TRB Annual Meeting

Pedestrian Perception of Vehicle Movement Information in Virtual Reality: A Subjective and Objective Analysis

--Manuscript Draft--

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Pedestrian Perception of Vehicle Movement Information in Virtual Reality: A Subjective and Objective Analysis

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ABSTRACT

Owing to high level of immersion and safety, Virtual Reality (VR) technology is currently considered to be an effective research tool for studying pedestrian-vehicle interaction behavior. This paper has examined how pedestrians perceive vehicle movement information in Virtual Reality (VR) versus real-world environments, crucial for understanding the reliability of interactions in VR settings. In this paper, we designed two tasks to estimate vehicle speed and time-to-arrival (TTA), conducting experiments in both environments and collecting subjective data with 37 participants. Using the analysis of variance (ANOVA) method, we compared subjects' perception of vehicle motion and explored how factors such as vehicle speed and individual characteristics influenced the results. Findings reveal that pedestrians often underestimate vehicle speed in VR compared to real-world scenarios, yet their estimation of time-to-arrival remains consistent. Regard of the estimation accuracy, vehicle speed has the same affect on subjects' estimation results in both environments. Furthermore, the study examines how individual characteristics affect perception outcome. Objective assessment by employing the Vienna Test System (VTS) indicates that subjects' perception of motion in VR can reflect their objective abilities in real-world environments. These research findings can provide theoretical insights for further research related to VR-based pedestrian-vehicle interactions, emphasizing the importance of environmental fidelity in research applications.

Keywords: Human-vehicle Interaction; Virtual Reality; Pedestrian Perception Characteristics; Vienna Test System

INTRODUCTION

In recent years, as new types of traffic participants represented by autonomous vehicles participate in the urban road commuting environment, the increasingly complex traffic environment has led to the highlighting of safety issues related to pedestrians, a vulnerable group of traffic participants. According to statistics, a total of 3907 road traffic accidents caused by pedestrians occurred in China in 2022, in which the mortality rate of pedestrians amounted to 36.1% and the injury rate was as high as 75.6%, which is at the forefront of all types of traffic accidents (*1*). Pedestrian's accurate perception of vehicle motion status is a prerequisite for making correct behavioral decisions. Therefore, pedestrian-vehicle conflict model can describe the relative positional relationship using parameters such as distance, speed, and time, thus realizing an accurate assessment of the severity of the conflict between pedestrians and motor vehicles (*2*). Mathematical modeling, statistical analysis, subjective questionnaires (*3*), video assessment (*4*), Wizard-of-Oz vehicle simulation experiments (*5*), and virtual reality (VR) simulation experiments are often used to study the behavioral and perceptual characteristics of pedestrians during pedestrian-vehicle conflicts.

With the advancement of virtual reality (VR) technology, the advantages of VR devices such as lower cost and higher environmental immersion are oustanding. Head-mounted displays (HMD) technology is employed to conduct pedestrian traffic behavior studies and try to verify the effectiveness of the technology (*6,7*). For instance, Deb et al. (*8*) used HMD to study the validity of VR technology in pedestrian safety research, analyzing the immersion experience of walking speed, collision situation and subjective feedback from the subjects. The results showed that the subjects' performance in the VR scene matched their behaviors in the real environments.

However, there still exists some differences between the behavioral and perceptual characteristics of pedestrians in real and VR environments. It has been shown that pedestrians tend to behave more aggressively while crossing in VR environment than in real environment, which may be related to a variety of factors such as the immersion level of VR environment, sensory realism, and experimental design approach (*3*). Some researchers have proposed experimental methods for quantitatively investigating such differences. For example, Bhagavathula et al. proposed a comparative study method for quantifiable data collection that required subjects to estimate and report information on the speed and separation distance of oncoming vehicles in two environments (*9*). However, this study was limited to an experimental design with a single vehicle moving at a single speed (25km/h) and still relied on subjective questionnaire evaluations.

In general, current studies often neglect the verification of the reliability of experimental data in VR environment, and the reliability conclusions of the studies are limited to the observation of experimental participants' subjective behaviors and rely too much on subjective questionnaire evaluations. There is not enough quantitative information on the perception characteristics of pedestrians in real and VR environments. Therefore, in this paper, we explored the characteristics of pedestrians' perception of vehicle motion information in VR environment from subjective and objective perspectives, respectively.

The main contributuons of this paper are shown as follows:

1. The estimated deviations of pedestrians' judgments of vehicle speed and time-to-arrival (TTA) are employed as objective quantitative perceptual indicators to qualitatively analyze the differences in pedestrians' perceptual characteristics of vehicle motion information in both real and VR environments.

2. To exclude the influence of irrelevant variables on the data collection results and to simplify the experimental process, this study used live video recordings in real environment and replicating scenarios in VR environment for the comparison experiment.

3. This study required subjects to use the Vienna Test System (VTS), a more reliable, result-confident, and widely used traffic psychological assessment tool, for the objective assessment of each subject's motion perception ability.

METHODS

Experimental Configurations

Real-world Video Footage Capture

In order to control the influence of irrelevant variables (e.g., light, weather, vehicle state, etc. in the real-world scenario) on the collection of experimental data, and to ensure that each subject has the same experimental experience, this paper adopts the method of watching the video recordings of vehicle driving in the real world (hereinafter referred to as the real-world video recordings) to carry out the experiments on the perception of vehicle motion information.

The real-world video recordings used in this paper were taken at the automobile test site of Chang'an University Weishui Campus, Xi'an City, Shaanxi Province, China. The test section selected for filming was a straight line, 300m long, with two lanes, each 3.75m wide. A high-definition camera was placed on the side of the road, and the shooting height was adjusted to 170 cm. The specific shooting route is shown in **Figure 1**, in which the arrow marking the road section is the driving route of the vehicle in the video recording, and the dot is the placement position of the high-definition camera. The vehicle used for video recording was a silver-gray Volkswagen Touran, which was equipped with cruise control to precisely control the vehicle's driving speed. The vehicle was asked to reach a specified driving speed before 200m from the camera placement and to maintain a constant speed. In this study, the vehicle was recorded traveling at a constant speed at seven speed levels, 30km/h, 35km/h, 40km/h, 45km/h, 50km/h, 55km/h, and 60km/h, in the lane close to the camera side.

Figure 1 Video recording location

Real-world Video Display Equipment

The real-world video was displayed by a large surround-screen display system that was able to provide a similar level of immersion as observing an oncoming vehicle in a real-world scenario through a high-resolution screen (5760*1920) and three stereo surround sound units, as shown in **Figure 2**, which was rated highly by the subjects in terms of subjective feedback. In addition, a handheld timing button (Bluetooth link) was provided to the subjects in this experiment to facilitate decision-making signal input during the vehicle movement information perception test.

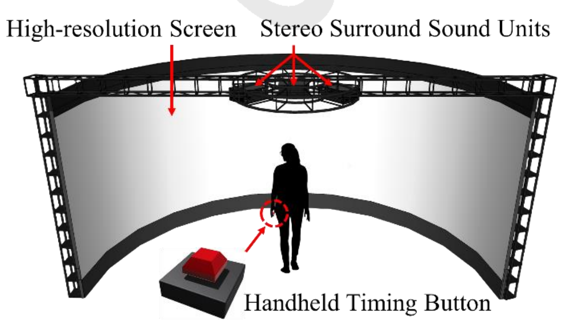


Figure 2 Diagram of real-world video test

VR Equipment

A pedestrian simulator equipped with HTC Vive head-mounted VR displays (**Figure 3**) is used to present the VR scenerio, which is constructed by using the SILAB traffic simulation software. The VR scenerio reproduces the real-world experimental roadway as much as possible, and the height of the pedestrian viewpoints is consistent with that of the real-world video. To exclude the possible influence of vehicle characteristics, the simulated vehicle used in VR scenerio has the same model and color as those in the real-world video.

Figure 3 Pedestrian simulator

Participants

A total of 40 volunteers were recruited as subjects, all of whom were in good physical health, and had a visual acuity of 4.8 or higher, either naked or corrected. During the later experiments, 3 participants dropped out because they reported strong discomfort with the VR environment, and their experimental data will not be used for analysis. Thus, 37 valid participants included 13 females and 24 males, ranging in age from 18 to 26 years old, with a mean age of 22 years old and a standard deviation of 2.2 years old. Because the main purpose of this study was to do a comparative study of the subjects' performance in the two environments, the age variable was not part of the main discussion of this paper, so the age distribution of the participants is only discussed as a control variable in this paper only.

Experimental Procedures

The whole experiment procedures in this paper are shown in **Figure 4**.

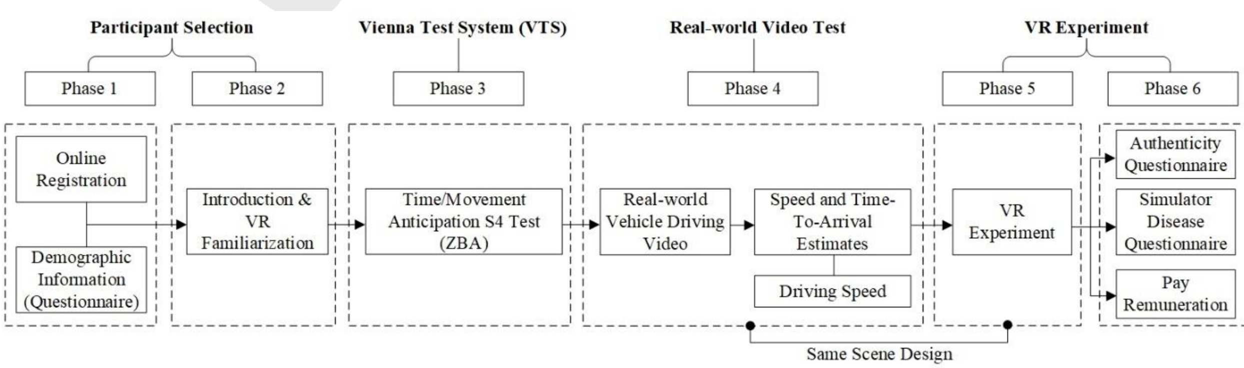


Figure 4 Experiment procedures

Experimental Tasks

The perception task of pedestrians to the ongoing vehicles in this study includes two main tests, namely the vehicle moving speed estimation task and the vehicle time-to-arrival (TTA) estimation task. Additionally, all subjects were required to participate in a time/movement anticipation test by Vienna Test System before Task 1 and Task 2.

Movement Perception Ability Test

Individuals may vary greatly in their ability to perceive information about the motion of objects. Traffic psychology theory reveals that the ability to spatially and temporally locate moving objects and predict their trajectories directly will affect an individual's safety in the traffic environment. As a professional assessment system that integrates personality traits, reactivity, perceptual abilities, and other psychological abilities (*11*), Vienna Test System (VTS) provides a reliable and objective method for evaluating personal motion perception. Many past studies have demonstrated its validity and some national officials have widely used this system in the field of psychological research (*12*).

The “Time/Movement Anticipation” S4 module of the VTS was employed to test each subject’s movement perception ability, and the test devices and interface are shown in **Figure 5**. The test was presented as follows: a green ball appeared on the screen and moved at a constant speed; at a random moment, the ball suddenly disappeared, and a red line appeared on the screen; subjects were required to press a specified button at the moment when they thought the ball had reached the red line. In a set of tests, subjects were required to perform the estimation task 30 times, and the speed of movement of the ball was variable in each task.

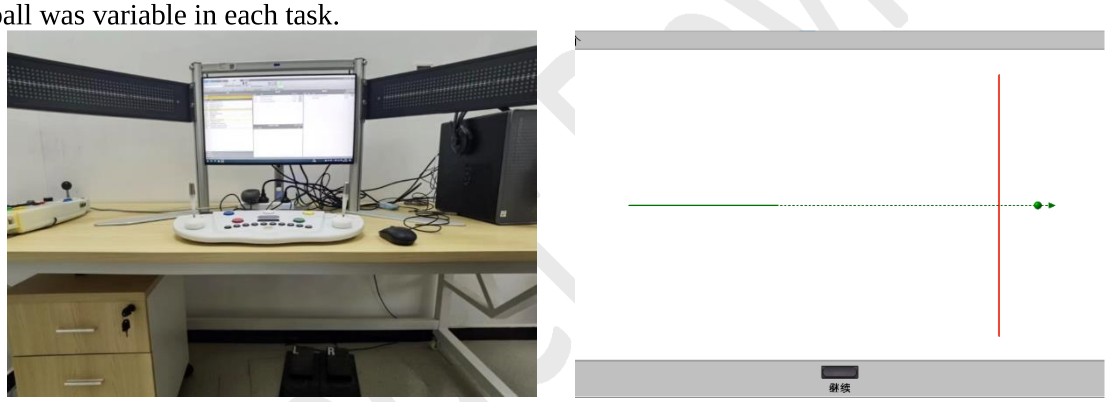


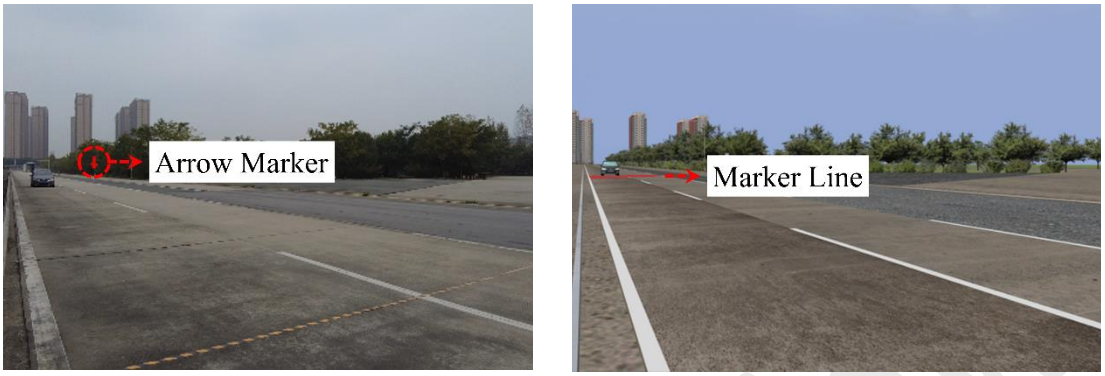
Figure 5 VTS devices (left) and “Time/Movement Anticipation” S4 module testing (right)

In this paper, the final score evaluation of this test is fitted based on the results of five indicators in the test result document: number of overestimations, number of underestimations, number of extreme over- and underestimations, median deviation time (total), and median direction deviation (total). Higher scores represent poorer personal movement perception abilities.

Task 1: Speed Estimation

In each real-world video clip, the vehicle approached at a constant speed from a position 200m away from the pedestrian. An arrow was added as a marker at a location 50m away from the pedestrian's main viewpoint location (**Figure 6 (a)**). When the vehicle reached the arrow marker, subjects were asked to immediately make a judgment about the vehicle's speed and report it verbally. During the experiment, video clips were presented in a randomized order. Each video clip appeared twice, and a 10-second countdown preparation time was set aside between adjacent video clips so that subjects were ready to watch the next video clip.

The VR environment scenario was set up in the same way as the real-world video clip scenario, and again the sitmulated vehicle was presented in a randomized order (different order than the real-world video) to avoid a learning effect. Similarly, each speed level will be repeated twice, and after 5 seconds of each vehicle moving out of the subject's field of view, the next vehicle will reappear at the same departure position. Instead of the indicator arrows in the real-world video, a marker line was set up 50m away from the pedestrian's position in the VR scene (**Figure 6 (b)**), and subjects should report their estimate of the vehicle's speed as soon as the vehicle reached the line.



(a) Real-world video (b) VR environment

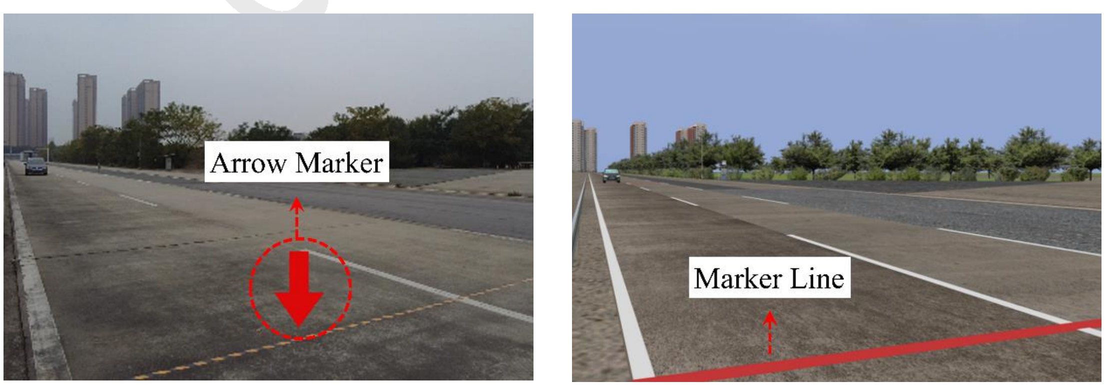
Figure 6 Schematic diagram of scenarios in Task 1

Task 2: Time-To-Arrival Estimation

The vehicle Time-To-Arrival (TTA) estimation task design used a classical occlusion paradigm (*10*), an experimental approach that has been widely recognized and used in past studies on arrival time estimation of moving objects.

The processing of the real-world video footage used in task 2 is similar with task 1. The difference is that the video footage will become still when the vehicle reaches the 50m marker and an arrow mark will appear at the stop line in front of the pedestrian's main viewpoint as the end of the TTA estimation interval. Subjects were asked to estimate the moment when the head of the vehicle reached the stop line and pressed the handheld timing button. The deviation of the estimated TTA from the correct one was automatically recorded in the computer system after the subject pressed the handheld timing button (in seconds, with three significant digits). This deviation value will not be known to the subjects until the end of the whole tasks, so as not to affect the results of both experiments.

In the VR environment scenario, similar to the change of the VR scenario in Task 1, the arrow marker was also replaced with marker lines. In order to avoid subjects' misunderstanding of the test task, the marker line will disappear directly when the vehicle touches the marker line 50m away from the pedestrian's main viewpoint position, instead of standstilling at the moment when the vehicle arrives at the marker line. The example task diagram is shown in **Figure 7**.



(a) Real-world video (b) VR environment

Figure 7 Schematic diagram of scenarios in Task 2

RESULTS

Analysis Indicators

The value of speed estimation bias is used to assess the subject's performance in task 1 and refers to the difference between the subject's reported speed estimation in the test task and the actual vehicle moving speed in km/h. It can be calculated by **Equation 1**:

$$\Delta(v) = v_{estimated} - v_{actual} \qquad (1)$$

In the equation, $\Delta(v)$ indicates the value of the speed estimation bias, $v_{estimated}$ and v_{actual} indicate the estimated speed and actual value of speed respectively. If $\Delta(v)$ value is positive, it represents that the subject overestimates the speed; conversely, it indicates an underestimation of the speed of the vehicle.

Similarly, the time-to-arrival estimation bias value is used to assess the subject's performance in task 2 and refers to the difference between the moment when the subject pressed the handheld timing button and the moment when the vehicle should have arrived at the marker line in seconds. It can be calculated by **Equation 2**:

$$\Delta(TTA) = TTA_{estimated} - TTA_{actual} \qquad (2)$$

In the equation, $\Delta(TTA)$ indicates the value of the TTA estimation bias, $TTA_{estimated}$ and TTA_{actual} indicate the estimated and actual value of TTA estimation respectively. If $\Delta(TTA)$ value is positive, it means that the subjects underestimated the vehicle's approaching speed and thus missed the moment when the vehicle arrived at the target position; if the deviation value is negative, it means that the subjects overestimated the vehicle's approaching speed and thus made the judgment that the vehicle had arrived at the target position earlier.

According to the results of the statistical analysis, the distribution of both deviation value variables conformed to normal distribution.

Impacts of Different Experimental Environments

Speed Estimation Bias

In Task 1, the overall distribution of the subjects' speed estimation bias values in both experimental environments is shown in **Figure 8**. According to the results, in the real-world video test, the mean value of speed estimation bias was -1.24km/h, with a standard deviation of 6.98. In the VR environment test, the mean value of speed estimation bias was -2.62km/h, with a standard deviation of 5.70. The ANOVA results showed that there was a difference in the deviation of the subjects' perceptions of the vehicle's speed between watching the real-world video and immersing in the VR environment (F (1,1034) =12.184, p<0.01). However, the absolute mean of the speed estimation bias in both environments was only 1.38 km/h, which can be negligiable in a real traffic environment.

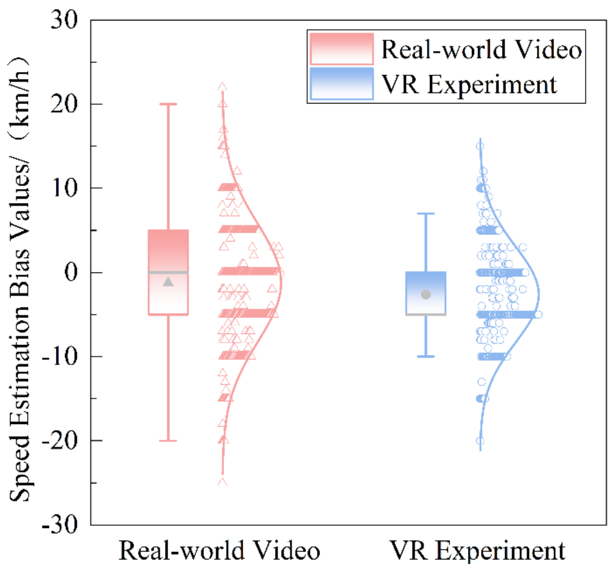


Figure 8 Bias values of speed estimation in two scenarios

TTA Estimation Bias

In Task 2, the overall performance of subjects' TTA estimation bias in both experimental environments is shown in **Figure 9**. In the real-world video test, the mean TTA estimation bias was 1.54 s, with a standard deviation of 1.76; in the VR environment test, the mean TTA estimation bias was 1.58 s, with a standard deviation of 1.65. The ANOVA results showed no difference in the subjects' performance of estimating the vehicle arrival time between watching the real-world video and in the VR environment (F (1,517) = 0.060, p= 0.806>0.05).

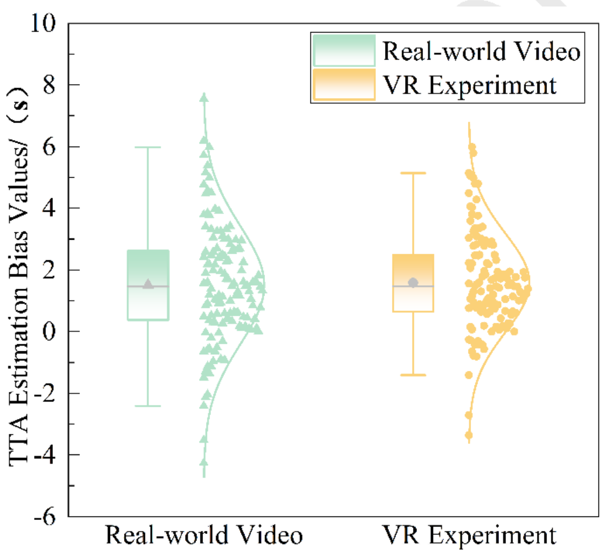


Figure 9 Bias values of TTA estimation in two scenarios

Impacts of Different Vehicle Speeds

Speed Estimation Bias

According to the statistical results, different vehicle moving speeds in the two environments had a significant effect on the speed estimation bias values (F (6,1034) = 76.936, p<0.01). The data indicated that within the range of established vehicle speed intervals in this paper, subjects generally made lower vehicle travel speed estimates in the VR environment compared to the performance made while watching the real-world video. The whole statistics of the speed estimation bias values in the two environments at the 7 speed levels are shown in **Figure 10** and **Table 1**. When estimating the vehicle speed for the speed interval range of 30km/h to 35km/h, the subjects' speed estimation bias values in both environments were positive, which indicated that the subjects generally showed overestimation of the vehicle moving speed in both environments. On the contrary, in the speed interval range of 40km/h to 60km/h, the subjects' speed estimation bias values in both environments were less than 0, which indicated that the subjects generally made underestimation of the speed in both environments.

Accounting for the interaction between vehicle moving speed and environment, there was no effect of the interaction between the two factors was found on the test results (F (6,1034) = 1.64, p=0.133>0.05).

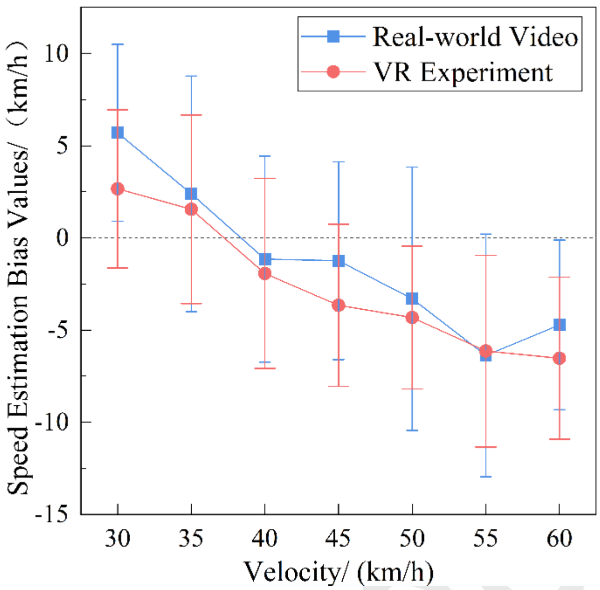


Figure 10 Bias values of speed estimation at different speed levels in two scenarios

TABLE 1 Statistical Measures of Speed Estimation Bias Values at Different Speed Levels in Two Environments

Speed	**Environments**			
	Real-world Video		**VR Environment**	
	Marginal Mean	**Standard Deviation**	**Marginal Mean**	**Standard Deviation**
30km/h	5.70	4.796	2.66	4.288
35km/h	2.39	6.391	1.55	5.118
40km/h	-1.15	5.593	-1.93	5.148
45km/h	-1.24	5.363	-3.66	4.402
50km/h	-3.30	7.140	-4.32	3.875
55km/h	-6.38	6.583	-6.14	5.206
60km/h	-4.72	4.601	-6.53	4.392

In terms of the trend of change, the results of simple linear regression analysis showed that the vehicle moving speed, both in the real-world video test (F (6,517) = 193.212, p<0.01, R^2=0.272) and the VR environment test (F (6,517) = 246.254, p<0.01, R^2=0.322), had a significant negative linear relationship with the speed estimation bias value. The linear models can be illustriated in **Equation 3 & 4**:

$$\Delta_{video}(v) = 15.134 - 0.364v_{vehicle} \quad (3)$$

$$\Delta_{VR}(v) = 11.949 - 0.324v_{vehicle} \quad (4)$$

In the equations, $\Delta_{video}(v)$ and $\Delta_{VR}(v)$ indicates the value of the speed estimation bias in real-world video and VR experiment tasks respectively, and $v_{vehicle}$ is the moving speed of the vehicle. According to the linear models, it is shown that as the vehicle speed increases, the subjects' speed estimation is more and more skewed towards underestimation in both environments. In addition, this predictive linear model showed that subjects made relatively accurate speed judgments in this study when the vehicle was moving at both 35km/h as well as 40km/h levels.

TTA Estimation Bias

The performance of all subjects in Task 2 in terms of Time-To-Arrival estimation bias values for vehicles with different speed levels in both environments is shown in **Figure 11**. The result showed that there was no effect of different vehicle moving speeds in the two environments on the TTA estimation bias values (F (6,517) = 0.660, p=0.682>0.05); and there was no effect of the interaction between vehicle moving speeds and the types of environments on the test results (F (6,517) = 1.114, p=0.353>0.05).

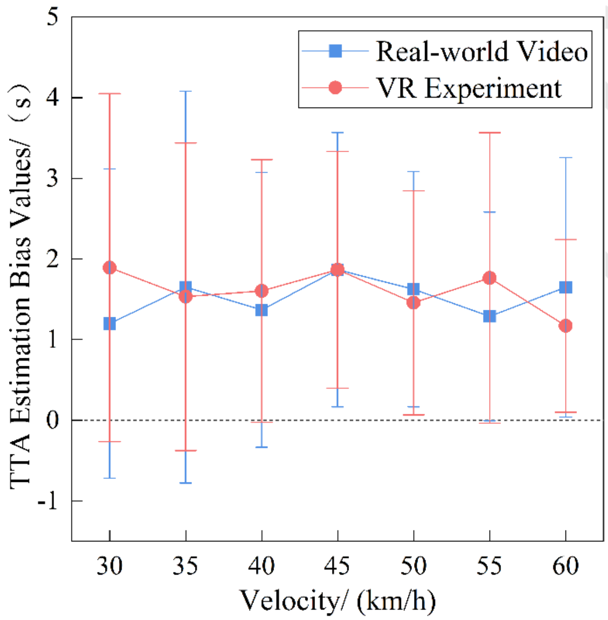


Figure 11 Bias values of TTA estimation at different speed levels in two scenarios

Impacts of Individual Characteristics

When assessing the impacts of individual characteristics (e.g., gender, age, etc.) on the estimation results, we still used the ANOVA method to explore the relationship between personal characteristics and experimental outcomes, analyzing subjects' gender as a fixed factor and individuals' age as a covariate.

Speed Estimation Bias

In task 1, the gender of the subjects did not reflect a significant effect effect on the test results (F (1,1034) = 0.010, p=0.922>0.05). Additionally, the interaction between gender and environment did not affect the experimental results (F (1,1034) = 2.892, p=0.089>0.05). As a covariate, age also did not have a significant effect effect on the test results (F (1,1034) = 1.175, p=0.279>0.05).

TTA Estimation Bias

In Task 2, there was a significant effect of subjects' gender on the test results (F (1,517) = 23.837, p<0.01) and a significant interaction effect of gender with environment (F (1,517) = 6.126, p=0.014<0.05). In addition, the covariate age factor (F (1,517) = 0.147, p=0.702>0.05) did not have a significant effect effect on the test results.

To compare the performance of male and female participants in each of the two environments, post hoc pairwise comparison analyses were conducted. The results of the post hoc pairwise comparisons are shown in **Figure 11** and **Table 2**. Although there was a significant difference between the performance of the male and female participants in this session of the test, the results of the pairwise comparisons indicated that there was no significant difference between the performance of the male (F (1,335) = 2.349, p=0.126>0.05) and the female (F (1,181) = 3.260, p=0.073>0.05) participants in each environment.

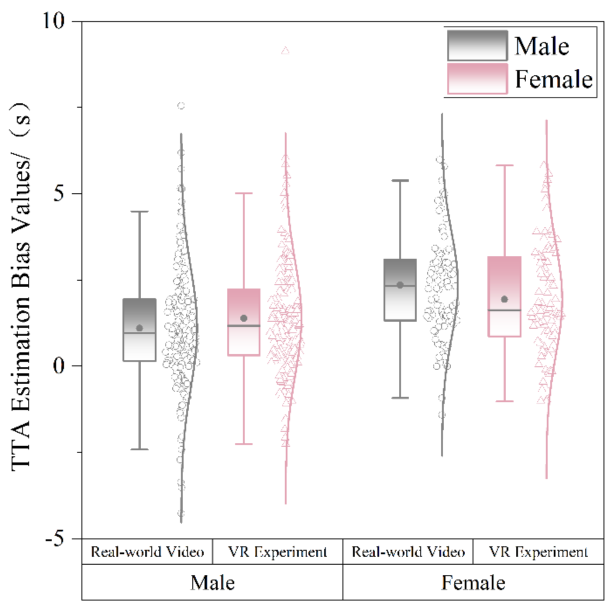


Figure 11 Bias values of TTA estimation for subjects of different genders in two scenarios

TABLE 2 Paired Comparison of Bias Values of TTA Estimation for Subjects of Different Genders in Two Environments

Gender	**Environments**				**Paired Comparison Test**	
	Real-world Video		**VR Experiment**			
	Marginal Mean	**Standard Deviation**	**Marginal Mean**	**Standard Deviation**	***F*-value**	***p*-value**
Male	1.11	1.731	1.39	1.650	2.349	0.126
Female	2.36	1.521	1.94	1.594	3.260	0.073

Relevance of Motion Perception Ability

To further verify whether the subjects' objective motion perception ability could be mapped to the performance in the VR environment, the motion perception ability grades obtained by the VTS "Time/Movement Anticipation" S4 module test were compared and analyzed with the performance of the estimated TTA values in the VR environment. The distribution of test results is shown in **Figure 12**. Since subjects whose motion perception ability was in the 5 to 6 grade range were missing from the subjects, the distribution of the motion perception ability grades of the whole population (removing the 5-6 grade range) and their corresponding TTA estimation bias values are shown in **Figure 13**.

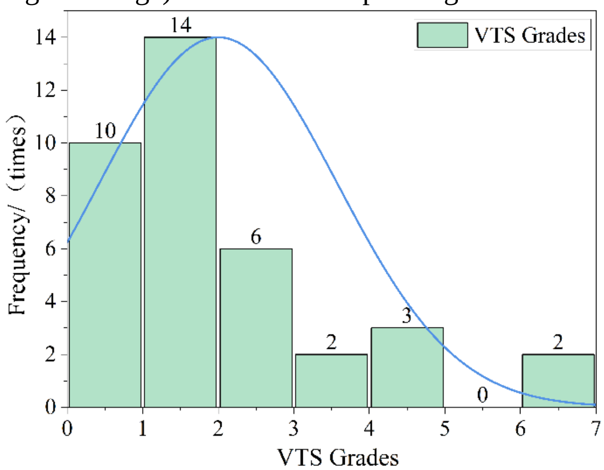


Figure 12 Distribution of overall motion perception grades of subjects

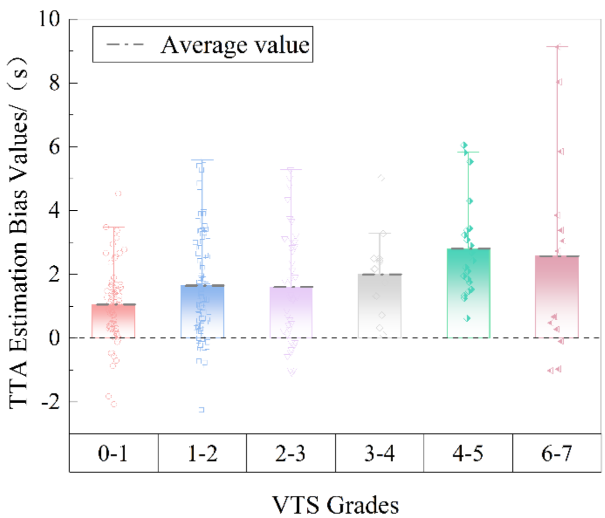


Figure 13 Distribution of bias values of TTA value estimation corresponding to all subjects' motion perception ability grades in the VR environment

According to the results of Spearman's correlation test, there was a significant monotonous positive correlation between subjects' motion perception ability scores and their performance on the vehicle TTA estimation task in the VR environment (ρ = 0.158, p<0.01). This indicates that subjects with good objective motion perception ability still maintain good overall performance when performing the vehicle TTA estimation task in the VR environment.

DISCUSSION

Difference between Real-world and VR environment

In order to control experimentally irrelevant variables and to avoid several limitations of field experiments, this paper used a method of watching a video of a real vehicle in moving as a substitute for pedestrians being in a real-world scenario. Previous studies have shown that the method of using video footage captured in the real world to investigate the perception of pedestrian-vehicle motion information has been widely adopted and applied (*13*). Related studies have pointed out that the human visual system specializes in understanding information about approaching objects through a separate retinal image processing mechanism (*14*). Although a certain amount of resolution may be reduced by playing recorded videos of real-word scenarios, existing photographic techniques are able to ensure that the quality of the video images remains essentially the same as the level of image detail that the human retina is able to receive (*15*). Therefore, this research methodology is sufficiently reliable for the present study, despite the differences between viewing a video and being in the real world.

To ensure the comparability of the experimental results, this study tried to restore all the conditions in the real-world video in the VR environment as much as possible, including site framing, vehicle appearance, and pedestrian observation angle. The results show that there are differences in the subjects' performance of perceiving vehicle movement information in the real-world scenario and the VR environment. In the vehicle moving speed estimation task, the speed estimation results in the VR environment were generally lower than those in the real-world video test. However, this discrepancy should not be over-interpreted to mean that pedestrians' speed estimation ability in the VR environment is unreliable. Although the statistical analysis showed a difference in speed estimation between the two environments, the average absolute value of this difference was only 1.4 km/h, a speed gap that would be difficult to detect directly by humans in a real road traffic environment.

In the vehicle TTA estimation task, subjects showed similar estimation abilities in both environments. According to **Figure 10**, subjects participating in the experiment overestimated vehicle arrival times in both the real-world and VR scenarios, which is consistent with the results of previous studies (*16*) and demonstrates the objective reliability of the data in this study. These results indicate that the VR equipment used in this study has a good ability to simulate real-world vehicle driving situations. Despite the discrepancies, the VR environment remains a reliable alternative for studying pedestrians' perceived interaction with ongoing vehicles.

It is important to note that VR technology itself still has some technical limitations that are difficult to address, and these limitations may affect the experience of VR users. For example, due to the limitations of human physiological properties, the viewers may suffer from fatigue, vertigo, and other adverse reactions when viewing 360° videos using head-mounted VR displays (*17*). A study by T. T. Tran et al. (*18*) has shown that the resolution encoding parameter of a VR video significantly affects the perceived quality of the viewer. In addition, the movement content and its complexity in the virtual scene are closely related to the system delay due to the technical limitations of rendering devices and modes. Complex motion content may lead to an increase in simulation system delays, which seriously affects the VR experience. Although this study did not observe a significant effect of factors such as display resolution and system delays of the VR environment on the experimental results, and all valid subjects did not report significant discomfort. However, it is undeniable that these factors do affect the experimenter's sense of presence in the VR environment (*18*). It has been suggested that a low sense of presence may reduce the level of threat perception of approaching vehicles by experimental participants (*19*). Therefore, in subsequent research on pedestrian-vehicle interaction behavior, attention should be paid to subjects' sense of presence in the VR environment to map more reliable information to real-world studies.

Vehicle Movement Speed Range

This study focused on the effect of vehicle moving speed on speed estimation bias values and vehicle arrival time estimation bias values in both real and VR environments.

The results of the study showed that different vehicle traveling speeds significantly affected the results of the speed estimation task. This is similar to the results of Sun et al (*20*), which showed that in real-world scenarios, pedestrians' speed estimation bias for moving vehicles was positively correlated with vehicle speed, and pedestrians tended to underestimate the speed of vehicles when the speed of the vehicle was over 40 km/h. This is consistent with the experimental results in this paper. However, Sun's study also showed that pedestrians' speed judgments were more accurate when vehicle speeds were below

40 km/h (*20*). The results of this paper show that subjects were more accurate in their estimation when the vehicle speed was 35 km/h and 40 km/h, but showed a tendency to overestimate the vehicle speed at 30 km/h in both environments. This may be related to the fact that the subjects knew that the minimum speed was 30 km/h before the experiment, which led to the psychological expectation that the subjects overestimated the speed during the experiment.

In the vehicle TTA estimation task, different vehicle speeds do not have a significant effect on subjects' TTA estimation. This result differs from the findings of Petzoldt (*16*) and Dommes and Cavallo (*21*). Their studies showed that the faster a vehicle approaches a pedestrian, the more the pedestrian tends to overestimate the vehicle's TTA. However, a study by Fldstein (*19*) noted that while vehicle TTA estimation was influenced by vehicle speed in VR environment, pedestrians' judgments of vehicle TTA were independent of vehicle speed in a real-world environment, and it is possible that technical deficiencies in VR equipment may have contributed to this result.

In addition to the possible technical deficiencies of VR equipment, it should be noted that the experimental design of this paper is different from previous studies. This study did not control the independent variable of the actual vehicle arrival time gap. Vehicle travel speeds were set at 30-60 km/h, and subjects began estimating arrival times when the vehicle was 50 m away from them, which implies that faster vehicles have shorter actual arrival time gaps. Petzoldt's study similarly demonstrated that shorter actual arrival time gaps allow subjects to more accurately judge vehicle arrival times (*16*). Therefore, not strictly controlling for the actual vehicle arrival time gap may have affected the results of the analysis of the correlation between vehicle speed and the estimated bias in TTA values. However, it should be emphasized that this paper is primarily concerned with comparisons across experimental settings rather than differences in TTA estimations across vehicle speeds. The results of previous studies are still replicated in this paper, supporting the overall validity of the methodology of this study. Although the results on the correlation between vehicle speed and vehicle TTA estimation need to be treated with caution, the findings on the differences in the pedestrian's estimation of vehicle TTA between real-world and VR environments are reliable.

Individual Factors

In examining pedestrians' ability to perceive vehicle movement information, it is essential to account for individual differences among subjects, as these differences can affect the outcomes. This study investigates the relationship between individual factors and experimental results, and further explores whether these individual factors influence performance in VR environment.

This study reveals no significant difference between male and female participants in vehicle speed estimation task in both environments. However, in the task of estimating TTA of vehicles, male and female participants show distinct differences. In addition, the age factor, used as a control variable, does not affect the results in either test task.

The gender differences in perceiving movement information of approaching objects have been a contentious topic in previous studies. Although further exploration and validation of the factors affecting different genders are necessary, our study's primary objective shows that there is no significant difference in the performance of participants with different genders in real-world and VR environments. This indicates that the VR technology used in our study is suitable for researching pedestrian-vehicle interactions across a diverse population.

In addition to evaluating participants' motion perception performance in real-world video tests and VR environment tests, we also compared the objective motion perception ability scores obtained through the VTS "Time/Movement Anticipation" S4 module with their performance in estimating vehicle arrival time in the VR environment. The comparison results show that participants with higher motion perception abilities tend to perform better in estimating vehicle arrival time in the VR environment. This further demonstrates that the VR technology used in this study can effectively reflect pedestrians' motion information perception abilities in the real world.

CONCLUSIONS

Before applying VR technology to study pedestrian-vehicle interactions in traffic environments, researchers should consider whether pedestrians exhibit consistent perceptual characteristics in VR and real-world environments. The main conclusions of this study are as follows:

1. In the vehicle speed estimation task, there is a statistically significant difference between the speed estimation deviations when participants viewed real-world videos and emerged in VR environment. Among both environments, the speed estimation in VR environment tended to be lower overall. However, the average absolute deviation in speed estimation between the two environments was only 1.4 km/h. This indicates that within the speed range set in this study, pedestrians' judgment of vehicle speed in the VR environment is effective.

2. In the vehicle time-to-arrival estimation task, the deviation in time estimation in the VR environment was consistent with that in the real-world videos, with no significant effect of vehicle speed on estimation deviation in either environment within the speed range set in this study. This suggests that pedestrians' perception of the time distance of approaching vehicles in VR environment is close to that in the real world.

3. The study found that participants' accuracy in perceiving vehicle motion distance in the VR environment corresponded to their objective motion perception ability. This demonstrates that the VR technology used in this study can effectively reflect pedestrians' objective movement information perception abilities in real-world pedestrian-vehicle interaction studies.

It is important to note that this study was based on a relatively concentrated age group of young adults, and future research should consider recruiting a broader age range to investigate vehicle information perception characteristics across different demographics. Additionally, as the conclusions were derived from urban vehicle speeds ranging from 30 to 60 km/h, the potential impact of higher speeds on experimental outcomes should be carefully considered. Despite these limitations, the significant advantages of VR technology in terms of experimental safety, scene reproducibility, and cost reduction highlight its continued relevance for pedestrian studies. This study validates the feasibility of VR environment as substitutes for real-world settings by comparing pedestrians' perceptual characteristics in both environments and discussing factors that might influence vehicle movement perception in VR environment. The findings provide a theoretical reference for future research on pedestrian-vehicle interactions using VR technology.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Yang Chen, Weicheng Sun; data collection: Yang Chen, Weicheng Sun; analysis and interpretation of results: Weicheng Sun; draft manuscript preparation: Yang Chen, Fuwei Wu. All authors reviewed the results and approved the final version of the manuscript.

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