



Research on driving behavior characteristics of older drivers based on drivers' behavior graphs analysis

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ABSTRACT

Considerable evidence suggests that the decline in physiological abilities prevalent in older drivers leads to a reduction in the visual and psychomotor functions required for safe driving. The purpose of this study is to further investigate the differences in driving behavior between older and younger drivers and to describe the change process of driving behavior. In this study, 19 younger and older drivers each were recruited for a driving simulation experiment that included five scenarios. Driving operation data, eye movement data, and physiological data of drivers in five conflict scenarios were collected. The differences in driving behaviors between the two groups were also compared and analyzed, on which the thresholds of different driving behavior nodes were determined and driving behavior graphs were established. The results show that the eye movement nodes of older drivers appear later in five scenarios, the operational nodes of older people appear later in two steering scenarios, and are closer to those of younger drivers in three straight ahead scenarios, indicating that older drivers were later in observing and collecting traffic information, and later in applying brakes and steering to avoid conflicts when steering. The study provides a reference for the analysis of driving behavior and driving safety of older people.

1. Introduction

At the beginning of the 21st century, China entered the stage of population aging and the population structure changed from young to old. By 2020, the population aged 65 and above was 190.64 million, accounting for 13.50%, and it is expected that the proportion of the population aged 65 and above will reach 24% by 2050. The problem of aging is global. From 2010 to 2030, the proportion of the United States population drivers aged 65 and older will increase from 13% to 20% [1]. Japan, the world's most aging country, accounts for 28.4% of the population over 65 by 2020, the highest level in the world [2].

With the increasing age of the population, various social problems caused by the aging process, such as traffic safety, need greater research attention. Historical trends show that from the age of 70, the number of traffic accidents reported by police per mile begins to increase [3], and crash severity and the expected costs of crashes significantly increase when age exceeds 75 [4]. In Japan, for example, about half of all motor vehicles accidents in 2018 occurred among old drivers aged 65 and older [5]. The safety of older drivers urgently needs to be ensured. With the acceleration of the aging process, China has abolished the age restriction of 70 for applying for a

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driver's license, providing older people individuals with alternative transportation options and thereby enhancing their quality of life [6]. Due to their reliance on vehicles during their younger years, they are hesitant to relinquish driving [7]. However, studies show that older drivers experience a gradual decline in their physical and mental state, as well as a reduced ability to recognize and respond to dangerous traffic situations, which leads to an increase in their traffic risk compared to younger drivers [8–10]. In terms of visual ability and responsiveness, the effectiveness of visual attention transfer decreases as older drivers experience more difficult tasks while driving [11]. Attentional distraction leads to an increase in errors in visually distracting driving operations [12]. Older drivers have lower frequency of saccade, lower gaze level, and lower visual abilities than younger drivers [13], resulting in limited traffic information available to older drivers by sight [14]. For older drivers, their driving risk is usually related to their reduced ability to cope with the inherent complexities of driving. The excess crash risk observed for older drivers (>74 years of age) are primarily associated with their more frequent risky driving behaviors and age-related loss of capabilities [15]. When it comes to comprehension and cognitive abilities, some older drivers need more time to understand information from traffic signs, which can lead to longer reaction times, less timely feedback, and increased risk of accidents. At the same time, some older drivers have weaker risk awareness than younger drivers [16], yet older drivers' assessment of their driving ability is significantly higher than their true situation [17], which prevents them from properly perceiving their driving abilities, and education and adoption of specific environments alone [18] do not improve driving safety, so it is necessary to study the driving behavior.

Currently, research on older drivers is focused on analyzing the direct relationship between certain behaviors and older drivers' driving ability, or on analyzing the relationship between various driving behaviors and driving ability in a comprehensive manner. However, currently there is a lack of research on how different driving behaviors influence the driving capabilities of older drivers over the course of time from the occurrence to the end of traffic conflicts. The driver's behavior graph can visualize the spatial and temporal changes of driver behavior trajectory by encoding driver behavior data and establishing association rules to realize the image description of the complex multidimensional behavior data characteristics of drivers in a particular situation. The graph can reveal the temporal and spatial changes in driving behavior and achieve a visual representation of changes in driving behavior. Chen et al. [19] first proposed the driving behavior graph theory, which is a comprehensive analysis of different driving behaviors at the same moment by using a graph (it is based on a driving habit graph (DHG) model highlighting the driving style of drivers), was constructed. Wu et al. [20] classified drivers according to their automobile fuel consumption and used a driving behavior graph to analyze drivers in different fuel consumption categories. Based on GPS data, Liu Chang [21] proposed a behavior risk assessment method under natural driving conditions based on information entropy, and constructed a graphical representation of individual driver behavior and visualized driving behavior risk characteristics. Qi [22] established a driving behavior graph based on micro-driving behavior indicators, classifying drivers into three categories: safety, general safety, and risk. Lavdim Halilaj [23] used knowledge graph and graph neural networks to categorize driving scenarios and demonstrate the effectiveness of this approach. Driving behavior data are characterized by high real time, poor stability, and continuous change, Qi and Zhao et al. [24] proposed the individual driving behavior graph construction method (DBGCM), which visually presents the time trajectory of driving behavior to explore safety–ecological (SAF-ECO) characteristics of individual drivers.

This study focuses on the use of driving behavior graph theory to construct characteristic graphs of drivers' eye movement behavior, psychophysiological behavior, driving operation behavior, and vehicle operation status under conflict situations, in order to accurately describe the change process of various behavioral characteristics of drivers under the constraints of conflict situations. The graph can not only be used to analyze the differences between two kinds of driver behavior processes in the same conflict situation, but can also provide the basis for the safety evaluation of driver behavior processes in conflict situations.

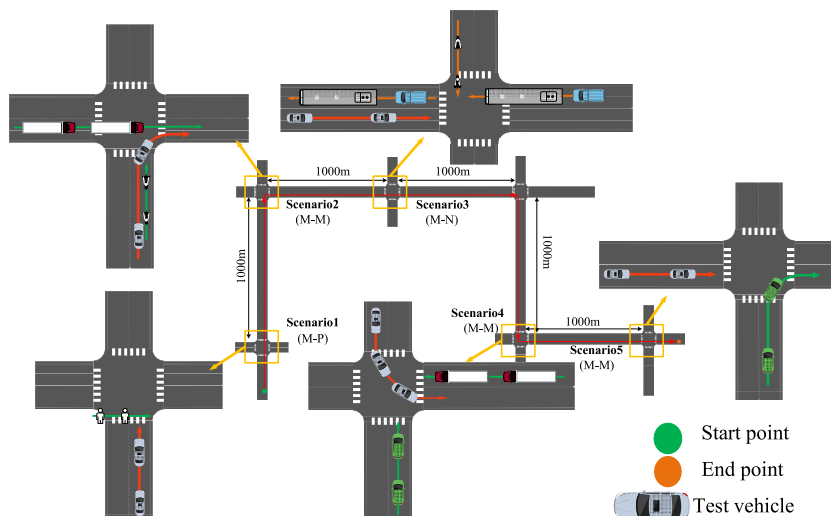


Fig. 1. Five conflict scenarios.

2. Experiment and methods

2.1. Driving simulation test

To study the changes of driving characteristics in conflict situations, the data of eye movement, psychophysiology, driving operation, and the vehicle operation of older drivers in different conflict situations were collected. The comparative analysis of the differences in behavioral indicators between older and younger drivers was conducted to determine the reasons for the differences and changes in the behavioral characteristics of older drivers.

2.1.1. Experimental design

The experimental scenario is designed using the VS-Design 3D scenario design software developed by the Traffic Engineering Faculty of the Kunming University of Technology. The experimental route contains six intersections, including three straight ahead intersections, one right-turn intersection and two left-turn intersections, with a route length of 6 km, where the red line indicates the experimental vehicle driving route, and there are different interfering vehicles and pedestrians in the intersections (Fig. 1 and Table 1 for specific scenarios information). Five intersections (including five different conflict types) were selected as the experimental scenarios. The test vehicle needs to follow the test route through the unsignalized intersection and complete the driving task of straight, right, and left crossing, respectively. Conflict situations include motor vehicles and pedestrians, direct conflicts between motor vehicles and non-motor vehicles, and conflicts between motor vehicles.

2.1.2. Experimental subjects and experimental equipment

In order to meeting the basic age requirements, the drivers recruited need to pass a cognitive impairment test, a basic vision test (no color blindness, color weakness, and a corrected visual acuity of at least 1.0), and complete the driving task normally without any physical discomfort, such as dizziness, when using the driving simulator. The older drivers recruited for this experiment were all retired, and considering the influence of driving experience on the experimental results, we required total driving mileage of more than 20,000 km and prohibited the recruitment of professional drivers to avoid the influence of professionally trained driving skills or habits on the experimental results. Recruitment details were disseminated through the official website, with participation in the experiment contingent upon voluntary registration. Prior to commencing the formal experiment, a brief preliminary assessment of participants' visual, cognitive and driving skills was conducted. Those who successfully cleared the assessment were deemed eligible to partake in the official experimentation process. To analyze the behavioral characteristics of older drivers in conflict situations, 19 older drivers (mean age 66 years, SD = 3.628, male 15, and female 4) were randomly recruited as a test sample; and 19 younger drivers (mean age 34, SD = 8.479, male 11, and female 8) were also recruited as a comparison test sample.

The main experimental equipment and related software used were the KMRTDS driving simulation platform, the ErgoLAB physiological instrument, iView ETG2W eye tracker, and the VS-Design three-dimensional traffic design software (Fig. 2 shows the experimental equipment), and the sampling rates of the driving simulation platform, the physiological instrument, and the eye tracker are 20 Hz, 1024 Hz, and 60 Hz, respectively. Eye movement data, psychophysiological data, driving operation data, and vehicle operation data were collected and compared in both groups of drivers in conflict situations.

2.1.3. Experimental procedure

The specific test procedure is as follows (Fig. 3 shows the experimental procedure):

- (1) Participants fill in the relevant basic information. The basic information form includes the subject's name, gender, driving age, driving mileage, etc;
- (2) Explain to the participants the specific operation of the driving simulator and related precautions, conduct pre-experiments to familiarize the participants with the driving simulator, and check the equipment for the experiments, and stop the pre-experiments after observing that the participants are adapted to the driving simulator and the equipment is working correctly;

Table 1

The details of five conflict scenarios.

Scenario	Driving Direction	Conflict Situation	Conflict Type
1	Straight	The test vehicle conflicted with pedestrians crossing the road from west to east when it drove straight into an unsignalized intersection from south to north.	M-P
2	Right-turning	The test vehicle drove from south to north and then turned right into the intersection and conflicted with a motor vehicle traveling straight from west to east.	M-M
3	Straight	When the road is full of vehicles on the left side, the test vehicle goes straight through the intersection and conflicts with non-motor vehicles traveling from north to south.	M-N
4	Left-turning	When the test vehicle turned left and passed an unsignalized intersection, it collided with the motor vehicle test in two straight directions (from west to east and from south to north).	M-M
5	Straight	The test vehicle drove straight through the intersection from west to east and conflicted with a right-turning motor vehicle entering the main lane.	M-M

Note: Mark motor vehicles, non-motor vehicles, and pedestrians as M, N, and P, respectively.

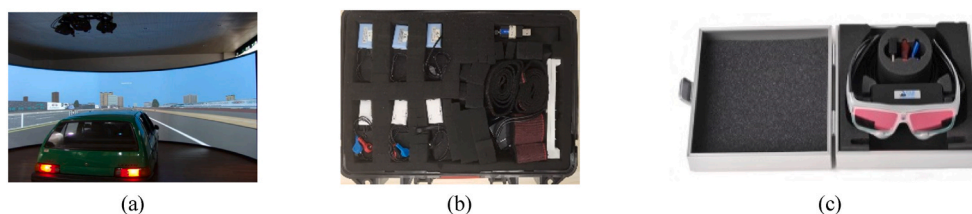


Fig. 2. Experimental equipment: (a) KMRTDS driving simulation platform; (b) ErgoLAB physiological instrument; and (c) iView ETG2W eye tracker.

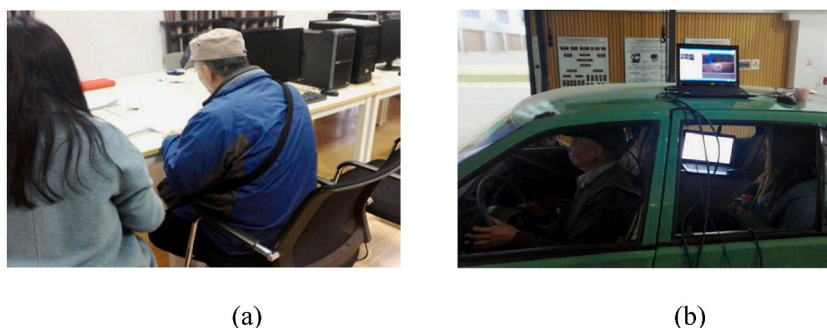


Fig. 3. Experimental procedure: (a) drivers fill in basic information; (b) driving simulation experiment.

- (3) The staff reads out the driving simulation experiment guidance: This experiment is a driving simulation test based on the behavioral characteristics of the drivers; there are five experimental scenarios, and you need to wear an eye-tracking device and a physiological instrument to complete the driving simulation tests on the driving simulator. In the driving process, try to keep your head stable, if you encounter unexpected situations, you should take emergency measures to ensure the safety of the vehicle, including changing the speed, parking brake, and changing the direction of travel and other measures. Please note that you must follow the prescribed lanes and routes during the driving process, do not drive into the opposite lane, and try to keep the speed at about 40 km/h when there is no unexpected situation;
- (4) The staff put on the physiological instruments and eye-tracking devices for the participants and performed debugging and calibration to check the data transmission;
- (5) The participants conducted driving simulation tests according to their daily driving habits and asked the participants to simulate driving in each experimental scenario in order. At the same time, the staff recorded the relevant data.

Participants are informed about the process and purpose of the experiment and the use of the experimental data, and agree to cooperate in conducting the experiment and participate in the follow-up study. All methods were performed in accordance with

Table 2
Analysis of gaze behavior indicators.

Experimental Scenario	Drivers	5s before Conflict Trigger		5s after Conflict Trigger	
		Number of Gaze (Times)	Gaze Duration (ms)	Number of Gaze (Times)	Gaze Duration (ms)
Scenario 1	Older	9.85	463.28	11.88	328.22
	Younger	11.33	342.73	14.67	250.80
	Sig.	0.192	0.032 ^a	0.015 ^a	0.102
Scenario 2	Older	12.14	357.83	10.09	402.66
	Younger	13.75	282.23	12.50	275.97
	Sig.	0.326	0.045 ^a	0.027 ^a	0.036 ^a
Scenario 3	Older	9.47	438.36	10.55	447.62
	Younger	10.67	393.85	12.67	303.25
	Sig.	0.354	0.143	0.052	0.029 ^a
Scenario 4	Older	10.57	347.77	11.15	327.99
	Younger	11.67	321.09	12.37	259.79
	Sig.	0.421	0.478	0.439	0.048 ^a
Scenario 5	Older	10.55	331.09	10.13	574.36
	Younger	12.42	281.73	12.25	265.19
	Sig.	0.137	0.051	0.112	0.017 ^a

^a Indicates significant difference at 0.05 level.

relevant guidelines and regulations, and all experimental protocols complied with the requirements of the Chinese National Science and Technology Ethics Committee.

2.2. Compare the behavioral differences between the two types of drivers

The data of 5 s each before and after the occurrence of the conflict, for a total of 10 s, were intercepted as the data source was used as a data source to analyze the driver behavior data collected in the test using an independent samples *t*-test to compare the behavioral differences between the two types of drivers.

2.2.1. Eye movement behavior

From the comparative analysis of gaze characteristics in Table 2, it was found that the differences in the number of gaze and gaze duration between the two groups of drivers in the 5 s before the conflict trigger were not significant; however, there were significant differences in the gaze duration between the two groups of drivers in the 5 s after the conflict trigger, and except for the conflict scenario 1, the other four scenarios reached significant differences in the gaze duration between the two groups of drivers in the 5 s after the conflict trigger, and within the five scenarios. In conflict scenarios, the average gaze time of the older group was greater than that of the younger group, which means that older drivers are less observant of road conditions than younger drivers when exposed to driving conflicts. This indicates that as the age of the drivers increases, the time required to observe lengthens and leads to an increase in reaction time, and the required safe stopping distance is longer when the vehicle travels at a certain velocity, thus increasing the possibility of traffic accidents.

The analysis of gaze characteristics shows that the difference between the two groups of drivers 5 s before the conflict trigger is not significant, so in the analysis of saccade characteristics, only the saccade indicators within 5 s after the trigger were analyzed, and Table 3 shows the results of the comparative analysis of the two groups of drivers' saccade amplitude and saccade velocity. The average saccade amplitude and velocity of the older drivers in five conflict scenarios were lower than those of the younger drivers. Compared to younger drivers, older drivers had a lower average saccade amplitude of 30.05%, 20.95%, 48.92%, 21.99%, and 16.01%, and a lower average saccade speed of 25.43%, 19.77%, 42.99%, 16.06%, and 14.73%, in five scenarios, respectively. This suggests that older drivers take more time to complete a saccade than younger drivers and are more likely to crash when a risk arises because the area covered by the saccade is smaller and less information is obtained.

2.2.2. Psychophysiological behavior

Changes in psychophysiological behavior can be used as an indirect indicator of the driver's state of tension, emotional changes, brain arousal, and level of alertness while driving; a 10 s data source was used to analyze the psychophysiological behavior of drivers. While the heart rate growth rate values of older people are generally lower than those of younger people under normal circumstances, in the case of conflict, the change in heart rate growth rate is just the opposite. Table 4 indicates that when driving in conflict scenarios, older drivers will experience more stress than younger drivers, which will result in stronger stress physiological behaviors and a rapid increase in heart rate, and the magnitude of heart rate increase for older drivers is greater than that of younger drivers. The mean value of electrodermal activity (EDA) indicates that the level of alertness of younger drivers during driving is always higher than that of older drivers, and that they can detect conflicts in advance, have sufficient time to cope, and are relatively less nervous, as shown by the lower growth rate of EDA than older drivers; the difference between the electromyography (EMG) indexes of older drivers and younger drivers is not significant, and the difference of EMG only exists in scenarios 4 and 5, so in this study, only the EMG signal is used as an auxiliary parameter.

2.2.3. Operation behavior

From Table 5, in five conflict scenarios, the earliest mean time for younger drivers to react to the conflict and apply the brake was more than 1 s earlier than that of the older drivers, but due to the different velocity of each driver when they encountered the conflict, the braking reaction times of the two groups were different. In addition, there were significant differences in the mean velocity, standard deviation of velocity, and lateral acceleration, but no significant difference in the maximum brake pedal depth between the two groups of drivers in five conflict scenarios. In three scenarios, the standard deviation of the velocity of the older drivers was higher than that of the younger drivers. The standard deviation of velocity is an index reflecting the dispersion of velocity, and the greater the dispersion, the lower the safety, indicating that the safety of the older drivers is lower in some conflict scenarios, but due to the limited

Table 3
Analysis of saccade behavior indicators.

Experimental Scenario	Saccade Amplitude SD (°)		Sig	Saccade Velocity SV (°/s)		Sig
	Older	Younger		Older	Younger	
Scenario 1	2.23	1.56	0.035 ^a	23.9	17.82	0.039 ^a
Scenario 2	2.17	1.58	0.045 ^a	23.73	19.00	0.049 ^a
Scenario 3	2.60	1.33	0.011 ^a	28.22	16.09	0.015 ^a
Scenario 4	3.26	2.54	0.048 ^a	30.87	25.91	0.051 ^a
Scenario 5	2.02	1.70	0.195	22.09	18.84	0.207

^a Indicates significant difference at 0.05 level.

Table 4
Analysis of physiological–psychological behavior indicators.

Behavior Indicators	Drivers	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Mean heart rate growth rate	Older	0.26	0.30	0.32	0.26	0.24
	Younger	0.23	0.25	0.25	0.23	0.19
	Sig.	0.107	0.039 ^a	0.045 ^a	0.245	0.026 ^a
Mean EDA growth rate	Older	0.33	0.43	0.62	0.42	0.57
	Younger	0.30	0.41	0.42	0.37	0.31
	Sig.	0.865	0.463	0.049 ^a	0.565	0.021 ^a
Mean EDA (μS)	Older	3.16	3.31	3.52	3.85	3.91
	Younger	7.90	8.29	8.75	8.61	8.36
	Sig.	0.004 **	0.003 **	0.003 **	0.003 **	0.004 **
Mean EMG (μS)	Older	42.16	49.13	52.19	62.21	63.63
	Younger	28.86	47.45	31.20	33.15	26.53
	Sig.	0.113	0.271	0.315	0.011 ^a	0.001 **

^a Indicates significant difference at 0.05 level, ** indicates significant difference at 0.01 level.

Table 5
Analysis of braking behavior indicators and vehicle movement indicators.

Experimental Scenario	Drivers	Earliest Braking Time(s)	Maximum Brake Pedal Depth	Mean Velocity (km/h)	SD of Vehicle Velocity (km/h)	Lateral Acceleration (m/s ²)
Scenario 1	Older	7.54	5.46	33.12	13.41	0.063
	Younger	6.38	5.09	24.82	12.80	0.088
	Sig.	0.200	0.560	0.013 *	0.440	0.035 *
Scenario 2	Older	6.67	3.61	19.50	6.14	0.66
	Younger	4.60	3.31	15.82	6.64	0.52
	Sig.	0.152	0.326	0.007 *	0.278	0.056
Scenario 3	Older	6.42	5.65	36.97	14.59	0.16
	Younger	4.36	7.27	34.97	10.95	0.06
	Sig.	0.083	0.458	0.007 **	0.000 **	0.018 *
Scenario 4	Older	6.00	4.84	20.05	6.46	0.24
	Younger	3.67	3.58	15.74	5.50	0.41
	Sig.	0.043 *	0.207	0.000 **	0.158	0.026 *
Scenario 5	Older	5.28	3.85	33.76	9.47	0.21
	Younger	3.00	4.41	30.17	12.16	0.06
	Sig.	0.194	0.704	0.215	0.015 *	0.013 *

Note: The maximum value of the simulator brake pedal opening in this study was 20, and the value when the brake pedal was pressed to the limit position was calibrated to 20; * indicates significant difference at 0.05 level, and ** indicates significant difference at 0.01 level.

number of scenarios and drivers in this research, this conclusion needs to be verified by further studies.

Since the conflict scenarios 2 and 4 in this driving simulation experiment are in conflict when turning right and left at the intersection, the normal operation of the drivers has steering behavior; thus, the study of steering stress operation behavior only considers the conflict scenarios 1, 3, and 5 for straight ahead.

According to the theory of steering wheel corner entropy [25], the corner entropy follows a normal distribution, an α value needs to be determined to divide the corner entropy into the following nine intervals:

$$(-\infty, -5\alpha], (-5\alpha, -2.5\alpha], (2.5\alpha, -\alpha], (-\alpha, -0.5\alpha], (-0.5\alpha, 0.5\alpha), [0.5\alpha, \alpha), [\alpha, 2.5\alpha), [2.5\alpha, 5\alpha), [5\alpha, \infty)$$

The value of α is determined by the following probability equation:

$$P\{-\alpha < x_i < \alpha\} = 90\% \tag{1}$$

Table 6
Analysis of steering behavior indicators.

Experimental Scenario	Drivers	Mean Wheel Corner Entropy Values	SD of Wheel Corner Entropy Values
Scenario 1	Older	0.20	0.19
	Younger	0.30	0.20
	Sig.	0.049 ^a	–
Scenario 3	Older	0.21	0.21
	Younger	0.45	0.16
	Sig.	0.002 **	–
Scenario 5	Older	0.30	0.21
	Younger	0.34	0.22
	Sig.	0.161	–

^a Indicates significant difference at 0.05 level, ** indicates significant difference at 0.01 level.

The distribution probability p_i for each interval is determined based on the frequency of the steering wheel corner values falling in each interval, and the steering wheel corner entropy value of the sample is determined by Equation (2).

$$H_p = - \sum_{i=1}^9 p_i \log_9 p_i \tag{2}$$

The statistical results of the mean and standard deviation of the steering wheel corner entropy values for the two groups of drivers in the conflict scenarios 1, 3, and 5 were calculated according to the above method and are shown in Table 6.

Table 6 shows that in the conflict scenarios 1, 3, and 5, the mean values of the steering wheel corner entropy of older drivers were lower than those of younger drivers, and in the conflict scenarios 1 and 3, there were significant differences in steering wheel corner entropy for both groups of drivers, indicating that more younger drivers implemented steering or brake plus steering maneuvers to avoid conflict.

To evaluate the safety of the physiological and driving behaviors of older drivers in conflict situations, it is necessary to analyze the differences of the physiological and driving behavior trajectory of younger and older drivers. Therefore, this study attempts to effectively describe the behavioral processes of drivers with significant differences in the above analysis using driving behavior graphs to demonstrate the integrated behavioral processes of eye movements, psychophysical, and driving maneuvers in conflict situations in a more vivid and visual way.

2.3. Establish drivers' behavior graphs

Data smoothing and noise reduction are carried out for all kinds of behavior index data in five conflict scenarios, dynamic thresholds T_u and T_d are calculated, the behavior node conflict scenario situations are identified, and drivers' behavior graphs are established.

2.3.1. Data processing and identify behavior nodes

Since the isolated noise data will affect the overall test results, to improve the accuracy of the test results, it is necessary to process noise reduction and smoothing processing on all kinds of raw data collected. The noise reduction and smoothing processing equation is shown in Equation (3).

$$x_i^s = (x_{i-1} + x_i + x_{i+1}) / 3 \tag{3}$$

where x_{i-1}, x_i, x_{i+1} represent the behavior index data collected in the $i - 1, i,$ and $i + 1$ three adjacent experiments; x_i^s represents the i -th behavior data value after noise reduction.










Based on the noise reduction data to determine the dynamic thresholds T_u and T_d of the driving behavior, the points whose behavioral indicators are greater than their corresponding dynamic thresholds T_u or less than their corresponding dynamic thresholds T_d are constructed as the corresponding behavioral nodes, indicating that the driver's behavioral trajectory changes at that point, as shown in Equations (4) to (7):

$$X_{max} = x_{max} - x_{min} \tag{4}$$

$$T_{10} = 10\% * X_{max} \tag{5}$$

$$T_u = m + \max (std, T_{10}) \tag{6}$$

Table 7
Driving behavior index parameters.

Type of Behavior	Behavioral Index	Symbol	Data Range	Node (Code)
Eye movement behavior	Gaze duration	F	59–6000 ms	
	Saccade amplitude	SD	0–150°	
	Saccade velocity	SV	0–500°/s	
Psychophysiological behavior	Heart rate growth rate	HR	0–2	
	EDA growth rate	DR	0–2	
Driving behavior	Brake pedal opening	B	0–20	
	Steering wheel angle	W	–720–720°	
Vehicle operation behavior	Velocity	V	0–150 km/h	
	Lateral acceleration	SA	–9.9 m/s ²	

$$T_d = m - \max(std, T_{10}) \tag{7}$$

where m is the mean value of the behavior index data after smoothing and noise reduction; and std is the standard deviation of the behavior index data after smoothing and noise reduction.

2.3.2. Construct drivers' behavior graphs

Based on the analysis of the driving behavior characteristics of young and old people, four behaviors (eye movement behavior, physiological and psychological behavior, driving behavior, and vehicle operation behavior) with five scenarios were selected to construct the graphs. Specific performance indicator parameters are shown in Table 7.

- (1) Establish a rectangular coordinate system: The X -axis represents the time and divides it equally according to 1 s; the Y -axis represents all kinds of behavior indicators of the drivers, and each behavior indicator is divided equally. The Y -axis contains nine indicators of four types of behavior. According to the various behavior nodes and the node occurrence time of the drivers obtained from the appeal analysis, mark the position of the node in the coordinate system and indicate the code and data of the node;
- (2) According to various behavior data obtained from driving simulation experiments in various conflict situations, calculate the behavior nodes of older and younger drivers within 15 s after the occurrence of the conflict are calculated, and compare them with the dynamic threshold T_u and T_d , determine the behavior node. Draw driving behavior trajectory graphs according to behavior nodes. Taking conflict situation 1 as an example, the calculation results of the behavior node discriminant parameters in each conflict scenario are shown in Table 8.

2.3.3. Calculating the similarity between the two types of drivers

Using the longest common sub-sequence distance (LCSS) algorithm, the difference between the behavioral trajectories of the two types of drivers is quantitatively analyzed, and the degree of similarity between the trajectories is expressed by a measure of the length of the longest subsequence. Equation (8) is shown below.

$$LCSS(R, S) = \begin{cases} 0 & \text{if } m = 0 \text{ or } n = 0 \\ LCSS(Rest(R), Rest(S)) + 1 & \text{if } |r_{1,x} - s_{1,x}| \leq \delta \text{ and } |r_{1,y} - s_{1,y}| \leq \epsilon \\ \max\{LCSS(Rest(R), S), LCSS(R, Rest(S))\} & \text{other} \end{cases} \tag{8}$$

Among them,

$LCSS(R, S)$ is the length between the behavior trajectory and the interval; m, n is the number of nodes of the behavior trajectory R and S ;

$Rest(R)$ and $Rest(S)$ are trajectory sequences of the trajectory R and the trajectory S after removing the first node; δ is the X -axis similarity threshold (the similarity threshold when the node occurs); and ϵ is the Y -axis similarity threshold (the similarity threshold of various behavior values of nodes).

In this research, the threshold δ is set to 1; that is, when the time difference between the occurrence time of two types of drivers for the same behavior node is 1 s, it is considered that the two nodes of this type of behavior are similar on the time axis; the threshold ϵ is set to $\min(r_{1,y}, s_{1,y}) * 0.3$, which means that when the difference of the same behavior of two types of drivers is less than 30% of the value of the smaller behavior, the two nodes of this type of behavior are considered to be similar in value.

Table 8

Calculation results of discriminant parameters for behavior indicators node construction in the first conflict scenario.

Driver Type	Behavior Index	After Smooth Noise Reduction		T10	T_u	T_d
		std	X_{max}			
Older drivers	Gaze duration (ms)	267.36	979.00	97.90	802.51	267.79
	Saccade amplitude (°)	0.76	3.00	0.30	1.96	0.44
	Saccade velocity (°/s)	7.87	28.70	2.87	23.80	8.06
	Heart rate growth rate (%)	2.60	8.30	0.83	16.60	11.40
	EDA growth rate (%)	12.00	6.10	0.61	14.20	11.80
	Brake pedal opening	1.08	4.21	0.42	1.59	-0.57
	Steering wheel angle	2.75	8.8	0.88	5.99	0.49
	Velocity (km/h)	12.74	39.8	3.98	45.86	20.42
Younger drivers	Lateral Acceleration (m/s ²)	0.056	0.22	0.02	0.119	0.007
	Gaze duration (ms)	200.43	1079	107.9	547.66	146.8
	Saccade amplitude (°)	1.06	3.6	0.36	2.47	0.35
	Saccadic velocity (°/s)	9.56	45.6	4.56	26.58	7.46
	Heart rate growth rate (%)	8.34	21.65	2.17	18.68	2.00
	EDA growth rate (%)	2.88	10.38	1.04	18.41	2.65
	Brake pedal opening	3.26	13.35	1.35	4.57	-1.94
	Steering wheel angle	6.63	22.171	2.217	12.76	-0.50
	Velocity (km/h)	12.82	44.375	4.44	41.68	16.04
	Lateral Acceleration (m/s ²)	0.107	0.36	0.04	0.20	-0.02

When the two points on the trajectories R and S of two drivers meet the similarity threshold condition, the trajectory points are similar, and the value of $LCSS(R, S)$ is increased by 1; otherwise, the value of $LCSS(R, S)$ remains unchanged.

Given that R and S are arbitrary behavior trajectories, it can be seen from Equation (8) that for behavior trajectories R and S , the value of the similarity discrimination index $LCSS(R, S)$ is between 0 and 1, and the similarity discrimination index $LCSS(R, S)$ is inversely proportional to the trajectory similarity. The larger the value of $LCSS(R, S)$, the smaller the similarity, and the greater the difference.

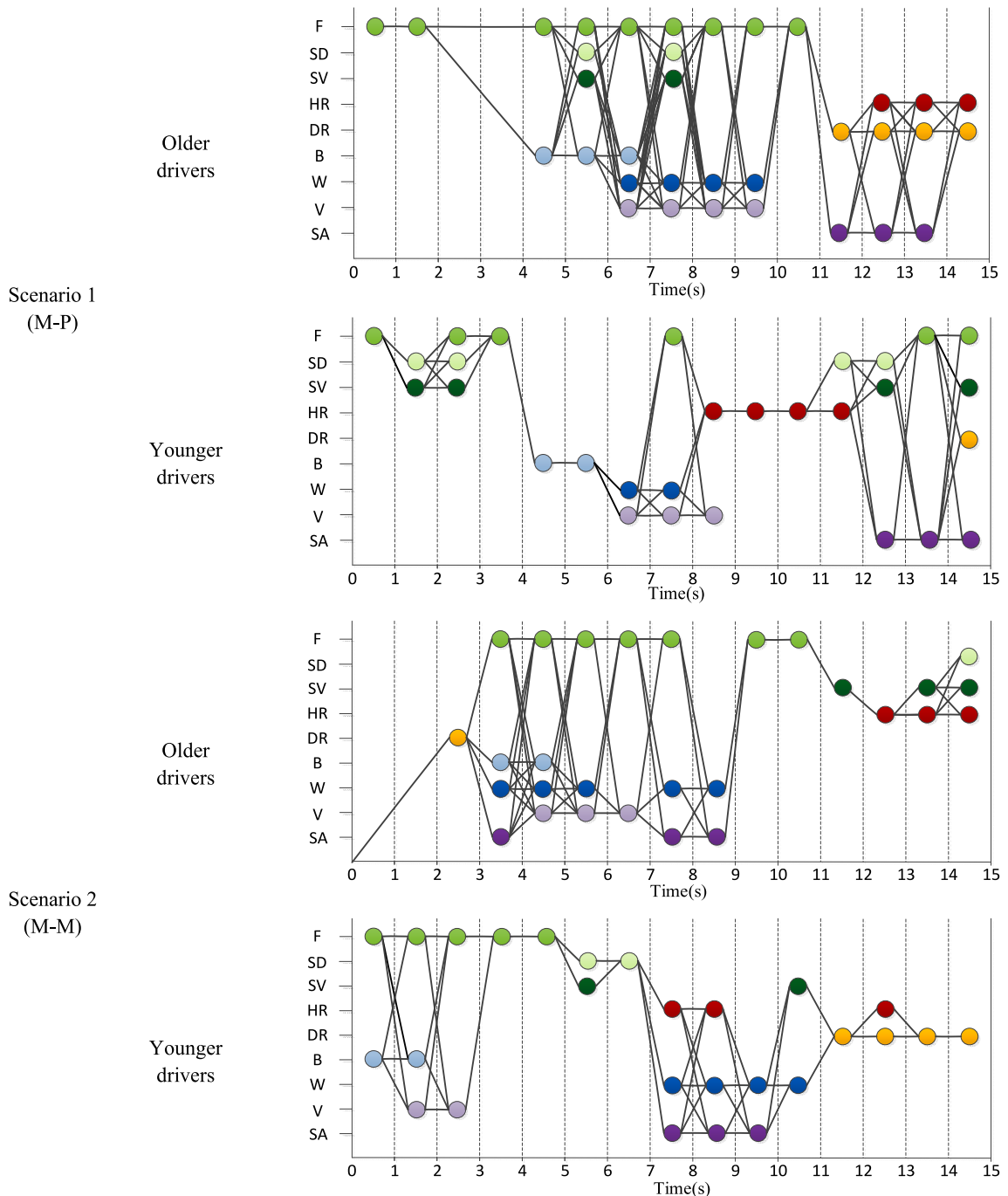


Fig. 4. The driving behavior graph of various drivers in various conflict scenarios.

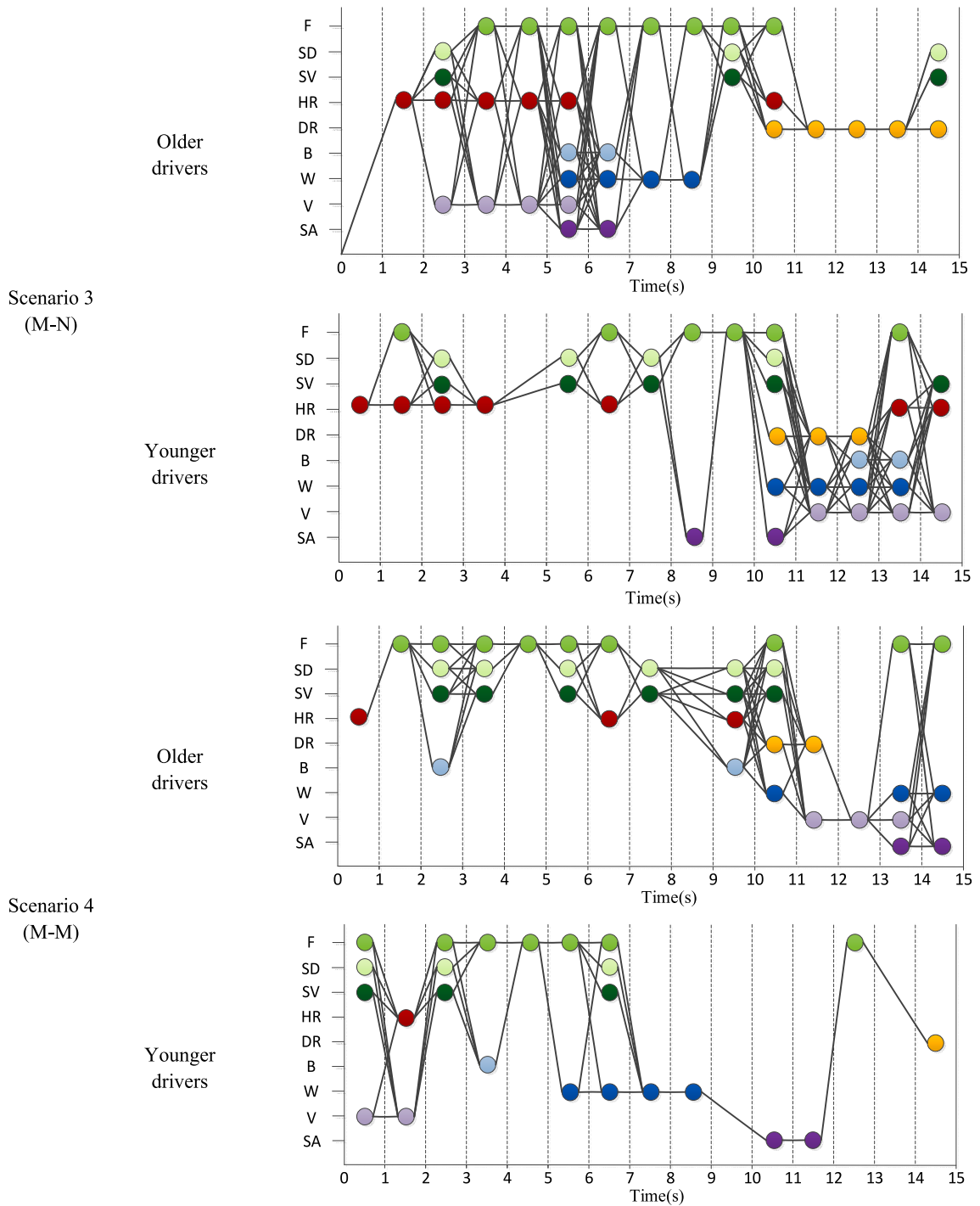


Fig. 4. (continued).

3. Results

3.1. Analysis of various drivers' behavior graphs

Based on the dynamic threshold T_u and T_d , the driving behavior graphs in the corresponding conflict scenarios are established, and the results are shown in Fig. 4.

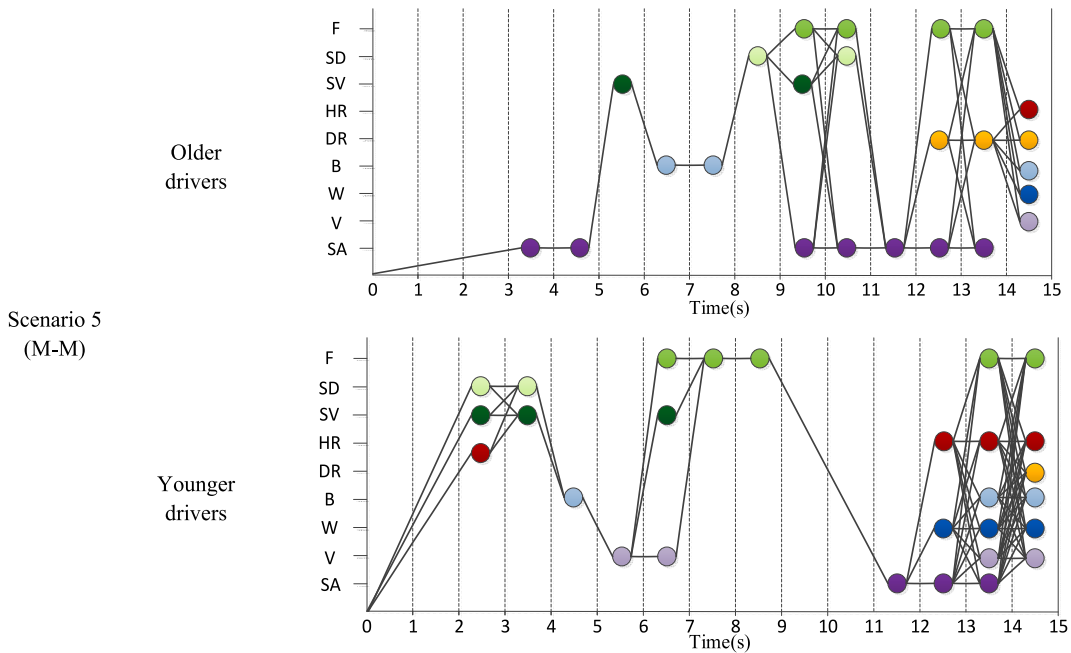


Fig. 4. (continued).

- (1) In the three straight ahead conflict situations of scenarios 1, 3, and 5, the nodes of change in saccade velocity and magnitude for young drivers appear ahead of older drivers in terms of eye movements, indicating that older drivers are less able to collect traffic information than younger drivers when entering intersections; in terms of driving operation behavior, the two drivers had similar driving behavior when exposed with the same conflict situation, but the resulting changes in lateral acceleration and vehicle velocity were different because the two types of driver had different steering and braking efforts; in terms of psychophysiology, the heart rate growth rate node of older drivers occurred earlier than that of younger drivers, but the nodes of both heart rate growth rate and electrodermal growth rate of both drivers occurred after the operation behavior node, indicating that the psychological changes of drivers occurred after the operation behavior of driving, and it is also worth noting that older drivers are more likely to experience psychological changes when they have conflicts with pedestrians crossing the road, and they feel more stress than younger drivers under the traffic conditions of mixed non-motorized and motorized vehicles;
- (2) In scenario 2 (right turn through intersection) and scenario 4 (left turn through intersection), the drivers' eye-movement behaviors were similar to those when going straight through the intersection, but there were larger gaps in vehicle operation and psychophysiological characteristics. When drivers turned into the intersection, the appearance of the braking node was later for older drivers, but the appearance of the steering behavior node was earlier for older drivers than younger drivers, and the time interval between braking and steering behavior nodes is shorter than that of younger drivers, and they are more nervous than younger drivers during the whole steering process, in which the difference between the left-turn behavior and the psychological changes of younger drivers is most obvious.

3.2. Analysis of the similarity of the behavior of the two types of drivers

According to the principle of LCSS calculation, the $LCSS(R, S)$ value is shown in Table 9.

According to the data in Table 9, it can be seen that both types of drivers have larger values in all five conflict situations, scenarios 1, 3, and 5 are straight through the intersection, and the $LCSS(R, S)$ are relatively close, indicating that in these three scenarios, older drivers and younger drivers show a similar degree of $LCSS(R, S)$. The $LCSS(R, S)$ is largest in the left turn through the intersection with 0.92, and smallest in the right turn through the intersection with an $LCSS(R, S)$ of 0.78, which indicates the greatest difference in the left-turn conflict case and the least variation in the right-turn conflict. With more conflict points, a larger turning radius and longer turning time in the left-turn scenario, older drivers are prone to emotional tension when encountering conflict situations during the turn, resulting in weaker information acquisition and processing and reaction ability than younger drivers; while with fewer conflict points, smaller turning radius, and shorter turning time in the right-turn scenario, older drivers can complete the right turn with their driving experience, resulting in a small difference.

4. Discussion

The purpose of this research is to analyze the impact of aging on driving behavior. We use the graph theory to draw the driver's

Table 9
Similarity indicator D_{LCSS} value of two kinds of drivers' behavior trajectories in five conflict scenarios.

Conflict Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
$LCSS(R,S)$	0.81	0.78	0.80	0.92	0.83

behavior graphs, describe the time and space changes of drivers' behavior in micro, and analyze the behavior differences between older drivers and younger drivers when facing five different traffic conflicts. The contribution of this research is to propose a graph method to analyze the driver's behavior. This method can consider the changes of a driver's eye movement behavior, operation behavior, physiological and psychological behavior, and vehicle operation status in time and space at the same time, and can more comprehensively analyze a driver's behavior; it can be found from the graphs analysis that there is a large difference in eye movement behavior between older drivers and younger drivers, and older drivers use eye movements to obtain road traffic information as quickly as younger drivers.

Based on the calculation results of the longest common sub-sequence distance (LCSS) algorithm, this research quantitatively analyzes the differences between the two types of drivers. The analysis results show that the differences between the various behavior trajectories of the two types of drivers are large, especially in Scenario 4: when turning left to cross the intersection, the two types of drivers show the largest differences.

Overall, the difference between older and younger drivers was mainly in eye movements, which is consistent with previous research, which found that older drivers tend to have more visual exploration to compensate for their visual field decline [26]. Through the graph's analysis, it is found that the eye movement behavior node of the older driver appears later than that of the younger drivers, especially the saccade behavior. The node appears relatively late and has a small value, indicating that the older driver searches for traffic information later and slower. This indicates that compared with the younger drivers, the older drivers have difficulty obtaining road traffic information through eye movement behavior. When the road traffic conditions are complex, older people need more eye movement behaviors to help them drive safely. For example, in Scenario 4, older drivers will have more frequent eye movement behaviors during vehicle operations when turning left to cross the intersection. In previous research, some scholars explained the decline of older drivers' visual ability and found that young drivers are more likely to use eye movement to track moving objects, and the older drivers pay more attention to the road signs and markings, which is the main reason for the difference between the two types of people's eye movement behavior [27].

It is worth noting that due to the decline of the visual ability of the older driver, there is a difference between the driving behavior of the subsequent older driver and the younger drivers. Through the graph analysis, it can be found that when turning at the intersection, the younger drivers have more continuous steering control nodes, the braking nodes appear earlier and last shorter, and the speed change is smoother. This finding is similar to Hong's conclusion. Their research found that older drivers are more susceptible to complex environments when approaching intersections, and the older drivers maintain faster driving speed before parking, and have a larger and more frequent braking behavior [28].

Generally speaking, the driver's behavior process is a process of eye movement, operational response, vehicle response, and psychophysiological changes. However, older drivers tend to have physiological behavior nodes in front of or behind eye movement behavior nodes and operation behavior nodes, and the growth rate of heart rate and EDA will increase. Takahashi et al. [29] studied drivers' EDA and skin potential reflex (SPR) and found that the higher the value of physiological indicators, the greater the risk drivers perceive, Kim et al. [30] believed that changes in physiological behavior can prepare drivers for perceived risk. Through the graph, we found that older drivers more frequently had physiological behavior nodes, indicating that the greater the perceived risk of older people in the same scenario, the more dangerous the driving process.

5. Conclusions

Due to the decline in physical function caused by age, older drivers have difficulty identifying and avoiding traffic conflicts in an accurate and timely matter compared to younger drivers. In this study, based on the driving simulation experiment in conflict situations, various behavior data were obtained, and the behavior trajectories of two types of drivers in five conflict situations were constructed using graph theory. It vividly shows the spatio-temporal change process of various driver behavior characteristics in conflict situations. This research analyzes the difference between the behavior track of the older drivers and that of the younger drivers by using the graphs method, which provides a theoretical basis and analysis method for studying the driving behavior and driving safety of the older drivers. The behavior graph can intuitively show the driving characteristics of different types of drivers under different conflict conditions, can reflect the time and space changes of drivers' behaviors when facing traffic conflicts, and can intuitively obtain whether different driving behaviors occur at the same time, as well as the emergence and duration of different driving behaviors. Through these graphs, the changes of driving behavior of the older drivers in dealing with conflicts can be analyzed microscopically, which can provide support for the safety research of driving behavior of the older drivers and the reliability research of human beings, making the research results more realistic. However, the current research lacks discussion on gender differences among older drivers, and is constrained by the limited number of participants in the driving simulation experiment. As a result, further investigations are necessary to delve deeper into the research findings. Subsequent studies will utilize naturalistic driving experiments to enhance the outcomes of the research and analyze the variations in driving behavior among older individuals of different genders when faced with traffic conflicts.

Author contribution statement

Jingyang Li: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
 Fengxiang Guo: Conceived and designed the experiments; Wrote the paper.
 Wei Li: Bijiang Tian: Performed the experiments; Contributed reagents, materials, analysis tools or data.
 Zheng Chen: Sirou Qu: Analyzed and interpreted the data.

Data availability statement

The authors do not have permission to share data.

Additional information

No additional information is available for this paper.

Founding

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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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References

- [1] J.M. Ortman, V.A. Velkoff, H. Hogan, *An Aging Nation: the Older Population in the United States*, Current Population Reports, Census Bureau, Washington, DC, USA, 2014, pp. 25–1140.
- [2] United Nations, *World Population Prospect*, United Nations, New York, NY, USA, 2019.
- [3] J.B. Cicchino, A.T. McCart, Trends in older driver crash involvement rates and survivability in the United States: an update, *Accid. Anal. Prev.* 72 (2014) 44–54.
- [4] M. Ayuso, R. Sánchez, M. Santolino, Does longevity impact the severity of traffic crashes? A comparative study of young-older and old-older drivers, *J. Saf. Res.* 73 (2020) 37–46.
- [5] National Police Agency Bureau of Traffic, *Heisei 30 Nen Koutsu Jiko Tokei Nenpo [Accidents Report in 2018]*, National Police Agency Bureau of Traffic: Tokyo, Japan, 2018.
- [6] L. Chen, C. Yang, P. Jing, et al., Are they willing to switch from non-driving to driving? An exploratory study among Chinese older people, *J. Trans.* 50 (2023) 1125–1163.
- [7] A. Ahern, J. Hine, Rural transport—Valuing the mobility of older people, *Res. Transport. Econ.* 34 (2012) 27–34.
- [8] G. Feng-xiang, X. Chang-an, W. Hua-sen, N. Ding-an, Z. Yan-ning, Behavioral characteristics of older drivers based on risk perception, *China J. Highw. Transp.* 34 (2021) 309.
- [9] L.A. Fraade-Blanar, B.E. Ebel, E.B. Larson, J.M. Sears, H.J. Thompson, K.C.G. Chan, P.K. Crane, Cognitive decline and older driver crash risk, *J. Am. Geriatr. Soc.* 66 (2018) 1075–1081.
- [10] S. Doroudgar, H.M. Chuang, P.J. Perry, K. Thomas, K. Bohnert, J. Canedo, Driving performance comparing older versus younger drivers, *Traffic Inj. Prev.* 18 (2017) 41–46.
- [11] M.P. Biernacki, R. Lewkowicz, How do older drivers perceive visual information under increasing cognitive load? Significance of personality on-road safety, *Accid. Anal. Prev.* 157 (2021), 106186.
- [12] M. Karthaus, E. Wascher, S. Getzmann, Distraction in the driving simulator: an event-related potential (ERP) study with young, middle-aged, and older drivers, *Saf. Now.* 7 (2021) 36.
- [13] G. Ziv, R. Lidor, The effect of age on gaze behavior in drivers and pedestrians—a review, *J. Eye Mov. Res.* 9 (2016) 1–13.
- [14] T. Falkmer, H. Lee, Investigating the spatial pattern of older driver's eye fixation behaviour and associations with their visual capacity, *J. Eye Mov. Res.* 9 (2016).
- [15] K. Gomes-Franco, M. Rivera-Izquierdo, L.M. Martín-delosReyes, E. Jiménez-Mejías, V. Martínez-Ruiz, Explaining the as-association between driver's age and the risk of causing a road crash through mediation analysis, *Int. J. Environ. Res. Publ. Health* 17 (2020) 9041.
- [16] J. Son, M. Park, The effects of distraction type and difficulty on older drivers' performance and behaviour: visual vs. cognitive, *Int. J. Automot. Technol.* 22 (2021) 97–108.
- [17] R. Kosuge, K. Okamura, Y. Nakano, G. Fujita, Characteristics of driving self-assessments and factors related to inaccurate self-assessment in Japanese older adults, *Accid. Anal. Prev.* 159 (2021), 106235.
- [18] B.A. Fausto, P.F.A. Maldonado, L.A. Ross, M. Lavallière, J.D. Edwards, A systematic review and meta-analysis of older driver interventions, *Accid. Anal. Prev.* 149 (2021), 105852.
- [19] S.-W. Chen, C.-Y. Fang, C.-T. Tien, Driving behaviour modelling system based on graph construction, *Transport. Res. C Emerg. Technol.* 26 (2013) 314–330.
- [20] Y. Wu, X. Zhao, C. Chen, Y. Yao, Research on eco-driving behavior characteristics identification and feedback optimization method, *J. Transport. Eng.* 17 (2017) 1–6.

- [21] L. Chang, Q. Hang, C. Chen, Graph expression method based on risk characteristics of safe driving behavior, *Traffic Eng.* 19 (2019) 13–18.
- [22] H. Qi, X.-H. Zhao, Y.-P. Wu, C. Liu, A graph based security description method of driving behavior characteristics, in: *Proceedings of the 20th COTA International Conference of Transportation Professionals, CICTP, Xi'an, China, 2020*, pp. 4254–4265. August 14–16 2020.
- [23] L. Halilaj, I. Dindorkar, J. Lüttin, S. Rothermel, A knowledge graph-based approach for situation comprehension in driving scenarios, in: *Proceedings of the European Semantic Web Conference, Virtual Event, 6–10 June 2021*.
- [24] H. Qi, X. Zhao, Y. Wu, Y. Ding, Y. Bian, Graph method for driving behavior optimization based on “SAF-ECO” description of behavior characteristics, *J. Transport. Saf. Secur.* (2022) 1–24.
- [25] O. Nakayama, T. Futami, T. Nakamura, E.R. Boer, Development of a steering entropy method for evaluating driver workload, *SAE Trans.* 108 (1999) 1686–1695.
- [26] M. Ranchet, R. Brémond, P. Pala, M. Colomb, V. Cavallo, The detection of vulnerable road users by younger and older drivers, *Transport. Res. F Traffic Psychol. Behav.* 91 (2022) 357–367.
- [27] T. Dukic, T. Broberg, Older drivers' visual search behaviour at intersections, *Transport. Res. F Traffic Psychol. Behav.* 15 (2012) 462–470.
- [28] S. Hong, B. Min, S. Doi, K. Suzuki, Approaching and stopping behaviors to the intersections of aged drivers compared with young drivers, *Int. J. Ind. Ergon.* 54 (2016) 32–41.
- [29] R. Takahashi, M. Kobayashi, T. Sasaki, Y. Yokokawa, H. Momose, T. Ohhashi, Driving simulation test for evaluating hazard perception: older driver response characteristics, *Transport. Res. F Traffic Psychol. Behav.* 49 (2017) 257–270.
- [30] B.S. Kim, Y.C. Yi, H.W. Kim, D.H. Lim, M.S. Bak, D.H. Ji, Y.K. Min, The characteristics of elderly drivers' driving behavior on intersection using graphic driving simulator, *J. Ergon. Soc. Korea* 29 (2010) 611–617.