual factors may significantly influence perceptual speed.

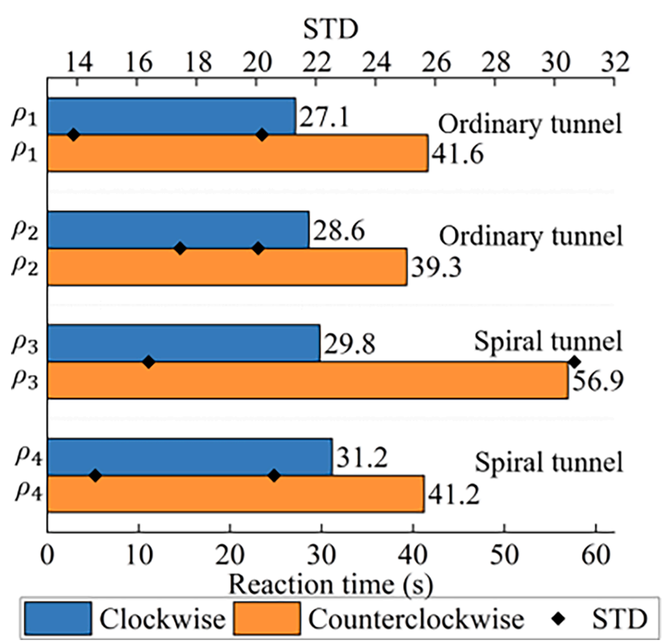

Fig. 11. Reaction time in different driving orientations in Trial 1.

4.2. Trial 2

4.2.1. Fixation characteristics

Distributions of participant's fixation points are illustrated in Fig. 12 (more samples are provided in Appendix B). The results reveal that drivers' fixation points predominantly clustered within the forward roadway area (OR) with little attentional allocation on other elements such as TRL or VGS. Notable variations in fixation distribution emerged across tunnel sections: the entrance section displayed dispersed patterns, the middle section achieved maximal concentration, while the exit section exhibited intermediate characteristics.

The fixation metrics from the experimental tests are presented in Figs. 13-14. The fixation duration exhibited an initial upward fluctuation at the entrance section (0.6 s for clockwise and 0.2 s for counterclockwise), followed by a significant peak at Part 7 at the internal section (2.0 s and 1.6 s, respectively), and ultimately decreased to the lowest values at the exit section (0.5 s and 0.9 s).

The fixation number reached its highest level at the entrance (15.0 and 14.5) and gradually declined, with a notable surge observed at Part 7–8 at the internal section (+3.1 and + 1.9), before dropping to the minimum values at the exit (3.6 and 5.0). Furthermore, the counterclockwise driving demonstrated higher fixation number than the clockwise driving at Part 7–9, accompanied by significantly reduced fixation durations, distinguishing its fixation characteristics from the clockwise pattern.

4.2.2. Curvature perception characteristics

Tests results about the degree of curvature illusion, as shown in Fig. 15, indicate a basically consistent trend when observed in both clockwise and counterclockwise directions. Within the spiral tunnel, the degree of curvature illusion is slightly higher at the entrance section, while it fluctuates minorly at the internal section, then peaking at the exit section. The perceived curvature experiences a slight decrease corresponding to the angle of curvature, with the lowest level of curvature illusion occurring in Part 7, specifically at the location of 115-119°. Notably, around Part 10, there is a marked rise in the degree of illusion, with values reaching 28.8 % under clockwise driving and 27.2 % under counterclockwise driving. This feature can be relevant to the prominent white-hole effect observed at the portal, which hinders the driver's capacity to adequately perceive visual reference information within the tunnel.

Tests results about the reaction time, as shown in Fig. 16, indicate that regardless of whether traveling clockwise or counterclockwise, reaction time shows slight fluctuations corresponding to the angle of curvature, with a general decreasing trend:

4.3. Correlation analysis

The results of correlation analysis are presented in Fig. 17. The Pearson correlation analysis reveals significant relationships between the significance of tunnel elements and drivers' fixation characteristics as well as curvature perception. However, it should be noted that correlation coefficients only indicate statistical associations between variables and cannot directly infer causality. The significances of TRL and VGS show a strong negative correlation with curvature illusion, while SLL exhibits the opposite trend. OR and VGS demonstrate weak correlations with reaction time. Additionally, fixation duration and number exhibit a moderate negative correlation with curvature illusion and a weak positive correlation with reaction time.

5. Discussion

In recent years, spiral tunnels have gained significant traction in engineering applications. However, it has been noted that drivers

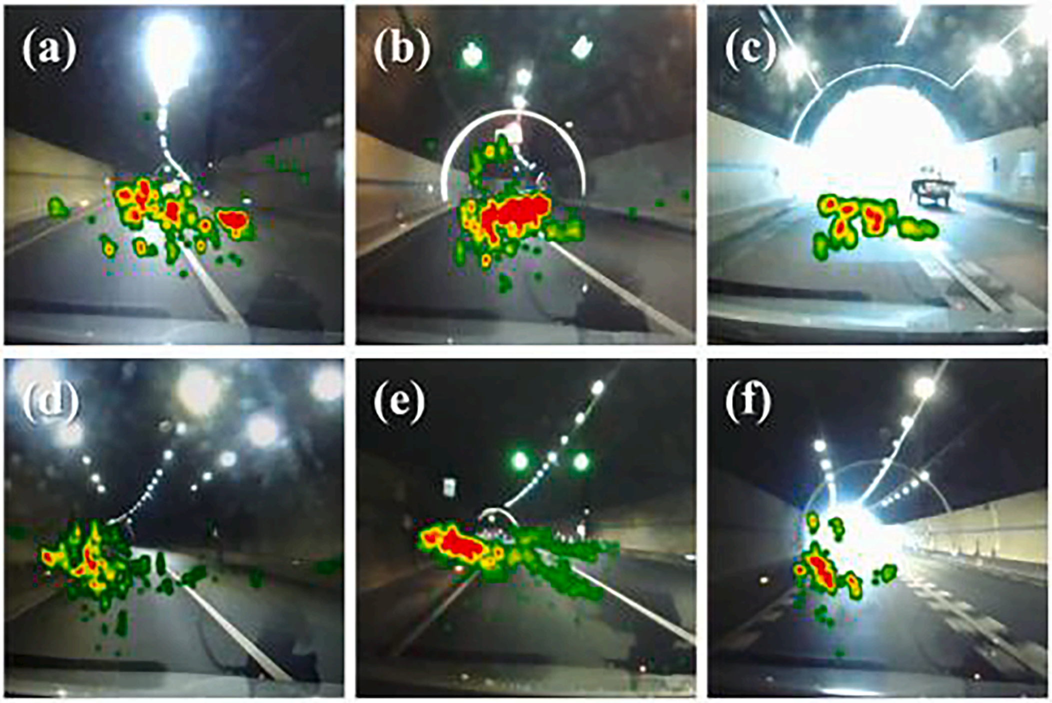

Fig. 12. Distribution of fixation points in Trial 2: (a) entrance section under clockwise driving, (b) internal section under clockwise driving, (c) exit section under clockwise driving, (d) entrance section under counterclockwise driving, (e) internal section under counterclockwise driving, and (f) exit section under counterclockwise driving. The fixation point would turn red if it exceeds 2 s in duration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

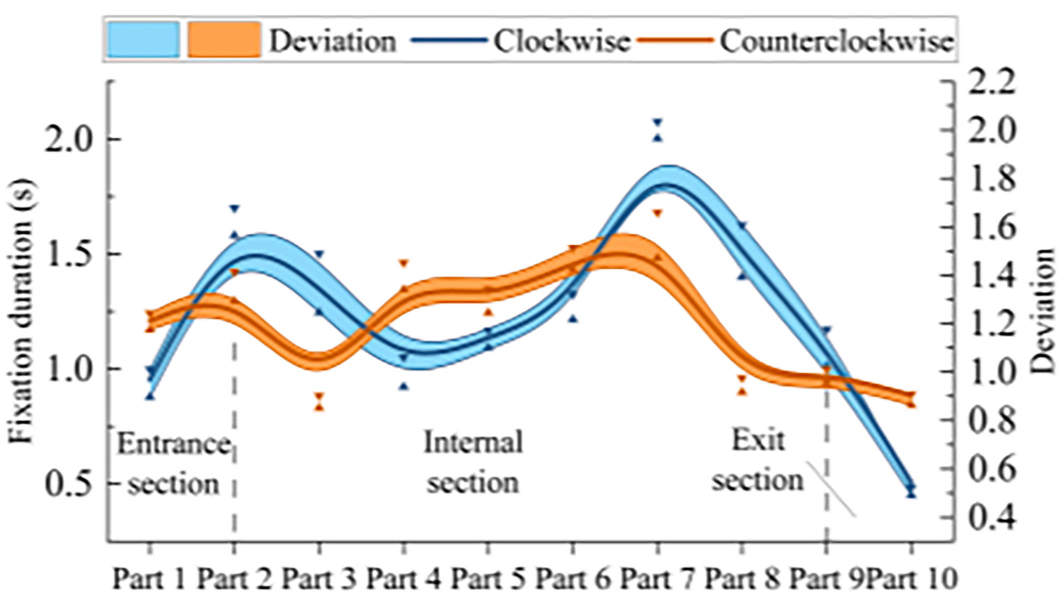

Fig. 13. Fixation duration in different parts in Trial 2.

traveling through these tunnels would experience greater cognitive loads and driving challenges (Du et al., 2023). While some studies have examined the impacts of spiral tunnels on driving behavior (Xing et al., 2024), the cognitive aspects of driving within these unique structures have not been sufficiently explored. To address this gap, we analyzed drivers' cognitive performance through SER theory, utilizing more targeted parameters towards spiral tunnels and more directed methodologies towards cognitive research.

5.1. *Characteristics of spiral tunnels compared to ordinary curved tunnels*

Compared to ordinary curved tunnels, the fixation duration in spiral tunnels is significantly shorter (0.55 s on average), while the fixation number is notably higher (16 counts on average). This indicates that the spiral design reduces the difficulty of extracting environmental information during each fixation but increases the need for updating dynamic environmental information. Specifically, the continuous, uniform curvature in spiral tunnels creates a homogeneous driving environment, making it easier for drivers to comprehend the road conditions but

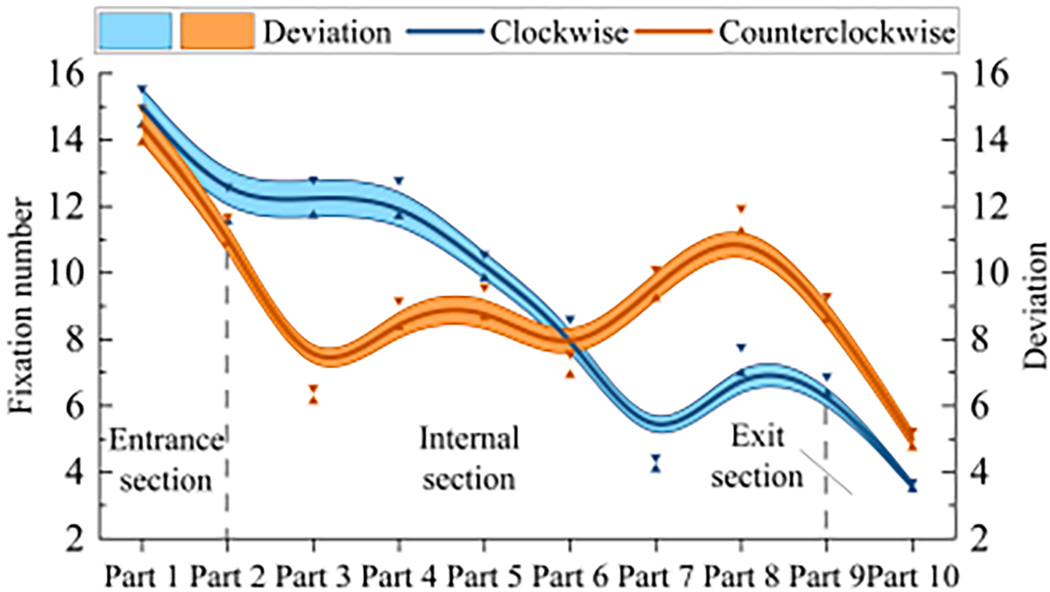

Fig. 14. Fixation number in different parts in Trial 2.

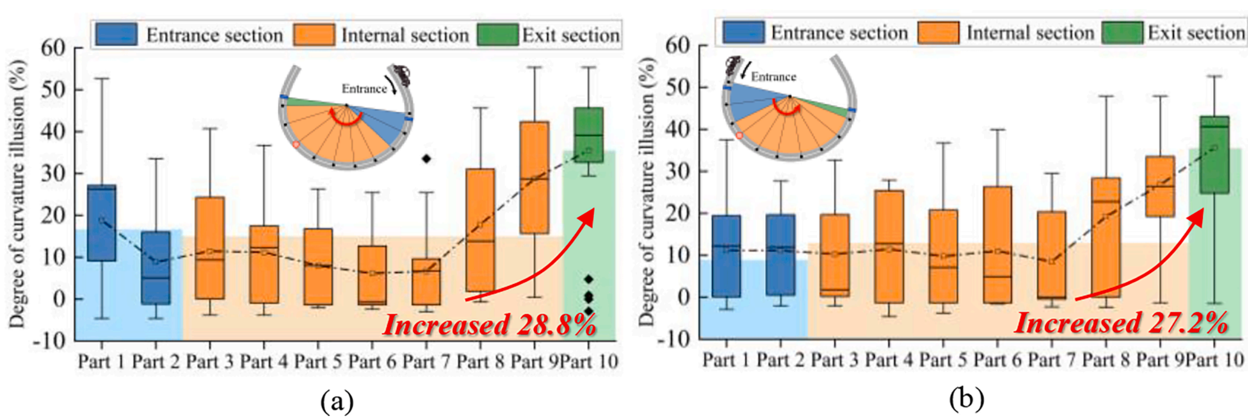

Fig. 15. Degree of curvature illusion in different parts in Trial 2: (a) clockwise driving, and (b) counterclockwise driving.

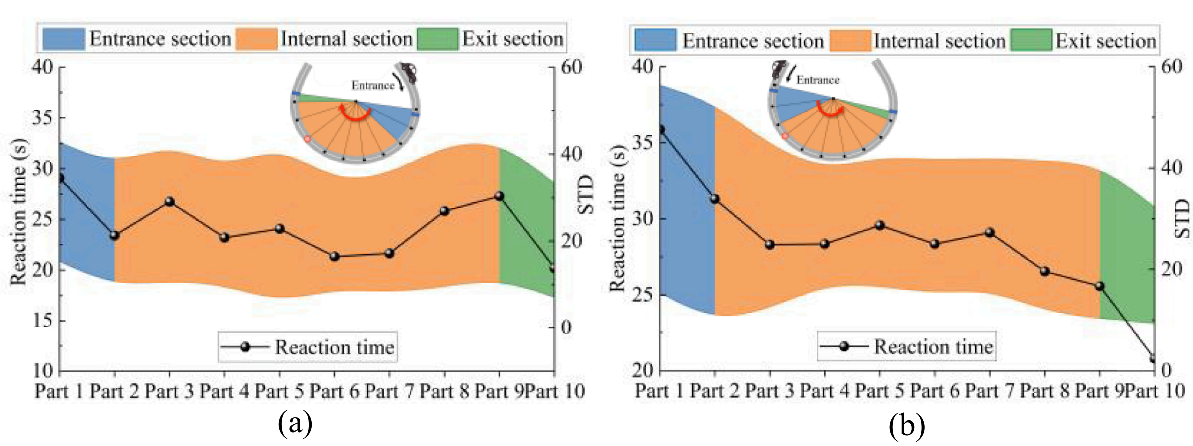

Fig. 16. Reaction time in different parts in Trial 2: (a) clockwise driving, and (b) counterclockwise driving.

requiring frequent attention to environmental elements to update curvature information.

It is somewhat surprising that drivers in spiral tunnels often spend more time (5.6 s) than those in ordinary tunnels, and always underestimate the curvature of spiral tunnels (3.69 %). These findings indicate that driving in spiral tunnels may lead to unsafe driving behaviors, such as delayed turning and impact with sidewalls (Bassan, 2015), which significantly increases the risk of severe outcomes,

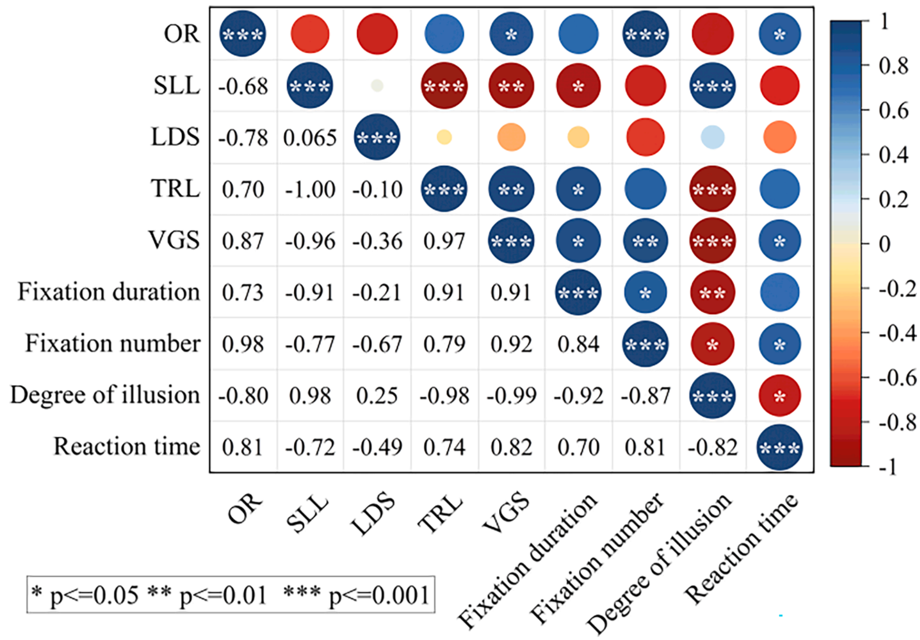

Fig. 17. Heat map for Pearson correlation analysis. The upper triangular portion of the figure displays the p-values, while the lower triangular portion presents the correlation coefficients.

especially collisions (Colonna et al., 2020). A possible explanation for this phenomenon is the high curvature the weak visual reference system (Du et al., 2023) within tunnels. This conclusion suggests that the environmental design of spiral tunnels should be optimized based on their unique driving cognitive characteristics.

5.2. Characteristics in different sections and turning directions

In the entrance section, drivers' attention was more dispersed than other sections, indicating their active exploration of the tunnel environment. Correspondingly, the highest number of fixations occurs in Part 1, while the fixation duration is relatively short, indicating that drivers face difficulties in recognizing and interpreting the tunnel entrance environment. As a result, curvature perception at the entrance exhibits the longest reaction time and a higher degree of curvature illusion, indicating that drivers feel challenging to swiftly and efficiently comprehend the environment. This phenomenon may be attributed to the abrupt environmental transition, which diminishes drivers' perception capabilities (Fu et al., 2020; Han et al., 2024).

In the internal section, drivers' fixation points become concentrated and locate on the road (OR). From Part 3 to Part 6, drivers' fixation duration remains relatively stable, while the number of fixations gradually decreases. Correspondingly, the degree of curvature illusion is significantly lower and the reaction time tends to decrease progressively. This trend is corroborated by (Hu et al., 2019), and suggests efficient and stable driving cognition in this section.

However, in the exit section, due to the intense light stimulation at the exit, drivers pay more attention to SLL and LDM and actively search for valuable environmental information. Before the exit, drivers' fixation duration and number reach their peaks at Part 7 and Part 8 (1.8 s and 9.5 counts, respectively), where the portal becomes visible. Although the fixation metrics begin to decline after the peaks, the degree of curvature illusion starts to rise significantly (28 % on average) from Part 7 to the end, resulting in the most unfavorable cognitive feature. Since the portal becomes visible, drivers are increasingly impacted by the changing optical environment, rendering them precisely perceive the environmental information for curvature judgment. The findings match those observed in the study of Wang et al. (2021), which indicates that the majority of fixation behavior is directly towards the portal when approaching the exit, and the limited visible area resulting from high curvatures of the spiral tunnel contributes to inaccurate curvature.

The results also show the discrepancies in indicators between both of the driving directions. From Part 7 to 9, the fixation behavior under counterclockwise driving exhibited a high-frequency, short-duration pattern, contrasting with the low-frequency, long-duration characteristics observed in clockwise driving. This distinction reveals that drivers tend to adopt a fragmented strategy for environmental information acquisition under counterclockwise conditions. Additionally, the degree of curvature illusion was more pronounced in the entrance section during clockwise driving, while reaction times were generally longer under counterclockwise driving. These finding indicate that drivers have significantly different performance under different turning directions. A possible explanation for these discrepancies may be attributed to an "inside/outside scanning bias" (Han et al., 2024), which arises from the varying lane positions on the inner and outer sides of the turn. To be more concise, drivers typically direct their visual attention toward the inner side of the turn under left turns, and conversely under right turns (Han et al., 2024). Furthermore, the position of the lane influences drivers' visual search patterns (Bassan, 2015), furtherly contributing to the differences observed in clockwise and counterclockwise scenarios. A prior study on fixation durations yielded similar findings, suggesting that the interplay of turn, lane position, and area also plays a significant role (Han et al., 2024; Yan et al., 2015). Consequently, the interactive effect among steering, lane positioning, and driving cognition warrants further research, which will also shed important insights into separated-driving curved tunnels.

5.3. Impact of environmental elements on driving cognition

This study reveals the complex linkages between environmental elements and visual attention behavior in spiral tunnels. Although the Attentional Resources Model (Wickens et al., 2021) and the Feature Integration Theory (Treisman & Gelade, 1980) hypothesize that salient environmental elements should enhance perceptual efficiency by reducing fixation demands, the actual results show that the significance of OR and VGS is positively correlated with fixation number, while the significance of SLL, TRL, and VGS is positively correlated with fixation duration. This contradiction may stem from the dynamic environmental characteristics of spiral tunnels: the continuous curves compel drivers to frequently update directional information, while the linear guidance provided by TRL requires sustained fixation to integrate curvature cues, yet significantly suppresses curvature illusion. Notably, although the increase in fixation duration and number reduces curvature misjudgment (negative correlation), it comes at the cost of prolonged reaction times (positive correlation), suggesting a trade-off between information integration and decision-making speed in attentional resource allocation. In spiral tunnels, moderate fixation investment is an inevitable requirement due to environmental complexity, and forcibly reducing fixation may sacrifice perceptual accuracy.

Therefore, the SER design of spiral tunnels should not solely aim to reduce fixation behavior but should instead optimize environmental cues to enhance the overall effectiveness of elements, thereby improving the quality of fixation: (i). Enhancing the intuitiveness of environmental elements – such as refining the layout of VGS and adopting a linear TRL arrangement – to minimize redundant visual searches and counteract the pronounced curvature illusion at clockwise-driving entrances; (ii). Balancing perceptual accuracy and operational efficiency – for instance, integrating gaze-guiding facilities at the entrance to address prolonged reaction times, while retaining driver-friendly designs (high-contrast signage) in the internal section; (iii). Mitigating perceptual biases at the exit – extending the gradual lighting transition zone from the point where the portal becomes visible, thereby reducing the abrupt optical stimulus and suppressing the surge in curvature misjudgment.

6. Conclusions

Based on the Self-Explaining Road (SER) principle, this study characterizes driving cognition in spiral tunnels. Utilizing two rounds of questionnaire surveys and curvature perception experiments, we concluded the effects of tunnel elements on drivers' fixation and curvature perceptual features, as well as the characteristics of driving cognition under different tunnel sections and driving directions. The study derives the following key conclusions:

(1) Compared to ordinary curved tunnels, spiral tunnels show significantly shorter fixation durations (avg. 0.55 s) and higher fixation counts (avg. 16), suggesting easier environmental information extraction but increased need for dynamic updates. Drivers in spiral tunnels spend more time (avg. 39.8 s) and underestimate curvature (avg. 3.69 %), raising the risk of severe accidents.

(2) In the entrance section of spiral tunnels, abrupt environmental changes lead to dispersed attention, resulting in intensified curvature illusion and the longest reaction time (avg. 29.9 s), which contributes to relatively poor cognitive performance. In the exit section, although drivers actively search for environmental information, intense optical stimulation causes a significant increase in curvature illusion (avg. 28 %), indicating substantial challenges in driving cognition.

(3) The study revealed that orientation of roadway (OR), longitudinal deceleration markings (LDM), solid lane line (SLL), tunnel roof lights (TRL) and visual guidance signs (VGS) were subjectively the most significant element. However, drivers' fixation points predominantly clustered on the OR area.

(4) This study reveals the complex relationship between environmental elements and visual attention in spiral tunnels: The significance of OR and VGS shows a positive correlation with fixation number, while the significance of SLL, TRL, and VGS exhibits a positive correlation with fixation duration. Although increased fixation number is negatively correlated with curvature illusion, it may prolong reaction times. Thus, moderate supplementation of environmental information may optimize curvature perception by enhancing the quality of attentional integration rather than simply reducing fixation behavior.

This study, while utilizing an actual multi-tunnel highway to ensure ecological validity, faced limitations in designing curvature intervals and maintaining variable consistency, highlighting key constraints of this pilot investigation. This study preliminarily explored the associations between tunnel elements and driving cognition through correlation analysis, and provides directions for cognitive optimization of spiral tunnels. However, due to limitations in sample size, experimental conditions, and uncontrolled confounding factors, the recommendations still require further validation through intervention experiments. Future research will employ virtual reality simulations to create controlled, reproducible tunnel environments, enabling precise analysis of driving behavior. Additionally, a multidimensional approach incorporating vehicle characteristics, visual field variations, and driver cognition mechanisms will be adopted to enhance traffic management. Advanced visualization techniques will ensure accurate information transmission, ultimately contributing to more robust solutions for spiral tunnel safety management.

CRediT authorship contribution statement

Yanzi Xia: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Chi Zhang:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Min Zhang:** Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Hong Zhang:** Writing – review & editing, Validation, Data curation. **Bo Wang:** Visualization, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Questionnaire for tunnel elements investigation

Dear Sir/Madam,

We are conducting a study on spiral tunnels to investigate drivers' experiences while driving, paving the way for further in-depth research. We require you to watch three authentic driving videos and then fill out the corresponding questions. Completing the entire questionnaire will take approximately 10 min.

The questionnaire consists of 9 questions: Questions 1–2 are single-choice questions, Questions 3–5 are ranking questions, and Questions 6–9 are also single-choice questions.

1 Are you willing to complete this survey?

○ Yes ○ No.

2 Do you possess a motor vehicle driver's license?

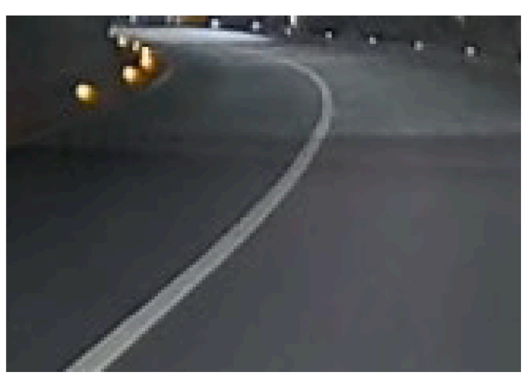
○ Yes ○ No.
[Video 1 Clip].

3 Based on your observation of Video 1, please rank the road elements in terms of their importance for understanding road information.

(Position 1 indicates the most important, and so on. Note that all elements should be selected.).
○ Orientation of the roadway.

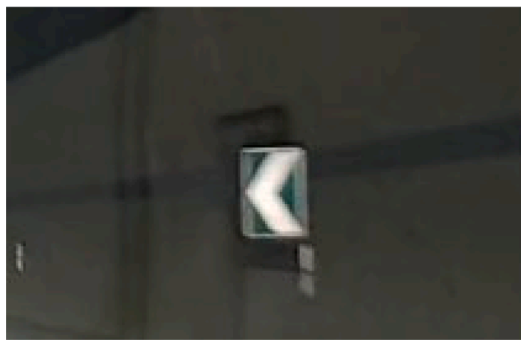
.
○ Longitudinal deceleration markings.

.
○ Solid lane lines.



.
○ Tunnel roof lights.

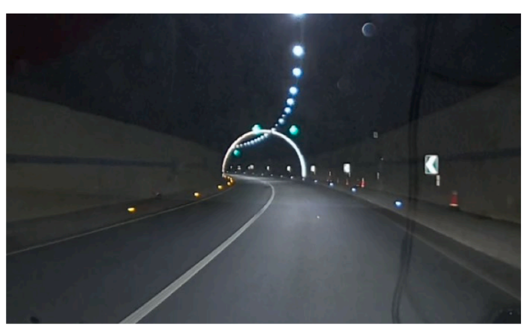
- ○ Visual guidance signs.



- [Video 2 Clip].

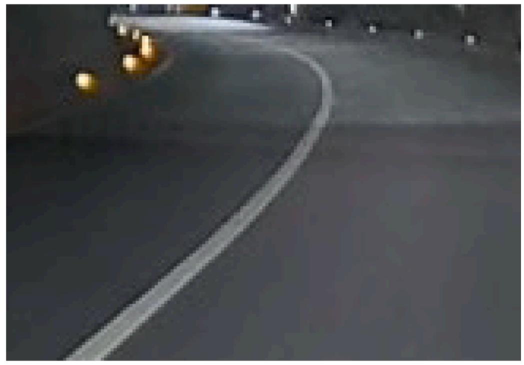
4 Based on your observation of Video 2, please rank the road elements in terms of their importance for understanding road information.

(Position 1 indicates the most important, and so forth. Note that all elements should be selected.).
○ Orientation of roadway.

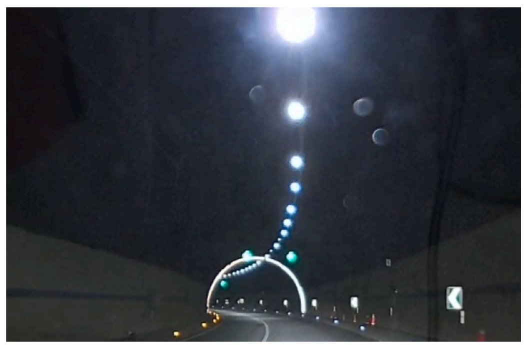


- ○ Longitudinal deceleration markings.

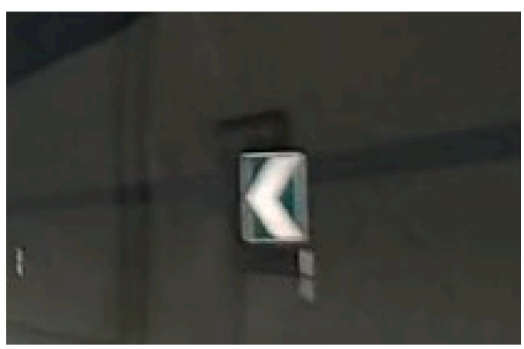
- ○ Solid lane lines.



○ Tunnel roof lights.



○ Visual guidance signs.



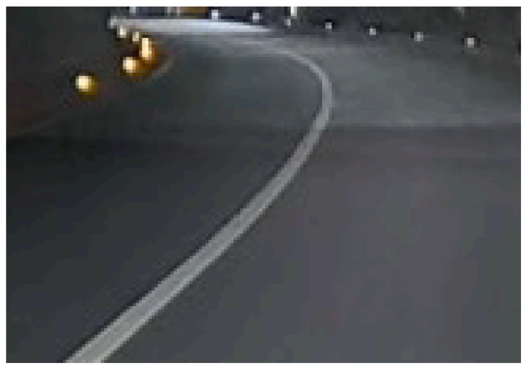
[Video 3 Clip].

5 Based on your observation of Video 3, please rank the road elements in terms of their importance for understanding road information.

(Position 1 indicates the most important, followed by subsequent positions accordingly. Please note that all elements should be selected.).
○ Orientation of roadway.

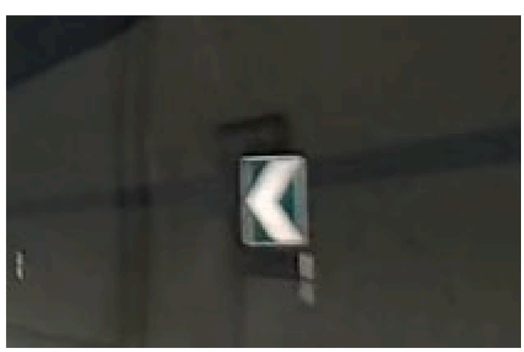
○ Longitudinal deceleration markings.

- ○ Solid lane lines.



- ○ Tunnel roof lights.

- ○ Visual guidance signs.



6 What is your age group?

○ Under 18 ○ 18–25 ○ 26–30 ○ 31–40 ○ 41–50 ○ 51–60 ○ Over 60.

7 What is your gender?

○ Male ○ Female.

8 How many years of driving experience do you have?

○ ≤2 years ○ 3–5 years ○ 6–10 years ○ >10 years.

9 Have you ever driven inside a tunnel?

○ Yes ○ No.

Appendix B

More samples of fixation points distribution

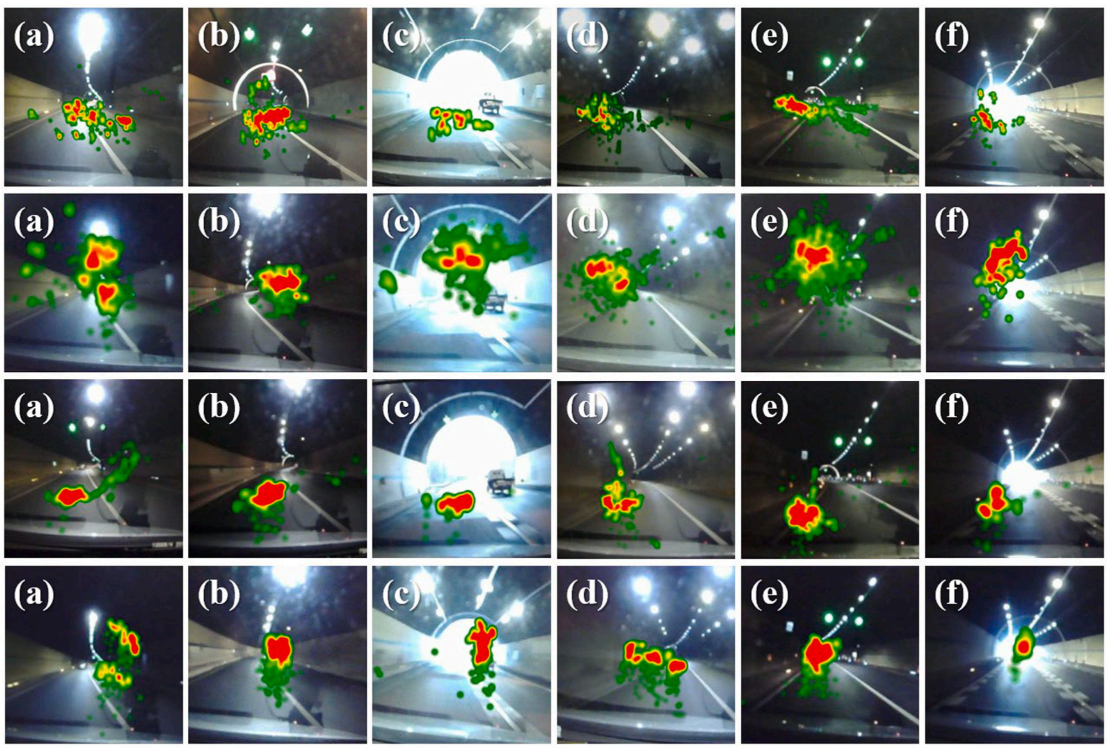


Fig. B1. Distribution of fixation points of more samples: (a) entrance section under clockwise driving, (b) internal section under clockwise driving, (c) exit section under clockwise driving, (d) entrance section under counterclockwise driving, (e) internal section under counterclockwise driving, and (f) exit section under counterclockwise driving.

Data availability

The authors do not have permission to share data.

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