International Journal of Vehicle Design

ISSN online: 1741-5314 - ISSN print: 0143-3369
https://www.inderscience.com/ijvd

How does AR-HUD system affect driving behaviour? Evidence from an eye-tracking experiment study

Cheng Yunuo, Zhong Xia, Tian Liwei

DOI: 10.1504/IJVD.2023.10056084

Article History:

Received:	04 July 2022
Last revised:	27 March 2023
Accepted:	29 March 2023
Published online:	04 September 2023

How does AR-HUD system affect driving behaviour? Evidence from an eye-tracking experiment study

Cheng Yunuo* and Zhong Xia

School of Architecture and Design,
China University of Mining and Technology,
Xuzhou, Jinagsu, 221116, China
Email: 17788376920@163.com
Email: 873426189@qq.com
*Corresponding author

Tian Liwei

Intelligent Research Institute,
Changan Automobile Group Co., Ltd.,
Chongqing, 401133, China
Email: brucetian@tinnove.com.cn

Abstract: In response to the issue of whether the AR-HUD system can effectively manage information complexity and improve driving safety, this article applied a driving simulator to experimentally measure the response ability of participants to risks in five risky driving scenarios. The experiment results showed that the augmented reality head-up display (AR-HUD) system can significantly improve the subjects' attention to risky dynamic areas of interest (AOI) in night driving situations, as well as reduce the difficulty of processing information in risky driving scenarios, thus reducing cognitive load. In terms of reaction time, the AR-HUD system can significantly reduce the driver perception time for risk driving scenarios and thus they can respond more quickly to high-risk situations. The experimental conclusions validate the role of AR-HUD technology in improving driving safety and driving behaviour and provide a new direction for further development of in-vehicle information systems (IVIS).

Keywords: augmented reality; head-up displays; driving behaviour; risk driving; eye movement; dynamic area of interest; driving simulator; human-machine interface; human factor.

Reference to this paper should be made as follows: Yunuo, C., Xia, Z. and Liwei, T. (2023) 'How does AR-HUD system affect driving behaviour? Evidence from an eye-tracking experiment study', *Int. J. Vehicle Design*, Vol. 92, No. 1, pp.1–21.

Biographical notes: Cheng Yunuo received his BS in Industrial Design from China University of Mining and Technology in 2020, where he is currently working toward the MS in Design. He is also doing an internship at Changan Automotive Intelligence Research Institute. His research interests include automotive HMI design, human factor, and design optimisation.

Zhong Xia is a Professor of School of Architecture and Design. Her research fields are design strategy and sustainable design.

Tian Liwei is an Automobile Engineer at Intelligent Research Institute of Changan Automobile Group Co., Ltd.

1 Introduction

Information technologies, represented by the internet and communication technologies, have a profound impact on the social basis and life forms of human beings (Venkatesh, 2003). As an important area and a direction to penetrate the mobile internet, the automobile will become the main area of digitisation in the future. A large number of in-vehicle information systems (IVIS), such as mobile phones, satellite radios, and in-vehicle applications are constantly pouring into the car, and the IVIS has developed from the early basic driving information into a multidimensional interaction system (Tan et al., 2015; Liang et al., 2007). Under this system, some driving tasks that are not directly related to driving or even not relevant occupy the driver's cognitive resources to varying degrees, resulting in distracted driving (Patten et al., 2004; Dong et al., 2011). According to National Highway Traffic Safety Administration (NHTSA) accident statistics, over 18% of injuries and 9% of fatalities in 2010 were attributable to driver distraction (NHTSA, 2010). While driving, in addition to performing the main driving task, drivers also perform many things which are not relevant to the main tasks (Ma and Kaber, 2005; Liu et al., 2017). However, given the limited cognitive resources, it is difficult for drivers to effectively allocate attention between tasks (Cooper et al., 2013; Castro et al., 2019; Ma et al., 2020). Therefore, in such a complex information system, how to manage the complexity of the IVIS effectively and further improve driving safety is a key problem that needs to solve urgently in the current IVIS.

The all-over display represents an important symbol in the digitisation and computerisation of the future automobile. In particular, 80% of driving information is visually perceived (Schewe and Vollrath, 2020), making visual support the top priority of the assisted driving system. The head-up display (HUD), as a visual assistive technology, has garnered considerable attention in recent decades (Wang and Qin, 2014). From the perspective of the display technique, HUD will gradually substitute part of the functions of the instrument panel to minimise the deviation of the driver's sight from the road ahead due to looking down at the instrument (Liu and Wen, 2008; Medenica et al., 2011). The content of the HUD system is mostly based on driver information. In addition, some secondary task information, such as music, telephone calls, etc., will also be displayed in the non-significant section of the HUD. The emergence of HUD minimises driver distraction from reading vehicle information while driving (Ward and Parkes, 1994; Grandi et al., 2022; Choi et al., 2002). As the HUD is positioned in the driver's field of view (FOV), it is preferable to reduce the occupation of visual, motive, and cognitive resources. Some research (Gibbered et al., 2013; Wang et al., 2016; Alice et al., 2022) indicates that HUD technology can reduce vehicular collisions by 25%. Augmented reality (AR) is a new type of human-computer interaction (HCI) technology based on virtual reality (Wu and Zhang, 2012; Fröhlich et al., 2010). The combination of AR and HUD technology allows vehicles to simultaneously transport natural and man-made displays. It superimposes virtual information such as road conditions, navigation, and non-geometrical information of real objects (e.g., pedestrians crossing the road) on real driving scenes (Smith et al., 2017; Lee et al., 2009). Due to its characteristics of combining virtual and real, and real-time interaction, it has played a strong driving role in the development of future vehicle-assisted driving in-vehicle entertainment and navigation (Choi et al., 2013; Hwang et al., 2015).

Over the past few years, the implementation of AR technology in IVIS has become a hot topic of research for large automotive companies. Researchers have carried out numerous experiments on driving assistance systems based on AR and HUD technologies, and have obtained many results. Park and Kim (2014) developed a vehicle-mounted AR-HUD system that can identify and project traffic safety information into the driver's FOV. The recognition rate of driver safety information can be up to 73%, and the recognition speed can be up to 15 fps. Yoon et al. (2014) proposed a pre-collision warning system that combines AR technology and HUD. The system detects vehicles and pedestrians ahead, judges dangerous driving situations based on the detection results and uses AR technology demonstrations to warn drivers. Bark et al. (2015) proposed an AR-HUD navigation assistance system design interface. By comparing the driver's reaction time in two situations with and without AR, the experiment result showed the AR-HUD navigation system can help the driver respond to the turning position faster. Lee et al. (2015) summarised the problems of vehicle AR-HUD systems in display equipment, target recognition equipment, information organisation and visual design methods, and experimental methods. Kim et al. (2016) used HUD to design a new pedestrian detection interface, and the virtual shadow of the pedestrian was covered by the front windshield in the driver's FOV. The results showed that applying the system interface resulted in better driving performance and smoother braking behaviour. Hwang et al. (2016) tested the impact of the AR-HUD system on the driver's risky-response ability and the driver's psychological change. Kim and Hwang (2017) verified through experiments whether the AR-HUD system can effectively improve driving safety and whether the visual symbols covered in the real driving environment will interfere with driving vision. Zhang (2015) used various methods of ergonomics and design psychology to explore the design of the visual interface of the HUD system to improve the driver's cognitive load and driving safety.

A comprehensive analysis of the research status found that there are two main aspects to the application of AR and HUD technology to IVIS:

1. Apply AR and HUD technology to the forward-collision warning system, project the detected information of obstacles such as pedestrians and vehicles on the front windshield, and combine with the real driving environment to improve the driver's situation awareness of risky driving ability;
2. Apply AR and HUD technologies to the vehicle navigation system, and the visual navigation information is directly covered in the road environment to improve the intuitive and easy-to-read navigation system.

Most research experiments are designed to evaluate the effectiveness of the proposed prototype system by comparing driving performance in different driving situations.

However, there is a lack of further discussion on the impact of the AR-HUD system on improving driving distraction and the cognitive and decision-making process in dealing with risky driving situations. Therefore, the main purpose of this paper is to investigate the influence of the AR-HUD system on driving behaviour. In this paper, a simulated driving experiment was conducted to investigate the impact of the AR-HUD system on driving behaviour, and we demonstrated a comparison between the AR-HUD group and the control group (without AR-HUD). The results of this comparison showed that AR-HUD technology plays a vital role in enhancing driving safety and driving behaviour, which is conducive to solving the current problems faced by IVIS, and provided a new direction for the future interface design of the AR-HUD system.

2 Method

2.1 Participants

Due to differences in gender, age, driving experience, and operating habits, etc., the acceptance of the AR-HUD system differs accordingly. In general, younger drivers are more interested in using intelligent assisted driving systems, while older drivers are more concerned about driving safety and stability. At the same time, the driver's mental state will also affect his driving behaviour.

The subjects were 30 drivers who volunteered to participate in Changan Automobile R&D Centre, including 20 males and 10 females, aged 21–52 years old, including novice drivers and professional test drivers, as shown in Table 1. All assigned subjects were healthy and mentally fit, vision (including corrected) is normal, and no achromatopsia or tritanopia. This experiment was authorised by the Safety Department and the Intelligent Research Institute of Changan Automobile Company.

Table 1 Basic information about participants

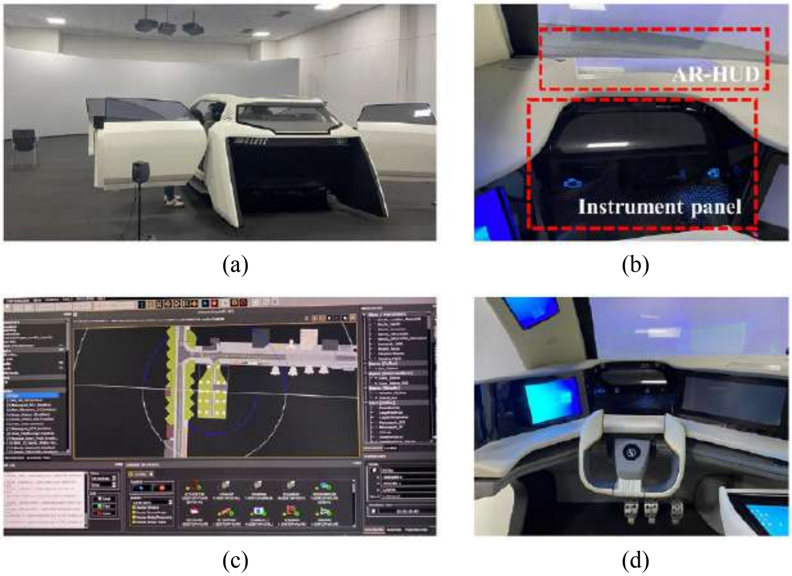
	Age		*Driving experience*/(year)		*Accumulated miles driven*/(100km)	
	M_{age}	SD_{age}	$M_{exp\cdot}$	$SD_{exp\cdot}$	M_{miles}	SD_{miles}
AR-HUD	30.60	9.27	4.72	2.88	5.31	8.25
Control group	31.00	9.18	5.13	3.51	6.02	7.42

The subjects were assigned randomly to the AR-HUD group and the control group. A one-way analysis of variance (ANOVA) result showed there was no statistically significant difference between the two groups.

2.2 Apparatus

This experimental apparatus consisted of a driver-centric driving environment through an intelligent car prototype (unpowered system), which was equipped with an AR-HUD system, and its FOV is 12 × 5°. The simulated driving scenarios are simulated and controlled by SCANeR Studio, as shown in Figure 1. In addition, the recording system for eye movements was the Tobii Pro Nano (Tobii Technology). This eye-tracking system has a sampling rate of 60 Hz that can accurately track the location of the focus of both eyes (the maximal time threshold is 75 ms, and the maximum angle threshold is 0.5°), as shown in Figure 2. The driving environment is portrayed through a large curved projection screen, which maximises the realisation of a vehicle simulation environment similar to the real driving environment.

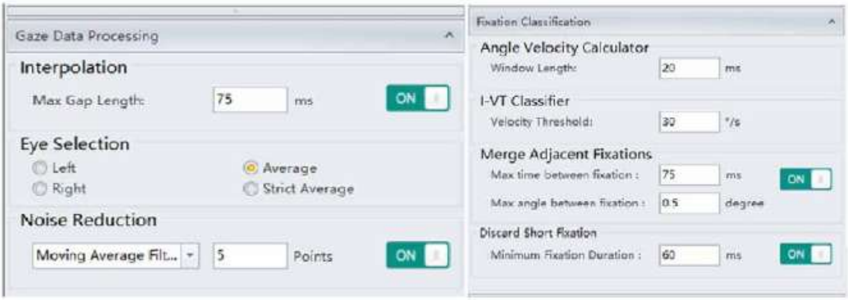
Figure 1 Vehicle simulation environment: (a) lab environment; (b) AR-HUD and IP; (c) SCANer software controller and (d) cockpit (see online version for colours)



(a) (b)

(c) (d)

Figure 2 Eye tracker parameter settings (see online version for colours)



Gaze Data Processing

Interpolation

Max Gap Length: 75 ms ON

Eye Selection

○ Left ● Average

○ Right ○ Strict Average

Noise Reduction

Moving Average Filt... 5 Points ON

Fixation Classification

Angle Velocity Calculator

Window Length: 20 ms

I-VT Classifier

Velocity Threshold: 30 °/s

Merge Adjacent Fixations

Max time between fixation : 75 ms ON

Max angle between fixation : 0.5 degree

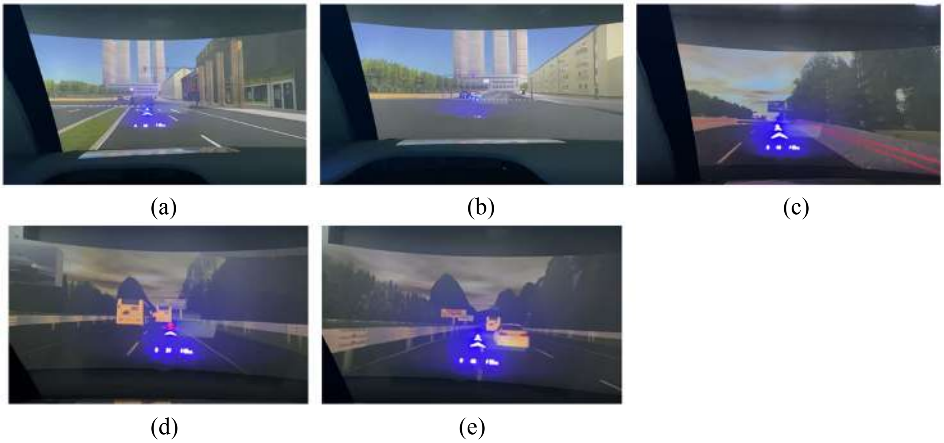
Discard Short Fixation

Minimum Fixation Duration : 60 ms ON

2.3 Stimuli

To corroborate the impact of the AR-HUD system on driving behaviour in different driving situations, the five principles for developing driver risky perception test proposed by Mark and Hill (2011), the five most typical risky driving scenarios were extracted, including pedestrian conflict (S1), turning at an intersection (S2), the vehicle ahead slows down (S3), ramp merge (S4) and expressway overtaking (S5), as shown in Figure 3. These five typical risky driving scenarios are interspersed in the fixed driving route respectively, forming two driving conditions, i.e., daytime and night.

Figure 3 Five most typical risky driving scenarios: (a) S1: pedestrian conflict; (b) S2: turning at an intersection; (c) (S3): ramp merge; (d) S4: vehicles ahead slow down and (e) S5: expressway overtaking (see online version for colours)


(a) (b) (c)
(d) (e)

2.4 Experiment design

We performed a 2×5 factorial design for the driving behaviour study. The independent variables are the AR-HUD group and control group (without AR-HUD), and the dependent variables are fixation behaviour and risky-response time of five AOIs in different scenarios. In this experiment, the count of fixations, mean fixation time, and fixation duration percentage was selected as indicators of the driver's fixation behaviour. Correspondingly, the risky-perception time and risky decision-making time were selected as indicators of the driver's risky-response capability.

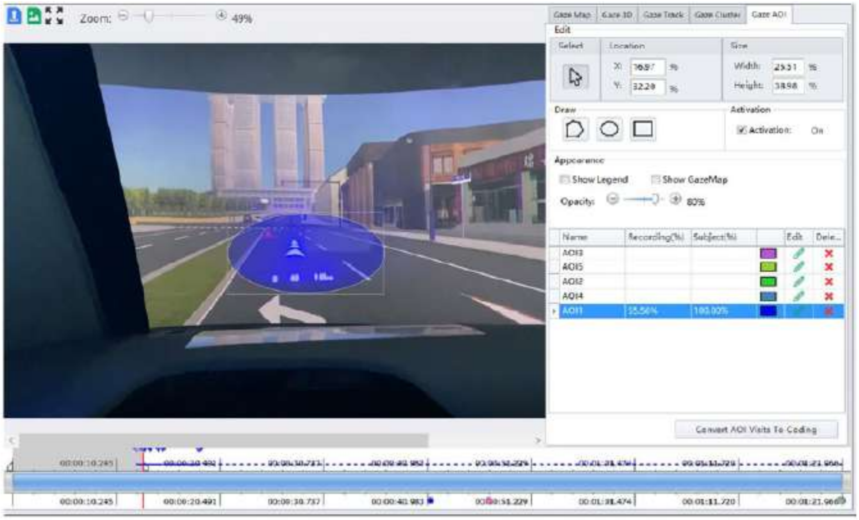
2.4.1 Fixation behaviour in AOIs

The dynamic area of interest (AOI) needs to be drawn to analyse the area where the risky driving scenario occurs separately. The shape and transformation of the AOI need to be defined based on keyframes, as shown in Figure 4. The driving simulation program for this experience contains five potentially risky driving scenarios, creating five dynamic AOIs for each scenario.

2.4.2 Risky-response time

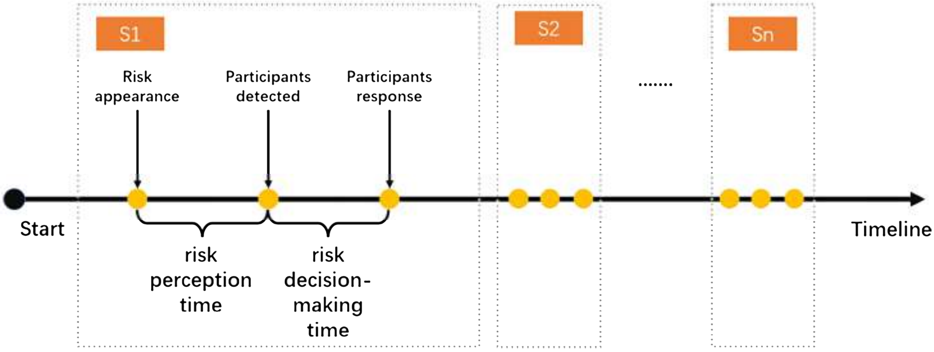
The risky-response time is divided into two parts: risk perception time and risk decision-making time. Risk perception time refers to the time difference between the appearance of the risk and participants detecting the risk. And risk decision-making time refers to the time when participants provide feedback after detecting the risk, as shown in Figure 5.

Figure 4 Dynamic AOI rendering in S1 (see online version for colours)



Name	Recording(%)	Subject(%)		Edit	Dele...
AOI3			🟪	✎	✗
AOI5			🟩	✎	✗
AOI2			🟩	✎	✗
AOI4			🟦	✎	✗
AOI1	55.56%	100.00%	🟦	✎	✗

Figure 5 The definition of risky-response time (see online version for colours)

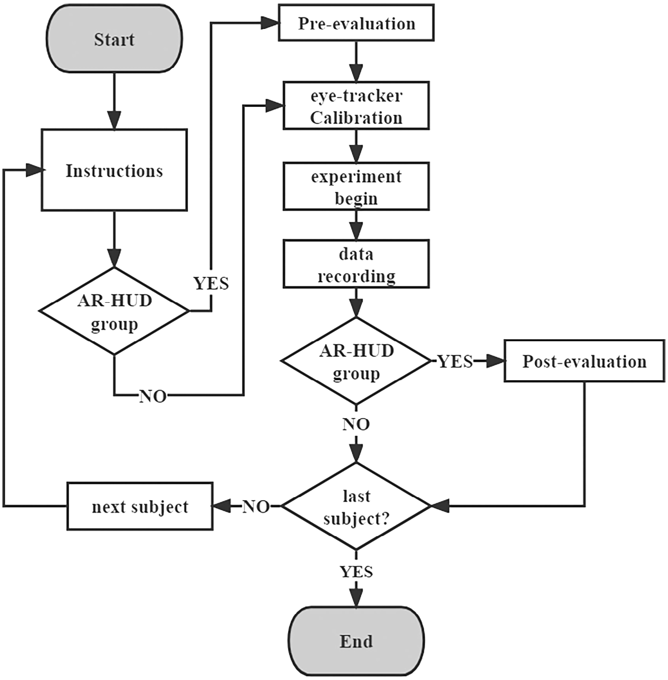


2.5 *Procedure*

The duration of the experiment was about 30 min. Participants were requested to read and accept a confidential consent statement. Afterward, participants were randomly divided into two groups (AR-HUD group and control group), which is not statistically different. Next, we introduced the experimental purpose, procedure, and precautions for both groups, and introduced the design conception, main content, and the meaning of each visual symbol of the AR-HUD system to the AR-HUD group. Before the experiment began, subjects in the AR-HUD group were reminded to fill in a subjective evaluation scale (pre-evaluation) to evaluate their first impression of the system interface and were required to complete the five-point calibration verification and the gaze accuracy test.

After entering the vehicle and adjusting the seat, 5 min of free driving practice was permitted. During the driving practice, participants had to drive manually and familiarise the surrounding environment. In the formal experiment, when subjects drove into a certain segment, a stimulus appeared, e.g., Pedestrian conflict. Subjects were expected to detect the stimulus as soon as possible and press the steering wheel button, then manoeuvre the vehicle to avoid pedestrians. These three-time points (stimulus appearance, risk detection, and button pressing) were automatically recorded by the system. After completing the experiment, the AR-HUD group was invited to re-fill the evaluation scale (post-evaluation), as shown in Appendix A. The next participant continued to experiment. Figure 6 shows the whole procedure of the experiment.

Figure 6 Experiment procedure



3 Results

Based on the experimental data collected by the eye tracker, the impact of the AR-HUD system on the driver's driving behaviour is analysed from three perspectives: eye movement data, risky reaction time, and subjective evaluation. SPSSAU (2022) was applied for the statistics and analysis of experimental data.

3.1 Fixation behaviour

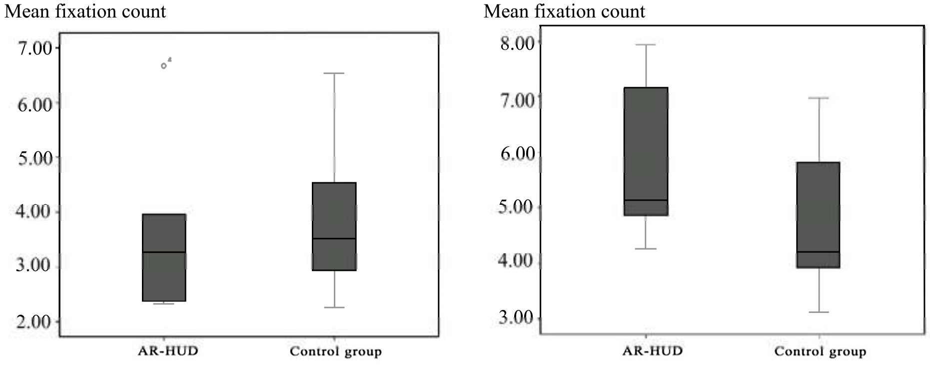
3.1.1 Fixation counts

Table 2 shows the mean fixation counts of the five AOIs of the two groups. Figure 7 shows the subjects' fixation counts on the AOI in two driving situations during daytime and night.

Table 2 Average fixation statistics (count)

		S1	*S2*	*S3*	*S4*	*S5*	*Mean*	*SD*
Daytime	AR-HUD	3.95	2.33	2.37	6.67	3.27	3.72	1.78
	Control group	4.52	2.92	2.26	6.53	3.50	3.94	1.67
Night	AR-HUD	7.15	4.86	4.26	7.93	5.13	5.87	1.58
	Control group	5.80	3.13	4.21	6.98	3.93	4.81	1.55

Figure 7 Mean fixation count on the AOIs: (a) daytime driving and (b) night driving



(a) (b)

In the daytime driving, results showed the mean count of fixation of the subjects in the AR-HUD group decreased by 5.82%, and the SD increased by 6.59% compared with the control group; the boxplot showed that the mean count of fixation in the AR-HUD group levels was slightly lower than those in the control group. In the night driving situation, results showed that the mean count of fixation in the AR-HUD group is 22.04% higher than that of the control group, and the SD increased by 1.94%; the boxplot showed the mean count of fixation in the AR-HUD group was significantly higher than the control group, and the box height IQR(interquartile range, IQR) was significantly higher than that of the control group, i.e., the data fluctuation degree of the AR-HUD group was significantly greater than that of the control group.

The paired sample T-test results of the fixation count data are shown in Table 3. In the daytime driving situation, $p = 0.226 > 0.05$, indicating the effect of the driver's fixation frequency in the driving situation is not significant; In the night driving situation, $p = 0.019 < 0.05$, which is significant, i.e., the use of the AR-HUD can significantly boost the driver's attention to the AOI in the night driving situation.

Table 3 Paired sample t-test for fixation count

		Coupled difference							
					95% confidence interval				
Test		*Mean*	*SD*	*SE*	*Lower limit*	*Upper limit*	*t*	*df*	*Sig. (2-tailed)*
Fixation count	Daytime	–0.232	0.363	0.162	–0.681	0.218	–1.431	4	0.226
	Night	1.058	0.625	0.280	0.281	1.835	3.782	4	0.019*

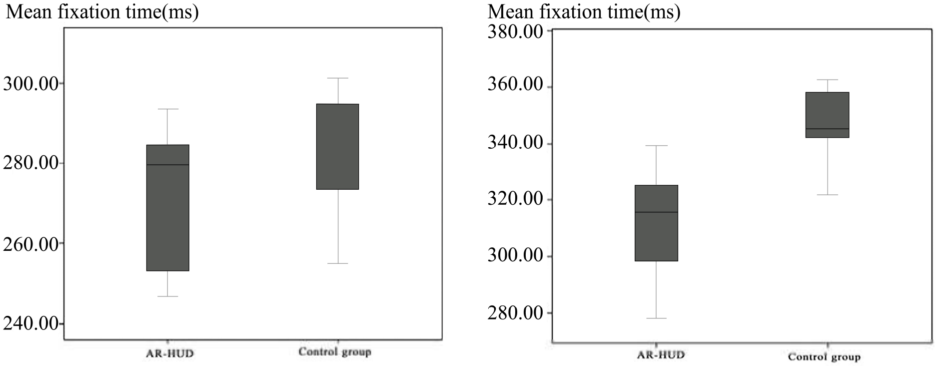
3.1.2 Mean fixation time

Table 4 shows the mean fixation time of the five AOIs in two groups, and Figure 8 shows the mean fixation time of the subjects to the AOI in two driving situations during the daytime and night.

Table 4 Average fixation time (ms)

		S1	*S2*	*S3*	*S4*	*S5*	*Mean*	*SD*
Daytime	AR-HUD	246.71	293.44	284.57	253.27	279.48	271.50	20.40
	Control group	254.93	294.58	301.21	273.45	273.54	279.54	18.54
Night	AR-HUD	298.45	315.78	324.96	278.41	339.27	311.37	23.64
	Control group	342.36	357.92	362.36	321.94	345.30	345.97	15.83

Figure 8 Average fixation time: (a) daytime driving and (b) night driving



(a) (b)

In the daytime driving situation, results showed that the mean fixation time of the AR-HUD group was reduced by 2.88%, and the standard deviation is increased by 10.03% compared with the control group; The boxplot shows that the mean fixation time of the AR-HUD group is lower than that of the control group, and the box height IQR is significantly higher than that of the control group. In the night driving situation, results showed that the mean fixation time of the AR-HUD group was reduced by 10.00%, and the standard deviation was increased by 49.34% compared with the control group; The boxplot shows that the mean fixation time of the subjects in the AR-HUD group was significantly lower than that of the control group, and the box height IQR was significantly higher than that of the control group.

The paired sample T-test results of the mean fixation time are shown in Table 5. In the daytime driving situation, $p = 0.170 > 0.05$, which is not significant, even if the AR-HUD assisted driving system is implemented, the effect on the mean fixation time of the driver in the daytime driving situation is not significant; In the night driving situation, $p = 0.009 < 0.05$, which is significant, i.e., the use of the AR-HUD system can significantly reduce the driver's cognitive load on the risky driving situation in the night driving situation.

Table 5 Paired sample t-test for the mean fixation time

Test		*Coupled difference*							
					95% confidence interval				
		Mean	*SD*	*SE*	*Lower limit*	*Upper limit*	*t*	*df*	*Sig. (2-tailed)*
Mean fixation time	Daytime	–8.044	10.778	4.820	–21.427	5.339	–1.669	4	0.170
	Night	–34.600	16.186	7.239	–54.697	–14.503	–4.780	4	0.009*

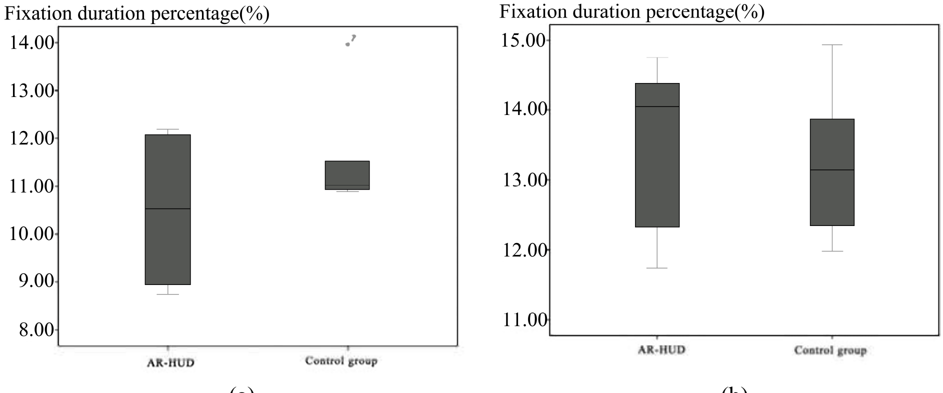
3.1.3 Fixation duration percentage

Table 6 shows the fixation duration percentage for the AOIs and the statistical results of the two groups. Figure 9 shows the fixation duration percentage on the AOI in two driving situations during the daytime and night.

Table 6 Statistical results of the percentage of fixation time (%)

		S1	*S2*	*S3*	*S4*	*S5*	*Mean*	*SD*
Daytime	AR-HUD	30.99	22.17	27.97	30.26	23.85	27.05	3.90
	Control group	35.58	27.38	28.71	31.22	26.49	29.88	3.65
Night	AR-HUD	45.72	32.75	35.79	42.38	30.28	37.38	6.50
	Control group	38.21	30.95	30.27	35.66	28.36	32.68	4.09

Figure 9 Fixation duration percentage: (a) daytime driving and (b) night driving



(a) (b)

In the daytime driving situation, results show that the mean fixation duration percentage of the AR-HUD group is 9.47% lower than that of the control group, and the standard deviation is increased by 6.85%. The boxplot shows that the mean fixation duration percentage of the AR-HUD group is slightly lower than that of the control group, but the box height IQR is significantly higher than that of the control group. In the night driving situation, results show that the AR-HUD group's mean fixation duration percentage, is 14.35% higher than that of the control group, and the standard deviation is 58.92%

higher. The boxplot shows that the mean fixation duration percentage and the box height IQR of the subjects in the AR-HUD group were significantly higher than those in the control group.

3.2 Risky-response capability

The time from the appearance of the danger signal to the time when the subject pressed the button was defined as the risky-response time, i.e., the perception-response reaction time. In this experiment, the risky-response behaviour is divided into risky perception time and risky decision-making time.

3.2.1 Perception time

In the ErgoLAB system, dynamic AOIs were plotted according to the event, location, and period of the danger signal. Of these, the point at which the dynamic AOI begins to be drawn is defined as the point at which the risky signal appears. And the moment subjects first entered the AOI recorded by the ErgoLAB system is defined as the moment subjects detected the signal. The specific data are shown in Table 7.

Table 7 Risk perception time data (s)

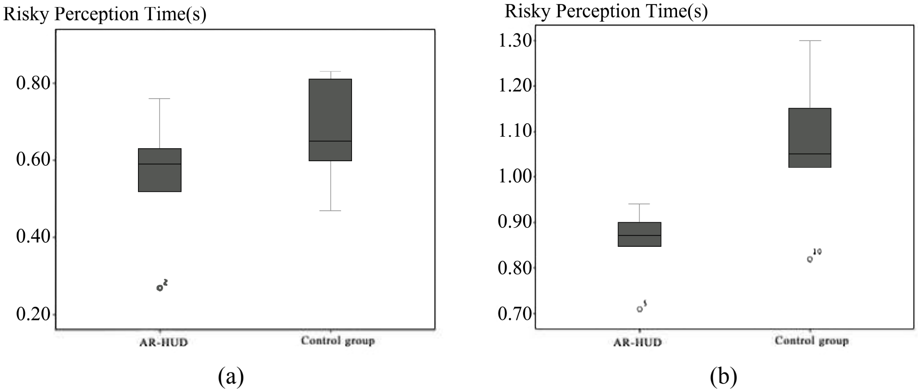
		Risk appears		*Risk detected*		*Perception time*	
		AR-HUD	*Control group*	*AR-HUD*	*Control group*	*AR-HUD*	*Control group*
Daytime	S1	12.34	14.53	12.97	15.36	0.63	0.83
	S2	34.12	34.60	34.39	35.07	0.27	0.47
	S3	35.95	39.88	36.71	40.69	0.76	0.81
	S4	58.39	59.68	58.91	60.33	0.52	0.65
	S5	63.94	70.95	64.53	71.55	0.59	0.60
Night	S1	10.22	12.47	11.12	13.49	0.90	1.02
	S2	18.24	18.57	19.18	19.72	0.94	1.15
	S3	44.43	45.32	45.30	46.37	0.87	1.05
	S4	54.96	55.67	55.84	56.97	0.84	1.30
	S5	75.79	70.47	76.50	71.29	0.71	0.82

As shown in Table 8 and Figure 10, the results show that in the daytime driving situation, the AR-HUD group's perception time in various risky driving situations is shortened by 17.91% compared with the control group, and the standard deviation is increased by 20%. The boxplot shows that the average level of risky perception time of the AR-HUD group is slightly lower than that of the control group, and the box height IQR is significantly lower than that of the control group. In the night driving situation, the AR-HUD group's perception time in various risky driving situations is shortened by 20.56% compared with the control group, and the standard deviation I reduced by 50%. The boxplot shows that the average level of risk perception time and the IQR of the box height of the AR-HUD group are significantly lower than those of the control group.

Table 8 Risky perception time statistical results (s)

		Mean	*SD*	*Minimum*	*Maximum*	*Midian*
Daytime	AR-HUD	0.55	0.18	0.27	0.76	0.59
	Control group	0.67	0.15	0.47	0.83	0.65
Night	AR-HUD	0.85	0.09	0.71	0.94	0.87
	Control group	1.07	0.18	0.82	1.30	1.05

Figure 10 Risky perception time: (a) daytime driving and (b) night driving



(a) (b)

The results of the paired samples T-test are shown in Table 9. When the significance level is 0.05, in the daytime driving situation, the daytime driving situation $p = 0.038 < 0.05$, the effect is significant; In the night driving situation, $p = 0.026 < 0.05$, the effect is significant, i.e., the implementation of the AR-HUD system can drastically reduce the perception time of subjects in risky driving situations.

Table 9 Paired sample T-test for risky perception time

Test		*Coupled difference*							
					95% confidence interval				
		Mean	*SD*	*SE*	*Lower limit*	*Upper limit*	*t*	*df*	*Sig. (2-tailed)*
Risky perception time	Daytime	–0.118	0.086	0.039	–0.225	–0.011	–3.053	4	0.038*
	Night	–0.214	0.138	0.062	–0.386	–0.042	–3.460	4	0.026*

3.2.2 Decision-making time

The risky decision-making time in this experiment was defined as the time from the subjects detected the danger signal to the time they responded. Among them, the time when the subject pressed the button was defined as the subject’s reaction time. Data are shown in Table 10.

Table 10 Risky decision-making time (s)

		Danger detected		*Respond moment*		*Decision-making time*	
		AR-HUD	*Control group*	*AR-HUD*	*Control group*	*AR-HUD*	*Control group*
Daytime	S1	12.97	15.36	13.48	16.07	0.51	0.71
	S2	34.39	35.07	34.91	35.61	0.52	0.54
	S3	36.71	40.69	37.22	41.25	0.51	0.56
	S4	58.91	60.33	59.34	60.80	0.43	0.47
	S5	64.53	71.55	64.99	72.11	0.46	0.56
Night	S1	11.12	13.49	11.87	14.32	0.75	0.83
	S2	19.18	19.72	19.71	20.29	0.53	0.57
	S3	45.30	46.37	45.87	46.97	0.57	0.60
	S4	55.81	56.97	56.30	57.59	0.49	0.62
	S5	76.50	71.29	77.13	71.88	0.63	0.59

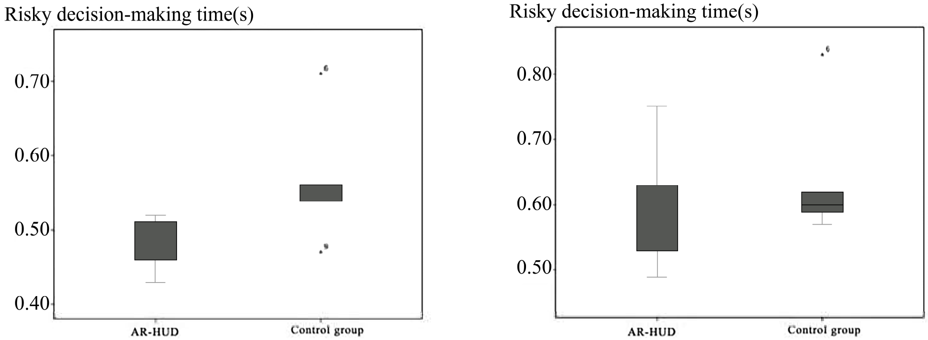
The decision-making time analysis is shown in Table 11, and the boxplot is shown in Figure 11. Results showed that in the daytime driving situation, the AR-HUD group's decision-making time in various risky driving situations was shortened by 14.04% compared with the control group, and the standard deviation was reduced by 55.56%; In the night situation, the driver's decision-making time in various risky driving situations in the AR-HUD group was reduced by 7.81% compared with the control group, and the standard deviation was reduced by 9.09%. The boxplot showed that in the daytime and night driving situations, the AR-HUD group's average level of risky decision-making time was lower than that of the control group, and the box height IQR was significantly higher than that of the control group.

Table 11 Risky decision-making time results (s)

		Mean	*SD*	*Minimum*	*Maximum*	*Midian*
Daytime	AR-HUD	0.49	0.04	0.43	0.52	0.51
	Control group	0.57	0.09	0.47	0.71	0.56
Night	AR-HUD	0.59	0.10	0.49	0.75	0.57
	Control group	0.64	0.11	0.57	0.83	0.60

A paired sample T-test was performed and the results are shown in Table 12. In the daytime driving situation, $p = 0.064 > 0.05$, the effect was not significant; in the night driving situation, $p = 0.164 > 0.05$, the effect was not significant, i.e., using the AR-HUD system has no significant effect on the perception time of the subjects' risky driving situations.

Figure 11 Risky decision-making time: (a) daytime driving and (b) night driving



(a) (b)

Table 12 Paired sample T-test for risky decision-making time

Test		*Coupled difference*					*t*	*df*	*Sig. (2-tailed)*
					95% confidence interval				
		Mean	*SD*	*SE*	*Lower limit*	*Upper limit*			
Risky decision-making time	Daytime	–0.082	0.072	0.032	–0.172	0.008	–2.538	4	0.064
	Night	–0.048	0.063	0.028	–0.126	0.030	–1.703	4	0.164

3.3 Subjective evaluation

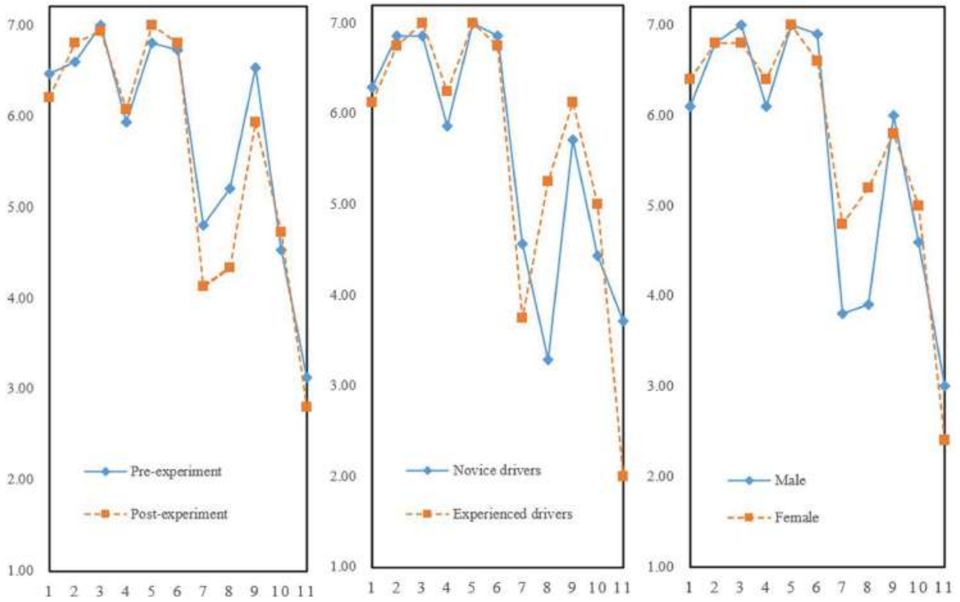
To obtain the driver's subjective evaluation of the effectiveness, interference, and reliability of the AR-HUD system, 15 participants in the AR-HUD group were asked to complete the subjective evaluation scales before and after the experiment. 15 valid evaluation scales were collected, and the data are shown in Table 13.

Table 13 Statistical results of subjective rating scale data

Question number	*Pre-experiment*	*Post-experiment*	*Novice drivers*	*Experienced drivers*	*Male*	*Female*
1	6.47	6.20	6.29	6.13	6.10	6.40
2	6.60	6.80	6.86	6.75	6.80	6.80
3	7.00	6.93	6.86	7.00	7.00	6.80
4	5.93	6.07	5.86	6.25	6.10	6.40
5	6.80	7.00	7.00	7.00	7.00	7.00
6	6.73	6.80	6.86	6.75	6.90	6.60
7	4.80	4.13	4.57	3.75	3.80	4.80
8	5.20	4.33	3.29	5.25	3.90	5.20
9	6.53	5.93	5.71	6.13	6.00	5.80
10	4.53	4.73	4.43	5.00	4.60	5.00
11	3.13	2.80	3.71	2.00	3.00	2.40

Figure 12(a) illustrates the comparison of the subjective evaluation of the AR-HUD system in different experiment stages. It can be seen that after implementing the AR-HUD system, the effectiveness evaluation of the subjects had been improved than expected, and worries about the system obscuring the driving environment, interfering with normal driving, and distracting the driver had lessened than expected as well, i.e., After using the system, the subjective acceptance of the AR-HUD system improved.

Figure 12 Subjective evaluation: (a) experiment stage; (b) driving experience and (c) gender (see online version for colours)



(a) (b) (c)

In the AR-HUD group, there are 7 novices and 8 skilled drivers. Data from the evaluation scale for participants with different driving experiences are analysed separately, as shown in Figure 12(b). For subjects with different driving experiences, the novice's evaluation of the system's legibility was higher, and the score of adding a pre-collision warning to the system and distinguishing it by different colours and frequencies was slightly lower. The primary reason is that a variety of warning forms are easily confusing and distracting to drivers (Jenness and Singer, 2013). A comprehensive analysis found that skilled drivers were more accepting of the system, believing that the system facilitated the driving process. Whereas novice drivers were more skeptical of the system, as the AR-HUD system makes drivers more nervous.

There were 10 male drivers and 5 female drivers in the AR-HUD group. The evaluation scale data of subjects of different genders are shown in Figure 12(c). Female drivers were found to have higher system interference scores, which obstructed the ambient environment and distracted the FOV. In Smith's research (Smith and Fu, 2011), it was noted that the location of the HUD interface is a significant factor influencing the reliability of the system for women. i.e., If the image was projected on the right side of the steering wheel, they felt 'relaxed', but if the image was projected on the left side, they felt 'anxious'. And female drivers relied more on the system and were more inclined to use the AR-HUD system to judge driving risks.

4 Discussion

In this study, we compared the effects of AR-HUD and the control group on driving behaviour in 5 driving scenarios, especially the driver's eye movement behaviour, i.e., the count of fixations, the mean fixation time and fixation duration percentage. Next, we will discuss each result-related variable separately.

Fixation behaviour includes fixation count, mean fixation time, and fixation duration percentage. The driver's fixation behaviour indicates the acquisition and processing of relevant driving information (Yamaguchi et al., 2019). Generally speaking, the more the count of fixations, the more information is received, and the more frequently the driver observes the area. This indicator mirrors the driver's AOI to a certain extent. In this experiment, the count of fixations is introduced, and the driver's AOI in risky driving situations is analysed by measuring the total count of fixations on the AOI when the driver is in a risky driving situation with (or without) the AR-HUD system. The results showed that the subjects in the AR-HUD group still allocated a small part of their attention to the state information display area of the AR-HUD system when they detected a risky situation during daytime driving, while the attention of the control group was mainly centred on risky AOI. It showed that in the daytime driving situation, the interface information of the AR-HUD system will intervene in the driver's FOV. Consequently, in the process of designing the system interface, the readability and rationality of the AR-HUD information must be taken into account repeatedly (Ward et al., 1995). During the night, the AR-HUD system helped the driver focus more on the risk area, but its impact varied across various driving scenarios. Thus, it was preliminarily estimated that in the night driving situation, the AR-HUD system can significantly improve the subjects' attention in risky driving areas. Park et al. (2015) also found a similar conclusion that the AR-HUD system can enhance the prompting of hazard signals in night driving and minimise the risk of collision.

The mean fixation time refers to the average duration of each fixation point in the AOI, and this indicator reflects the difficulty for drivers to grasp driving information in the AOI to a certain extent (Lehtonen et al., 2014). In this experiment, the mean fixation time characterisation index was introduced to verify whether the AR-HUD system can effectively reduce the driver's cognitive load in risky driving situations. The results showed that in the daytime situation, the AR-HUD system was beneficial in mitigating the difficulty of processing information and reducing cognitive load. However, the effect is not significant and the degree of influence varies considerably with risky driving situations. The primary reason may be that external ambient luminance affects the visibility of AR-HUD, resulting in a discrete display interface (Moffitt and Browne, 2019). While in the night situation, the AR-HUD system significantly reduced the difficulty for the driver to process the information of the dangerous driving situation and reduced the cognitive load. Furthermore, the degree of influence varied with risky driving situations.

The fixation duration percentage refers to the percentage of the sum of the duration of all fixation points in the AOI to the total time of the AOI (Zhang et al., 2021). Since the duration sum of fixation points reflects the interaction between the count of fixation and the mean fixation time, this characterisation index was introduced in this experiment to comprehensively evaluate the effects of the AR-HUD system on driver distraction and cognitive load. The results showed that in the daytime situation, the ability of the AR-HUD system to reduce distracted driving and the driver's cognitive load is not apparent, and the data fluctuates significantly. In the night situation, the AR-HUD system can significantly reduce the driver's driving distraction and cognitive load, and the degree of impact varies significantly in different risky driving situations.

In addition, the risky response capability (risk perception time and risk decision time) reflects the ability to be aware and respond to risky situations. As for risk perception time, participants who used the AR-HUD system can obtain risky driving situation information more quickly according to the warning information of the system. And with the help of the system, the risk perception time tended to be of value in different driving situations, which was more significant in night driving situations. Regarding risk decision-making time, The AR-HUD system improved the cognitive load of participants in handling risky driving information to some degree and improved the effectiveness of information processing. However, in different risky driving situations, the degree of influence was different.

The main purpose of this research is to investigate the effect of the AR-HUD system on driving behaviour in 5 different risky scenarios. Nevertheless, this work still has some limitations, for example, the simulation experiment was not carried out on the actual road, ignoring the influence of psychological factors brought by driving, such as stress, fatigued driving, etc. Moreover, real road driving often experiences more complex environmental conditions, which are more difficult for drivers to make decisions. Therefore, real road experiment on driving behaviour is a process worth further studying.

5 Conclusion

In this paper, we conducted experimental research on the impact of the in-vehicle AR-HUD system on driving behaviour, comprehensively analysed the subjects' eye movement data and risky reaction time during driving, and obtained the independent variable with (or without) the AR-HUD system. The experimental results with the count of fixations in the AOI, the mean fixation time, fixation duration percentage, the risky perception time, and the risky decision-making time as the dependent variables, the main conclusions are listed as follows:

1. In the night driving situation, the AR-HUD system can significantly improve the subjects' attention to risky AOI, reduce the difficulty of processing information in risky driving scenarios, and reduce recognition load. In different risky driving situations, the extent of the impact is significantly different accordingly. While in the daytime driving situation, the impact is not significant.
2. The AR-HUD system can significantly shorten the subjects' perception time of risky driving scenarios and respond to risky situations more quickly, but it has no significant impact on risky decision-making time.

3 Subjective acceptance of the AR-HUD system exceeded expectations following implementation of the system and the subjects' evaluation of the effectiveness, interference and reliability of the system was affected by driving experience and gender significantly.

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.

Acknowledgement

This paper was funded by the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX21_2128). We also thank Changan Automobile Group Co., Ltd for assistance with the experiment.

References

Bark, K., Tran, C., Fujimura, K. and Ng-Thow-Hing, V. (2015) 'Personal Navi: benefits of an augmented reality navigational aid using a see-thru 3D volumetric HUD', *International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ACM, Seattle, pp.1–8.

Bellazzi, A., Bellia, L., Chinazzo, G., Corbisiero, F., D'Agostino, P., Devitofrancesco, A., Fragliasso, F., Ghellere, M., Megale, V. and Salamone, F. (2022) 'Virtual reality for assessing visual quality and lighting perception: a systematic review', *Building and Environment*, Vol. 209.

Castro, S.C., Strayer, D.L., Matzke, D. and Heathcote, A. (2019) 'Cognitive workload measurement and modelling under divided attention', *Journal of Experimental Psychology Human Perception and Performance*, Vol. 45, No. 6, pp.826–839, doi: 10.1037/xhp.0000638.

Choi, W.J., Lee, W.J., Lee, S.H. and Park, Y.K. (2013) 'Vehicle HUD's cognitive emotional evaluation-focused on colour visibility of driving information', *Korean Journal of the Science of Emotion and Sensibility*, Vol. 16, No. 2, pp.195–206.

Choi, S.Y., Kim, M.Y., Jeo, H.I., Mun, H.R., Byeun, S.C. and Ryu, S.K. (2002) 'A study on the performance index and visibility for LED variable message sign', *Proceedings of the KIEE Conference*, The Korean Institute of Electrical Engineers, pp.1286–1288.

Cooper, J.M., Medeiros-Ward, N. and Strayer, D.L. (2013) 'The impact of eye movements and cognitive workload on lateral position variability in driving', *Human Factors*, Vol. 55, No. 5, pp.1001–1014, doi: 10.1177/0018720813480177.

Dong, Y.C., Hu, Z.C., Uchimura, K. and Murayama, N. (2011) 'Driver inattention monitoring system for intelligent vehicles: a review', *IEEE Transactions on Intelligent Transportation Syste ms,* Vol. 12, No. 2, pp.596–614, doi: 10.1109/TITS.2010.2092770.

Fröhlich, P., Schatz, R., Leitner, R., Bal-dauf, M. and Mantler, S. (2010) 'Augmenting the driver's view with realtime safety-related information', *Augmented Human Int. Conf.*, Megève, France, pp.1–11.

Gibbered, D.L., Jameson, S.L. and Carsten, O.M.J. (2013) 'Managing in-vehicle distraction: evidence from the psychological refractory period paradigm', *The 2nd International Conference on Automotive User Interface and Interactive Vehicular Applications*, Pittsburgh, pp.213–215.

Grandi, F., Prati, E. and Peruzzini, M. (2022) 'Design of ergonomic dashboards for tractors and trucks: innovative method and tools', *Journal of Industrial Information Integration*, Vol. 25, p.100304, https://doi.org/10.1016/j.jii.2021.100304

Hwang, Y., Park, B.J. and Kim, K.H. (2015) 'The effects of augmented-reality head-up display system on the perception of precautionary situation', *International Conference on Information and Communication Technology Convergence*, IEEE, Jeju Isl, pp.1146–1148.

Hwang, Y., Park, B.J. and Kim, K.H. (2016) 'Effects of augmented-reality head-up display system use on risk perception and psychological changes of drivers', *Etri Journal*, Vol. 38, No. 4, pp.757–766.

Jenness, J.W. and Singer, J. (2013) 'Visibility and conspicuity of detectable warnings for pedestrians with visual impairments', *Transportation Research Record*, Vol. 2073, pp.104–113.

Kim, H., Miranda, A., Misu, T., Li NJ, Tawari, A. and Fujimura, K. (2016) 'Look at me: augmented reality pedestrian warning system using an in-vehicle volumetric head-up display', *International Conference on Intelligent User Interfaces*, Sonoma, CA, pp.294–298.

Kim, K. and Hwang, Y. (2017) 'The usefulness of augmenting reality on vehicle head-up display', *Advances in Human Aspects of Transportation*, pp.25–36.

Lee, J.W., Park, B.J., Yoon, C.R. and Kim K.H. (2015) 'A study of issues and considerations for development of a vehicle AR system', *International Conference on Information and Communication Technology Convergence*, pp.1160–1162.

Lee, S.H., Choi, J. and Park, J. (2009) 'Interactive e-learning system using pattern recognition and augmented reality', *IEEE Transactions. Consum. Electron.*, Vol. 55, No. 2, pp.883–890.

Lehtonen, E., Lappi, O., Koirikivi, I. and Summala, H. (2014) 'Effect of driving experience on anticipatory look-ahead fixations in real curve driving', *Accident Analysis and Prevention*, Vol. 70, pp.195–208, doi: 10.1016/j. aap.2014.04.002.

Liang, Y.L., Reyes, M.L. and Lee, J.D. (2007) 'Real-time detection of driver cognitive distraction using support vector machines', *IEEE Transaction on Intelligent Transportation Systems.*, Vol. 8, No. 2, pp.340–350, doi: 10.1109/TITS.2007.895298.

Liu, Y. and Wen, M. (2008) 'Comparison of head-up display (HUD) vs. head-down display (HDD): driving performance of commercial vehicle operators in Taiwan', *Int. J. Hum. Compute. Stud.*, Vol. 61, No. 5, pp.679–697.

Liu, N.C., Xie, L., Wu, C.Z., Fu, Q. and Deng, C. (2017) 'Driver's cognitive workload and driving performance under traffic sign information exposure in complex environments: a case study of the highways in China*'*, *International Journal of Environmental Research and Public Health*, Vol. 14, No. 2, pp.203–210, doi: 10.3390/ijerph14020203.

Ma, R.Q. and Kaber, D.B. (2005) 'Situation awareness and workload in driving while using adaptive cruise control and a cell phone', *International Journal of Industrial Ergonomics*, Vol. 35, No. 10, pp.939–953, doi: 10.1016/j. ergon.2005.04.002.

Ma, Y.L., Qi, S.M., Zhang, Y.P., Lian, G., Lu, W.X. and Chan, C.Y. (2020) 'Drivers' visual attention characteristics under different cognitive workloads: an on-road driving behaviour study', *International Journal of Environmental Research and Public Health*, Vol. 17, No. 15, pp.53–66, doi: 10.3390/ijerph17155366.

Mark, A.W. and Hill, A. (2011) 'The development and validation of a hazard perception test for use in driver licensing', *Accident Analysis and Prevention*, Vol. 43, No. 5, pp.1759–1770.

Medenica, Z., Kun A.L. and Palinko, O. (2011) 'Augmented reality vs. street views: a driving simulator study comparing two emerging navigation aids', *Proc. Int. Conf. HCI Mobile Devices Services*, August, Stockholm, Sweden, pp.265–274.

Moffitt, K. and Browne, M.P. (2019) 'Visibility of colour symbology in head-up and head-mounted displays in daylight environment', *Optical Engineering*, Vol. 58, No. 5, p.1064209, doi: 10.1117/1.OE.58.5.051809.

NHTSA (2012) *Traffic Safety Facts: Distracted Driving 2010*, NHTSA's National Centre for Statistics and Analysis, Washington, pp.113–120.

Park, H.S. and Kim, K.H. (2014) 'AR-based vehicular safety information system for forward collision warning. virtual, augmented and mixed reality', *Applications of Virtual and Augmented Reality*, Springer International Publishing, Switzerland, pp.435–442.

Park, B.J., Lee, J.W., Yoon, C. and Kim, K.H. (2015) 'Augmented reality and representation in vehicle for safe driving at night', *International Conference on ICT Convergence (ICTC)*, Jeju Isl, pp.1261–1263.

Patten, C.J.D., Kircher, A., Ostlund, J. and Nilsson, L. (2004) 'Using mobile telephones: cognitive workload and attention resource allocation', *Accident; Analysis and Prevention*, Vol. 36, No. 3, pp.341–350, doi: 10.1016/S0001-Vol. 4575, No. 03)00014-9.

Schewe, F. and Vollrath, M. (2020) 'Ecological interface design effectively reduces cognitive workload – the example of HMIs for speed control', *IEEE Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 72, pp.155–170.

Smith, M., Gabbard, J.L., Burnett, G and Doutcheva, N. (2017) 'The effects of augmented reality head-up displays on drivers' eye scan patterns, performance, and perceptions', *International Journal of Mobile Human-Computer Interaction*, Vol. 9, No. 2, pp.1–17.

Smith, S. and Fu, S.H. (2011) 'The relationships between automobile head-up display presentation images and drivers' Kansei', *Displays*, Vol. 32, No. 2, pp.58–68, doi: 10.1016/j.displa.2010.12.001.

Tan, H., Tan, Z. and Jing, C. (2015) *Design of Human-Computer Interface*, Electronic Industry Press, Beijing, pp.6–9.

The SPSSAU project (2022) *SPSSAU (Version 22.0)*, [Online Application Software]. Retrieved from https://www.spssau.com

Venkatesh, V., Morris, M.G. and Davis, G.B. (2003) 'User acceptance of information technology: toward a unified view', *MIS Quarterly*, Vol. 27, No. 3, pp.425–478, doi: 10.2307/30036540.

Wang, Z.S., Li, J., Feng, C.K. and Guo X.G. (2016) 'A new method to evaluate the readability of head-up display', *2016 2nd IEEE International Conference on Computer and Communications*, Chengdu, pp.1019–1023.

Wang, X. and Qin, Q. (2014) 'Vehicle head-up display technology', *Electro-Optics and Control*, Vol. 47, No. 01, pp.55–58.

Ward, N.J. and Parkes, A. (1994) 'Head-up displays and their automotive application: an overview of human factors issues affecting safety', *Accident Anal. Prevention*, Vol. 26, No. 6, pp.703–717.

Ward, N.J., Parkes, A. and Crone, P.R. (1995) 'Effect of background scene complexity and field dependence on the legibility of head-up displays for automotive applications', *Human Factors*, Vol. 37, No. 4, pp.735–745, doi: 10.1518/001872095778995625.

Wu, F. and Zhang, L. (2012) 'Review of augmented reality technology development and application', *Computer Knowledge and Technology*, No. 34, pp.8319–8325.

Yamaguchi, K., Nakayama, M., Sun, Q. and Xia, J.H. (2019) 'Prediction of cognitive performance of drivers using eye fixation behaviours', *2019 23RD International Conference Information Visualisation (IV)*: *Biomedical Visualisation and Geometric Modelling and Imaging*, Paris, pp.186–190, doi: 10.1109/IV.2019.00040.

Yoon, C., Kim, K., Park, H.S., Park, M.W. and Jung, S.K. (2014) 'Development of augmented forward collision warning system for head-up display', *Proceedings of 17th International IEEE Conference on Intelligent Transportation Systems*, Qingdao, pp.2277–2279.

Zhang, H. (2015) *Research on HUD Visual Interface Design of Vehicle Head-Up Display*, South China University of Technology.

Zhang, Y.J., Yang, T., Zhang, X., Zhang, Y.J. and Sun, Y.C. (2021) 'Effects of full windshield head-up display on visual attention allocation', *Ergonomics*, Vol. 64, No. 10, pp.1310–1321, doi: 10.1080/00140139.2021.1912398.