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Implications of Retrograde Behaviours on Visual and Cycling Behaviour of Normal Cyclists

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ABSTRACT

In China and other developing countries, some bicycle riders exhibit retrograde behaviour, which affects the riding safety of normal cyclists. The effect of retrograde behaviour on visual search and cycling behaviours of normal cyclists is investigated and quantified in this study. First, cyclists are instructed to wear an SMI iView ETG head-mounted mobile eye tracker and a mobile phone equipped with a Global Positioning System real-time location monitoring function to cycle on a road to obtain the times of fixation, saccade and blink, as well as the pupil diameter, gaze position and velocity in normal and retrograde conditions. Subsequently, the effect of retrograde behaviour on the attention of normal cyclists is analysed using three indexes: proportion of fixation time, coefficient of variation of pupil diameter and area of interest. Then, the effect of cycling behaviour is analysed using three indexes: the cycling trajectory, the velocity at three stages and the coefficient of variation of velocity. Finally, polynomial regression analysis is performed to analyse the visual and cycling behaviour impact indexes under the retrograde condition. The results show that retrograde behaviour significantly affects the vision and cycling behaviour of normal cyclists and that the two indexes are positively correlated.

KEYWORDS

visual behaviour; cycling behaviour; traffic safety; retrograde behaviour.

1. INTRODUCTION

The number of bicycles in China is one of the highest worldwide. In recent years, there has been rapid development in bicycle-sharing systems (BSS) in China. More than 80% of public transport travellers take walking and shared bicycles as feeder modes [1]. However, a bicycle's motion track is flexible and unstable, which renders road traffic management challenging. Some cyclists exhibit weak legal awareness and tend to speed, cross lines, retrograde, etc., thereby causing social security problems in China and other developing countries, which caused widespread concern.

Article 35 of the Road Traffic Safety Law of the People's Republic of China stipulates that motor vehicles and bicycles should pass on the right side of the road. Therefore, when the destination is near or on the same side of the road as the starting point, some cyclists are inclined to use the most convenient route to reach the destination. So the act of cycling on the left side of the road in the forward direction is defined as a retrograde behaviour.

In response to the above safety issues, we launched a bicycle traffic safety questionnaire survey, it was found that cyclists are commonly disturbed by retrograde behaviours. Some of them regard it as a safety hazard, while whether retrograde behaviours affect traffic safety deserves more in-depth consideration. How to quantify and analyse the degree of its disturbance has become an urgent problem to be solved.

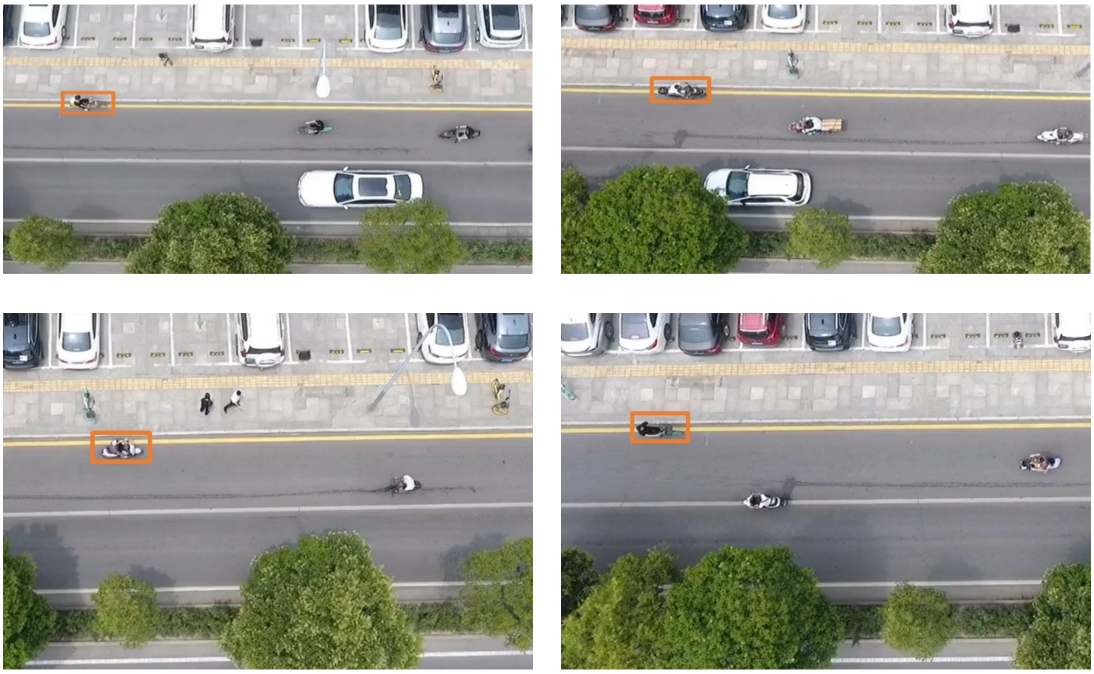


Figure 1 – Some normal cyclists encountering retrograding cyclist

Based on the riding state of normal cyclists when encountering a retrograding cyclist, this paper proposes the following three hypotheses.

1) Normal cyclists will spend more attention on the retrograding cyclist and the rear side vehicles when encountering the retrograding cyclist.
2) Inattention will alter the cyclist's state of motion.
3) The attention of normal cyclists is correlated with cycling behaviours.

According to a study on bicycle safety, the number of deaths due to traffic accidents in the United States was the lowest at 32,744 in 2014. However, the number has been increasing annually [2]; as such, researchers have focused more on cycling safety [3]. Recently, researchers have extensively investigated bicycle traffic movement, to analyse the characteristics of bicycle movement and flexible cycling behaviours, through the analysis of the cycling state of cyclists found that the phenomenon of distraction is common, involving visual, cognitive attention and cycling characteristics, this requires that the cyclists can correctly perceive the information and analyse the road traffic situation during cycling. Research has found that the lack of necessary crossing facilities for cyclists has a significant impact on the likelihood of injury severity [4].

Initially, exposure data were used to analyse bicycle crashes, and the results showed that safety problems were prominent [5], which indicates that bicycle riders are one of the most vulnerable road users [6]. Furthermore, irregular movements have been shown to increase the severity of injuries [7]. In subsequent studies, researchers combined questionnaires and the image degradation and edge detection method, from which they discovered a strong correlation between bicycle crash accidents and the visual characteristics of bicycle facilities [8].

Bicycling behaviour has been investigated the most. Some research on cycling behaviour has focused on the characteristics of cycling, researchers began to consider the effect of bicycle traffic behaviour on road traffic [9]. Bicycle is one of the main factors that affect traffic safety and capacity in pedestrian-bicycle mixed traffic sections [10]. In general, the cyclist's cycling behaviours control the speed, position and specific behaviour of the bicycle. Based on observed data, the researchers determined the relationship between bicycle volume and cyclists' speed [11], meanwhile, the relationship between the position, time and volume of vehicles and a two-dimensional velocity function was used to describe the effect of the lateral movement or specific behaviours of cyclists on traffic performance [12], and a three-parameter model of mixed traffic flow was validated [13]. Research shows that there are considerable differences in preferences for locations of shrubs, hedges, flowers and grass between cyclists and pedestrians [14].

As research continues and the status of bicycle traffic in road traffic changes, researchers have begun to focus on the flexible and variable riding behaviours of cyclists. Cyclists moving arbitrarily on the road may affect the normal passage of other traffic participants [15]. Researchers use video data to extract the longitudinal distance of cyclists, lateral distance and speed difference between interacting cyclists to cluster and describe the manoeuvring characteristics of bicycles under the interaction of chasing and passing [16]. In addition, the analysis based on GPS data found that bicycles had a higher probability of violation, 45% of cyclists rode in the wrong direction. Cyclists have a greater risk of safety behaviour [17]. Random lane changes and retrograde behaviour of cyclists can also have a significant impact on the efficiency of roadway intersections [18]. A multilevel macro-model of bicycles was established [19], which successfully verified the adverse effect of unacceptable cycling behaviour on the overall performance of urban road traffic under different traffic conditions. Therefore, the characteristics of unacceptable cycling behaviour must be investigated to refine the management system and improve road safety.

Some studies have shown that five factors of risky riding behaviour including traffic violations, impulsive behaviour, common violations, distractions and errors can be explained by gender, age, perceived risk and perceived riding skills [20]. Results of multiple regression analysis showed that distraction was common among cyclists, rule and aggressive violations, common violations and distraction were associated with bicycle accidents, risk phenomena were strongly associated with risky behaviour [21, 22]. Further studies found that these psychological determinants were not only associated with higher risky behaviour frequency but also with higher crash frequency [23]. As a result, distraction poses a significant safety risk to cyclists and plays an important role in predicting the accident rate of cyclists, how to quantify and analyse the level of distraction of cyclists is an urgent problem we need to solve.

To further quantify the safety risks for cyclists, researchers began to focus on the visual cognitive characteristics and risk perception of traffic participants new avenues for bicycle safety research were identified [24, 25]. During cycling, a cyclist focuses on the path and target area, which causes the cyclist's line of sight to shift to the end of the lane and the outside area. Higher speeds result in a more distant gaze and more travel gaze [26], and a low-quality path results in distractions [27]. However, at uncontrolled intersections, the effect of speed on cyclists' fixation behaviour and cross-judgment ranges from insignificant to intermediate [28]. In addition, the study showed that adults scored better than adolescents on the risk perception test for cyclists [29], although no significant differences were indicated in terms of visual tracking [30, 31]. Meanwhile, another study showed that participants focused more on pedestrians instead of on other cyclists on complex roads [32] and that the insufficient physical and visual separation between cyclists and pedestrians increased the risk of crashes [33]. In summary, the visual characteristics of cyclists significantly affect bicycle safety.

A literature review regarding the operation of bicycle traffic shows that the attention and cycling behaviours of cyclists are important factors that affect cycling safety. Most related studies investigate the cyclists' own attention and cycling characteristics, researchers rarely focused on the safety risks posed by the outside environment especially retrograde behaviours and the resulting interference to the visual and cycling behaviours of normal cyclists. Therefore, exposure data are obtained through real-bicycle experiments in this study, the primary objective of which is to investigate the effects of retrograde behaviours on normal cyclists' visual and cycling behaviours, and to provide quantitative data for evaluating normal cyclists' cycling safety under the effect of retrograde cycling. In particular, the aim of this study is as follows: (1) to provide a quantitative description of the visual and cycling characteristics of normal cyclists; (2) to provide a quantitative analysis of the visual characteristics of normal cyclists encountering retrograding cyclists, and to determine the effect of retrograding cyclists on normal cyclists' attention; (3) to propose a kinematic model of cyclists encountering retrograding cyclists; (4) to investigate cyclists' cycling behaviour during an encounter with a retrograding cyclist such that the safety risk to normal cyclists can be quantified.

2. DATA ACQUISITION

2.1 Participants

Twenty-five adults (13 males and 12 females, of ages ranging from 20 to 35 years old with a mean age of 26.47 years old, SD = 3.49) with a range of cycling experiences were recruited through opportunistic sampling. Because young people use bicycles more often in China and research shows that young people score higher on risky behaviours [20], the participants in this study were more likely to be young people. All participants demonstrated an uncorrected or corrected visual acuity (corrected by wearing clear contact lenses) of 5.0 (i.e. based on a test using a logarithmic distance chart placed at a distance of 5 m, with Line 11 specified as the standard visual acuity of 5.0) and no astigmatism, thereby allowing the eye tracker to capture the participants' eye movement data.

2.2 Apparatus

Visual behaviour was recorded using an SMI iView ETG head-mounted mobile eye tracker (Senso Motoric Instruments GmbH, Warthestr. 21, 14513 Teltow, Germany). The eye tracker continuously recorded data (at a sampling rate of 60 Hz) by ingesting infrared light reflected from the cornea and pupil of the human eye; subsequently, the data were recorded on a mobile phone (Samsung) installed with iView ETG recording software. The participants were instructed to carry another mobile phone equipped with a GPS tracking function to record their velocity (at a sampling rate of 1 s) in real-time.

2.3 Scenario characteristics

To avoid the effect of intense sunlight on the participants' normal cycling and eye tracker data acquisition, the experiment was performed during cloudy weather with good visibility; the experiment was performed from 7:00 to 10:00 or 16:00 to 18:00. Simultaneously, considering the experimental content and safety of the participants, a section with a large road width was selected.

To accommodate the requirements of the experiment, Nan'er Huan Road of Xi'an (a two-way six-lane road with one bicycle lane measuring 2.5 m wide) was selected to perform the experiment. The bicycle flow was 374 vel/h per hour, the retrograde rate was 5.64%, and the total length of the experimental section was 600 m. The experiments were performed between 4 March 2021 to 21 April 2021.

2.4 Protocol

Those who demonstrated enthusiasm for participating in the experiment were asked to fill out a form to provide basic personal information about themselves. The participants were well-rested prior to their participation in the experiment. Ethical approval is generally not mandatory for traffic safety research [34], but in order to ensure the safety of the participants, we took a series of safety precautions. First, a pre-experiment was performed, where the wear method of the eye tracker was explained to the participants such that they were able to wear the eye tracker comfortably in advance as well as avoid the inaccuracy of the experimental data caused by discomfort. After the participants familiarised themselves with the eye tracker, they proceeded to perform the experiment (see *Figure 2*).

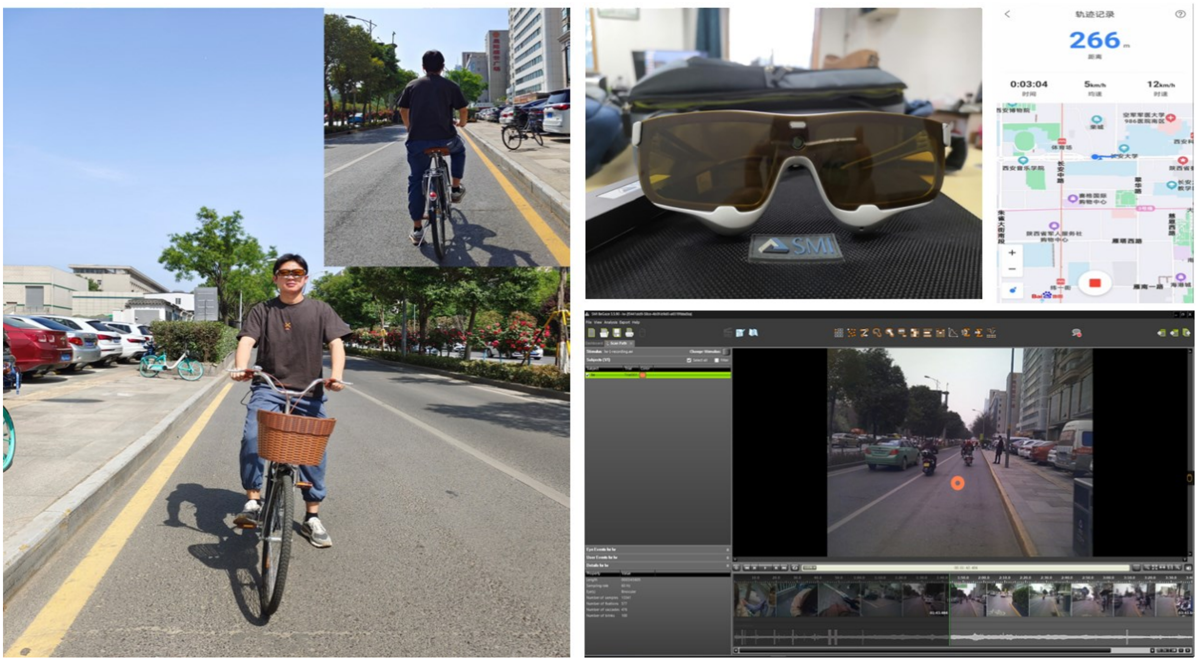


Figure 2 – Demonstration of experimental process

BeGaze software was used to locate and calibrate the eyeball using the three-point method near the initial position of an outdoor experimental road section to ensure the accuracy of the visual data. After calibration, the participants carried a mobile phone with GPS tracking capabilities and rode normally along the route specified for the experiment to obtain the participants' eye movement data, including the times of fixation, saccade and blink, as well as the pupil diameter, fixation areas of interest (AOIs) and other data information, to record and analyse the eye tracking process. Simultaneously, they recorded the velocity of the subjects at 1 s intervals for analysis and model building. To ensure the authenticity and accuracy of the experiment, the content was not revealed to the participants. To manage unexpected situations, the researchers trailed the participants for a distance of 1 – 3 m.

3. RESULTS

Three methods are used for the analysis: (1) an outlier analysis method is utilised to evaluate the differences between the acquired data; (2) a statistical formula for visual characteristics is used to analyse the cyclists' fixation positions, fixation time, AOIs, etc.; (3) a kinematic model to describe the cycling behaviours of cyclists when they encounter a retrograding cyclist.

3.1 Statistical methodology

All participants successfully cycled along the route without any unexpected incidents and managed to acquire data from 25 groups. The mean, median, standard deviation and coefficient of variation are based on the formulas shown in *Equations 1 – 3*, respectively;

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{X_1 + X_2 + \cdots}{n} \tag{1}$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \tag{2}$$

$$CV = \frac{SD}{\bar{X}} \tag{3}$$

n: the sample size.

To obtain the range of the effective values, we used a box graph to eliminate outliers, at the same time, according to the principle of eye movement data screening, if the tracking rate of the eye movement tracking data exceeds 90%, then the group of data are considered stable and acceptable [27]. The complex and volatile environment of the outdoor bicycle experiment yielded some experimental data of unsatisfactory quality; therefore, invalid data were rejected, and 18 groups (10 males; 8 females) of reliable data were utilised.

3.2 Characteristic indexes for visual behaviour

To quantitatively describe the changes in the visual behaviour of normal cyclists when they encounter a retrograding cyclist, the following two indexes are selected; their calculation formulas are shown in *Equations 4 and 5*, respectively.

(1) Percentage of fixation

$$P_{be} = \frac{T_{be}}{T_{total}} \tag{4}$$

T_{be} : Duration of fixation in retrograde encounters

T_{total} : Total duration of three states during the encounter with retrograding cyclist

The proportions of the normal cyclists' times of fixation (mean = 0.371; SD = 0.142), and retrograding cyclists' times of fixation (mean = 0.522; SD = 0.191) were extracted from the statistical data (see *Table 1*).

Table 1 – Proportion of fixation time of cyclists in normal and retrograding conditions

Number	1	2	3	4	5	6	7	8	9
Normal	0.34	0.26	0.43	0.55	0.53	0.43	0.57	0.27	0.21
Retrograde	0.64	0.27	0.74	0.81	0.59	0.61	0.46	0.16	0.12
Number	10	11	12	13	14	15	16	17	18
Normal	0.16	0.18	0.28	0.43	0.56	0.33	0.21	0.53	0.41
Retrograde	0.26	0.33	0.39	0.63	0.60	0.46	0.55	0.60	0.71

(2) Coefficient of variation of pupil diameter

$$P_{cv} = \frac{\overline{P}_R}{\overline{P}} \tag{5}$$

$\overline{P}_R$: Average pupil diameter during retrograde motion

$\overline{P}$: Average pupil diameter during the normal stationary state

The proportions of the normal cyclists' pupil diameter (mean = 2.388; SD = 0.459), and retrograding cyclists' pupil diameter (mean = 2.834; SD = 0.570) were extracted from the statistical data (see *Table 2*).

Table 2 – Proportion of pupil diameter of cyclists in normal and retrograding conditions

Number	1	2	3	4	5	6	7	8	9
Normal	2.58	2.24	2.24	2.55	3.31	1.96	1.96	1.76	1.54
Retrograde	3.03	2.53	3.56	2.68	3.55	2.43	2.21	1.86	1.83
Number	10	11	12	13	14	15	16	17	18
Normal	2.62	2.33	2.45	2.35	2.66	2.97	2.01	3.12	2.33
Retrograde	2.73	2.67	3.21	3.48	2.98	3.65	2.43	3.43	2.76

(3) AOI

When cycling, cyclists pay attention to near path, middle path, far path, retrograde cyclist, other path users, greening facilities and others, the definitions are shown in *Table 3*.

Table 3 – Definitions of areas of interest

AOI	**Definition**
Near path	The cycling path within 3.5 m of the front wheels
Middle path	The cycling path between 3.5 m and 8 m of the front wheels
Far path	The cycling path of more than 8 m of the front wheels
Retrograde cyclists	The cyclists of retrogradation
Other path users	Other path users except the retrogradations and himself, including other cyclists in the same direction, motor vehicle, pedestrian and so on
Greening facilities	Greening facilities on the road side
Others	Other or non-specified features in the environment

The normal cyclists were able to focus more on the path and greening facilities, as indicated by the results listed in *Table 4*.

Table 4 – Areas of interest of cyclists in normal condition

AOI	Near path	Middle path	Far path	Retrograde cyclist	Other path users	Greening facilities	Others
Normal	0.08	0.37	0.06	0.00	0.15	0.18	0.15
Retrograde	0.04	0.32	0.07	0.19	0.17	0.02	0.20

3.3 Kinematic model of motor behaviour

A single retrograde trip can disrupt a normal cyclist for 5 – 8 s (see *Figure 3*). The specific encounter process can be summarised as follows. (1) Decision process: the normal cyclist identifies the retrograding cyclist and decelerates promptly; (2) judgment process: the normal cyclist determines that the encounter will be safe, the normal cyclist shifts from decelerating to accelerating; (3) recovery process: the encounter occurs, and the normal cyclist accelerates to the normal speed.

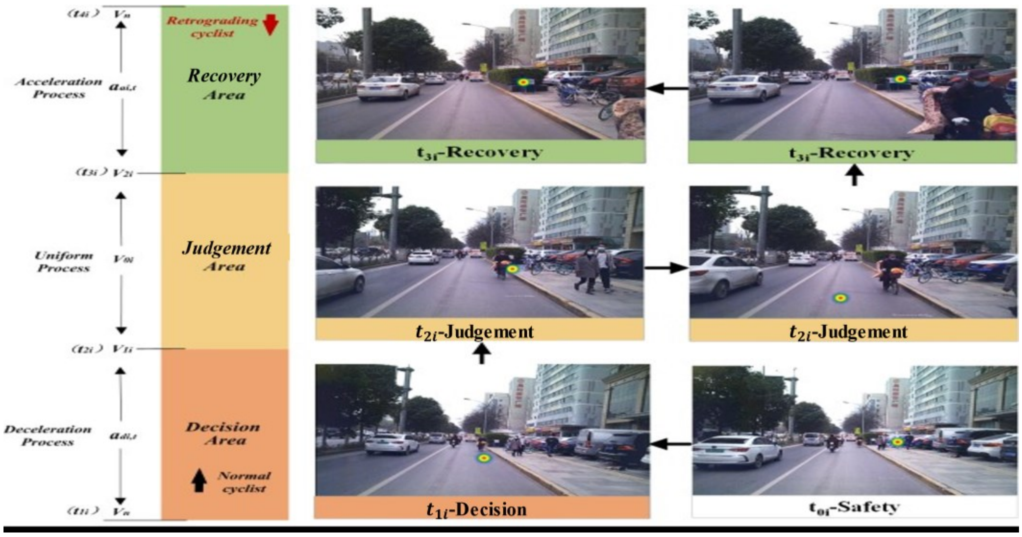


Figure 3 – Process of normal cyclists encountering retrograding cyclist

Suppose that a normal cyclist i encounters a retrograding cyclist on the road ahead and makes a decision promptly. During the decision-making, the deceleration rate of $a_{di,t}$ decreases from the normal speed V_n to V_{1i}, when they confirm that the encounter with the retrograding cyclist is safe and stable, at which point they enter the judgement area from the left and right sides in the vertical position. Subsequently, the normal cyclists decelerate to a minimum speed of V_{0i} and then switch to accelerating from V_{2i} to the normal speed in the recovery area with $a_{di,t}$. The following two indexes were calculated using their respective formulas shown in *Equations 6 and 7*, respectively.

(1) Speed difference

$$\Delta V_i = |V_n - V_{0i}| \tag{6}$$

(2) Coefficient of variation of velocity

$$V_{cv} = \frac{|V_{\max} - V_{\min}|}{\bar{V}_R} \tag{7}$$

$V_{\max} / V_{\min}$: Maximum/minimum values during normal stationary ride

$\bar{V}_R$: Average cyclist speed during the retrograde encounter

The coefficient of variation of velocity is shown in *Table 5*.

Table 5 – Statistical table of coefficient of variation of velocity

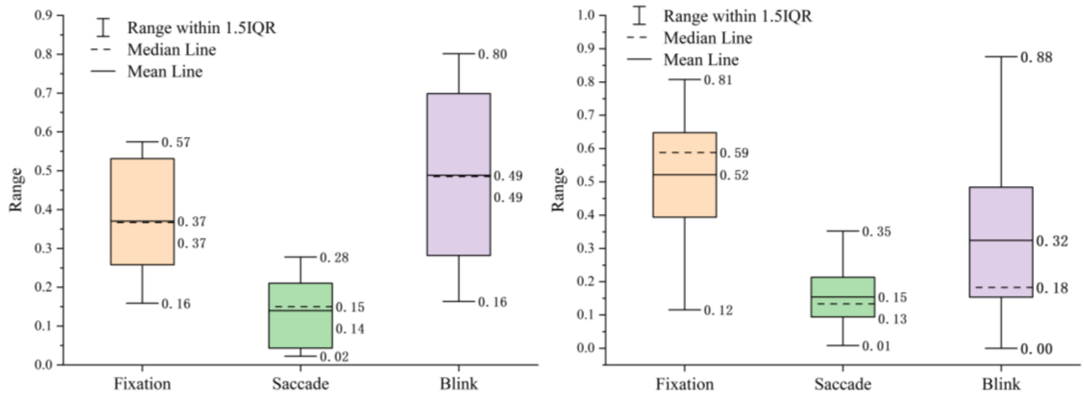
Rider number	1	2	3	4	5	6	7	8	9
Retrograde average [km/h]	8.75	9.33	8.92	5.44	3.80	7.40	11.80	12.33	8.40
Normal range [km/h]	13.00	8.00	12.00	9.00	5.00	10.00	13.00	9.00	6.00
Variable coefficient	1.49	0.86	1.35	1.65	1.32	1.35	1.10	0.73	0.71
Rider number	10	11	12	13	14	15	16	17	18
Retrograde average [km/h]	11.40	8.71	12.50	5.00	4.83	8.36	9.67	4.40	5.45
Normal range [km/h]	9.00	7.00	9.00	7.00	5.00	10.00	10.00	7.00	8.00
Variable coefficient	0.79	0.80	0.72	1.40	1.04	1.20	1.03	1.59	1.47

4. DATA ANALYSIS

4.1 Effect on the attention of normal cyclists in retrograde condition

Proportion of fixation time

The proportions of fixation, saccade and blink times were extracted from the participants in the normal and retrograde cycling conditions (see *Figure 4*). The percentages of the participants' fixation during normal cycling (mean = 37%; SD = 0.14) and retrograde conditions (mean = 52%; SD = 0.19) are shown in *Figure 4*. At the same time, the t-test was used to study the difference in the proportion of fixation time between the two states, and $p = 0.038 < 0.05$, which implies that the retrograding cyclist distracts the normal cyclists.



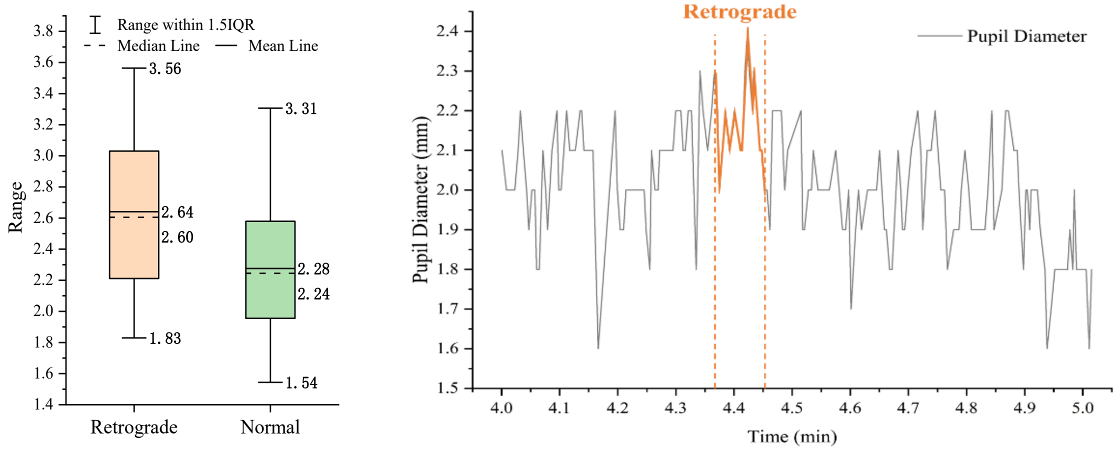
(a) Without retrograde behaviour *(b) With retrograde behaviour*

Figure 4 – Proportional distribution of three visual behaviours without (a) and with (b) retrograde behaviours

The results show a statistically significant difference in the proportion of fixation time between the normal and retrograde conditions. Additionally, the retrograde behaviour appears to significantly affect the safety of bicycles. When encountering the retrograding cyclist, the fixation point of the normal cyclists is more concentrated; moreover, the proportion of fixation time increases by 18.2% – 45.8%, the dispersion value is lower, and the percentage of saccade difference between the two types of cyclists is insignificant.

Coefficient of variation of pupil diameter

The pupil diameters of cyclists in the normal and retrograde conditions and those of cyclists in the retrograde condition were analysed. The pupil diameters of the participants during normal cycling (mean = 2.28; SD = 0.51) and retrograde conditions (mean = 2.64; SD = 0.61) are shown in *Figure 5*. At the same time, a t-test was used to study the difference in pupil diameter between the two states, $p = 0.014 < 0.05$, the sample showed a significant difference.



(a) Pupil diameters of cyclists in two conditions

(b) Distribution of pupil diameters of participants during normal and retrograde cycling

Figure 5 – Global distribution (a) and distribution of (b) of pupil diameter

The results show that the cyclists were anxious when encountering a retrograding cyclist, as demonstrated by their pupil dilation rate of 4.98% – 24.15%. However, the degree of pupil dilation among the cyclists differed slightly because of the degree of interference with different cyclists under different road conditions.

AOI

The frequency of the participants' fixation on the near path, middle path, far path, retrograde cyclist, other path users, greening facilities and others are presented in *Figure 6*, which means the areas of interest.

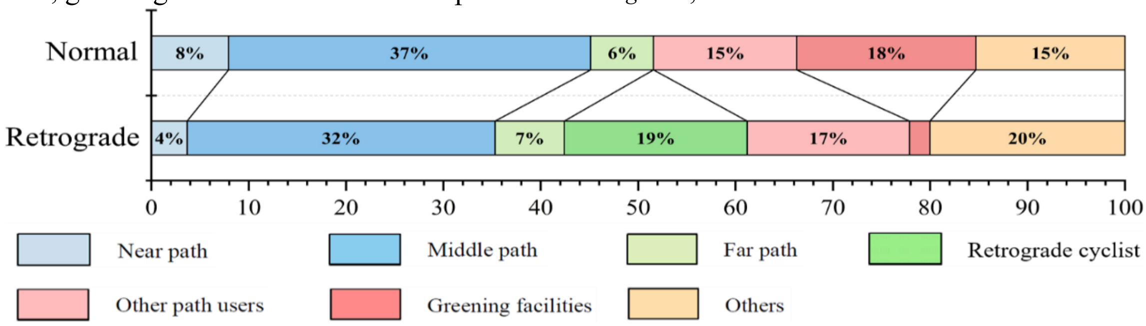


Figure 6 – Comparison of areas of interest between normal and retrograding cyclists

The results show that the AOIs of the cyclists in the two states are statistically significant. Under normal conditions, the cyclists' AOIs were more concentrated on the road, with an average of approximately 51%. When encountering the retrograding cyclist, the cyclists focused more on the retrograding cyclist, with a mean rate of 19%, and focused less on the greening facilities and roads. Also, the cyclists focused more on other path users, especially when the cyclist was near the motor vehicle lane, he would pay more attention to the vehicles behind him.

4.2 Effect on the state of motion of normal cyclists in retrograde condition

Cycling trajectory

George software was used to extract the trajectories of both normal and retrograding cyclists in a retrograde condition, as shown in *Figure 7*. Analysis revealed that, for their safety, retrograding cyclists are more likely to decelerate on the side of a pavement, forcing normal cyclists to cycle near the motor lane, which jeopardises the safety of normal cyclists. Normal cyclists must focus more on retrograding cyclists when they encounter them; they typically swerve to avoid the retrograding cyclists and promptly decelerate in a limited space. If normal cyclists misjudge the cycling tendency of retrograde cyclists or fail to focus on the dynamic traffic conditions around them in a timely manner, then traffic accidents may occur.

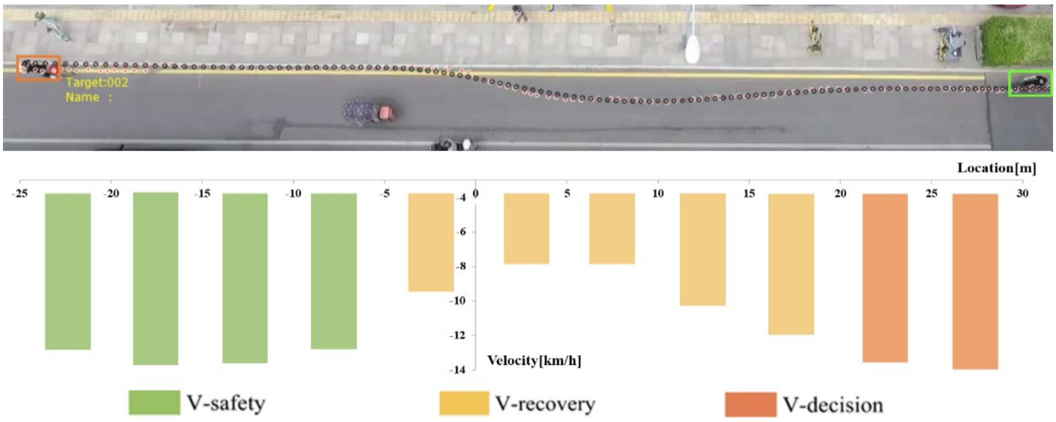


Figure 7 – Normal cyclist cycling trails during the encounter

Velocity at three-stage

The velocity of each participant when encountering the retrograde cyclist is classified into three stages and summarised. Subsequently, the frequency histogram and cumulative frequency curve are drawn (see *Figure 8*). The difference in velocity between the decision and recovery stages is insignificant, and the velocity of the judgement stage remains lower than those of the other two stages. When the abscissa is less than 5 km/h, the normal velocity of the cyclist is lower, and the velocity decrease is less during the encounter with the retrograding cyclist. As the abscissa increases, the difference in velocity between the judgment stage and each of the other two stages increases gradually, which implies that the higher the velocity of the cyclists, the more prominent the effect of the retrograde behaviour on the velocity of the cyclists is. However, the mental safety velocity of cyclists cycling at different velocities is expected to be the same.

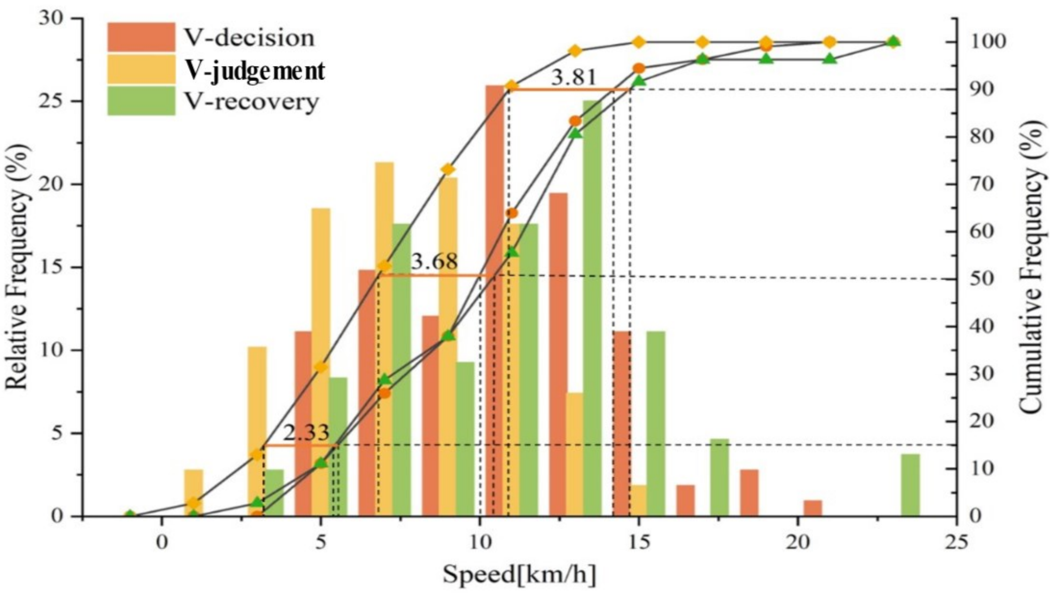


Figure 8 – Frequency histograms and cumulative distribution curves of three stages of velocity

4.3 The relationship between attention and cycling behaviour of normal cyclists in retrograde condition

The velocity of the cyclists when encountering a retrograding cyclist and during normal cycling and the coefficient of variation of the velocity (mean = 1.14; SD = 0.32) of 18 cyclists when encountering the retrograde behaviour was calculated based on the data in *Table 5*.

Polynomial regression statistics were used to regress the coefficient of variation of velocity and proportion of fixation time, where the proportion of fixation time was used as an independent variable, and the coefficient of variation of velocity as a dependent variable. The regression results (R^2 = 0.80445; α =5%;, the residual distribution is independent; see *Figure 9*) indicate a good fit and a positive correlation.

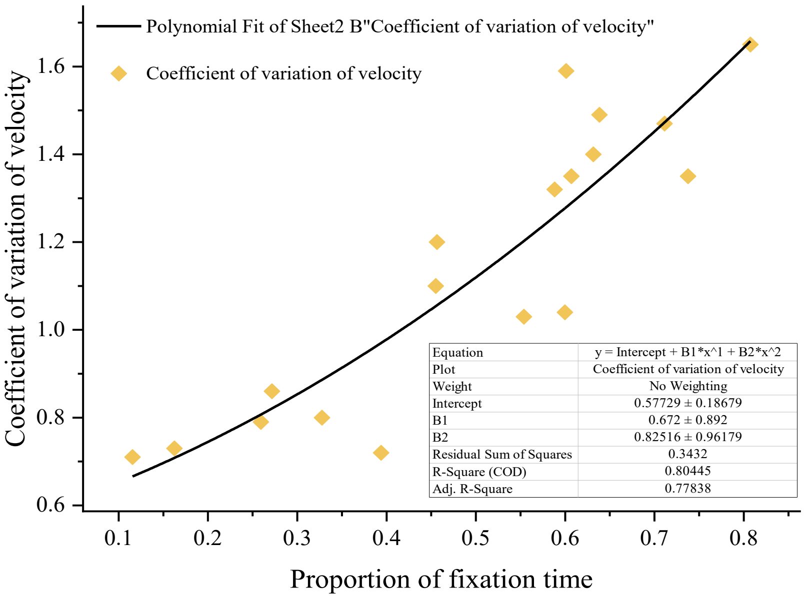


Figure 9 – Fitting curve of coefficient of variation of velocity and proportion of fixation time

The coefficient of variation of the velocity and the proportion of fixation time for each participant are shown in *Figure 10*. The graph shows a positive correlation between the coefficient of variation of velocity and the proportion of fixation time, i.e. the changing trends of the two indexes are the same. During an encounter with the retrograde behaviour, the lower the velocity of the cyclists, the lesser the interference and coefficient of variation of velocity are, which implies that a smaller coefficient of variation of velocity corresponds to a more stable traffic flow, a lower concentration requirement for the cyclists, as well as a safer and more comfortable cycling process.

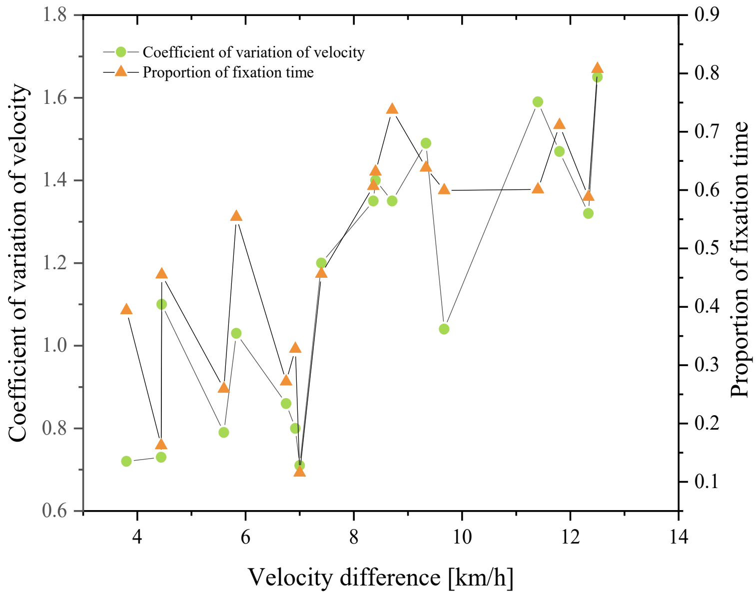


Figure 10 – Ratio diagram of coefficient of variation of velocity and proportion of fixation time

5. DISCUSSIONS

The aim of the current study is to determine the effect of visual and cycling behaviours of normal cyclists when encountering a retrograding cyclist. Hence, data were acquired along a 600-m-long road. Statistical analysis was performed to validate the visual and motor data. Characteristic indexes for visual performance and a kinematics model under retrogradation were proposed to calculate the cyclists' degree of interference. Next, the findings are discussed in terms of visual and cycling behaviours.

5.1 Visual distractions due to retrograde behaviours of normal cyclists

Human motion is primarily guided and controlled by visual information [35], which is consistent with the results of this study, i.e. the retrograde behaviour significantly affects the normal cyclists' visual behaviour, as evident from the proportion of fixation time, pupil diameter and AOI. A normal cyclist disrupted by a retrograding cyclist will spend more time gazing instead of blinking, as reported by Godley, to increase the steering workload [36]. Meanwhile, pupil size changes can provide valuable information on traffic hazard perception with a relatively low temporal delay [37], when the degree of distraction increased, the pupil diameter of the normal cyclists increased and the fixation duration became longer, which is similar to the finding of Niu, J et al. [38]. This implies that normal cyclists must focus more on assessing the degree of danger to ensure safety and hypothesis 1 is confirmed. In addition, undisrupted normal cyclists focus the most on the path owing to a visual "surplus capacity" [39], which is similar to the finding of Trefzger et al. [32]. When encountering retrograding cyclists, normal cyclists would be distracted from their path to focus on the retrograding cyclist; in fact, normal cyclists would focus less on other road facilities, particularly greening facilities. Furthermore, the experimental results show that perceiving danger will cause anxiety in normal cyclists, as evident from their high degree of dilated pupils, which further illustrates the distracting effect of the retrograde behaviour on normal cyclists.

In terms of the fixation sequence and scan path, the normal cyclists' visual behaviour when encountering a retrograding cyclist can be classified into three stages: (1) when a retrograding cyclist is observed, the gaze point of a normal cyclist shifts to the retrograding cyclist; (2) after assessing that the encounter can be completed safely, the eyesight shifts; (3) the encounter is completed. Normal cyclists tend to assess their own safety risks when encountering a retrograding cyclist. Furthermore, they must perform steering avoidance and decelerate timely within a limited space; as such, their workload increases, which results in a reduced functional horizon [40]. If a normal cyclist misjudges the driving tendency of a retrograding cyclist or fails to focus on the surrounding dynamic traffic conditions in a timely manner, then a traffic accident is likely to occur.

As expected, normal cyclists are affected by retrograding cyclists, and their visual behaviours are statistically significant. Furthermore, the visual and cycling behaviours of different cyclists are affected differently during an encounter with a retrograding cyclist.

5.2 Cycling interference due to retrograde behaviours of normal cyclists

Although the retrograde behaviour will affect the visual and cycling behaviours of normal cyclists, the mechanism and degree of the effect are yet to be elucidated. This study shows that the retrograde behaviour significantly affects the velocity of the cyclists, which implies that the higher the velocity of the cyclists, the greater the effect is and hypothesis 2 is confirmed; however, the mental safety velocity of normal cyclists cycling at different velocities tends to be the same. This may be due to the attributes of the cyclists and the bicycle, i.e. the cyclists' control over the velocity of the bicycle is certain, and they are more concerned with safety, which is similar to the findings of Zhu et al. [41]. When the velocity was within the controllable range for the cyclists, they felt safe. In addition, the coefficient of variation of velocity and the proportion of fixation time changed similarly, i.e. a more stable traffic flow corresponded to a lower coefficient of variation of the velocity of the cyclist and a smaller proportion of fixation time change, which implies less interference by the retrograding cyclists to the normal cyclists. This finding confirms that distraction is associated with a higher frequency of risk behaviours, as demonstrated by Twisk, D. et al [23] came to similar conclusions and hypothesis 3 is confirmed.

In conclusion, the interference from retrograding cyclists distracts normal cyclists and causes them to perform more cycling manoeuvres. A flexible cycling trajectory results in an unstable traffic flow, the cycling behaviours of normal cyclists when encountering retrograding cyclists are statistically significant, and environmental factors significantly affect the cyclists [42]. Recognising the cycling behaviour of normal cyclists is helpful for the design and sign guidance of traffic facilities, as well as providing a higher level of protection to normal cyclists who are vulnerable to conflicts.

5.3 Limitations

Based on experimental eye movement and cycling data, the effect of retrograde behaviour on the visual and cycling behaviour of normal cyclists was investigated in this study. This study presents a few limitations. First, the experimental data acquired were limited to a section in Xi'an, China and did not account for the different conditions in different areas. Future studies should be conducted in different cities using the same method. Second, eye movement characteristics were used to characterise the cyclists' attention. Although eye movement characteristics and attention are correlated [43], the gaze point and gaze behaviour of humans cannot be changed when their attention is shifted [44]. Therefore, the application of this method is limited. Third, the effect of road infrastructure such as lane width and traffic volume were not considered in the experiment. In future studies, the comprehensive effect of these elements should be incorporated into the experiment to adapt it to a wider range of scenarios. Finally, despite its limitations, this study extends the understanding of the safety of normal cyclists disrupted by retrograding cyclists.

6. CONCLUSIONS

The main objective of this study was to evaluate the effect of retrograde behaviour on cycling. The following three main conclusions were inferred based on the results of data analysis:

1) Retrogradation significantly affected the cyclists' attention and cycling behaviours, and a positive correlation was discovered between the two effects. Hence, countermeasures are urgently required to reduce or eliminate the effects of retrogradation on bicycling safety, efficiency and comfort.
2) When encountering a retrograding cyclist, a normal cyclist spent more time on fixation behaviours and focused less on their path and greening facilities. Therefore, visual behaviour was used to quantify the degree of attentional distraction in normal cyclists.
3) An encounter with a retrograding cyclist resulted in a lower cycling velocity, and the recovery stage resulted in the lowest cycling velocity. The safety risk of an ordinary bicycle and the instability of non-motor vehicle traffic flow were revealed based on the third-order velocity and the coefficient of velocity variation.

In general, the results showed that the normal cyclists' gaze behaviour and speed were significantly affected during the retrograde encounter. The results of this study provide researchers and decision-makers with a better understanding of the interactions among cyclists, traffic participants and cycling environments.

In the future, we will use the same method in different cities and incorporate the effects of road infrastructure such as lane width and traffic flow into experiments for research.

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王宝杰，杨威，刘子垚，梁国华

逆行行为对正常骑车人的视觉和骑车行为的影响

摘要

在中国和其他发展中国家，一些自行车骑行者存在逆行行为，影响了正常骑车人的骑行安全。本研究调查并量化了逆行行为对正常骑车人视觉和骑行行为的影响。首先，骑车人被要求佩戴 SMIiView ETG 头戴式移动眼动仪和配备全球定位系统实时位置监测功能的手机在道路上骑行，以获得正常和逆行条件下的注视、扫视和眨眼次数，以及瞳孔直径、注视位置和速度指标。随后，利用三个指标分析了逆行行为对正常自行车骑行人注意力的影响，包括注视时间比例、瞳孔直径变化系数和感兴趣区域。然后，利用三个指标分析了逆行对骑行行为的影响:骑行轨迹、三阶段速度和速度变化系数。最后，对逆行条件下正常骑行人的视觉和骑行行为影响指标进行了多项式回归分析。结果表明，逆行行为对正常骑车人的视觉和骑行行为有显著影响，且两者呈正相关。

关键词

视觉行为、骑行行为、交通安全、逆行行为