Heliyon 10 (2024) e35291

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effect of expressway exit deceleration markings on distracted drivers in China

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ARTICLE INFO

Keywords:
Deceleration marking
Expressway exit
Distracted driver
Driving simulation
Eye movement
Electroencephalogram data

ABSTRACT

Expressway exit areas experience traffic diversion and complex road conditions, making them accident-prone areas. In this study, transverse and fishbone visual illusion deceleration markings were selected to optimize the induction facilities at expressway exits. The research aims to investigate the impact of these markings on the driving behavior, cognitive load, and physiological characteristics of drivers in various distracted scenarios at expressway exit areas. Furthermore, a comprehensive evaluation of each experimental scheme is conducted using the Matter-Element Extension Model. The study found that the implementation of deceleration markings can effectively enhance driver alertness and lane change awareness, enabling drivers to reduce their speed to near the speed limit in exit areas without compromising driving comfort. Compared to the situation without markings, drivers begin to decelerate approximately 600 m earlier and exit the ramp when markings are present. Fishbone deceleration markings, in contrast to transverse markings, result in lower vehicle speeds, smoother deceleration, and more effectively stimulate drivers' intention to change lanes, guiding them to make the final lane change earlier. Based on the comprehensive evaluation results, it is recommended that transverse or fishbone deceleration markings be considered in engineering practice. These markings have not produced significant effects on driver visual fatigue and driving load, with fishbone markings demonstrating superior comprehensive evaluation outcomes. These research findings can provide valuable insights for future expressway exit area marking design schemes, further enhancing driver safety.

1. Introduction

China had a total of 169,000 km of operational expressways in 2021, ranking first globally [1]. However, the traffic accident mortality rate on Chinese expressways is 22.2 % higher than that on national roads. Approximately 10 % of road crashes are related to road network construction, with over 40 % of them occurring at expressway exits [2]. The monotonous driving environment on expressways often leads to reduced driver attention to the surrounding facilities and environment, resulting in lower alertness and an increased risk of driver fatigue and distraction [3]. In complex exit areas, if drivers fail to decelerate and change lanes promptly, they may enter exit ramps at relatively high speeds, significantly increasing the risk of accidents (see Figs. 4–7).

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https://doi.org/10.1016/j.heliyon.2024.e35291
Received 8 March 2024; Received in revised form 23 July 2024; Accepted 25 July 2024

Driver distraction refers to the hazardous behavior of drivers diverting their attention from the driving task to engage in other non-driving tasks, known as "secondary tasks," leading to reduced perception, decision-making, and operational capabilities, thereby compromising driving safety [4]. Secondary tasks can be broadly categorized into two types: cognitive distraction and visual distraction. Cognitive distraction competes for central processing resources with the driving task, requiring participants to process auditory information and provide verbal responses. Visual distraction in drivers primarily occurs when their gaze shifts away from the road area, often when using in-vehicle interactive devices [5]. Moreover, distractions may not necessarily be mutually exclusive and can co-occur. To assess the combined effects of these distractions in highly realistic and diverse driving scenarios, both types of distractions can be simultaneously imposed on drivers, creating a composite distraction [6].

The research findings from a study involving 100 drivers in naturalistic environments indicate that distracted driving poses a significant risk to traffic safety, with 78 % (n = 100) of collisions and 65 % of near-miss accidents being associated with driver distraction and inattention [7]. There is a negative correlation between drivers' saccade frequency and the degree of cognitive distraction [8]. The results of the n-back experiment indicate that blink frequency increases with the level of cognitive distraction [9]. When driving with cognitive distraction compared to everyday driving, alpha waves exhibit significant changes with increasing cognitive load [10]. In distracted driving scenarios, composite distraction has a more pronounced impact than single distractions [11]. In complex road environments, distracted drivers show significantly increased variations in speed control [12]. Under cognitive distraction, drivers experience significantly longer reaction times [13]. Although lane-keeping remains effective, it can lead to more emergency braking events [14]. Visual distraction increases time with drivers' eyes off the road, reduces average speeds [15], and increases speed fluctuations [6]. Distracted driving has varying degrees of adverse effects on drivers' eye movements, electroencephalography activity, deceleration, braking, lane-changing, and other driving behaviors.

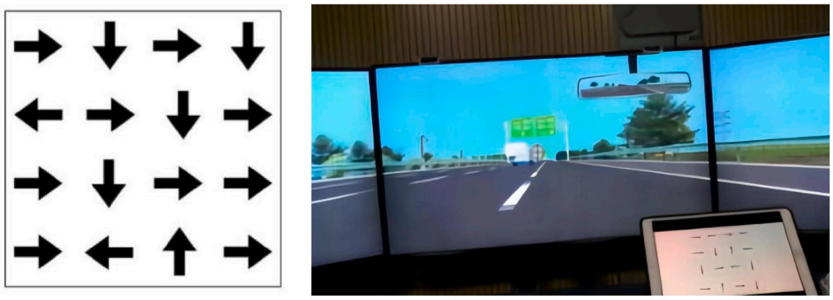
The "Highway Engineering Technical Standards" stipulate that the speed on expressway ramps should be less than 40 km/h [16]. However, according to a traffic accident analysis conducted by the Chinese Traffic Police Bureau, 38 % of road crashes are highly correlated with drivers' misperception of their driving speed, often resulting in drivers exceeding the speed limit on ramps [17]. Unreasonable speed control in exit areas is one of the main reasons for frequent expressway accidents. In traffic safety, visual illusion deceleration markings create an illusion of lane narrowing and increased speed to stimulate drivers' psychological and physiological responses and draw their attention to specific traffic rules or dangerous information. This is achieved through a reasonable combination of colors and graphics [18,19]. Visual illusion deceleration markings include speed-increasing types (transverse and fishbone), lane-narrowing types (longitudinal and comb-tooth), and three-dimensional types, among which vehicle speed-type deceleration markings are the most widely used. Research on expressway curve deceleration markings indicates that side lane vehicles significantly reduce speed, while those in the middle lane are less affected [20]. Transverse markings reduce accident rates by 5 %–50 %, while V-shaped markings reduce them by 25 %–50 % [21]. Meanwhile, transverse markings are most effective in reducing speed, particularly for high-speed vehicles [22].

Based on the characteristics of expressway driving, this study investigates the impact of no-markings, transverse, and fishbone deceleration markings on drivers' cognitive, visual, and compound distraction. Considering extreme factors, this study induced driver distraction through sub-tasks before the 2 km exit warning sign. The findings could enhance the visual environment in expressway exit zones, prompting drivers to slow down in advance, change lanes progressively to the outermost lane, and safely exit the expressway, reducing accident risks. This research has vital implications for boosting safety at expressway exits and offers a theoretical basis for optimizing exit warning facilities.

2. Methods and materials

2.1. Distraction tasks

Cognitive distraction primarily refers to drivers engaging in thoughts or activities unrelated to driving. In this study, it was induced using an improved 2-back task, a delayed digit recall task widely utilized as an educational tool for distraction awareness in drivers and pedestrians [23]. Upon entering the experimental task segment, the experimenter played random digits from 0 to 9 at intervals of 2.25



(a) (b)

Fig. 1. (a) Arrow matrix & (b) The process of visual distraction experiment.

s. When the nth stimulus appeared, participants were required to repeat both the nth digit and the (n-2)th digit.

Visual distraction refers to a state in which drivers divert their gaze from the road and driving environment to focus on other objects or activities. In this study, visual distraction was induced using an arrow task, which involves a matrix of arrows presented sequentially to the driver [24]. The task was displayed on an iPad positioned in the upper right corner of the dashboard. Participants were required to identify whether the 4 × 4 matrix of arrows contained an upward-pointing arrow (as illustrated in Fig. 1); if so, they responded with "yes"; otherwise, they responded with "no." Each image automatically changed every 5 s.

Compound distraction is achieved using an enhanced clock task. The original clock task [25] causes pure cognitive distraction. To simultaneously induce cognitive and visual distraction, participants must view a specific time (e.g., 11:25, displayed as numbers only, as showed in Fig. 2) on a tablet and mentally visualize the corresponding image of a clock. Then, answer the relationship between the angles of the hour hand and the minute hand and 90. If the angle is greater than 90°, click "greater than"; otherwise, click "less than" Each picture switches automatically after 10 s. All distraction tasks conclude once the participants have driven beyond the exit. During the experiment, the examiner recorded the subjects' accuracy in completing the three distraction tasks to confirm participation (see Fig. 3).

2.2. *Deceleration markings optimization design*

In contrast to bidirectional four or six-lane expressways, driver behavior at the exits of bidirectional eight-lane expressways is more complex, especially for vehicles traveling in the lanes closest to the median strip [26]. Firstly, during the reaction phase, drivers visually recognize deceleration markings and combine the exit advance signs to determine whether the upcoming exit is their intended destination, making decisions accordingly. Secondly, during the lane-changing phase, drivers adjust their speed and wait for a suitable headway distance to change the vehicle from the existing lane to an adjacent lane. Finally, to ensure driving comfort and safety, drivers should continue to travel a certain distance after lane-changing before exiting the expressway. To sum up, the setting length of the deceleration marking is the sum of the reaction distance, lane change distance, and safety distance.

The length and placement of deceleration markings as shown in Table 1 were set based on AASHTO, China's Highway Route Design Code [27], and other pertinent research findings [28–30].

The transverse deceleration markings are perpendicular to the lane centerline, with a single line width of 45 cm, arranged in pairs with an intra-pair spacing of 45 cm [31]. The spacing between the markings gradually reduces from 32 m to 17 m, decreasing by 3m each time.

The fishbone markings are "V"-shaped stripes arranged at specific intervals. It is not uniformly stipulated in the current specifications. In this study, the parameters for them were determined as follows: a single stripe has a width of 15 cm, a transverse design width of 1m, a fishbone angle of 120°, with two stripes per group, an intra-group spacing of 0.20m, and an inter-group spacing of 20m [32].

2.3. *Experimental scene*

Based on the aforementioned research, nine experimental scenarios were created using the method of controlling variables, consisting of two variables: deceleration markings and distraction tasks. All experimental road sections were designed as dual-direction eight-lane expressways, with a total mileage of approximately 4 km. The overall road condition was well-maintained, with uniform elements except for the type of deceleration markings. The experiments were conducted during the daytime, and nighttime driving conditions were not considered. A maximum traffic flow rate of 2000 pcu/h under stable flow conditions was selected [33]. The route passed through an interchange where the participants exited the expressway.

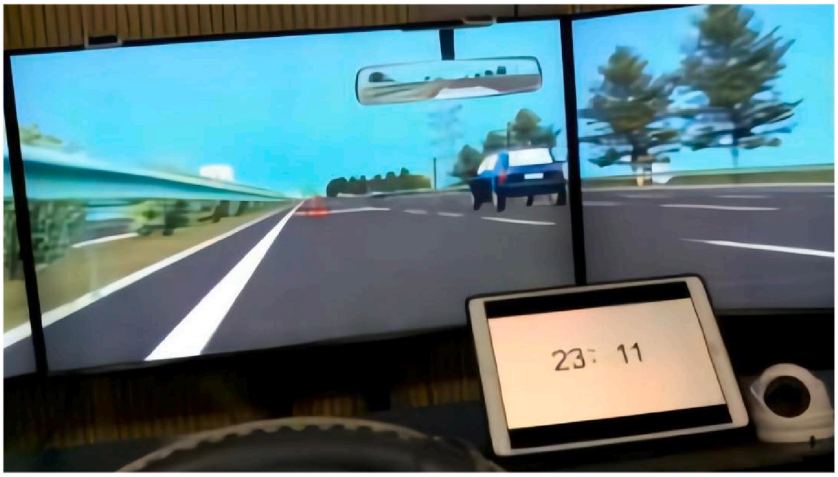
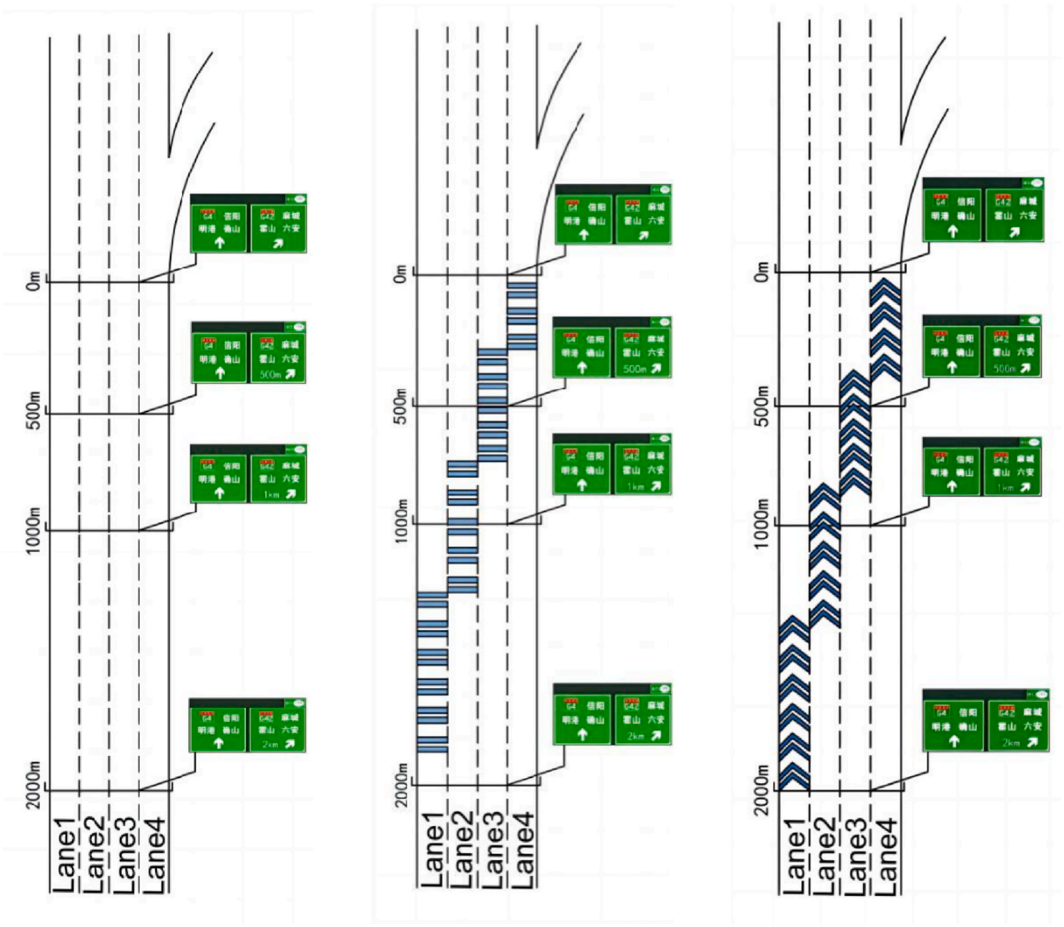


Fig. 2. The process of compound distraction experiment.



(A)Unmarked （B） Transverse （C） Fishbone

Fig. 3. Experimental scene.

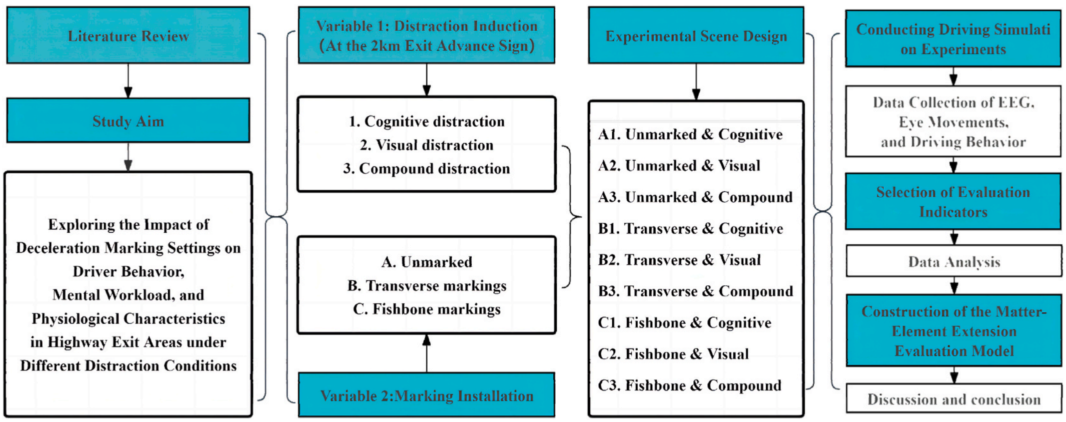
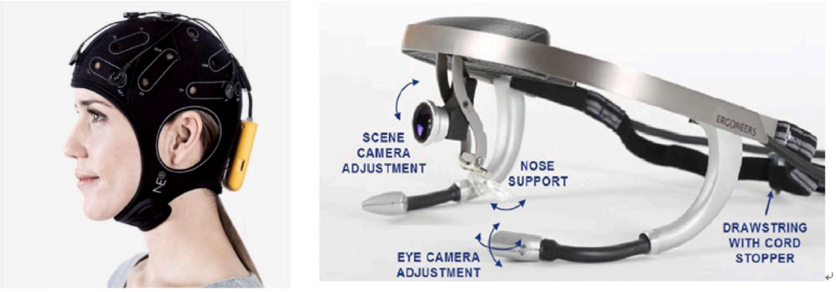


Fig. 4. The design of tested measures.

(a) Cockpit & Display (b) Console

Fig. 5. Driving simulation system.



(a) (b)

Fig. 6. (a) 32-channel NE wireless EEG device & (b) Dikablis glasses eye tracker.

Fig. 7. Experimental process.

2.4. Participants

Use G*power software to estimate the sample size [34], and f = 0.25 was set [35]. Twenty-two subjects were calculated while taking $\alpha = 0.01$ and 1-β = power = 0.95 [36]. In practice, 33 drivers were recruited through relevant channels, including university campuses and taxi companies. Participants' ages ranged from 20 to 48 years (Mean = 30.5, SD = 1.825), and their driving experience

Table 1
Length of deceleration marking for each lane.

Lane No.	Expected Speed (km/h)	Marking Length(m)			Total length (m) (Rounded up)
		Reaction Distance	Lane Change Distance	Safe Distance	
Lane 1	100–120	143.6	434.86	/	580
Lane 2	80–120	130.50	368.6	100	600
Lane 3	80–100	117.5	304.14	100	530
Lane 4	60–80	91.35	/	100	200
Total	/				1910

ranged from 1 to 26 years (Mean = 10, SD = 1.22). Prior to the experiment, all participants were ensured to have adequate sleep, no alcohol consumption, good physical condition, and emotional stability. The study received approval from the relevant ethics committee, and all participants signed the written informed consent form for the simulated driving experiment. They voluntarily participated in the experiment and were compensated with ¥50.

During the experiment, one driver failed to record gaze points, and two drivers reported discomfort and exhibited abnormal EEG signals. After excluding this invalid data, the final valid experimental data were obtained from 30 drivers.

2.5. *Experimental equipment*

2.5.1. *DSR-1000TS2.0 driving simulator*

The DSR-1000TS 2.0 driving simulation system is mainly composed of a cockpit, console, and display. During driving, the system collects experimental data such as steering wheel angle and vehicle speed in real time.

2.5.2. *NE and EEG system*

NE wireless EEG system is a wearable EEG cap with 32 channels, 500SPS sampling rate, and 24-bit resolution. This system collects real-time EEG data, and MATLAB software is used for data analysis to obtain energy values for various EEG indicators.

2.5.3. *Dikablis glasses eye tracker*

With an accuracy of 0.1°–0.3° and a frequency of 60 Hz, the Dikablis Glasses eye tracker monitors changes in participants' eye characteristics during the driving process and records multiple indicators such as pupil area and PERCOLS.

2.6. *Procedure*

(a) Import the experimental scene file into the driving simulator central control system, load the traffic flow, and check the device connection;
(b) Subjects were required to read the experimental instructions, fill in the personal information questionnaire, and undergo distraction task training;
(c) Provide participants with instructions on the proper use of each device and ask them to practice driving on non-experimental roads for a few minutes until they are familiar with the operations. Participants then wear the experimental equipment, conduct calibration, and proceed to the formal experiment.
(d) In the formal simulated driving, participants are informed that the driving speed should not exceed 120 km/h. After each scenario, participants rest for 3 min before proceeding to the next one. The order of the experimental scenarios was randomized. The above steps are switched nine times, and the completion of all scenarios takes approximately 35–40 min. Finally, the experimenter collects and exports data from various platforms.

2.7. *Evaluation indicators*

The study selected PERCOLS and beta waves to represent the driver's alertness. PERCOLS is the percentage of time the driver's eyes are closed within a unit of time, measured in %. A decrease in driver alertness is accompanied by an increase in PERCOLS [37]. Beta waves primarily occur when the driver is alert or actively focused and are measured in $\mu v^2/Hz$. The larger this value, the more alert the driver is [38,39].

In the driving behavior indicators, speed and AAA were selected to represent the deceleration effect of the study. Speed, measured in km/h, represents the driver's control over the vehicle's speed. AAA, the Average Absolute Acceleration, refers the absolute value of the speed change rate. It reflects the stability of the driver's acceleration and deceleration processes as well as driving comfort, measured in m/s^2. A smaller value indicates a more stable driving state.

Last Lane Change (LLC) Distance and saccade frequency are used to represent the effectiveness of lane changes. In this study, LLC Distance is defined as the distance between the end of the third lane change and the beginning of the transition zone, measured in meters. The longer this distance, the earlier the driver confirms the exit and completes the LLC operation, indicating stronger lane change awareness and higher safety [40]. Saccade frequency represents the efficiency of searching for target objects per unit of time

[41], measured in times per second. During the lane-changing intention phase, drivers engage in multiple scanning behaviors, with a lower scan rate during lane-keeping compared to lane-changing [42].

α/β ratio and pupil area are used to represent driving load. α/β is negatively correlated with responses related to stress and tasks [43]. A ratio below 1 indicates a higher cognitive load, while a ratio above 1 suggests a lower cognitive load [44]. The pupil area represents the driver's psychological load and tension, measured in pixels. This value increases with the increase in visual load [45,46].

2.8. Data process

Eye movement data preprocessing was conducted using the D-Lab platform. Pupil area data could be exported separately, while measures such as PERCLOS, number of saccades, and saccade duration were extracted using Eye Tracking Statistics.

EEG data are processed in batch through the EEGLAB toolbox and code in Matlab, mainly including filtering, deleting all fragments containing parsmal artifacts and bad channels, data denoising, removing artifacts, re-interpolating damaged channels, and re-referencing [47].

The 200 m in front of the exit warning sign (the starting point of visual recognition) to the destination exit is used as the experimental measurement section of this study [48], a total of 2200 m. Experimental data are directly exported from the driving simulator to Excel format.

3. Experimental results

3.1. Statistical analysis

To investigate the differences and changes in various indicators of drivers under different distraction conditions in highway exit areas with different visual illusion deceleration markings, the experimental data were analyzed using two-way repeated measures ANOVA in SPSS 25.0 software. Prior to this, all data were tested for normality using the Shapiro-Wilk test. The sphericity assumption for single variables and interaction variables in the experimental design was tested using Mauchly's test of sphericity. For variables that met the sphericity assumption ($p > 0.05$), the significance test results were based on the sig values under the sphericity assumption; otherwise, the Greenhouse-Geisser corrected sig values were used. Interaction effects were tested for all designs, and only the interaction effect of the LLC distance indicator was significant. Therefore, a simple effects analysis was performed only for this indicator. The interaction effects of the remaining indicators were not significant, and the within-subject effect of the "distraction" variable in the AAA indicator was also not significant. Post hoc pairwise comparisons were conducted for indicators with significant within-subject effects. All statistical results are shown in the Appendix.

3.2. Effects on alertness

The within-subject effect test results of PERCLOS and beta values both indicated statistical differences in the markings variables. ($F(2,58) = 31.708$, $p < 0.05$, $\eta^2 = 0.522$; $F(2,58) = 21.846$, $p < 0.05$, $\eta^2 = 0.430$). There were statistical differences in the distraction variables ($F(2,58) = 100.834$, $p < 0.05$, $\eta^2 = 0.777$; $F(2,58) = 27.782$, $p < 0.05$, $\eta^2 = 0.489$). There were no statistically significant differences in interaction variables ($F(4,116) = 2.364$, $p = 0.057 > 0.05$, $\eta^2 = 0.075$; $F(4,116) = 0.109$, $p = 0.979$, $\eta^2 = 0.004$) (see Fig. 8).

Pairwise comparisons show that the difference in beta wave energy between transverse and fishbone-shaped markings is not

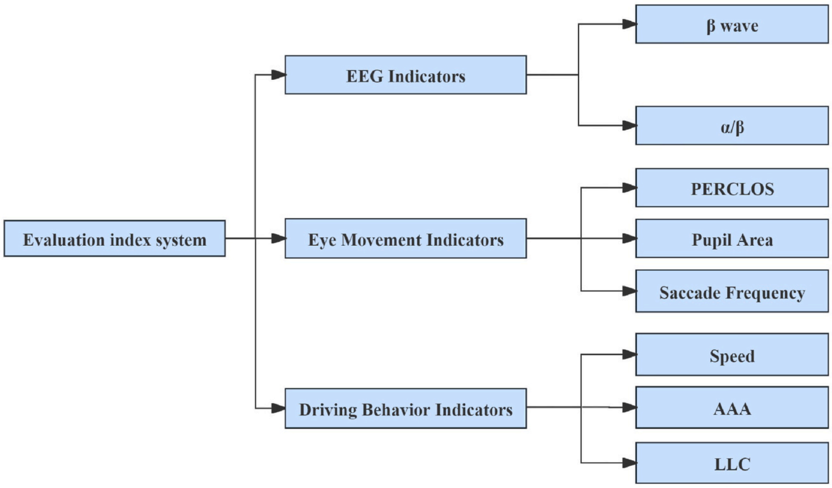


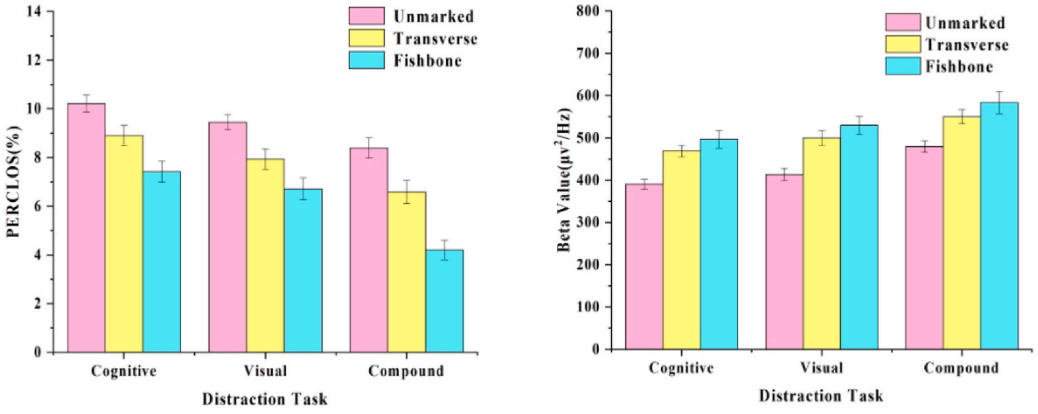
Fig. 8. Evaluation indicator system.

significant, whereas the differences between no markings and transverse markings, as well as between no markings and fishbone markings, are significant. The differences in PERCLOS among the marking conditions are all significant, indicating that the presence of markings significantly enhances driver alertness. For both of these indicators, the differences between distraction categories are significant. By comparing the mean differences between groups, it can be observed that with the implementation of non-marked, transverse, and fishbone deceleration markings, as well as the application of cognitive, visual, and compound distractions, PERCLOS gradually decreases and beta wave energy gradually increases. This indicates that as the complexity of the markings and the level of distraction increase, the driver's alertness in the exit area gradually improves (Fig. 9a and b). The driver's alertness reaches its peak with the setting of fishbone markings and compound distractions.

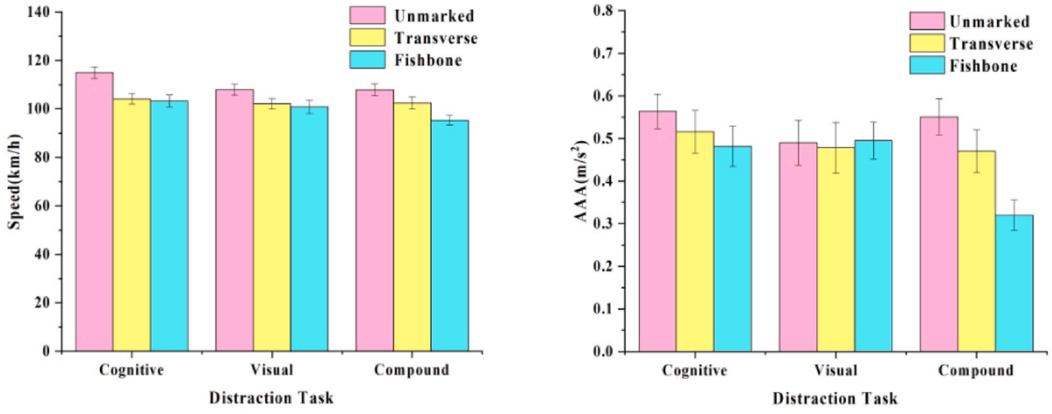
3.3. Effects on deceleration

The results of the within-subject effect test for speed and AAA indicated a statistical difference in the markings variable ($F(2,58) = 34.263$, $p = 0.000 < 0.05$, $\eta^2 = 0.542$; $F(2,58) = 3.319$, $p = 0.043 < 0.05, \eta^2 = 0.103$). For the speed indicator, there was a statistical difference in the distraction variable ($F(2,58) = 8.465$, $p = 0.001 < 0.05, \eta^2 = 0.226$). For the AAA indicator, there was no significant difference in distraction variables ($F(2,58) = 2.789$, $p = 0.070 > 0.05, \eta^2 = 0.088$). The interaction variable showed no significant difference ($F(4,116) = 1.823$, $p = 0.151 > 0.05$, $\eta^2 = 0.059$; $F(4,116) = 1.989$, $p = 0.101 > 0.05$, $\eta^2 = 0.064$).

The paired comparisons of speed variables showed that the vehicle speed gradually decreases with no marking, transverse, and fishbone-shaped markings and the application of cognitive, visual, and compound distractions. The presence of markings is effective in reducing speed. More specifically, the deceleration effect of fishbone markings significantly exceeds that of transverse markings, and the deceleration effect with markings is significantly greater than without markings. The paired comparison of AAA for the markings variables shows that AAA decreases with the setting of unmarked, transverse, and fishbone markings. Especially when fishbone-shaped markings are applied, drivers' deceleration is the smoothest, with a significant difference in deceleration stability between no markings



(a) PERCLOS (b) Beta wave



(c) Speed (d) AAA

Fig. 9. Comparison of various deceleration indicators.

and fishbone markings (see Fig. 9c and d). Additionally, the pairwise comparison results of the speed indicator within distraction categories show significant differences between cognitive distraction and visual distraction, as well as between cognitive distraction and compound distraction. However, the differences in the effects of visual distraction and compound distraction on deceleration are not significant.

An experimental task sectional is divided every 200m to extract driving behavior data. This experiment consisted of 11 task sectionals, and a heat map was generated based on speed data (Fig. 10). The results show that when there is no marking, drivers only exhibit noticeable deceleration behavior between 400 and 600 m before the exit. Conversely, drivers begin to consciously decelerate between 1000 and 1200 m away from the exit after setting markings.

3.4. *Effects on lane changing*

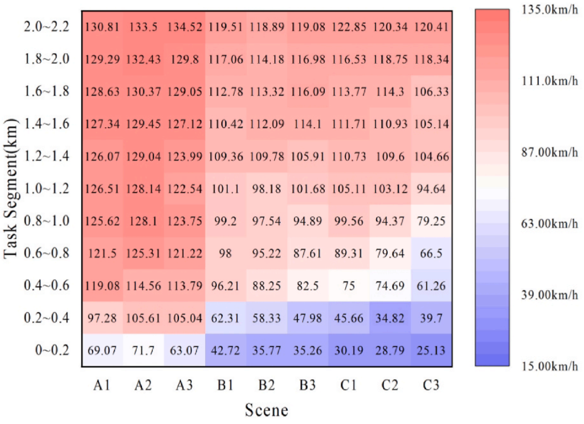
The results of the within-subject effect test of the LLC distance showed that there was a statistical difference in the interaction variable ($F(4,116) = 7.538$, $p = 0 < 0.05, \eta^2 = 0.206$). Additionally, the results of the simple effects analysis show that in the no-marking scenario, with the application of cognitive, visual, and compound distractions, the LLC distance significantly increases, indicating a substantial enhancement in drivers' intention to change lanes. The trend of the impact of transverse and fishbone-shaped deceleration markings on drivers' lane change intentions is consistent with the no-marking scenario, although the effects are not significant. Under compound distraction conditions, fishbone markings have the most pronounced effect on enhancing drivers' lane change intentions. Under cognitive distraction conditions, with the implementation of no markings, transverse markings, and fishbone-shaped markings, the LLC distance significantly increases, and drivers' lane change intentions are also significantly enhanced. Similar trends are observed under visual and compound distraction conditions, with significant differences among the various marking types. Fishbone-shaped markings are the most favorable setting for influencing lane change intentions under any type of distraction (see Fig. 11a).

The within-subject effect test results for saccade frequency showed that there were statistical differences in markings and distraction variables respectively ($F(2,58) = 95.199$, $p = 0 < 0.05, \eta^2 = 0.767$; $F(2,58) = 25.806$, $p = 0 < 0.05, \eta^2 = 0.471$) while there was no significant difference in their interaction variable ($F(4,116) = 1.781$, $p = 0.137 > 0.05, \eta^2 = 0.058$). The pairwise comparison results show that with the implementation of no markings, transverse markings, and fishbone-shaped markings, as well as the application of cognitive, visual, and compound distractions, the saccade frequency gradually increases, and the differences among these conditions are all significant. This suggests that drivers, especially under conditions of visual and compound distractions, exhibit an increased frequency of scanning behaviors (Fig. 11b), with significant differences in the effects between visual distraction and compound distraction. The presence of markings further intensifies drivers' focus on the road environment and reinforces their intentions to change lanes, with the effect of fishbone-shaped markings being significantly greater than that of transverse markings. The most significant impact of markings on drivers' lane change intentions occurs under compound distraction conditions.

3.5. *Effects on load*

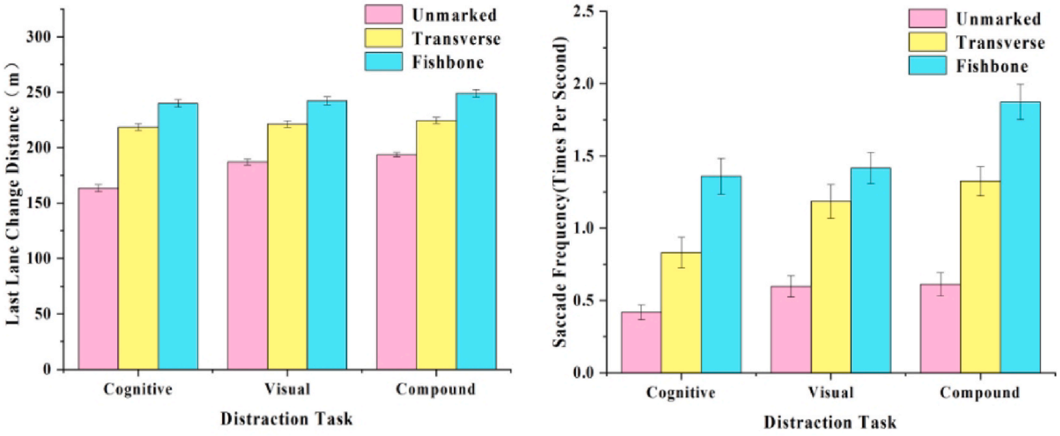
The within-subject effect test results of α/β and pupil area both showed that there were statistical differences in the markings variables ($F(2,58) = 43.2$, $p = 0 < 0.05$, $\eta^2 = 0.598$; $F(2,58) = 37.836$, $p = 0 < 0.05$, $\eta^2 = 0.566$). Meanwhile, there were statistical differences in distraction variables ($F(2,58) = 67.708$, $p = 0 < 0.05$, $\eta^2 = 0.7$; $F(2,58) = 7.337$, $p = 0.001 < 0.05$, $\eta^2 = 0.202$)while there was no significant difference between interaction variable ($F(4,116) = 2.245$, $p = 0.098 > 0.05$, $\eta^2 = 0.072$; $F(4,116) = 1.288$, $p = 0.279 > 0.05$, $\eta^2 = 0.043$).

Bar charts and pairwise comparisons show that the difference between visual distraction and compound distraction in the pupil area indicator is not significant, indicating that while both visual and compound distractions affect the driver's visual load, the



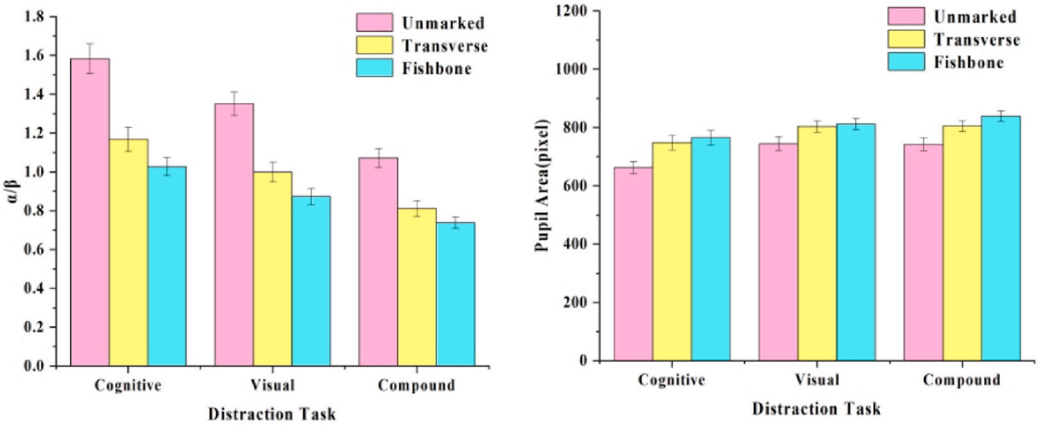
Task Segment(km)	A1	A2	A3	B1	B2	B3	C1	C2	C3
2.0~2.2	130.81	133.5	134.52	119.51	118.89	119.08	122.85	120.34	120.41
1.8~2.0	129.29	132.43	129.8	117.06	114.18	116.98	116.53	118.75	118.34
1.6~1.8	128.63	130.37	129.05	112.78	113.32	116.09	113.77	114.3	106.33
1.4~1.6	127.34	129.45	127.12	110.42	112.09	114.1	111.71	110.93	105.14
1.2~1.4	126.07	129.04	123.99	109.36	109.78	105.91	110.73	109.6	104.66
1.0~1.2	126.51	128.14	122.54	101.1	98.18	101.68	105.11	103.12	94.64
0.8~1.0	125.62	128.1	123.75	99.2	97.54	94.89	99.56	94.37	79.25
0.6~0.8	121.5	125.31	121.22	98	95.22	87.61	89.31	79.64	66.5
0.4~0.6	119.08	114.56	113.79	96.21	88.25	82.5	75	74.69	61.26
0.2~0.4	97.28	105.61	105.04	62.31	58.33	47.98	45.66	34.82	39.7
0~0.2	69.07	71.7	63.07	42.72	35.77	35.26	30.19	28.79	25.13

Fig. 10. Heat map of speed.



(a) LLC distance

.(b) Saccade frequency



(c) α/β

(d) Pupil area

Fig. 11. Comparison of driver behavior indicators.

difference in their impact is not substantial. The differences between groups within the same variable for all other comparisons are significant. With the implementation of no marking, transverse, and fishbone-shaped markings, as well as the application of cognitive, visual, and compound distractions, there is a gradual decrease in the α/β ratio and a progressive increase in the pupil area (Fig. 11c and d). This trend signifies an escalating cognitive load imposed on drivers by the driving task, with the fishbone markings imposing the greatest load. Additionally, there is a substantial difference in load between the fishbone and transverse markings, and a significant difference in load between conditions with markings and those without.

In particular, the α/β values of scenes A1 and A2 are greater than 1, indicating a lower driving load. After applying compound distraction or dragging markings, the α/β value becomes greater than 1, signifying an increased driving load.

4. Comprehensive influence analysis

The Matter-Element Extension Analysis (MEEA) method is a comprehensive evaluation approach suitable for multi-index evaluation systems of complex systems. Its evaluation results effectively preserve the characteristics of the indicator data, providing an objective and comprehensive reflection of the merits and evaluation grades of various solutions [49]. The K-means algorithm is an iterative clustering analysis technique known for its simplicity and efficiency. The entropy weighting method is a relatively objective approach for determining the weights of indicators. The greater the variation in the indicator, the smaller the information entropy, resulting in a larger weight for that indicator and vice versa. This paper selects a matter-element extension model based on a combination of entropy weight and K-Means to evaluate the effectiveness of the setting of deceleration markings under different distracted driving conditions in the expressway exit area. The main steps are as follows: indicator weight determination via the entropy weight

Table 2
Comprehensive correlation degree and evaluation grade of each scheme.

Scenes	Alternatives	Correlation Degree of Alternatives					Evaluation Grade of Alternatives	Evaluation Grade of Scenes
		Worst	Poor	Fair	Good	Excellent		
A	A1	−0.394	−0.156	0.278	−0.189	−0.408	3.0260	3.025
	A2	−0.406	−0.168	0.268	−0.169	−0.400	2.9953	
	A3	−0.386	−0.139	0.238	−0.197	−0.412	3.0522	
B	B1	−0.408	−0.149	0.151	−0.177	−0.412	3.0205	3.041
	B2	−0.378	−0.121	0.285	−0.225	−0.429	3.0902	
	B3	−0.397	−0.156	0.235	−0.176	−0.401	3.0133	
C	C1	−0.410	−0.165	0.210	−0.180	−0.411	3.0088	3.108
	C2	−0.372	−0.062	0.105	−0.249	−0.450	3.2201	
	C3	−0.389	−0.112	0.184	−0.214	−0.429	3.0962	

method; constructing the matter-element matrix R; determining the classical and sectional domain; determining the target matter-element R_0; calculating the correlation function K_j; determining evaluation grades and selecting the best scheme [50].

In this comprehensive evaluation process, the data used for each scheme are the average values of all subjects. After standardizing the data, the K-means clustering method divides the data for each indicator into five categories: Worst, Poor, Fair, Good, and Excellent. The common characteristics among the clustered cases are significant ($p < 0.05$). Next, each indicator's classical domain, sectional domain ranges, and weights are calculated. Based on the weight values of each indicator, the correlation degree between the evaluated schemes and each level is computed, ultimately deriving the comprehensive correlation degree between the evaluated schemes and each evaluation level (as shown in Table 2). The level corresponding to the highest correlation degree is used as the evaluation grade for the scheme. The five evaluation grades for quantitative analysis are assigned 1, 2, 3, 4, and 5, respectively.

The value range of correlation is (−1, 1). The larger the value, the better the consistency between the indicator and its level. As shown in Table 2, the ranking of the alternatives from best to worst is C2 > C3 > B2 > A3 > A1 > B1 > B3 > C1 > A2. Overall, the comprehensive evaluation result is fishbone-shaped (3.108) > transverse (3.041) > no markings (3.025).

5. Discussion

In this experiment, various equipment such as a driving simulator, eye tracker, and electroencephalogram (EEG) were used to collect data on participants, including PERCLOS, EEG beta wave, speed, AAA, LLC distance, saccade frequency, pupil area, and EEG α/β data. A matter-element comprehensive evaluation model was established to explore the effects of no markings, transverse and fishbone deceleration markings on driver's cognition, vision, compound distraction, and their impact on the psychological and driving behavior in the expressway exit zone.

To the best of our knowledge, this is the first study to investigate the effects of deceleration markings on driver alertness and load. Results indicate that markings enhance driver alertness in the exit zone. The decrease in PERCLOS and the increase in beta waves suggest that using relatively complex fishbone deceleration markings, compared to the more familiar and simpler transverse markings, can improve driver attention and alertness more effectively. As the grade of distraction increases, drivers may exhibit heightened alertness while driving, possibly due to concerns about their own driving safety and the need to complete the task of exiting the ramp safely. This finding aligns with the results of another study [51].

Implementing markings aids in deceleration, alertness, and smooth lane changes. However, workload indicators show that this also increases drivers' visual and psychological burden, possibly due to the additional attention demands and driving tasks elicited by the markings. During the decision-making process, as the grade of distraction difficulty increases, drivers become more engaged in cognitive processes and are less likely to relax, leading to a gradual decrease in α/β values [52].

For the deceleration indicators, both speed and AAA gradually decrease with the presence of no markings, transverse markings, and fishbone markings. The addition of markings effectively reduces vehicle speed and results in smoother driver deceleration. Furthermore, the effectiveness of fishbone deceleration markings surpasses that of transverse markings. However, the study by Ref. [22] indicated that transverse lines were considered the most promising speed reduction measure. This discrepancy may be due to different experimental conditions and research methodologies. In this study, compared to the scenario with no markings, the presence of markings results in drivers initiating the deceleration process approximately 600 m earlier. Speed gradually decreases with cognitive, visual, and compound distraction. Notably, significant speed differences are observed between cognitive distraction and visual distraction, as well as between cognitive distraction and compound distraction. The differences in speed between visual distraction and compound distraction are not significant, which may be attributed to visual distraction being a significant contributing factor to unsafe driving. The multiple resource theory suggests that secondary tasks occupying the auditory channel result in relatively minor conflicts, whereas the visual channel is the primary channel heavily utilized in driving tasks. When a driver's gaze deviates from the road for more than 2 s during the driving process, driving safety significantly decreases, potentially leading to phenomena such as “blind driving” [53].

For the lane-change indicator, the driver’s LLC distance gradually increases with the unmarked, transverse, and fishbone shapes, while the saccade frequency also progressively rises. This indicates that the setting of markings effectively enhances the driver’s lane change intention. Simultaneously, with increasing distraction difficulty, both the driver’s LLC distance and saccade frequency also increase. This may be attributed to the need for more visual scanning to locate and acquire necessary information as driving information increases and driving complexity rises. According to the risk compensation strategy [54], distracted drivers adopt compensatory measures by increasing the advance lane change distance to mitigate distraction-related risks.

Based on the matter-element model evaluation, overall, the schemes with deceleration markings are superior to those without, with the fishbone markings being the best and no markings being the worst (C > B > A). This demonstrates the effectiveness and feasibility of installing markings. Therefore, it is recommended to consider installing transverse or fishbone deceleration markings in practical engineering applications, particularly the fishbone markings. The visual fatigue and driving load caused by these markings do not have a significant adverse impact on the overall evaluation. The order of merit of all schemes to be evaluated is C2 > C3 > B2 > A3 > A1 > B1 > B3 > C1 > A2. Among them, the comprehensive effects of the fishbone visual (C2), fishbone compound (C3), and transverse visual (B2) scenarios are relatively better. This may be attributed to their ability to provide good warning effects, enabling drivers to smoothly decelerate and change lanes in advance. The top four schemes, C2, C3, B2, and A3, all involve visual distraction or composite distraction. This indicates that visual distraction, by partially shifting the driving task, may reduce the visual fatigue and driving load caused by the markings. However, the cognitive effect of the fishbone pattern (C1) is relatively poor, possibly because drivers have no visual distractions and focus more on the stimulation of the fishbone markings on the road, which may result in another degree of distraction or driver anxiety. Therefore, in the design of road markings, it is essential to balance visual stimuli and cognitive load to avoid excessively interfering with drivers’ normal driving behavior.

There are still some deficiencies in this study. First, this study is based on the two-way eight-lane expressway scene with traffic flow set according to the C-grade service grade. The experimental conclusion may not be universal to other grades of service-grade roads. Secondly, the types and lengths of markings in this study were determined based on previous setting experiences and relevant standards and regulations. The selection of different types and positions of markings may have a significant impact on the driving state and behavior of drivers on expressway exits. Further in-depth research in this area is warranted.

6. Conclusions

This paper set up a comprehensive set of experimental tests to study the effects of expressway deceleration marking design on distracted drivers. The results can be used to guide practical engineering applications. According to the research results, the following conclusions are drawn:

Regarding the impact on driver alertness and workload, the addition of markings and distractions, especially the compound distractions or fishbone markings, although causing relatively greater visual fatigue and workload for drivers, also significantly enhances driver alertness and lane-changing intentions, reducing vehicle speed in the exit area.

Regarding the impact on driving behavior, drivers are more conscious of decelerating after seeing deceleration markings. Their intention to decelerate and change lanes are earlier and stronger than when there are no markings, and the deceleration process is smoother.

In light of the comprehensive evaluation model findings, practical engineering applications should consider incorporating transverse or fishbone deceleration markings. Particularly, fishbone markings are recommended as they do not notably detract from the overall assessment regarding visual fatigue and driving load.

Education and training should emphasize the cognitive demands of distracted driving and allow drivers to safely experience the effects of distraction during training. This may help them understand the severity of its impact [55]. In exit areas, drivers should be particularly vigilant about visual distractions, as these can significantly reduce their attention to exits, potentially leading to greater danger and causing serious road crashes.

Data availability statement

The data associated with this study has not been deposited into a publicly available repository. Data will be made available on request.

Ethical statement

This research adhered to the American Psychological Association Code of Ethics and was approved by the Fuzhou University Traffic Engineering Research Center (Approval No.: 20221009SS001, Approval Date: October 21, 2022). All participants provided informed consent.

CRediT authorship contribution statement

Yanqun Yang: Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **Mingtao Li:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Said M. Easa:** Writing – review & editing, Validation. **Jie Lin:** Writing – original draft, Methodology, Data curation, Conceptualization. **Xinyi Zheng:** Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgments

This study was funded by the Fujian Provincial Social Sciences Fund Project (2021B063), Guangxi Communications Design Group Co., Ltd., and Joint International Research Laboratory on Traffic Psychology & Behaviors of Fuzhou University.

Appendix

Sphericity, within-subject effect, and interaction test results

Indicator	Mauchily's Test of Sphericity		Within-subject effect and interaction test			
	Inspection item	Sig.	Test Method	F	Sig.	η^2
PERCLOS	Markings	0.881	Sphericity	31.708	0.000*	0.522
	Distraction	0.992	Sphericity Sphericity	100.834	0.000*	0.777
	Markings*distraction	0.625		2.364	0.057	0.075
Beta value	Markings	0.825	Greenhouse-Geisser	21.846	0.000*	0.430
	Distraction	0.195	Sphericity	27.782	0.000*	0.489
	Markings*Distraction	0.177	Sphericity	0.109	0.979	0.004
Speed	Markings	0.185	Sphericity	34.263	0.000*	0.542
	Distraction	0.693	Sphericity	8.465	0.001*	0.226
	Markings*Distraction	0.723	Greenhouse-Geisser	1.823	0.151	0.059
AAA	Markings	0.237	Sphericity	3.319	0.043*	0.103
	Distraction	0.890	Sphericity	2.789	0.070	0.088
	Markings*Distraction	0.375	Sphericity	1.989	0.101	0.064
LLC distance	Markings	0.680	Sphericity	324.055	0.000*	0.918
	Distraction	0.188	Sphericity	28.583	0.000*	0.496
	Markings*Distraction	0.097	Sphericity	7.538	0.000*	0.206
Saccade frequency	Markings	0.109	Sphericity	95.199	0.000*	0.767
	Distraction	0.350	Sphericity	25.806	0.000*	0.471
	Markings*Distraction	0.218	Sphericity	1.781	0.137	0.058
Pupil area	Markings	0.312	Sphericity	37.836	0.000*	0.566
	Distraction	0.742	Sphericity	7.337	0.001*	0.202
	Markings*Distraction	0.064	Sphericity	1.288	0.279	0.043
α/β	Markings	0.058	Sphericity	43.200	0.000*	0.598
	Distraction	0.227	Sphericity	67.708	0.000*	0.700
	Markings*Distraction	0.650	Greenhouse-Geisser	2.245	0.098	0.072

Analysis of the simple effect of LLC distance

Simple effects of distraction variables							Simple effects of marking variables						
Markings	Pairings	M.D.	S.E.	Sig.	95 % CI		Distraction	Pairings	M.D.	S.E.	Sig.	95 % CI	
					Low	Up						Low	Up
A	1&2	−23.613	3.261	0.000*	−30.282	−16.944	1	A&B	−55.137	3.576	0.000*	−62.452	−47.823
	1&3	−30.363	3.389	0.000*	−37.294	−23.433		A&C	−76.656	4.154	0.000*	−85.151	−68.160
	2&3	−6.751	2.366	0.008*	−11.589	−1.912		B&C	−21.518	4.269	0.000*	−30.250	−12.786
B	1&2	−2.715	3.236	0.408	−9.334	3.904	2	A&B	−34.240	3.543	0.000*	−41.487	−26.993
	1&3	−5.943	3.919	0.140	−13.957	2.071		A&C	−55.293	4.605	0.000*	−64.712	−45.874
	2&3	−3.228	3.598	0.377	−10.586	4.130		B&C	−21.053	5.176	0.000*	−31.639	−10.467
C	1&2	−2.250	4.716	0.637	−11.896	7.396	3	A&B	−30.717	2.934	0.000*	−36.717	−24.717
	1&3	−9.056	4.814	0.070	−18.901	0.789		A&C	−55.349	3.257	0.000*	−62.011	−48.686
	2&3	−6.807	3.522	0.063	−14.011	0.397		B&C	−24.632	3.875	0.000*	−32.557	−16.706

Analysis of paired comparison

Indicator	Paired comparison of markings						Paired comparison of distractions					
	Pairings	M.D.	S.E.	Sig.	95 % CI		Pairings	M.D.	S.E.	Sig.	95 % CI	
					Low	Up					Low	Up
PERCLOS	A&B	1.547	0.389	0.000*	0.751	2.342	1&2	0.816	0.169	0.000*	0.469	1.162
	A&C	3.244	0.411	0.000*	2.403	4.084	1&3	2.452	0.181	0.000*	2.082	2.822
	B&C	1.697	0.422	0.000*	0.834	2.560	2&3	1.636	0.177	0.000*	1.274	1.998
Beta value	A&B	−78.541	12.550	0.000*	−104.208	−52.875	1&2	−28.773	10.306	0.009*	−49.851	−7.694
	A&C	−108.899	18.350	0.000*	−146.428	−71.369	1&3	−85.826	13.482	0.000*	−113.400	−58.253
	B&C	−30.357	19.318	0.127	−69.867	9.152	2&3	−57.054	11.142	0.000*	−79.842	−34.266
Speed	A&B	7.399	1.150	0.000*	5.047	9.751	1&2	3.795	1.280	0.006*	1.177	6.414
	A&C	10.501	1.504	0.000*	7.425	13.576	1&3	5.564	1.385	0.000*	2.731	8.398
	B&C	3.101	1.230	0.017*	0.585	5.618	2&3	1.769	1.473	0.240	−1.244	4.782
AAA	A&B	0.047	0.040	0.247	−0.034	0.128	/					
	A&C	0.103	0.045	0.030*	0.010	0.195						
	B&C	0.056	0.034	0.114	−0.014	0.126						
Saccade frequency	A&B	−0.571	0.069	0.000*	−0.712	−0.431	1&2	−0.197	0.052	0.001*	−0.304	−0.090
	A&C	−1.007	0.063	0.000*	−1.137	−0.878	1&3	−0.401	0.063	0.000*	−0.529	−0.272
	B&C	−0.436	0.086	0.000*	−0.612	−0.260	2&3	−0.204	0.052	0.000*	–0.310	−0.098
α/β	A&B	0.342	0.043	0.000*	0.254	0.431	1&2	0.184	0.036	0.000*	0.111	0.258
	A&C	0.455	0.061	0.000*	0.331	0.580	1&3	0.386	0.035	0.000*	0.313	0.458
	B&C	0.113	0.047	0.024*	0.016	0.210	2&3	0.201	0.027	0.000*	0.145	0.258
Pupil area	A&B	−69.611	10.391	0.000*	−90.684	−48.359	1&2	−61.238	18.471	0.002*	−99.015	−23.460
	A&C	−89.541	12.198	0.000*	−114.489	−64.593	1&3	−70.334	20.769	0.002*	−112.811	−27.857
	B&C	−19.929	9.680	0.049*	−39.727	−0.132	2&3	−9.096	20.596	0.662	−51.219	33.027

In the above table, “markings” refers to deceleration marking variables, while “distraction” refers to distraction task variables. A, B, and C represent unmarked, transverse, and fishbone markings, respectively; 1, 2, and 3 represent cognitive, visual, and compound distractions, respectively. Additionally, “*” indicates significance in the “sig.” column.

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