Evaluating the moderating effect of in-vehicle warning information on mental workload and collision avoidance performance

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Abstract

Purpose – The presentation of in-vehicle warnings information at risky driving scenarios is aimed to improve the collision avoidance ability of drivers. Existing studies have found that driver's collision avoidance performance is affected by both warning information and driver's workload. However, whether moderation and mediation effects exist among warning information, driver's cognition, behavior and risky avoidance performance is unclear.

Design/methodology/approach – This purpose of this study is to examine whether the warning information type modifies the relationship between the forward collision risk and collision avoidance behavior. A driving simulator experiment was conducted with waring and command information.

Findings – Results of 30 participants indicated that command information improves collision avoidance behavior more than notification warning under the forward collision risky driving scenario. The primary reason for this is that collision avoidance behavior can be negatively affected by the forward collision risk. At the same time, command information can weaken this negative effect. Moreover, improved collision avoidance behavior can be achieved through increasing drivers' mental workload.

Practical implications – The proposed model provides a comprehensive understanding of the factors influencing collision avoidance behavior, thus contributing to improved in-vehicle information system design.

Originality/value – The significant moderation effects evoke the fact that information types and mental workloads are critical in improving drivers' collision avoidance ability. Through further calibration with larger sample size, the proposed structural model can be used to predict the effect of in-vehicle warnings in different risky driving scenarios.

Keywords In-vehicle warning information, Driving simulator, Mental workload, Moderation effect, Forward collision warning

Paper type Research paper

1. Introduction

Improving driver's collision avoidance performance at risky driving scenarios such as sudden deceleration of the front vehicle is a major countermeasure to improve traffic safety. In general, collision avoidance performance is affected by many factors involving the risky driving scenario and driver's cognitions

(Oron-Gilad and Shinar, 2000). Although the relationship between risky driving scenarios and collision avoidance performance is clear in manual driving vehicles, the occurrence of in-vehicle warnings may increase the uncertainty and complexity. Such warnings of the in-vehicle information system (IVIS) are originally aimed to improve risk perception and safety performance by providing information on the risky driving scenario. However, the effect of additional information on drivers' collision avoidance performances is not always positive, such as increasing the mental workload or reaction time (RT).

Many previous studies have found that the mental workload induced by in-vehicle warnings plays an essential role in affecting collision avoidance performance. The higher mental workload can either increase or decrease driver's risk perception ability (Rudin-Brown and Parker, 2004; Carsten *et al.*, 2012). Yerkes and Dodson (1908) have found that a low level of workload might make the driver bored and distracted, whereas a high level of workload might rapidly decrease the reliability of perception and decision-making; thus, increasing the risk of information overload and crashes.

Existing researches have previously discussed how risky driving scenarios or in-vehicle warnings affect collision avoidance performance separately (Uang and Hwang, 2003; Zhang *et al.*, 2019). When analyzing the effect of in-vehicle warnings, only these warnings are considered to be responsible for collision avoidance performance, such as reaction time (RT), time to collision (TTC) and time headway (TH). Other factors were not investigated specifically, including characteristics of vehicle interaction subject vehicle (SV) movements in risky driving scenarios. In fact, collision avoidance performance is a result of various factors concerning driver, vehicle and environment. Besides the individual effect of these factors, the interactive effects between them should be further investigated.

However, an integrated model to identify the intrinsic mechanism between environmental risk, warning information and collision avoidance behavior has yet to be fully developed. Hence, this paper's main objective is to explore the relationship between them by extracting microscopic driving-related indicators to represent vehicle interaction and collision avoidance performance. ANOVA tests were used to analyze the effects of the forward collision warning (FCW) information. Furthermore, the moderating effect of FCW information was analyzed to investigate its impact on driver performance under different risk levels, contributing to identifying interactive effects of the extracted indicators.

The rest of this paper is organized as follows. Section 2 summarizes related research studies on the effect of traffic environment complexity, mental workload and in-vehicle warnings on collision avoidance behavior. Section 3 describes the experimental design and measurements. Section 4 presents the results of simulations researching the moderating effects of in-vehicle warnings. Section 5 presents the conclusions and discussions of this research.

2. Literature review

2.1 The effect of mental workload on collision avoidance behavior

Mental workload, which refers to the amount of operator resources required to meet task demands, is found to be a critical factor in explaining the complex relationship between risky driving scenarios and collision avoidance behavior. Martens and Winsum (2000) have found that mental workload increases driver's RT at driving scenarios with more surrounding vehicles and higher traffic complexity. In high workload conditions, initiating nondriving-related tasks, such as phone use, may lead to perception and decision failure because of the attention division between different sensory modalities (Brown *et al.*, 1969). The switch between ears and eyes can vastly increase mental workload, impairing their perception and decision-making ability (Spence *et al.*, 2001). It has been widely proved that high complexity in risky driving scenarios requires the driver to work harder and may arouse inaccurate perception and insufficient time for information processing (Brookhuis and Waard, 2000; Dadashi *et al.*, 2013; Pereira and Silva, 2014).

Previous studies quantified mental workload through indicators such as subjective evaluation, physiological indicators and behavior measures. Subjective evaluation is a widely used way of reflecting mental workload due to the advantage of operability, high readability and low cost. National Aeronautics and Space Administration task load index (NASA-TLX), subjective workload assessment technique, driving activity load index and workload profile are four questionnaires widely used in workload-related research studies (Hart and Staveland, 1988). Compared with the other three methods, NASA-TLX includes more dimensions by requiring participants to rate the demands in terms of mind, physics, time, frustration, effort and performance. Also, it has higher validity and intrusiveness (Paxion *et al.*, 2014). Driving behavior measures are also common indicators to reflect workloads, such as speed, headway, lateral position, steering wheel angle and surrogate safety indexes (Regan *et al.*, 2008; Gemou, 2013; Li *et al.*, 2017; Malhotra *et al.*, 2018).

2.2 Effect of in-vehicle warning information on collision avoidance behavior

With the growing development of intelligent vehicles, in-vehicle warnings have become much more common in commercial vehicles. Existing studies have assessed the effect of in-vehicle warnings in various aspects, such as trigger time, risk levels and multimodal information (Brannstrom *et al.*, 2008; Cabrera *et al.*, 2012). A general positive effect is found in most studies. Over 70% of warnings with a reliable system performance could improve collision avoidance behavior (Wickens and Dixon, 2007). However, little is known about the difference between giving the warning to assist decision-making or the command guidance for collision avoidance.

To the best of our knowledge, only a few studies compared the effect of different information of collision warnings. Uang and Hwang (2003) proposed that warning information (reminding potential risks) is suitable in less critical scenarios, while command information (operational guidance) is suitable for helping to avoid urgent risks. Zhang *et al.* (2019) further investigated the effect of these two information contents. It has been found that command led to shorter brake RT and significantly more velocity reduction than a warning. The effect of in-vehicle information on collision avoidance behavior has been investigated. However, the specific influencing mechanism of information type on collision avoidance behavior has rarely been discussed. Because mental workload could

affect driving behavior, it seems that workload may play a role in the relationship between in-vehicle warning information and collision avoidance behavior. This assumption remains to be investigated quantitatively.

2.3 Effect of in-vehicle warnings on mental workload

Previous studies have shown that in-vehicle information should keep the level of attention distributed to the primary driving task. In normal driving scenarios, drivers may have up to 50% of spare attention capacity during everyday driving (Hughes and Cole, 1986). About 40% of attention could be assigned to nondriving related tasks (Green and Shah, 2004). In-vehicle warnings are effective in reducing the crash risk because the attention allocated to warning information was extra resources instead of occupying primary driving tasks. However, the peripheral detection task and tactile detection response task have proved that driver's risk perception is sensitive to workload change and distraction caused by in-vehicle warnings of IVIS (Jahn *et al.*, 2005; Chang *et al.*, 2017; Nilsson *et al.*, 2018). With the occurrence of multisource and multimodal in-vehicle warnings, the spare attention capacity can soon be occupied, thus arousing high workload and information overload if unexpected risk events were not well managed. Therefore, the measurement of mental workload is critical in evaluating the design of in-vehicle warnings.

Based on existing studies, the effect of in-vehicle warnings on mental workload and mental workload on collision avoidance behavior has been found. However, the integrated relationship among in-vehicle warning information, mental workload and collision avoidance behavior in risky driving scenarios have rarely been discussed. In this study, it is assumed that mental workload may influence the effect of warning information and the forward collision risk on collision avoidance performance. To quantitatively investigate this assumption, a driving simulator experiment with 30 participants was designed. With experiencing an emergency brake of the forward vehicle with the different visual content of warning information, driving behavior measures were collected. Drivers' mental workload was evaluated by NASA-TLX scales after each drive in the experiment.

3. Simulator experiment

3.1 Participants

Thirty drivers (20 males, 10 females) participated in the study. The participants' average age was 28.11 years old (SD = 8.79),

and their average driving experience was 7.95 years (SD = 7.41). All participants held valid driver licenses and were randomly recruited upon the Institutional Review Board's approval of Tongji University (No. tjdx059). A cash reimbursement of 150CNY (US$22) was offered to each participant after the experiment.

3.2 Apparatus

The whole apparatus in the experiment is shown in Figure 1. Simulated driving scenarios were developed by SCANeR^{TM} studio software and projected onto three screens (23.8-inch, 34-inch curved, 23.8-inch from left to right) located 0.5 m in front of the participant. The field of view was approximately 173°, presenting the central front view. In addition, two additional 10-inch screens were used as the central dashboard and warning display, respectively. The steering wheel, accelerator and brake pedals used in this experiment were Logitech G29 Racing Wheel and Pedals. Appropriate resistance was set as 20% spring return to the center position for guaranteeing a real-world feeling. Data of driving behavior was collected by Simulink at 20 Hz.

3.3 Experimental design

3.3.1 Traffic environment

The traffic environment was an urban road with traffic flow in two lanes of each direction under good weather conditions during the daytime. Surrounding vehicles were programmed to drive at 0–50 km/h, observing traffic signs and emergencies automatically. Participants were instructed to drive as normal by following all traffic rules. The primary driving task was to follow a lead vehicle (LV) at a safe distance. Participants were unfamiliar with the intersections and were required to make left turns on green.

Two kinds of traffic environments, simple and complex, were designed (Figure 2). In a simple traffic environment, there were no other traffic participants except the lead and the SV. In a complex traffic environment, the SV needed to make the left turn across oncoming traffic. Some traffic participants would have potential conflicts with the SV. Specifically, while the SV was turning left, an oncoming vehicle was approaching. Although the oncoming vehicle would stop at the intersection and did not cause conflict with the SV, it required participants to allocate attention. Meanwhile, a pedestrian on the was
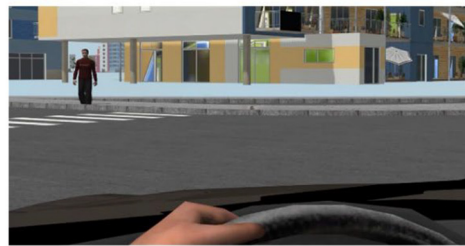
Figure 1 Experiment apparatus

Figure 2 Simple and complex traffic environments

(a)

(b)
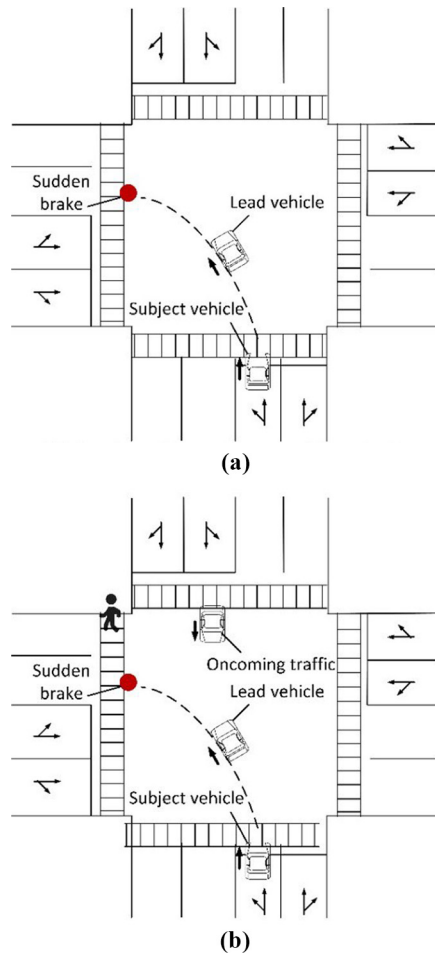
(c)

(d)

(e)

waiting for a gap to cross the street, which also required participants' attention to the behavior of this pedestrian.

3.3.2 Forward collision risk scenario

The forward collision risk scenario was designed as the LV making a sudden brake at a specific point. Each drive includes two risky scenarios (emergency brakes) at random of four possible locations, as shown in Figure 3(a). Grey arrows marked the specific locations of risks. To reduce the learning effects and familiarity with the road environment, two kinds of the driving route was randomly assigned in each drive, as shown in Figures 3(b) and (c).

3.3.3 Forward collision warning

Co-simulation of SCANeR^TM studio and MATLAB Simulink was conducted for triggering in-vehicle warnings in the forward collision risk scenario. The FCW was triggered by setting thresholds based on collision risk and driving speed that affected drivers' risk perception. The collision risk in this paper was defined by TTC. It is a time interval index usually measured in seconds, which was required for one vehicle to strike another vehicle if both vehicles continue driving along the same path at constant velocities (SAE International, 2015). The detailed framework of warning triggering is shown in Figure 4. To calculate the key indicator TTC, speeds and positions of subject

and LV was transferred from SCANeR^TM studio to MATLAB Simulink through application programming interface. Under the speed limit of 50 km/h, TTC was calculated at 100 Hz and compared with the threshold (3 s) in real-time. The 3 s threshold has been widely used in previous studies to assess the safety margin of drivers. Once the value of TTC was less than 3 s, the FCW would be triggered instantly to provide drivers with information for collision avoidance.

The FCW interface was designed, including a silver car following a red car with looming text to the right. Once reaching the warning threshold (e.g. TTC < 3s), a red halo appeared around the screen and rapidly flashed at 3 Hz. A rapid beep occurred at the same time to draw the driver's attention. As shown in Figure 5, warning and command were designed in this study to inform the driver about the forward collision risk and urge them to perform appropriate collision avoidance behavior. The only difference is the visual content of information presented to drivers. Command information ("Brake. Rear-end collision") provided direct guidance on the braking operation while warning information ("Warning. Rear-end collision") did not.

3.3.4 Experiment procedure

Thirty participants were divided into two groups equally and randomly. *T*-tests of age, gender and driving experience were

Figure 3 Forward collision risk scenario and driving routes
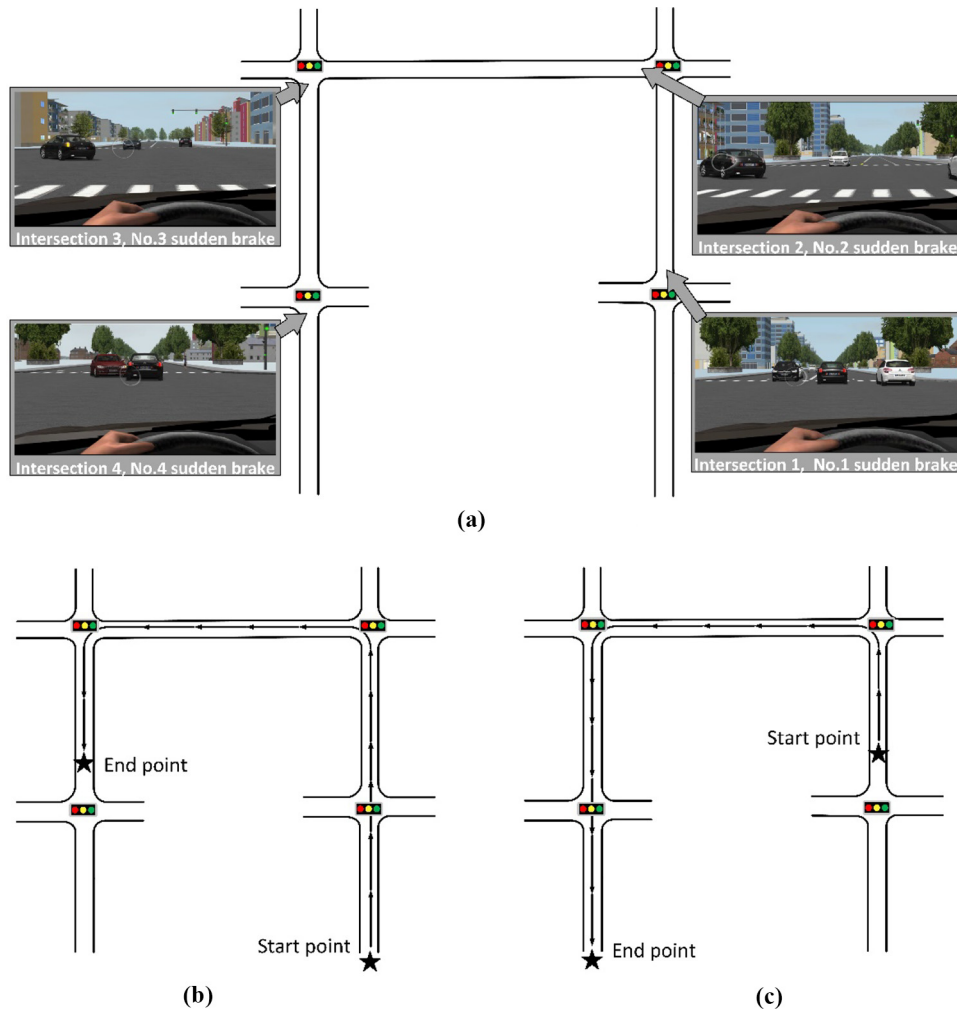
conducted. Results were shown in Table 1, and there were no significant differences between the two groups. The participants were instructed to drive and comply with traffic rules as in the real traffic environment. Before the experiment, each driver had a 5-min brief test drive to get familiar with the driving simulator operations. During the formal experiment, each participant drove six times with two emergency brakes of the LV in each drive. All the scenarios were presented in a counterbalanced order for two groups to reduce experiment

order effects such as fatigue or learning (Figure 6). Each drive lasted about 4 min. After each drive, participants filled in NASA-TLX to rate their subjective workload toward the forward collision risk scenario and warning information. NASA-TLX requires participants to rate the demands in mind, physics, time, frustration, effort and performance. The first three dimensions (mental demands, physical demands and temporal demands) are used to compute the average workload score.

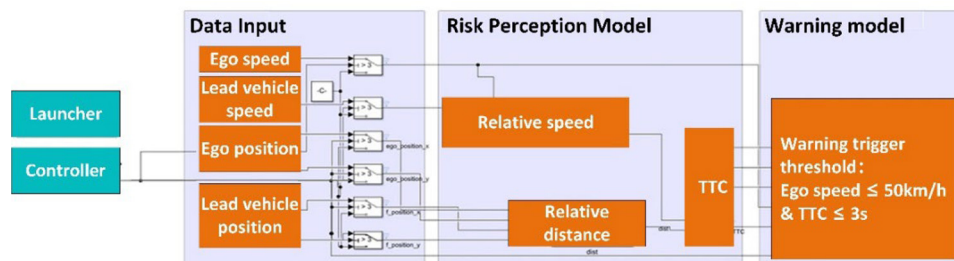**Figure 4** Simulink framework for warning triggering

Figure 5 FCW information content design

(a)   (b)

3.4 Measures

The experiment was designed as a 3 (FCW information type) × 2(risky driving scenarios) within-subjects repeated measures. The moment of braking onset was taken as the key time point to calculate variables (as summarized in Table 2). To evaluate the risk levels of the forward collision risk scenario, three variables of vehicle movement characteristics and three variables of vehicle interaction characteristics before the braking onset were collected. To compare the collision avoidance behavior, six variables after the braking onset were collected. It is noteworthy that the calculations of TTC and TH during the left turns were modified. The Euclidean distance between two vehicles subtracting one vehicle length was used as the relative distance. The relative velocity was calculated as the difference between the longitudinal velocity of them. Then TTC was calculated as the modified relative distance divided by relative velocity. TH was calculated as the modified relative distance divided by the SV's velocity. In case the value of velocity or velocity difference close to zero would lead to quite unreal large time headway or TTC, we took the logarithm base 10 of TH and TTC in this study.

Figure 7 demonstrated the vehicle movements characteristics and vehicle interaction characteristics before and after the warning, including the velocity of SV and LV, the brake and gas pedal force of SV, the average TH and TTC. The two-time windows used for feature extraction before and after a driver's first brake was painted as light and dark grey, respectively.

For the convenience of observation and comparison, RT was calculated as the time elapsed from reaching the warning threshold to the driver stepping on the brake. Because the warning was triggered at the same time as the LV braked, in the condition without warnings, RT was calculated as the time elapsed from the braking onset of the LV to the driver's stepping on the brake. Then RT could be compared with the same definition. Based on previous studies, time for most drivers in response to risky driving scenarios is 1 s; thus, the time windows painted in grey were 1 s in this study (Eriksson and Stanton, 2017).

3.5 Data analysis

Excluding data of participants with motion sickness or malfunctions of apparatus, a total of 143 collision avoidance events were collected in terms of sudden brakes of the LV on the straight road or during a left turn. Specifically, there were 49 events under the baseline condition without FCW, 53 events under warning condition and 41 events under command condition. As a preliminary analysis, ANOVA was first used to investigate whether the warning type had an impact on the variables about the safety of collision avoidance performance, including $\overline{TH}_{t_0 + \Delta t}$, $\overline{TTC}_{t_0 + \Delta t}$, RT, with a significance level at 0.05 ($\alpha = 0.05$). Those variables were selected for the following model building. Besides, correlation analysis was conducted to investigate the effects of driver demographical variables (age, gender and driving experience) on collision avoidance behavior, and effects of these variables would be controlled in further models.

Moderating effect model and mediating effect model were then developed to examine the hypothesis, namely, the role of workload and FCW information type in the relationship of the forward collision risk scenario and collision avoidance behavior. SPSS PROCESS V3.5, developed by, was used to quantify the moderating and mediating effects. Based on the results of the moderating models, the direct effect of the forward collision risk scenario, FCW information, and their interactive effects on collision avoidance performance could all be analyzed specifically. This contributes to identifying the role of FCW information content in the multi-factor system, including driver, vehicle and environment. Concerned with the mediating effect model, the specific impact path from independent variables to dependent variables can be identified.

4. Results and discussions

4.1 Summary of collision avoidance performance with different forward collision warning

As the evaluation of average driver's collision avoidance performance, results in Table 3 showed that drivers behaved differently with and without FCW provided. In general, FCW helped drivers quickly take safer and stable behaviors to avoid a collision. RT became shorter in the warning or command condition compared with the no warning condition, indicating drivers take a shorter time to react to the emergency. Shorter RT could lead to smaller maximal braking force (larger Bmax) and longer time to reach the maximum (smaller Tmax); in other words, less sudden and violent brakes appeared with FCW provided. Furthermore, with the introduction of FCW, the TH and TTC within 1 s after braking onset were larger than

Table 1 Results of t-tests between two groups

Tested statistics	Descriptive statistics					t-tests (df = 14)	
Mean	SD	Min	Max	*t-value*		*p-value*	
Age							
Group 1 (*m* = 10, *f* = 5)	27.80	7.02	23.00	51.00	−0.33		0.74
Group 2 (*m* = 10, *f* = 5)	28.80	8.82	22.00	59.00			
Driving experience							
Group 1 (*m* = 10, *f* = 5)	6.93	7.50	1.00	33.00	0.08		0.94
Group 2 (*m* = 10, *f* = 5)	6.73	6.36	1.00	28.00			

Figure 6 Counterbalanced experiment procedure for the two groups
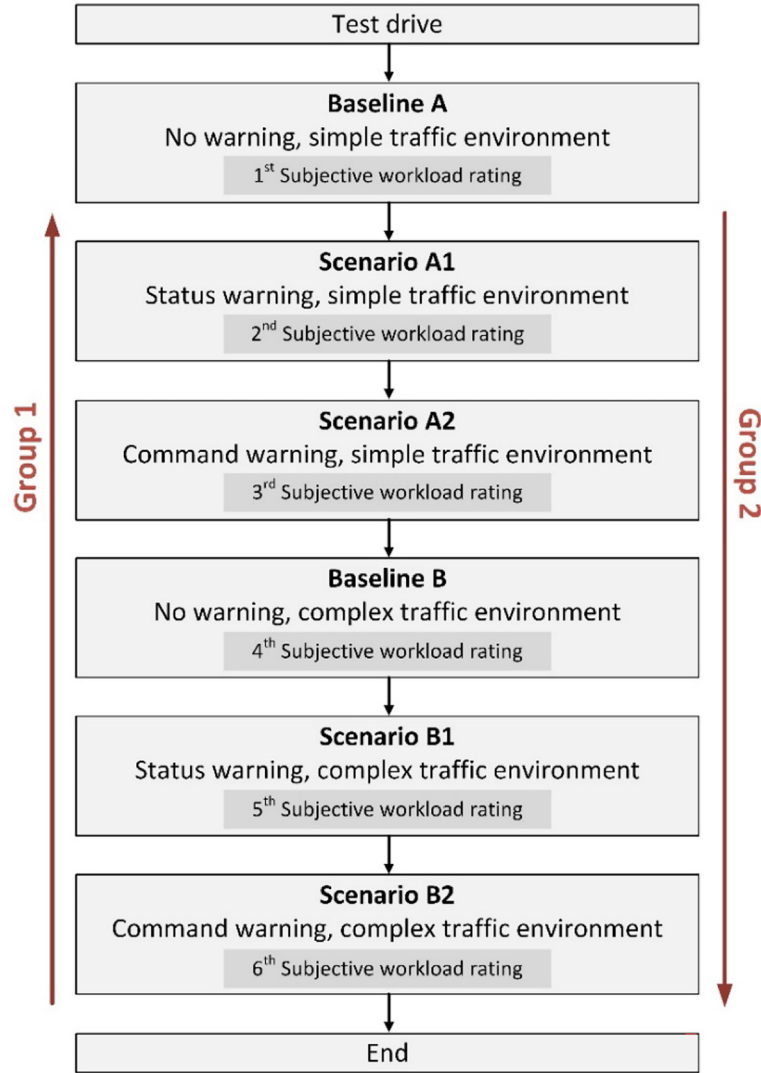
those without warnings. It indicates the effect of improving the safety of collision avoidance, especially when turning left.

During analyses of RT, we found that a small number of drivers received the FCW some seconds later than the LV braked. Then the values of calculated RT were shorter than their real RT as they may be braked before the warning information. These inaccurate values were excluded from this study.

ANOVA results for evaluating collision avoidance performance under three FCW conditions are shown in Table 4. Statistically significant differences ($p < 0.05$) in $Lg(\overline{TH}_{t_0 + \Delta t})$, $Min\overline{TH}_{t_0 + \Delta t}$, $Lg(\overline{TTC}_{t_0 + \Delta t})$ were found. Because $\overline{TH}_{t_0 + \Delta t}$, $\overline{TTC}_{t_0 + \Delta t}$ failed to meet a normal distribution required by ANOVA tests, the logarithm base 10 of them $Lg(\overline{TH}_{t_0 + \Delta t})$, $Lg(\overline{TTC}_{t_0 + \Delta t})$ was taken. Based on these results, $Lg(\overline{TH}_{t_0 + \Delta t})$ $Min\overline{TH}_{t_0 + \Delta t}$, $Lg(\overline{TTC}_{t_0 + \Delta t})$ were selected as variables in further models to evaluate the safety of collision avoidance performance.

4.2 Correlation between driver demography and the forward collision risk scenario

Correlation analysis results showed weak correlations between variables of driver demography (i.e. age, driving experience and gender) and the forward collision risk scenario (including vehicle movement and vehicle interaction). It was found that age was positively related to the velocity of SV ($r = 0.17$, $p < 0.01$) and the average distance between lead and SV ($r = 0.27$, $p < 0.01$). The driving experience was also positively related to the velocity of SV ($r = 0.13$, $p < 0.01$) and average distance ($r = 0.23$, $p < 0.01$). Gender showed a positive correlation with average distance ($r = 0.11$) and the SV's acceleration ($r = 0.16$). It means male drivers had a larger average distance and SV's acceleration than females. Though the demographic variables showed weak correlations with the variables of vehicle interaction characteristics, they still affected the risk levels of driving scenarios. We used them as control variables to rule out

Table 2 Descriptions of collected variables

Category	Variable	Explanation
Demography	Age	Driver's age
	Driving experience	Driver's driving experience
	Gender	Driver's gender
Time interval	Δt	Small time interval (e.g.1 s)
Vehicle movements characteristics	$\overline{V}_{t_0 - \Delta t}^{SV}$	Average velocity of subject vehicle during Δt before subject vehicle braking
	$\overline{a}_{t_0 - \Delta t}^{LV}$	Average acceleration of lead vehicle during Δt before subject vehicle braking (negative values denote deceleration)
	Min $a_{t_0 - \Delta t}^{LV}$	Minimal acceleration of lead vehicle during Δt before subject vehicle braking
Vehicle interaction characteristics	$\overline{D}_{t_0 - \Delta t}$	Average distance between lead and subject vehicle during Δt before subject vehicle braking
	$\overline{TH}_{t_0 - \Delta t}$	Average time headway between lead and subject vehicle during Δt before subject vehicle braking
	$\overline{TTC}_{t_0 - \Delta t}$	Average time-to-collision (TTC) of subject vehicle during Δt before subject vehicle braking
Mental workload	W	Driver's subjective rating of workload during car-following based on NASA-TLX
Collision avoidance behavior	$Lg\left(\overline{TTC}_{t_0 + \Delta t}\right)$	Take the logarithm base 10 of average TTC between lead and subject vehicle during Δt after subject vehicle braking
	$Lg\left(\overline{TH}_{t_0 + \Delta t}\right)$	Take the logarithm base 10 of average time headway between lead and subject vehicle during Δt after subject vehicle braking
	$Min\overline{TH}_{t_0 + \Delta t}$	Minimal time headway between lead and subject vehicle during Δt after subject vehicle braking
	RT	Driver's braking reaction time from lead vehicle braking to subject vehicle braking
	Bmax	The maximal brake pedal force exerted by the driver after the lead vehicle braked
	Tmax	The time of reaching the maximal brake pedal force

the potential effect on collision avoidance performance in the further model.

4.3 Moderating effect of in-vehicle warnings
To further identify how different warning information affects the relationship between the forward collision risk scenario and collision avoidance performance, we proposed moderating models based on ANOVA results in Table 4. Three significant collision avoidance behavior variables ($Lg\left(\overline{TH}_{t_0 + \Delta t}\right)$, $Min\overline{TH}_{t_0 + \Delta t}$, $Lg\left(\overline{TTC}_{t_0 + \Delta t}\right)$) were dependent variables and six independent variables were investigated to describe risk levels of driving scenarios. While RT did not exhibit significant differences in different FCW conditions, it

Figure 7 Variables extracted before and after driver's first brake for collision avoidance
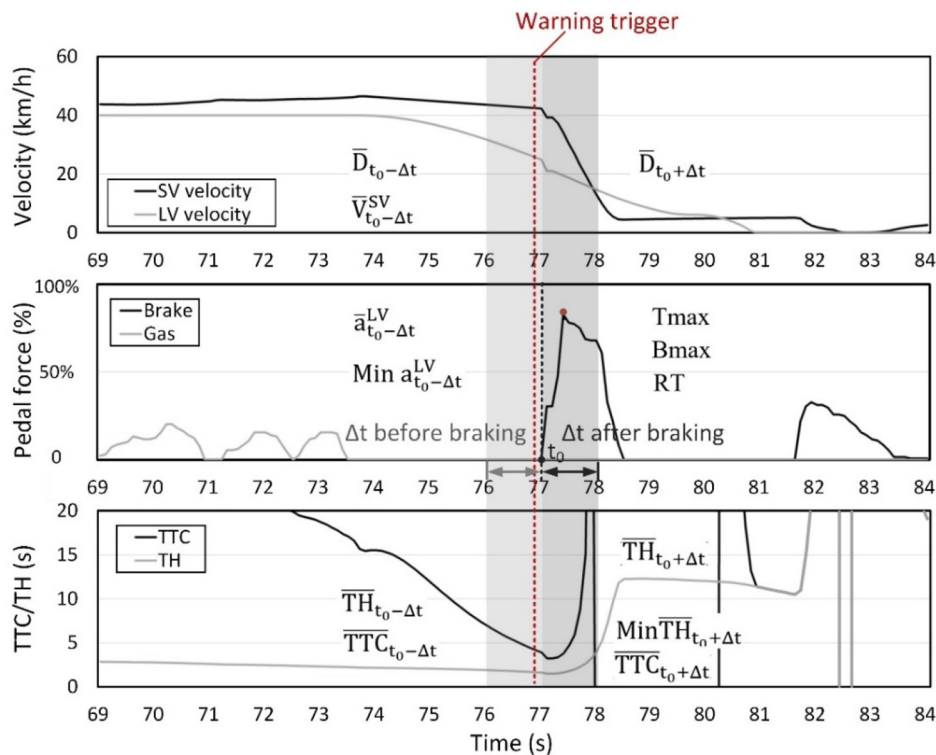
Table 3 Differences of driver's collision avoidance performance under different road environment

FCW	Scenario	$\overline{D}_{t_0 + \Delta t}$	$\overline{TH}_{t_0 + \Delta t}$	$\overline{TTC}_{t_0 + \Delta t}$	Bmax	RT	Tmax
None	Straight	15.44	0.64	2.90	0.94	0.81	0.41
None	Turn left	13.93	0.52	2.83	0.86	1.00	0.57
Warning	Straight	14.75	0.95	2.83	0.90	0.76	0.53
Warning	Turn left	14.85	1.73	3.02	0.83	0.73	0.84
Command	Straight	18.37	2.75	3.35	0.86	0.78	0.59
Command	Turn left	15.54	0.78	4.20	0.78	0.70	0.66

Table 4 ANOVA results in three FCW conditions

Variables	FCW information (M±SD)				df = 140
None	Warning	Command	*F*-value	*p*-value	
(*n* = 49)	(*n* = 53)	(*n* = 41)			
$\overline{D}_{t_0 + \Delta t}$	16.15 ± 6.68	16.28 ± 6.61	18.26 ± 5.74	1.493	0.228
$\mathbf{Lg}\left(\overline{TH}_{t_0 + \Delta t}\right)$	−0.26 ± 0.18	−0.22 ± 0.36	−0.09 ± 0.39	3.518	0.032*
$\mathbf{Min}\overline{TH}_{t_0 + \Delta t}$	0.42 ± 0.14	0.42 ± 0.13	0.53 ± 0.17	8.175	0.000**
$\mathbf{Lg}\left(\overline{TTC}_{t_0 + \Delta t}\right)$	0.39 ± 0.31	0.39 ± 0.26	0.48 ± 0.29	3.087	0.049*
Time of Max Brake	0.48 ± 0.40	0.65 ± 0.67	0.62 ± 0.47	1.447	0.239
Max brake	0.91 ± 0.17	0.87 ± 0.22	0.83 ± 0.25	1.595	0.207
RT	0.91 ± 0.13	0.80 ± 0.11	0.70 ± 0.15	1.946	0.120

Notes: $^*p < 0.05$ $^{**}p < 0.01$

was still used as the independent variable due to the explicitly and importance of indicating drivers' responses. Then twenty-four moderating models were established based on these variables. All the continuous independent variables were standardized to further compare their relative importance of them.

In four of these models, warning type showed a significant moderating effect, as shown in Figure 8. The estimated coefficients (*B*) and their significance (*p*) results are listed in Tables 5 and 6. All independent variables included in the four models significantly explained the 4.3%–19.3% variation of the collision avoidance performance. The coefficients of demographical variables were around 0.1 and could not be excluded from the model. Because they were just control variables, their

effects on collision avoidance performance (dependent variables) could be influenced by other unobserved factors.

The rest of the models showed no significant moderating effects of FCW information, and they will not be discussed in this paper. One possible reason for the insignificance may be the small sample size. The second possible reason may be the individual difference. Drivers can have different feelings, understandings and responses toward the FCW information, thus blurring the moderating effect. Third, warning information did not have a moderating effect on some variables. These independent variables did not directly affect the dependent variables, and the relationship between them can also not be changed by FCW information. Key findings are summarized as follows:
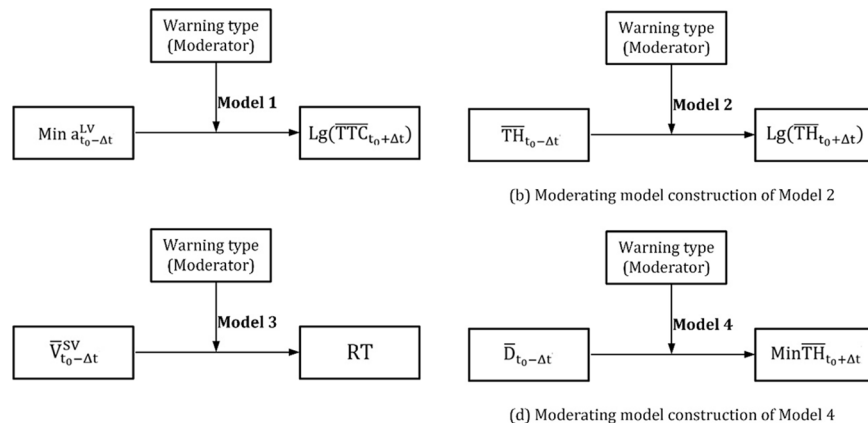
Figure 8 Three models with significant moderating effects of FCW information

(b) Moderating model construction of Model 2

(d) Moderating model construction of Model 4

Table 5 Moderating effects of FCW information on $Lg\left(\overline{TTC}_{t_0+\Delta t}\right)$ and $Lg\left(\overline{TH}_{t_0+\Delta t}\right)$

Independent variables	Model 1 ($Lg\left(\overline{TTC}_{t_0+\Delta t}\right)$): F = 5.833; p < 0.001		Model 2 ($Lg\left(\overline{TH}_{t_0+\Delta t}\right)$): F = 7.741; p < 0.001	
Independent variables	B	p	B	p
Age	−0.145	0.220	−0.085	0.513
Driving experience	0.073	0.538	0.105	0.42
Gender	−0.019	0.629	−0.096	0.03
Min $a_{t_0-\Delta t}^{LV}$	0.130	0.036		
FCW information	0.132	0.095		
Min $a_{t_0-\Delta t}^{LV}$ * FCW information	0.111	0.047		
$\overline{TH}_{t_0-\Delta t}$			0.346	0.000
FCW information			0.041	0.639
$\overline{TH}_{t_0-\Delta t}$ * FCW information			−0.133	0.040

Table 6 Moderating effects of FCW information on RT and $Min\overline{TH}_{t_0+\Delta t}$

Independent variables	Model 3 (RT): F = 1.46; p < 0.01		Model 4 ($Min\overline{TH}_{t_0+\Delta t}$): F = 7.390; p < 0.001	
Independent variables	B	p	B	p
Age	0.093	0.370	0.005	0.883
Driving experience	−0.092	0.376	−0.006	0.859
Gender	0.026	0.447	−0.006	0.612
$\overline{V}_{t_0-\Delta t}^{SV}$	−0.040	0.397		
FCW information	−0.065	0.347		
$\overline{V}_{t_0-\Delta t}^{SV}$ * FCW information	−0.090	0.044		
$\overline{D}_{t_0-\Delta t}$			0.046	0.007
FCW information			0.017	0.471
$\overline{D}_{t_0-\Delta t}$ * FCW information			0.049	0.036

- The risk level of the driving scenario was significantly related to collision avoidance performance, and the relationships were moderated by warning type.

The significant moderating effects of FCW information on $Lg\left(\overline{TTC}_{t_0+\Delta t}\right)$ and $Lg\left(\overline{TH}_{t_0+\Delta t}\right)$ were shown in Table 5. Model 1 showed there was a positive effect of minimal acceleration of LV (Min $a_{t_0-\Delta t}^{LV}$) on $Lg\left(\overline{TTC}_{t_0+\Delta t}\right)$) after braking ($b = 0.130, p < 0.05$), and this effect was significantly moderated by FCW type ($b = 0.111, p < 0.05$). This indicates low acceleration of the LV (higher deceleration rate) could lead to a small average TTC, reflecting high collision risk. With FCW provided, the collision risk could be further increased by the additional moderating effect on the relationship between minimal acceleration and average TTC.

Model 2 showed the average time headway before braking ($\overline{TH}_{t_0-\Delta t}$) had a positive effect on $Lg\left(\overline{TH}_{t_0+\Delta t}\right)$ after braking ($b = 0.346, p < 0.001$), and this effect was moderated by FCW information shown by the significant coefficient of the interaction term ($b=-0.133, p < 0.05$). This finding suggests large average time headway before braking, indicating a low-risk level of the driving scenario was related to a safe performance indicated by large average time headway after braking. In this model, FCW information moderated the collision avoidance performance to be less safe as its negative coefficient both affected the direction and effect size of the relationship between average time headway before and after the braking onset.

Results in Table 5 showed the FCW information could significantly affect driver's RT and time headway. Model 3 indicated the SV's velocity before braking ($\overline{V}_{t_0-\Delta t}^{SV}$) had a negative effect on the driver's braking RT ($b = -0.040$, $p > 0.05$). Though this effect between independent and dependent variables was not significant, it was significantly moderated by FCW information ($b = -0.090$, $p < 0.05$). Specifically, larger velocity was related to shorter RT, and with FCW provided, the RT could be significantly shorter.

In terms of Model 4, it indicated the average distance between the LV and SV ($\overline{D}_{t_0-\Delta t}$) had a significant positive effect on $Min\overline{TH}_{t_0+\Delta t}$ after braking ($b = 0.046, p < 0.05$) and was moderated by FCW information ($b = 0.049, p < 0.05$). A short average distance showing the high-risk level of driving scenarios was related to small minimal time headway after braking. With the moderating effect of FCW, the minimal time headway could be significantly smaller:

- Command better improves collision avoidance performance compared with warning by weakening the negative effect of the forward collision risk scenario on collision avoidance performance

To further analyze the significant moderating effect of warning type, a simple slope analysis was carried out (Figure 9). Simple slope indicated the regression relation between independent and dependent variables under the condition of different levels or categories of the moderating variable. For continuous variables, the different levels included a low level (one standard

Figure 9 Simple slope analysis of the forward collision risk scenario and collision avoidance performance under warning and command FCW
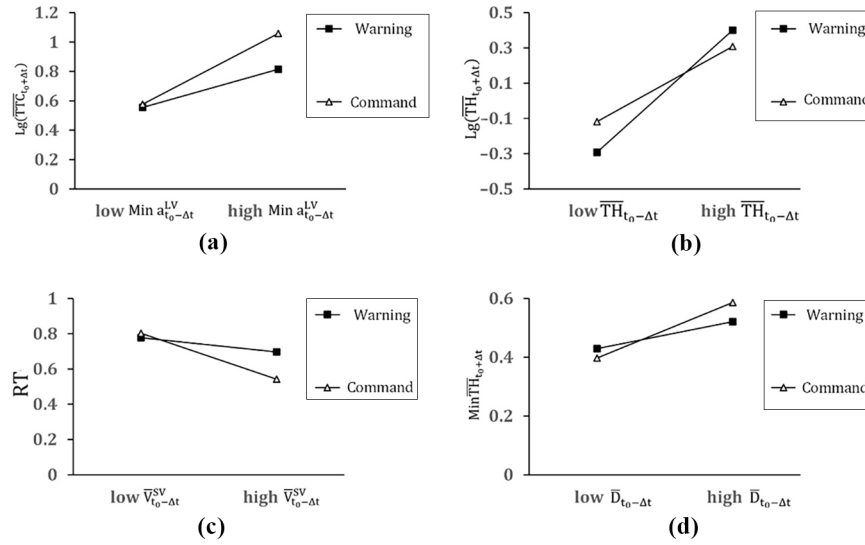
deviation below the mean) and a high level (one standard deviation above the mean). Independent variables also ranged from these two levels. When independent variables were standardized, the value of low level was -1, and the value of high level was 1, indicating variation of two units of independent variables.

In Figure 9, different slopes represented different effects of low and high-risk levels (independent variables) on collision avoidance performance after braking onset (dependent variables) with two FCW information provided, respectively, warning and command.

As shown in Figure 9(a), simple slope results demonstrated $Lg(\overline{TTC}_{t_0 + \Delta t})$ was larger in command condition than in warning condition. As the minimal acceleration ($Min\ a^{LV}_{t_0 - \Delta t}$) increased from the low level to the high level (the deceleration rate of LV became smaller), $Lg(\overline{TTC}_{t_0 + \Delta t})$ increased faster when the command was introduced ($b_{simple}=0.240$, $p < 0.001$) compared with providing warning ($b_{simple}=0.130$, $p < 0.05$). In other words, the command can lead to better safety benefits, especially when the driving scenario was less risky, indicated by a small deceleration of LV (high level of minimal acceleration).

Figure 9(b) demonstrated the relationship between average headway ($\overline{TH}_{t_0 - \Delta t}$) before braking and after braking ($Lg(\overline{TH}_{t_0 + \Delta t})$) under two FCW conditions. The command could lead to larger $Lg(\overline{TH}_{t_0 + \Delta t})$ ($b_{simple}=0.213$, $p < 0.001$) than warning at risky situations with the low level of $\overline{TH}_{t_0 - \Delta t}$. However, when the situation was less risky with a high level of $\overline{TH}_{t_0 - \Delta t}$, warning performed better in increasing $Lg(\overline{TH}_{t_0 + \Delta t})$, the average time headway after braking ($b_{simple} = 0.346$, $p < 0.001$).

Figure 9(c) plotted the relationship between the velocity of SV ($\overline{V}^{SV}_{t_0 - \Delta t}$) and brake RT with warning and command as moderators, respectively. As $\overline{V}^{SV}_{t_0 - \Delta t}$ became larger, RT was generally shorter in the command condition ($b_{simple} = -0.131$, $p < 0.05$) compared with the warning condition ($b_{simpl}= -0.040$, $p > 0.05$). The difference of RT was the largest under the condition of high level $\overline{V}^{SV}_{t_0 - \Delta t}$. This indicates command can significantly reduce RT when drivers drive at a high velocity before an emergency occurs.

Figure 9(d) showed the relationship of minimal headway after braking ($Min\overline{TH}_{t_0 + \Delta t}$) and the average distance between LV and SV ($\overline{D}_{t_0 - \Delta t}$) moderated by FCW information. Simple slope tests demonstrated that when the command was introduced, $Min\overline{TH}_{t_0 + \Delta t}$ was larger ($b_{simple}=0.095$, $p < 0.001$) than that in warning condition ($b_{simple}=0.046$, $p < 0.05$) at the high level of $\overline{D}_{t_0 - \Delta t}$. When $\overline{D}_{t_0 - \Delta t}$ was at a low level, the warning condition could lead to a little larger $Min\overline{TH}_{t_0 + \Delta t}$. The result indicates command has a positive effect on increasing minimal time headway when the driving scenario was less risky with a longer average distance.

To summarize, the command can more effectively improve the safety of collision avoidance performance compared with a warning when the driving scenario tends to be riskier. Specifically, average TTC was larger in the command condition when the deceleration rate of LV was small (high-level acceleration). Besides, RT could be reduced with a command provided when driving at a high velocity before an emergency occurred.

4.4 Mediating role of mental workload
To investigate the hypothesis that mental workload plays a mediating role in the relationship between the forward collision risk scenario and collision avoidance performance, mediating effect models were further built on the model structure of the four moderating models above. A total of 5,000 replications bootstrap analyses were carried out using SPSS PROCESS V3.5 developed by Hayes (2013).

Significant mediating effects were found on the basis of the above Models 2 and 3, which were between the velocity of SV and RT (Figure 10), average time headway before and after braking onset (Figure 11). The arrows show the direction of effects between pairs of relationships, and values above the arrows represent the regression coefficients of independent variables. Workload did not play a mediating role in the structure of Models 1 and 4, and these two models were not further discussed in this study.

- Statistical analysis of mental workload evaluated by NASA-TLX.

In this study, the mental workload was measured by NASA-TLX, ranging from 0 to 100 after each drive in the 3 (FCW information type) × 2(the forward collision risk scenarios) within-subjects repeated measures. The distribution of NASA-TLX scores was summarized in Table 7. When the visual content of FCW information was none or command, more than 75% of participants (75% in none, 81.8% in command) had a workload under 80. But in the warning condition, only 69.9% of the participants showed workload under 80. It indicates the warning information could lead to a higher level of mental workload than no FCW. But the results of low workload in command conditions may be due to the imbalanced number of events (53 under warning vs 41 under command).

Based on Figures 10 and 11, it can be found that increased workload induced by warning or command could result in shorter RT and longer time headway, showing improved collision avoidance performance. The finding is corresponding to the upward part of the inverted U-shape curve in Yerkes-Dodson Law (1908), which exhibits the proper workload increases improve performance. The specific comparison of warning and command were as follows.

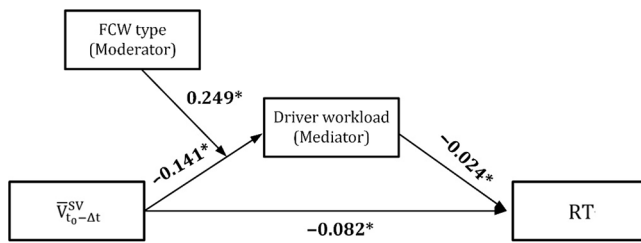**Figure 10** Mediated moderation between subject vehicle velocity and reaction time

- Command leads to shorter RT than warning by increasing moderate mental workload

Figure 10 demonstrated the velocity of SV could affect RT both directly and through the mediating effect of the driver's mental workload. Based on moderating effect models in the previous section, it was shown that FCW information played a role in the relationship of the velocity and RT (Model 3). Herein, a more accurate impact mechanism of FCW information was found in affecting velocity and workload as a moderator.

In addition, the shorter RT due to high velocity (...) ($b = -0.082$, $p < 0.05$), the command could also reduce RT by increasing the driver workload than warning. As shown by the path mediated by the mental workload in Figure 10, FCW showed significant moderating effects on velocity and mental workload ($b = 0.249$, $p < 0.05$). Larger velocity was related to decreased workload under warning conditions ($b = -0.141$, $p < 0.05$) but related to increased workload under command conditions ($b = 0.108$, $p < 0.05$). It means that the introduction of command can raise the mental workload reduced by a larger velocity of SV, and then leads to shorter RT.

- Command also leads to larger time headway than a warning by increasing moderate mental workload

Figure 11 showed that the direct relationship between time headway before and after braking was significant ($b = 0.263$, $p < 0.01$), and the relationship was also mediated by mental workload. Similarly, FCW information was found to significantly affect time headway before braking and workload ($b = -0.134$, $p < 0.05$) on the basis of moderating effect Model 2.

In the mediated path, shorter average time headway before braking was related to increased workload ($b = -0.027$, $p < 0.05$) under warning and command ($b = -1.161$, $p < 0.05$).

Figure 11 Mediated moderation between average time headway and collision avoidance performance
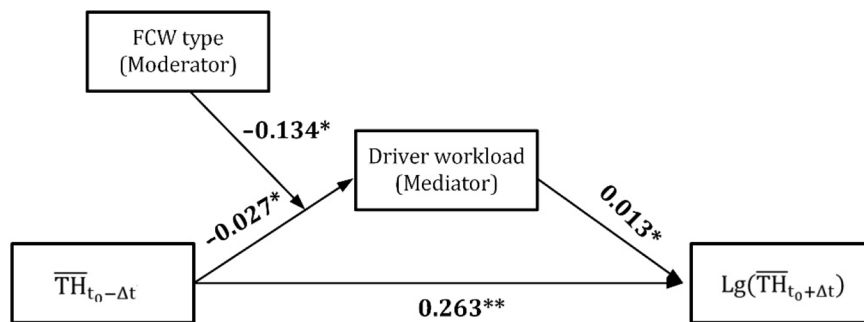
Table 7 Range of mental workload evaluated by NASA-TLX in three FCW conditions

FCW	NASA-TLX score				
	0–20	20–40	40–60	60–80	80–100
None (85% quantile = 62.0)	0.0%	50.0%	25.0%	25.0%	0.0%
Warning (85% quantile = 66.3)	3.3%	33.3%	33.3%	26.8%	3.3%
Command (85% quantile = 59.6)	0.0%	27.3%	54.5%	18.2%	0.0%

When time headway before braking was short (higher risk levels), the command can lead to higher levels of workload compared with the warning, further contributing to large headway after braking. This indicates command was more effective to improve collision avoidance performance in the forward collision risk scenario.

5. Conclusions

This simulator-based study analyzed the effect of in-vehicle FCW information on the relationship between the forward collision risk scenario and collision avoidance performance. A positive moderating effect of FCW information content was found between them. Command was found to increase collision avoidance performance with larger time headway and shorter RT. This conclusion is consistent with previous findings that command is suitable for yielding safety benefits in urgent situations.

Contributions of this paper can be summarized as follows. First, mediated moderation models were developed to further investigate the specific way that moderating effect of FCW information works. Modeling results suggest that mental workload serves as a mediator between vehicle interaction characteristics and collision avoidance performance. During the car-following task, the mental workload was positively correlated with collision avoidance performance, which corresponds to the upward of the U-shape curve in Yerkes-Dodson Law. The results showed that command could yield greater safety benefits than warning under urgent situations during car-following. These findings provide guidance to the designers of in-vehicle warnings.

According to ISO 15623(2013), a preliminary collision warning is optional. Therefore, a preliminary collision warning can be used when the average time headway between LV and SV is relatively large. The warning is suitable as a preliminary cue of collision. When the situation is riskier, such as when the time headway is shortening or when driving at high velocity, the command can lead to more safety benefits by shortening RT.

Moreover, the mediating effect of driver workload is also useful for dynamic and personalized warning design. Because the increase of driver workload can help shorten the driver's RT and increase time headway, it can be possible to modify collision warning information content according to mental workload. Driver workload can be estimated by previous driving behavior, along with the surrounding traffic environment perceived by sensors. When the driver has been shown to be under a high level of mental workload, the command will not be suitable. Because it may increase workload, the overload risk may result in worse performance. Under this condition, no warning can be a good option to reduce the disturbance to drivers. Future studies would consider increasing the sample size for further examining the results in this paper.

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