Mechanism underlying the impact of perception time on detection and recognition distance: New insights into bicycle safety

Abdur Rahman (ceeabdur09@gmail.com)
Saitama University
Kojima Aya
Saitama University
Kato Teppei
Saitama University
Kubota Hisashi
Saitama University

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Abstract

Perception time (PT) is a major factor affecting a driver's ability to detect and recognize a bicycle. Researchers have attempted to enhance the PT and gain insights into why drivers fail to see bicyclists before collisions despite looking, even when they are at a safe driving distance from the bicycle. Previous studies have focused on the detection distance and recognition distance of bicycles within 600 milliseconds (ms). PT is the main factor for avoiding collisions; however, it has been shown that a control bicycle as well as treated bicycles can be detected from greater distances. This study aims to evaluate the early detection and recognition of bicycles owing to the impact of conspicuity treatments such as white stripes on a red background (WRED), a high-visibility jacket (HVJ), reflective tape (RT), and their combinations in order to achieve longer detection and recognition distances under day/night conditions. The detection and recognition distances of WRED tire treatment were compared with those of an HVJ, RT, and their combinations, based on PTs of 250 and 600 ms. The same treatments were applied and compared at the required PT for the safe driving distance of a bicycle. The respondents provided their perceptions based on video surveillance data presented on a computer screen. The detection and recognition distance of WRED treatment combined with an HVJ was significantly greater under all conditions except twilight with car headlights and nighttime with car headlights for a PT of 600 ms. Furthermore, for this combination, the PT was significantly shorter under all conditions except nighttime with car headlights. The effects of gentle self-signaling of a bicycle via the combination of WRED treatment and an HVJ can reduce the PT for detecting a bicycle and increase the detection and recognition distance under all lighting conditions. Passive safety measures based on these results can support drivers, who might otherwise look but fail to see bicyclists in time. In summary, the combination of WRED treatment with an HVJ is strongly recommended to achieve cost-effective self-signaling of a bicycle.

1. Introduction

A bicycle is a healthy and environmentally friendly means of transportation [1]–[3] that can be used by people of different ages. Where safe space is available, people enjoy walking and cycling more than any other mode of transportation [4]. However, the increasing number of road networks created for vehicles has contributed to a higher frequency of collisions on roads. Bicyclists are more vulnerable to such accidents than other road users [5], [6]; however, they have a low priority in terms of allocating a safe space in many countries. Less protected groups, including pedestrians, bicyclists, and motorcyclists, account for nearly half of all deaths from collisions on roads [7]. In Japan, the number of bicyclist fatalities due to vehicular collisions is higher than the number of vehicle driver fatalities; this number is higher than that in any other G7 country [8]. Although many researchers have attempted to reduce bicycle–vehicle collisions by improving the conspicuity of the rear end of bicycles, the number of bicycle–vehicle collisions has not decreased significantly. Self-signaling of a bicycle can help identify the bicycle sooner; this can solve the problem of drivers looking but failing to identify bicyclists and thus prevent collisions. Although drivers may look in the right direction at the right time, they may fail to identify vulnerable objects such as bicycles. Late detection and recognition are the major problems associated with collisions. Thus far, no study has investigated the short perception time for detecting and recognizing a bicycle in day/night conditions. An initial study aimed to improve a novel approach that emphasizes gentle self-signals to indicate the presence of a bicycle; to this end, a pattern of white stripes on a red background was designed to enhance the detection distance [9]. The results showed that this pattern enhances the detection distance within 600 ms; however, the detection distance of this pattern for control bicycles was greater than the safe driving distance (25 m based on a vehicle speed of 30 km/h) [9]. Therefore, self-signaling is a key requirement for early detection and recognition, which can solve the problem of drivers looking in the right direction but failing to identify vulnerable objects in time.

The number of bicyclist casualties due to vehicle collisions is higher on residential roads with no bicycle lane than on other road patterns [10]. Among all the casualties involving bicyclists and vehicles, nearly 50% are attributed to rear-end collisions between the vehicle and the bicycle. Bicycles are extremely narrow and have no self-signaling capability to alert road users. Despite looking, drivers may fail to identify bicyclists in time owing to a lack of self-signaling. Many conspicuous objects on the road require a driver’s attention. Therefore, the insufficient conspicuity of bicyclists may aggravate the problem of late detection by vehicle drivers and thus increase the likelihood of collisions.

In general, cycling in the dark is more dangerous than cycling in daylight; however, the injury rate is usually higher early in the morning than late in the evening [11]. Moreover, the risk of cycling in the dark in rural areas is higher than that in urban areas by a factor of around five. However, the majority of serious bicyclist injuries occur in daylight [11]. Many researchers have attempted to enhance nighttime conspicuity by proposing the use of a high-visibility jacket (HVJ) for bicyclists as well as reflective tape (RT) on bicycle frames and pedals [12]–[15], [15]–[18]. Promising results have been achieved in terms of improving the detection and recognition distance at night; however, collisions continue to occur [12]. Moreover, in daylight and twilight conditions without car headlights, no measure has been found to be effective. In addition, wearing an HVJ is not feasible for all bicyclists. *Detection distance (DD)* refers to the distance at which a road user can detect the presence of an object in the environment, and *recognition distance (RD)* refers to the distance at which a road user can classify an object.

On a residential road, the safe distance for drivers is 25 m considering the head-to-tail distance at a vehicle speed of 30 km/h [9], [19]–[21]. Based on this safe driving distance, a sufficient distance is available for the detection and recognition of bicycles under day and night conditions [9]. Therefore, late detection promotes looked-but-failed-to-see crashes, whereas the effect of conspicuity treatments, such as white stripes on a red background, can improve the perception time and thus enhance the detection and recognition distance. *Perception time (PT)* refers to the time required to notice the presence of something. This measurement is subjective and is based on the perception of an individual. Detecting a bicycle within a short time can solve the problem of drivers looking but failing to see bicyclists in time. Self-signaling of a bicycle may enhance the early detection of the bicycle. Within a video frame of 600 ms, respondents can detect objects at a distance greater than the safe driving distance [9]. However, as drivers move forward, they must focus on identifying any possible hazards within a very short time.

A modification of the conspicuity treatment of white stripes on a red background (WRED) can facilitate self-signaling of a bicycle, which may enhance its DD, RD, and PT [9]. In the case of rear-end collisions due to a lack of self-signaling of bicycles, drivers look but fail to see the bicycle in time. WRED treatment combined with an HVJ and RT can improve the timely perception of drivers regarding the presence of an object in both day and night conditions. An HVJ is highly conspicuous compared to WRED and RT conspicuity treatments; however, during riding, an HVJ has no rotating condition to indicate dynamic behavior. By contrast, although WRED involves less conspicuous materials compared to an HVJ, its rotation during riding highlights its dynamic behavior. In addition, RT also exhibits dynamic behavior, albeit only of retroreflective areas. Modifying the tire color not only costs less than attaching a blinking light but also facilitates self-signaling without any active behavior by the bicyclist. Signal noise from the use of blinking lights on the rear end of a bicycle may result in severe bicycle–vehicle collisions [22], [23]. Finding the optimal level of signaling for the presence of a bicycle can reduce the signal noise and improve the cognitive errors of drivers.

2. Literature Review

Bicycle–vehicle collisions are classified into many categories. Among them, rear-end and angular collisions account for nearly 70% of all bicycle–vehicle collisions [9], [10]. Such collisions have been found to result from of a lack of conspicuity treatment of bicycles. Thus, drivers may look but fail to see bicyclists and hence cannot avoid collisions [24], [25]. A bicycle is extremely narrow, and self-signaling of its presence is not available under all lighting conditions. A large amount of sensory conspicuity is present in front of a driver, whereas bicycle conspicuity is not at a remarkable level. Although bicyclists believe that they are visible to drivers, distinguishing a bicycle from the various sensory signals received during driving is difficult for drivers, as such signals are overloaded and deleted frequently [26]. Moreover, a bicycle typically has no prominent conspicuous material that can enable drivers to detect it.

Many researchers have aimed to enhance the sensory conspicuity of bicycles by proposing the use of fluorescent jackets by bicyclists, reflective tape on the bicycle frame, fluorescent accessories and reflectors, reflective tires, retroreflectors, biomotion, blinking lights, and flashing beacons [27]–[35]. All these conspicuity treatments focus on the enhancement of detection and recognition distances and times under nighttime conditions; however, collisions also occur during the daytime owing to perception problems within short time frames. Moreover, on a residential road, although detection and recognition distances are greater than safe driving distances under both day and night conditions [9], drivers look but fail to see bicyclists in time [27], [36]. According to Hills (1980), drivers actually look in the direction of bicyclists but do not perceive their presence in time. Therefore, looked-but-failed-to-see accidents constitute a specific phenomenon in which the visual perception of objects is interrupted [38]. The time to detect and time to react varies among drivers according to their age [39].

A driver who needs to move forward spends a certain amount of time in searching. In the laboratory, the search is simplified as follows: the subject views a set of video frames, and respondents are asked to give their response within a certain period. Laboratory studies have shown that a glimpse of 100 ms allows a person to gain a basic understanding of the scene[40], [41]. Images are shown to the respondents for gauging their perception, and the results indicate that an average of 167 ms is required for 90% detection

[42]. Previous studies have suggested that on average, a driver requires 220 ms for perception of a signal, 400 ms for object recognition, and 90 ms for searching the direction of an object [43], [44].

Studies on conspicuity treatments with reflective materials have focused on car headlights, providing no effective measures in daylight conditions. None of the conspicuity treatments facilitates self-signaling, except for blinking lights. In these studies, although the drivers looked in the right direction, they could not perceive the signal in time [37], [38]. In the case of a rear light, the flashing beacon signals the presence of a bicycle; however, it is often perceived as light noise that distracts road users and possibly causes cognitive errors [22].

Different types of bicycles are available. Most bicyclists use their bicycles for short-distance commuting, daily shopping, going to school, etc. In developed countries, such as Japan, people use their bicycles regularly. Regular bicyclists tend to focus on their daily activities rather than increasing their conspicuity for other road users. Many conspicuous dynamic sensory signals are obtained from the road, such as those from advertisements, traffic signals, and moving vehicles. Drivers must scan for signals from all such objects continuously, while bicyclists appear to have a low priority because of their relatively low numbers. Gentle self-signaling of a bicycle can facilitate detection of the bicycle within a short PT and improve the insight of drivers who look but fail to see bicyclists in time. Some treatment of the bicycle is required to enable drivers to detect the bicycle easily in both day and night conditions; however, bicyclists usually do not to pay attention to this requirement.

3. Purpose

This study focuses on the effectiveness of WRED treatment on early detection and recognition in day/night conditions. In addition, WRED treatment is combined with other highly conspicuous materials, including reflective materials, to enhance the results under night conditions. An experiment was conducted on a straight-ahead approach road under the following conditions: sunlight, twilight without car headlights (TW-CH), twilight with car headlights (TW + CH), and nighttime with car headlights (NCH). The following conspicuity treatments were employed: WRED, HVJ, white ECE/ONU 104 RT on the bicycle frame, WRED treatment with HVJ (WRED_HVJ), WRED treatment with RT (WRED_RT), HVJ with RT (HVJ_RT), and a black jacket worn for the control bicycle (CB). The control bicycle with no fender, rear reflector, pedal reflector, or conspicuity treatment was considered the baseline. Two perception times, 250 and 600 ms, were considered in this study to measure the impact of the perception time on the detection and recognition distance. We expect that WRED treatment combined with other treatments will significantly enhance early detection and recognition and reduce signal noise under day and night conditions.

4. Methods

4.1 Respondents. The perceptions of respondents were recorded on the basis of video surveillance of conspicuity treatments presented on a computer screen. The respondents were recruited through the Internet with a recruitment notice based on their binocular visual acuity and on a first-come, first-served basis. The sample comprised 20 male and 10 female respondents. The mean age of the male respondents was 31.4 ± 5.16 years, with ages ranging from 21 to 36 years, and the mean age of the female respondents was 26.4 ± 5.79 years, with ages ranging from 20 to 35 years. All the respondents reported that they regularly rode bicycles, which is common in Japan. Among the 30 respondents, the licensed drivers included 8 male respondents (3.75 ± 1.6 years, ranging from 1 to 6 years) and 5 female respondents (3.6 ± 1.14 years, range 2 to 5 years). All respondents had passed the minimum driver's licensing criteria for binocular visual acuity (6/6 in Snellen notation and 0 in LogMAR notation).

4.2 Bicycle Conditions. Japan's ubiquitous city bicycle was used as a control bicycle in the experiment. The control bicycle had no rear fender, rear reflector, or pedal reflector, as shown in Fig. 1(a). During the experiment, the bicycle was modified using WRED, an HVJ, and RT, and ridden under various combinations of the four lighting conditions. In the first treatment, modified by the authors, WRED was used, with a width of 4 cm and a height of 5.5 cm for the white stripes; there were four sets of four-stripe patterns, with an allocated gap between them. The gap between the stripes was 2 cm, and the longitudinal middle gap was 1.5 cm, as shown in Fig. 1(b). The white-striped area was 352 cm^2, and the red area was 889.9 cm^2. Both colors were applied using adhesive tape (PVC duct tape) as a conspicuous material. In the second treatment, a yellow HVJ (EN471-class 2) with a reflective area of 792 cm^2 on the back, i.e., a large conspicuous area, was used, as shown in Fig. 1(c). In the third treatment, white RT (983 3M Adhesive ECE 104 R reflective tape) was applied to the left and right forks (20 × 2.0 cm each), the bicycle seat post (one strip of 10 × 4.0 cm), and the pedal cranks (12 × 2.5 cm each), as shown in Fig. 1(d). The total area of coverage visible from the rear was 150 cm^2. In the control condition, the test bicyclist was wearing a black jacket to avoid the effects of any conspicuity of the clothing.

4.3 Road and Experimental Vehicle. The experiment was performed on a 340-m long, straight, single-lane, bidirectional residential road located between the university and a residential area, where the traffic volume was low. The road width was 5.31 m, including a sidewalk of 1.06 m on the side opposite to the university, with a low pedestrian boundary along a segment of the residential road. The other side of the road had no sidewalk and no segment of residential road along the entire length of 340 m. The streetlights were on the opposite side of the road, 35 m from the sidewalk, and the first streetlight was 10 m ahead of the camera position, as shown in Fig. 2(a). The video surveillance camera (GoPro Hero 6) was placed on the road surface under sunlight, TW-CH, and TW + CH conditions and inside a car under night conditions. The camera was positioned at a height of 120 cm from the ground, which is similar to the height of a driver's eyes. The treated bicycles moved away from the camera at 18 km/h under sunlight, TW-CH, and TW + CH conditions. At night, the camera-containing car (with low-beam headlights) moved toward the treated bicycles. The bicycle position was fixed, whereas its tires rotated at a speed of nearly 18 km/h.

The experiment was conducted with seven conspicuity treatments, namely WRED, HVJ, RT, WRED_HVJ, WRED_RT, HVJ_RT, and CB, as shown in Fig. 2(b–h), under (i) sunlight conditions without any clouds from 11:30 am to 12:30 pm, (ii) twilight conditions with the sun 0–6° from the horizon and the car headlights both on and off, and (iii) typical streetlight conditions at night with the car headlights on. The mean speed of the experimental bicycles was 18 km/h under all the lighting conditions, and the speed of the car with low-beam headlights was 30 km/h in the NCH conditions.

4.4 Task. Before beginning their tasks, the respondents were given detailed instructions and asked to view one sample video of each distance and each treatment on a computer screen (screen size, 21.5"; aspect ratio, 16:9; resolution, 1920 × 1080). For each condition, at intervals of 10 m starting from the camera up to 160 m away (16 frames), the video was prepared with exposure times of 250 ms and 600 ms separately. The order of the video scenes was random, including some scenes without bicycles; the respondents were not shown the scenes in order. After the perception, or lack thereof, of each target image was recorded, a black screen appeared. The respondents were assigned two tasks, i.e., determining the detection and recognition distance, and the required perception time. To determine the detection distance with respect to the perception times of 250 ms and 600 ms, each video scene was viewed separately, and the respondents stated their perception accordingly. Similarly, to determine the recognition distance, the respondents stated their perception accordingly with respect to the video scenes of 250 ms and 600 ms, as shown in Fig. 3. They were allowed only one glimpse of each sample and were prohibited from viewing the scene again. Before the next sample was displayed, the respondents were requested to fill “1” in the prescribed form if they could detect and recognize the bicycle. To measure the maximum detection and recognition distance, each participant’s highest detection and recognition distance was considered from the 16 above-mentioned frames. To determine the required perception time for detecting the bicycle from the perception time of 600 ms, the respondents reported their perceptions by pressing the print screen button within the time frame of 600 ms. Each 600-ms video was played only once, but in a random sequence. If the respondents could detect the bicycle within the specified limits, they were asked to press the print screen button at the time of detection. The subjects were informed about this study, particularly that it was being conducted to understand how drivers detected a bicycle as an object and recognized it as a bicycle on a defined track. During the experiment, the experimental bicycle was the only bicycle present in the scene, and no pedestrians were present. The lighting conditions and conspicuity treatments were successively provided in a random order. To scrutinize the procedure with ANOVA, the detection $F\left(1, 58\right)=0.145$, $p=0.70$ and recognition $F\left(1, 58\right)=0.001$, $p=0.97$ distances of the first respondent were compared with those of the subsequent respondent, and the difference was not significant. In addition, the perception times $F\left(1, 58\right)=0.023$, $p=0.88$ for WRED and $F\left(1, 58\right)=0.08$, $p=0.78$ for HVJ of the first respondent under the sunlight condition were compared with those of the subsequent respondent, and the difference was not significant.

5. Data Analysis

The PTs for the seven conspicuity treatments under the four lighting conditions were calculated on the basis of the respondents’ perceptions. The data were analyzed using analysis of variance (ANOVA) in Statistical Package for the Social Sciences (SPSS) and Excel. In addition, a post hoc (Tukey HSD) analysis was performed to explore the differences between multiple groups of means using SPSS.

6. Results And Discussion

6.1 Detection Distance. The mean DDs and standard deviations for the two PTs under all the lighting conditions are listed in Table 1. The DDs with standard errors are shown in Fig. 4.

A two-factor ANOVA with replication analysis was performed. The results are summarized in Table 2. The dependent variable was DD, and the independent variables were the seven conspicuity treatments (WRED, HVJ, RT, WRED_HVJ, WRED_RT, HVJ_RT, and CB) and two PTs (250 ms and 600 ms). The results obtained in the sunlight condition indicated that the two independent variables had interaction effects on the DD. The WRED_HVJ, WRED_RT, and HVJ_RT treatments had static and dynamic conditions compared to the other conspicuity treatments. A post hoc (Tukey HSD) analysis revealed a statistically significant difference between the WRED_HVJ and HVJ treatments for the PT of 250 ms as well as between the WRED_HVJ and WRED treatments for the PT of 600 ms. However, no statistically significant difference was observed between the RT treatment and the CB for any of the PTs. The DD of the WRED_HVJ treatment was significantly greater than that of the CB for all the PTs.

Table 1: DD (m) and standard deviations for the two PTs under the four lighting conditions.

	Conspicuity treatment	Sunlight	TW-CH	TW+CH	NCH
250 ms	WRED	67.67 ± 7.28	62.67 ± 6.40	62.33 ± 7.74	35.33 ± 5.07
	HVJ	65.33 ± 8.60	51.33 ± 7.76	59.33 ± 7.85	37.67 ± 7.28
	RT	48.33 ± 7.91	24.67 ± 5.07	49.00 ± 8.85	34.33 ± 5.04
	WRED_HVJ	71.67 ± 5.92	63.67 ± 6.15	65.67 ± 5.68	40.33 ± 5.56
	WRED_RT	68.67 ± 7.76	63.67 ± 6.15	62.67 ± 7.40	37.67 ± 4.30
	HVJ_RT	66.00 ± 7.70	51.33 ± 7.30	61.00 ± 6.62	38.00 ± 7.15
	CB	48.33 ± 6.48	24.67 ± 5.07	26.33 ± 4.90	24.33 ± 5.04
600 ms	WRED	138.33 ± 7.91	97.33 ± 7.85	94.33 ± 5.04	58.33 ± 7.91
	HVJ	140.67 ± 10.81	89.67 ± 7.18	103.67 ± 7.65	158.67 ± 8.19
	RT	89.67 ± 7.65	44.67 ± 5.07	110.33 ± 11.29	163.67 ± 7.65
	WRED_HVJ	145.33 ± 8.19	98.67 ± 8.19	104.67 ± 6.29	158.67 ± 8.19
	WRED_RT	139.00 ± 7.59	98.67 ± 7.30	110.67 ± 10.81	163.67 ± 7.65
	HVJ_RT	140.67 ± 10.81	89.67 ± 7.18	112.67 ± 9.44	165.67 ± 6.26
	CB	88.33 ± 7.91	44.67 ± 5.07	50.33 ± 8.90	40.33 ± 7.65

Table 2: Effects of PT and conspicuity treatments on DD.

Type	Lighting condition	Perception time (A)			Conspicuity treatment (B)			A*B		
		F	*df*	*P*	*F*	*df*	*P*	*F*	*df*	*P*
Detection distance	Sunlight	6428.6	1, 406	***	277.5	6, 406	***	56.9	6, 406	***
	TW-CH	2376.6	1, 406	***	599.4	6, 406	***	22.2	6, 406	***
	TW+CH	3038.1	1, 406	***	279.8	6, 406	***	36.8	6, 406	***
	NCH	20449.9	1, 406	***	1156.3	6, 406	***	864.6	6, 406	***

*** = significant at *P<0.001*

In the TW-CH condition, the two independent variables had significant interaction effects on the DD. More conspicuously, the combined WRED_HVJ and WRED_RT treatments had a greater impact on the DD in the TW-CH condition. A post hoc (Tukey HSD) analysis revealed no statistically significant difference between the WRED_HVJ treatment and both the WRED *(P=0.996)* and the WRED_RT *(P=1.0)* treatments for any of the PTs. Moreover, there was no statistically significant difference between the RT and the CB for any of the PTs. The DD of the WRED_HVJ and WRED_RT treatments was significantly greater than that of the CB for all the PTs.

The two independent variables had significant interaction effects on the DD under the TW+CH condition. The reflectivity along with the large conspicuous area of the treatments was advantageous for the DD under the TW+CH condition during the short perception time, and the reflectivity along with the dynamic behavior was advantageous during the perception time of 600 ms. A post hoc (Tukey HSD) analysis revealed no statistically significant difference between the WRED_HVJ treatment and the WRED *(P=0.540*), WRED_RT *(P=0.661)*, and HVJ_RT *(P=0.151)* treatments for the PT of 250 ms.

Moreover, there was no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P=0.999*), RT *(P=0.162*), and WRED_RT *(P=0.115*) treatments for the PT of 600 ms. The DD of the WRED_HVJ treatment was significantly greater than that of the CB for the PT of 250 ms; however, the DD of the HVJ_RT treatment was significantly greater than that of the CB for the PT of 600 ms

In the NCH condition, the two independent variables had significant interaction effects on the DD. The total reflective area and cyclic conditions influenced the DD. The large conspicuous area with reflectivity influenced the detection during the shortest PT. A post hoc (Tukey HSD) analysis revealed no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P=0.548*), WRED_RT *(P=0.548)*, and HVJ_RT *(P=0.697)* treatments for the PT of 250 ms. Moreover, there was no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P>0.05*), RT *(P>0.05)*, and WRED_RT *(P>0.05)* treatments for the PT of 600 ms. The DD of the WRED_HVJ treatment was significantly greater than that of the CB for the PT of 250 ms. However, the DD of the HVJ_RT treatment was significantly greater than that of the CB for the PT of 600 ms.

Both the self-generated color-blinking signal of the WRED and the additional conspicuous area of the reflective materials of the HVJ played a significant role in the detection of the bicycle within the shortest PT (250 ms) under all the lighting conditions. The DD of the WRED_HVJ treatment was significantly greater than that of the other conspicuity treatments under sunlight and TW-CH conditions for all the PTs. In addition, the DD of the WRED_HVJ treatment was greater under the TW+CH and NCH conditions for the PT of 250 ms, while the DD for the HVJ_RT treatment was significantly greater in the TW+CH and NCH conditions for the PT of 600 ms.

Table 3: RD (m) and standard deviations for the two PTs under the four lighting conditions.

	Conspicuity treatment	Sunlight	TW-CH	TW+CH	NCH
250 ms	WRED	51.33 ± 7.76	47.00 ± 4.66	49.33 ± 6.39	33.00 ± 6.51
	HVJ	49.00 ± 9.23	43.67 ± 4.90	48.33 ± 6.99	36.33 ± 6.15
	RT	41.67 ± 6.99	22.67 ± 4.49	44.67 ± 5.07	30.67 ± 8.68
	WRED_HVJ	54.33 ± 8.58	47.00 ± 4.66	52.67 ± 5.20	38.67 ± 5.07
	WRED_RT	52.33 ± 7.28	47.00 ± 4.66	50.00 ± 5.87	33.33 ± 6.61
	HVJ_RT	50.00 ± 8.71	43.67 ± 4.90	50.33 ± 5.56	38.67 ± 5.07
	CB	41.67 ± 8.34	22.67 ± 4.49	24.00 ± 4.98	20.33 ± 5.56
600 ms	WRED	94.67 ± 9.37	72.67 ± 7.85	74.67 ± 5.71	50.67 ± 7.40
	HVJ	102.33 ± 8.58	68.33 ± 5.92	89.67 ± 9.28	98.67 ± 7.76
	RT	71.67 ± 7.47	44.33 ± 7.28	88.67 ± 7.76	101.67 ± 7.47
	WRED_HVJ	105.00 ± 5.72	74.33 ± 6.26	89.67 ± 9.28	98.67 ± 7.76
	WRED_RT	94.67 ± 9.37	72.67 ± 7.85	88.67 ± 7.76	101.67 ± 7.47
	HVJ_RT	102.33 ± 8.58	68.33 ± 5.92	93.33 ± 7.58	104.33 ± 6.79
	CB	71.33 ± 6.29	44.33 ± 6.79	48.33 ± 7.47	40.00 ± 6.43

6.2 Recognition Distance. The mean RDs and standard deviations considering the two PTs under all the lighting conditions are listed in Table 3. The RDs with standard errors are shown in Fig. 5.

A two-factor ANOVA with replication analysis was performed. The results are summarized in Table 4. The dependent variable was RD, and the independent variables were the seven conspicuity treatments (WRED, HVJ, RT, WRED_HVJ, WRED_RT, HVJ_RT, and CB) and the two PTs (250 ms and 600 ms). The results obtained in the sunlight condition showed that the two independent variables had interaction effects on the RD. The WRED_HVJ treatment had static and dynamic conditions that allowed easy recognition of the bicycle compared to the other conspicuity treatments. A post hoc (Tukey HSD) analysis revealed no statistically significant difference between the WRED_HVJ treatment and the WRED *(P=0.789),* HVJ *(P=0.154),* WRED_RT *(P=0.964)*, and HVJ_RT *(P=0.383)* treatments for the PT of 250 ms.

Table 4: Effects of PT and conspicuity treatments on RD.

Type	Lighting condition	Perception time (A)			Conspicuity treatment (B)			A*B		
		F	*df*	*P*	*F*	*df*	*P*	*F*	*df*	*P*
Recognition distance	Sunlight	2976.0	1, 406	***	83.1	6, 406	***	22.9	6, 406	***
	TW-CH	1814.7	1, 406	***	262.9	6, 406	***	1.94	6, 406	0.074
	TW+CH	2875.3	1, 406	***	198.4	6, 406	***	20.8	6, 406	***
	NCH	6082.8	1, 406	***	335.5	6, 406	***	171.3	6, 406	***

*** = significant at *P<0.001*

Moreover, there was no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P=0.857)* and HVJ_RT *(P=0.857)* treatments for the PT of 600 ms. The RD for the WRED_HVJ treatment was significantly greater than that of the CB for all the PTs.

Under the TW-CH condition, the two independent variables had significant effects on the RD. The WRED treatment enhanced the bicycle recognition under the TW-CH condition. The RD of the WRED_HVJ treatment was significantly greater than that of the CB for all the PTs.

The two independent variables had significant interaction effects on the RD under the TW+CH condition. The large conspicuous area with reflectivity of the HVJ and the cyclic condition of the WRED treatment were advantageous within the PT of 250 ms. By contrast, the large reflective area and cyclic condition of the HVJ_RT treatment were effective for recognizing the bicycle in the PT of 600 ms. A post hoc (Tukey HSD) analysis revealed no statistically significant difference between the WRED_HVJ treatment and the WRED (*P=0.280*), WRED_RT *(P=0.556),* and HVJ_RT *(P=0.704)* treatments for the PT of 250 ms. In addition, there was no statistically significant difference between the WRED_HVJ treatment and the WRED_RT *(P>0.990),* HVJ (*P>0.850*), RT *(P>0.992),* and HVJ_RT *(P>0.257)* treatments for the PT of 600 ms. The RD of the WRED_HVJ treatment was significantly greater than that of the CB for the PT of 250 ms, and the RD of the HVJ_RT treatment was significantly greater than that of the CB for the PT of 600 ms.

In the NCH condition, the two independent variables had significant interaction effects on the RD. A post hoc (Tukey HSD) analysis revealed no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P=0.788*) and HVJ_RT *(P=1.0)* treatments for the PT of 250 ms. Moreover, there was no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P>0.05*), RT *(P>0.05),* WRED_RT *(P>0.05),* and HVJ_RT*(P>0.05)* treatments in the PT of 600 ms. The RD of the HVJ_RT treatment was significantly greater than that of the CB for all the PTs.

The combined effects of the WRED_HVJ and HVJ_RT treatments provided additional advantages for recognizing the bicycle within the shortest PT. The RD of the WRED_HVJ treatment was significantly greater for the PT of 250 ms under all the lighting conditions. In the sunlight and TW-CH conditions, the RD of the WRED_HVJ treatment was significantly greater for all the PTs. However, the RD of the HVJ_RT treatment was significantly greater for the PT of 600 ms under the TW+CH and NCH conditions.

6.3 Perception Time. A two-factor ANOVA with replication analysis was performed on the PT at a distance of 25 m from the camera. The dependent variable was PT, and the independent variables were the seven conspicuity treatments (WRED, HVJ, RT, WRED_HVJ, WRED_RT, HVJ_RT, and CB) and the four lighting conditions (sunlight, TW-CH, TW+CH, NCH). There was a statistically significant interaction between the conspicuity treatments and the lighting conditions The post hoc analysis revealed no statistically significant difference between the WRED_HVJ treatment and the WRED *(P=0.737)* and WRED_RT *(P=0.737)* treatments under the sunlight condition. The PT of the WRED_HVJ treatment (184.88 ± 4.64 ms, *P*<0.001) was significantly shorter than that of the CB (241.33 ± 10.78 ms) under the sunlight condition, as shown in Fig. 6(a). Under the TW-CH condition, the PT of the WRED_HVJ treatment (186.88 ± 6.25 ms, *P*<0.001) was significantly shorter than that of the CB (244.24 ± 10.03 ms), as shown in Fig. 6(b). There was no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P=0.394)*, WRED_RT *(P=1.0),* and HVJ_RT *(P=0.694)* treatments for the PT under the TW+CH condition. The PT of the WRED_HVJ treatment (205.69 ± 6.46 ms, *P*<0.001) was significantly shorter than that of the CB (264.13 ± 10.32 ms), as shown in Fig. 6(c). Under the NCH condition, there was no statistically significant difference between the WRED_HVJ treatment and the HVJ *(P=1.0)*, WRED_RT *(P=1.0)*, and HVJ_RT *(P=1.0)* treatments for the PT. The PT of the WRED_HVJ treatment (216.87 ± 6.93 ms, *P*<0.001) was significantly shorter than that of the CB (249.51 ± 10.03 ms), as shown in Fig. 6(d).

Under the sunlight and TW-CH conditions, the WRED, WRED_HVJ, and WRED_RT conspicuity treatments played a significant role in the detection of the bicycle within the shortest PT, and the mean PT was shorter than that of the other conspicuity treatments. However, under the TW+CH condition, the PT for detecting the bicycle was the shortest in the case of the WRED_HVJ and WRED_RT treatments. In addition, the PTs of the WRED_HVJ, WRED_RT, and HVJ_RT treatments were the shortest in the NCH condition.

In this study, the effectiveness of different conspicuity treatments and their combinations in detecting a bicycle within a short PT was evaluated on the basis of the self-signaling of a bicycle and its reflective area, as compared to a control. In comparison to the CB, the combined WRED_HVJ treatment resulted in an improvement in the DD and RD within the PT of 250 ms under all the lighting conditions. Moreover, the DD and RD of the WRED_HVJ treatment were significantly greater than those of the CB for all the PTs under the sunlight and TW-CH conditions. However, for the PT of 600 ms and under the TW+CH and NCH conditions, the DD and RD of the HVJ_RT treatment were significantly greater than those of the CB. Based on a residential road, a restricted speed of 30 km/h, and a safe driving distance of 25 m, the required PTs of different conspicuity treatments were evaluated. The PT of the combined WRED_HVJ treatment was significantly shorter under the sunlight, TW-CH, and TW+CH conditions compared to that of the other conspicuity treatments. By contrast, the PT of the HVJ_RT treatment was shorter under the NCH condition.

7. Conclusion

Gentle self-signaling of a bicycle toward road users without active behavior of the bicyclist can facilitate detection of the bicycle as an object on the road and thus mitigate the problem of drivers looking but failing to identify the bicycle in time, without affecting the driver’s concentration. Late detection and recognition contribute toward bicycle–vehicle collisions, which can be prevented through conspicuity treatments such as white stripes on a red background. Furthermore, a large conspicuous area with reflective materials helps identify bicycles at night. The detection and recognition distances of WRED and WRED_HVJ were found to be nearly the same during the video frame of 250 ms. However, wearing the HVJ is not feasible for all bicyclists.

Under sunlight and TW-CH conditions, the self-signaling of a bicycle via WRED treatment plays an important role in the detection and recognition of bicycles within a short PT. The total area of conspicuous or reflective materials is also an important factor under the TW + CH and NCH conditions for the detection and recognition of a bicycle within a short PT. Self-signaling of a bicycle and the use of reflective materials can address the problem of drivers failing to see a bicycle in time under all lighting conditions by improving the DD and RD. Without any additional effort, a bicyclist can benefit from WRED and RT; however, in the case of an HVJ, extra focus and care are required.

On a residential road in Japan with a non-demarcated lane, the frequency of rear-end collisions between vehicles and bicycles was the highest between 2012 and 2016 [10]. Drivers were looking but failing to see bicyclists in time [22] owing to a lack of self-signaling. Dynamic objects have a greater potential to attract the attention of road users compared to static objects. The two rotating objects (tires and pedals) can create dynamic signals without any additional effort, although the tire has a larger visible area in the case of a short fender. The WRED treatment on the tire amounts to self-signaling of the bicycle by taking advantage of the above-mentioned points to help drivers recognize the bicycle within a short PT.

The main objective of this study was to assess the possible contribution of different bicycle treatments under various conditions in order to address the problem of drivers looking but failing to see bicyclists in time. Focused drivers with sufficient PT can see bicyclists under any lighting condition, even at night with proper street lighting. However, at the minimum required distance for safe driving on a residential road, the PT to detect a bicycle in the road environment is crucial. Drivers could not identify a bicyclist properly when the PT was less than 600 ms. The required PT to detect a bicycle and the DD and RD under all lighting conditions were evaluated while considering two different PTs. The WRED_HVJ treatment was significantly better in terms of improving the DD and RD within a PT of 250 ms under all the lighting conditions. In addition, under the sunlight and TW-CH conditions, the WRED_HVJ treatment had higher DD and RD for all the PTs. Moreover, the required PT to detect the bicycle was significantly shorter than that of the other conspicuity treatments, and the mean PTs of the WRED_HVJ, WRED_RT, and HVJ_RT treatments were similar under the NCH condition. By contrast, the HVJ_RT treatment showed better performance for the PT of 600 ms under the TW + CH and NCH conditions.

A limitation of this study is that permanent tire color modification is not possible. Instead, adhesive tape was used during the experiments. Moreover, the sharpness of the hue can affect the PT in the long run. This observation was not considered in the present study. In addition, the respondents stated their perceptions of the scene by viewing a computer screen, which does not replicate an exact scene or a real event. The DDs and RDs were measured on the basis of the data on the computer screen to evaluate the impact of a short perception time, which cannot be judged in the real world. Further, the respondents were not recruited randomly. Thus, there is a possible bias in their observations. On a residential road, based on the circumstances and vehicle speed (≤ 30 km/h), the safe driving distance for drivers is 25 m. However, this distance may vary with the circumstances and vehicle speed. Four different lighting conditions were considered. However, the effects of weather conditions, such as rain, snow, and clouds, were not considered in this study. In Japan, the standard bicycle has a rear reflector and pedal reflectors for enhancing nighttime detection; however, during this experimental study, the control bicycle was used without the rear reflector and pedal reflectors to classify the enhancement due to the desired conspicuity treatments. Despite these limitations, a critical evaluation of the seven conspicuity treatments under the same circumstances provided comparable features to ensure consistency.

This study showed that, compared to driving safely on a residential road, ample DD and RD are available through bicycle conspicuity treatments assessed under various lighting conditions. The PT required to detect the bicycle was different under different lighting conditions. The WRED treatment, especially when combined with an HVJ and RT, is well suited for early detection under all lighting conditions. In summary, the WRED_HVJ treatment is the best conspicuity treatment. However, further investigation is required to determine any adverse effects related to the widespread use of the WRED_HVJ treatment as well as to evaluate drivers' perception of the road. To measure the real-world perception of drivers regarding the detection and recognition distance, future studies can be conducted by employing eye-tracking devices, and the results may clarify their effectiveness in reducing bicycle–vehicle collisions.

Declarations

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Figures

Figure 1

(a) Control bicycle (CB) with no fender, rear reflector, or pedal reflector. (b) WRED conspicuity treatment applied to the rear tire. (c) HVJ. (d) RT applied to the bicycle frame.

Figure 2

Illustration of experimental stimuli. (a) Experimental, straight-ahead route and snapshots of (b) WRED, (c) HVJ, (d) RT, (e) WRED_HVJ, (f) WRED_RT, (g) HVJ_RT, and (h) CB during the experiment.

Figure 3

Schematic representation of video scene every 10 m from the camera during an exposure time of (a) 250 ms and (b) 600 ms in random order.

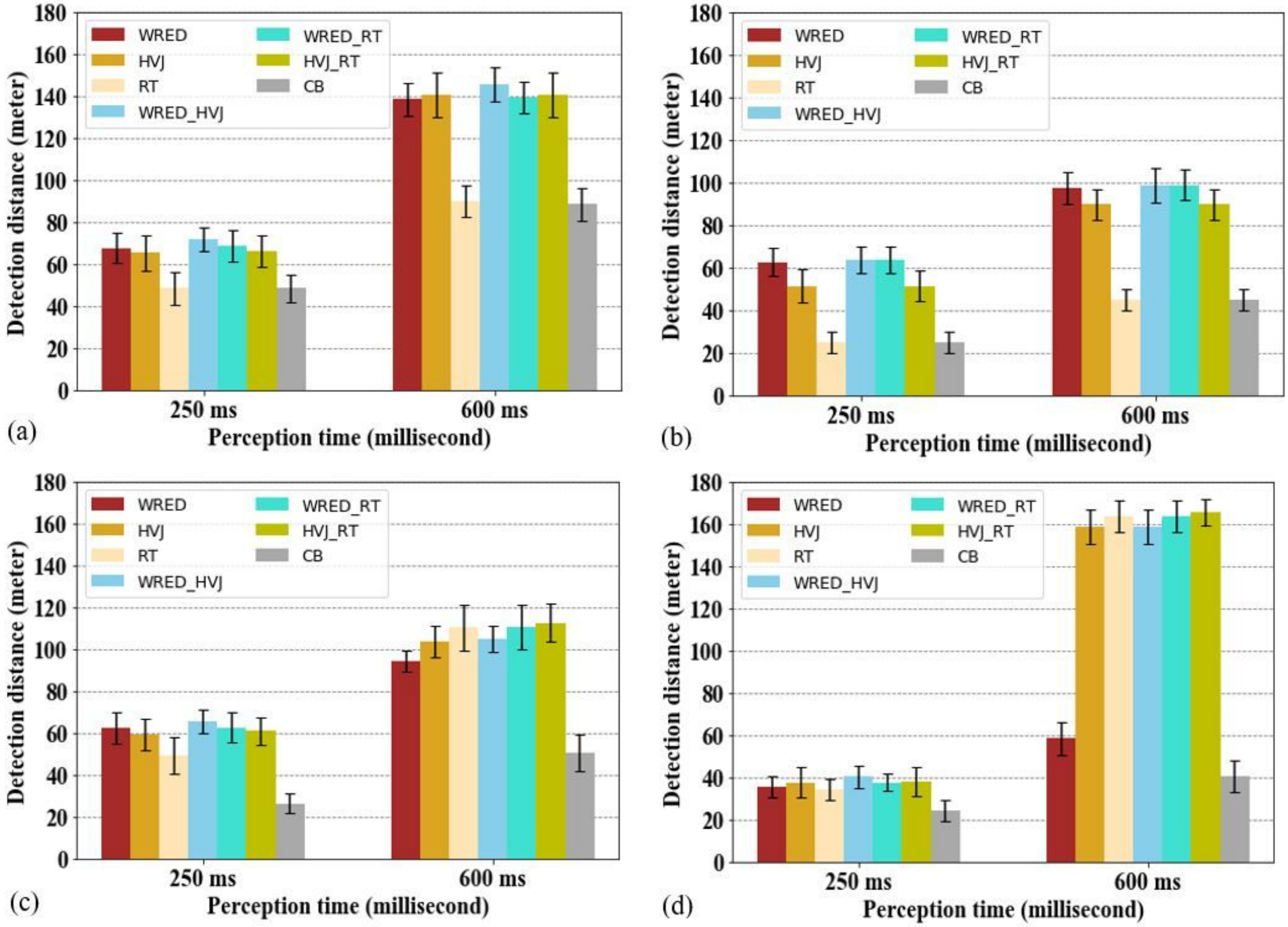

Figure 4

DD with standard error bars for different conspicuity treatments under (a) sunlight, (b) TW-CH, (c) TW+CH, and (d) NCH conditions.

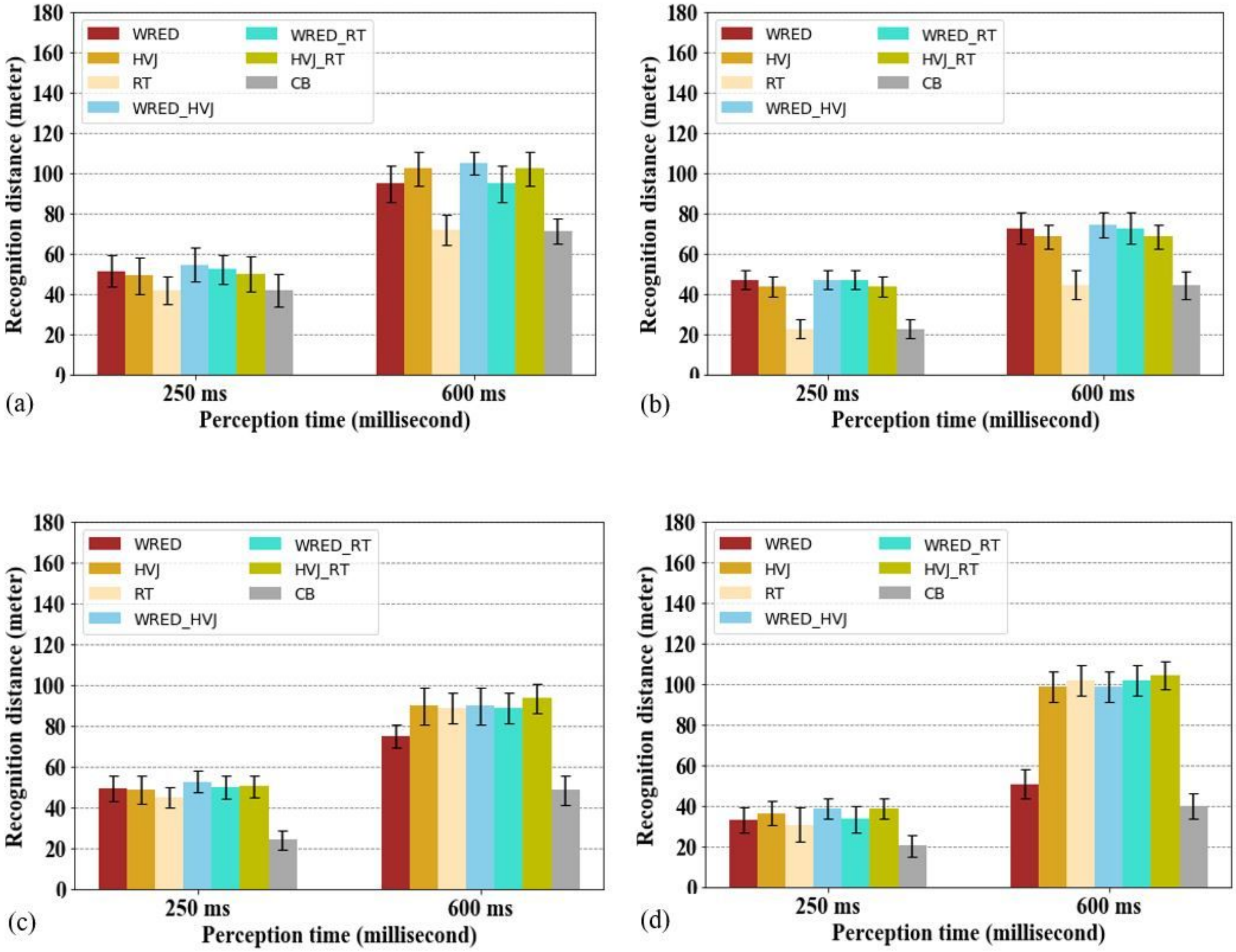

Figure 5

RD with standard error bars of different conspicuity treatments under the (a) sunlight, (b) TW-CH, (c) TW+CH and (d) NCH conditions.

Figure 6

Required PT for detecting the seven conspicuity-treated bicycles under (a) sunlight, (b) TW-CH, (c) TW+CH, and (d) NCH conditions at a distance of 25 m from the camera.