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NSTSCE

National Surface Transportation Safety Center for Excellence

Bicycle Visibility

Conspicuity of Bicycle Headlamps, Tail Lamps, and Retroreflective Garments in Nighttime Roadway Environments

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA	analysis of variance
ANCOVA	analysis of covariance
DAS	data acquisition system
HL	headlamp
HSD	honest significant difference
lm	lumens
NHTSA	National Highway Traffic Safety Administration
PBIC	Pedestrian and Bicyclist Information Center
RR	retroreflective
TL	tail lamp
UFOV	useful field of view
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

In 2018, 857 bicyclists died while riding on roads in the United States. Although only about 1% of trips are taken on bicycles, they make up 2% of roadway fatalities, making cyclist deaths overrepresented among traffic fatalities (National Highway Traffic Safety Administration [NHTSA], 2014; Pedestrian and Bicycle Information Center [PBIC], 2018). Cyclists are also 2 or 3 times more likely to die on a trip than those in passenger vehicles (Beck et al., 2007). In crashes that occurred during the day, 68% of cyclists had no safety equipment or conspicuity markings, such as reflective clothing or lighting. In crashes occurring at night, 81% of cyclists had no safety equipment or conspicuity markings (NHTSA, 2014). Increasing cyclist conspicuity to drivers could potentially reduce cyclist deaths, particularly at night, when visibility is lower.

This report describes research regarding the factors influencing cyclist death rates, pedestrian and cyclist conspicuity, and factors influencing whether cyclists adopt conspicuity markings. It also describes an experiment with various commercially available bicycle visibility-enhancement systems in terms of their conspicuity to drivers during the day and at night. The experimental systems included a headlamp, tail lamp, spoke lights, and retroreflective (RR) clothing, including garments that highlight biomotion. At its conclusion, the report includes recommendations for bicycle visibility-enhancement systems and other methods to reduce cyclist fatalities.

BACKGROUND

Researchers have identified a number of risk factors involved in cyclist crashes: being an older rider, riding while intoxicated, riding on roadways not designed to accommodate bicycles, and riding at night (Beck et al., 2007; Bil et al., 2010; Hagel et al., 2014; Kim et al., 2007; Klop & Khattak, 1999; Lacherez et al., 2013; PBIC, 2018). The last two factors are more relevant to bicycle conspicuity at night and are the focus of this report and the studies discussed herein.

Time of Day

Riding at night is linked with more severe crashes than riding during the day. When cyclist collisions with motor vehicles in Czechoslovakia were categorized by the severity of injury to the cyclist, results showed that the fatality rates were higher at night on unlit roadways than during the day. Statistics as far back as 1991 showed that 35% of crashes involving bicycles occurred after dark, but only about 13% of riding occurred after dark; thus, riding after dark is 3.8 times riskier than riding during the day (Rodgers, 1995). Finally, crashes involving bicycles are more severe on rural roadways without lighting (Kim et al., 2007; Klop & Khattak, 1999), but that could be because of two factors: a typically longer emergency response time for roads of that type and the visibility of the cyclist (Klop & Khattak, 1999). The latter issue is the focus of the studies discussed in this report.

A cyclist’s conspicuity is related to a number of factors, including the ambient light level, the color of the rider’s clothing, and the presence of RR materials and lights. Those factors have been examined in a number of observational and experimental studies. Studies examining pedestrian conspicuity are included here because many of the conspicuity aids used for pedestrians, including biomotion markers, are applicable to cyclist conspicuity (Wood et al., 2012).

Some researchers have performed observational studies and examined crashes involving cyclists to compare crash severity with the types of visibility aids the rider was using (Hagel et al., 2014). Other researchers performed experiments where they varied the clothing types, positions, activities, and other conspicuity elements of the pedestrian or cyclist, and measured detection and/or recognition distances (Moberly & Langham, 2002; Sayer & Medford, 2003; Tyrrell et al., 2009; Wood et al., 2010). Detection distance is the distance at which a driver first sees an object on the road, and recognition distance is the distance at which the driver recognizes that the object on the road is a pedestrian. If cyclists were more conspicuous, they would be more visible to drivers on the road. During the day, wearing fluorescent red, yellow, and orange, as well as non-fluorescent yellow, increased driver detection distances for pedestrians and cyclists, as did wearing white on the upper body (Hagel et al., 2014; Kwan & Mapstone, 2009). Also, when crash rates were compared across one group of cyclists using daytime running lights versus a group not using lights, daytime crash rates were 33% lower for the former group, and rates for crashes producing injuries were 41% lower for those using the running lights (Madsen et al., 2013).

Nighttime Conspicuity

At night, cyclists wearing RR materials in red and yellow, wearing a light-colored top, and using flashing lights and a tail lamp, or pedestrians carrying a handheld light, increased detection and recognition distances (Hagel et al., 2014; Kwan & Mapstone, 2009). Wearing RR garments increased detection and recognition distances at night (Wood et al., 2005). The intensity of retroreflection was less important than the presence or absence of RR materials (Sayer & Mefford, 2003). This could be because at night even a small amount of retroreflection is conspicuous against a dark background.

Biomotion

Human visual processing can easily recognize human patterns of motion, such as walking. Research (Johansson, 1973) has shown that when lights or reflective material were attached to a walker’s ankles, knees, hips, shoulders, elbows, and wrists, and a video was taken, observers were easily able to identify the disembodied moving lights as a walking person. That held true even when lights were added and removed from the video, showing that human ability to detect other human motion is robust (Johansson, 1973). The ability to selectively identify biological motion, or biomotion, is leveraged by many conspicuity aids. Biomotion markers on the limbs, in most studies, enable drivers to recognize walking pedestrians and pedaling cyclists at distances greater than RR markers on the torso alone (Koo & Dunne, 2012; Kwan & Mapstone, 2004; Kwan & Mapstone, 2009; Sayer & Mefford, 2003; Tyrrell et al., 2009; Wood et al., 2010; Wood et al., 2005). Biomotion is an important factor in pedestrian and cyclist conspicuity. However, there is some evidence that RR clutter or roadway lighting may interfere with the biomotion effect (Moberly & Langham, 2002; Wood et al., 2012).

Pedestrians’ and Bicyclists’ Perceptions of Their Visibility

Pedestrians and cyclists do not necessarily use visibility-enhancing devices, even though research shows that they increase conspicuity—of 652 cyclist fatalities recorded in the U.S. in 2012, in only 19 were cyclists wearing reflective equipment, and in only 18 were cyclists using lighting at the time of their fatal crashes. The lack of conspicuity marking could be because cyclists overestimate their visibility or do not make the connection between visibility and crashes. For example, of a group of 184 cyclists surveyed online who were in a crash said they thought the driver of the motor vehicle did not see them (61%), but only two mentioned visibility as a factor in the collision. Of the 184 respondents, 19% were riding at night without lights, 25% were wearing reflective clothing, and 20% were wearing fluorescent clothing (Lacherez et al., 2013). In an experimental study, when participant cyclists were asked to press a button when they thought an approaching driver definitely saw them, they overestimated their detection distance by 1.2 times. The overestimations were greatest when cyclists were wearing a black outfit, at 2.6 times the actual detection distance. They also underestimated their visibility (by a factor of 0.8) when they were the most conspicuous and wearing RR biomarkers (Wood et al., 2013). Additionally, participants in another study were willing to pay more for sports clothing with RR markings but were less willing to pay more for RR markings in garments with highly-effective biomotion locations, like gloves and arm bands (Costello & Wogalter, 2007). The results of the studies discussed above show that although much is known about pedestrian and cyclist visibility and biomotion markings, this knowledge is not being passed on to the general population.

RESEARCH GAPS

As previously noted, cyclists are overrepresented in traffic fatalities (PBIC, 2018). Infrastructure designs separating cyclists from motorists provide the most benefits in terms of cyclist safety (Reynolds et al., 2009), but are not always feasible. Increasing cyclist conspicuity is a more approachable and cost-effective means to potentially reduce the number of cyclist injuries and fatalities.

Studies on bicycle conspicuity and related research on pedestrian conspicuity mostly fall into two categories: studies that examine crashes that have occurred to determine which factors led to more severe crashes (Hagel et al., 2014) and experiments examining visibility on a closed test track (Moberly & Langham, 2002; Sayer & Mefford, 2003; Tyrrell et al., 2009; Wood et al., 2005). Promising conspicuity treatments stemming from such research include lights on cyclists and bicycles, fluorescent clothing, RR clothing, and markings enhancing biomotion. Neither type of study, however, captures cyclist visibility in realistic scenarios. There could be meaningful differences between visibility factors that lead to crashes and those that lead to unreported near-misses or minor crashes. It is important to investigate which conspicuity markings are likely to prevent a crash altogether, as well as those which might prevent incidents that result in less-severe injuries. There are also meaningful differences between driving on a test track and on a public road, including cognitive load, driver distraction, changing ambient lighting conditions, and a natural variety of cyclist positions and speeds. The recommendations stemming from real-world research have the potential to be more applicable to the actual traffic conditions under which cyclists and motor-vehicle drivers must share the road. Naturalistic research could be performed during the day and at night, in different nighttime lighting conditions, and in complex visual environments.

This report presents a multi-phase research project, which was conducted on a test track (two studies) and on a public road (one study) to accurately evaluate the visibility of bicycle conspicuity treatments. The test-track studies provided the opportunity to evaluate the visibility of several combinations of bicycle conspicuity treatments in several bicycle-to-vehicle orientations in a controlled environment. The results of these test-track studies served as inputs for the realistic roadway study. The public-road study was conducted to produce high-validity recommendations for bicyclist conspicuity in a real-world environment. The work performed here investigated bicyclist visibility to participant drivers on public roads both by day and at night, in various nighttime lighting conditions, and while bicyclists used a variety of commercially available conspicuity treatments.

CHAPTER 2. PRELIMINARY TEST-TRACK STUDY – 1

INTRODUCTION

This study was a preliminary investigation into the nighttime visibility of different kinds of commercially available bicycle conspicuity treatments in a test-track environment. In this study, a bicyclist wearing different kinds of bicycle conspicuity treatments approached a driver perpendicularly and the detection distances were recorded.

METHODS

Experimental Design

A mixed factorial design was used to analyze the effect of bicycle conspicuity treatments on drivers' nighttime visual performance. Visual performance was measured using detection distance while participants were exposed to several bicycle conspicuity treatments. The presentation order of the conspicuity treatments or visibility-enhancement conditions was randomized with blanks (no bicycle presentation) to minimize confounding effects related to order of presentation. Experimental sessions took place on clear nights after civil twilight. The independent variables and their levels are shown in Table 1.

Table 1. Independent variables and levels used in Preliminary Test Track Study – 1.

Independent Variables	Subcategory	Levels
Age		Younger (18–34 years)
		Older (65+ years)
Bicycle Visibility-Enhancement Condition	Control	No treatments
	Active	Headlamp
		Monkey Lights
		Spoke Lights
	Passive	Reflectors
		RR Biomotion (1 inch wide)

Participants

Twenty-four people were recruited from the Virginia Tech Transportation Institute (VTTI) participant database to participate in this study. The participants were divided into two age groups: younger (18–34) and older (65 and older). The participant sample was both age and gender balanced. Participants had to have a valid U.S. driver's license and a minimum visual acuity of 20/40. Participants were recruited for a single session and all the procedures used were approved by the Virginia Tech Institutional Review Board. Participants were compensated $20 per hour for their time.

Independent Variables

Age

Participants were divided into to two age groups: younger (18–34 years) and older (65 and older). The two age groups were meant to encompass a broad range of visual capabilities and driving experiences.

Bicycle Visibility-Enhancement Condition

Five commercially available bicycle conspicuity treatments were selected to be evaluated. These treatments included the standard reflectors (including pedal reflectors) that came with all the bicycles (Figure 1a–c), a standard headlamp used on a bicycle (Figure 1d), lights mounted on the spokes of a bicycle (two commercially available brands: Monkey Lights® and SpokeLit®) (Figure 1e & f), and RR biomotion bands, which were strapped on the bicyclist's ankles. These bicycle visibility conditions were further classified into control, active, and passive treatments. Active treatments included the headlamp, Monkey Lights, and Spoke Lights. Passive treatments included the biomotion bands and standard reflectors. A bicycle with no treatments was used as a control.

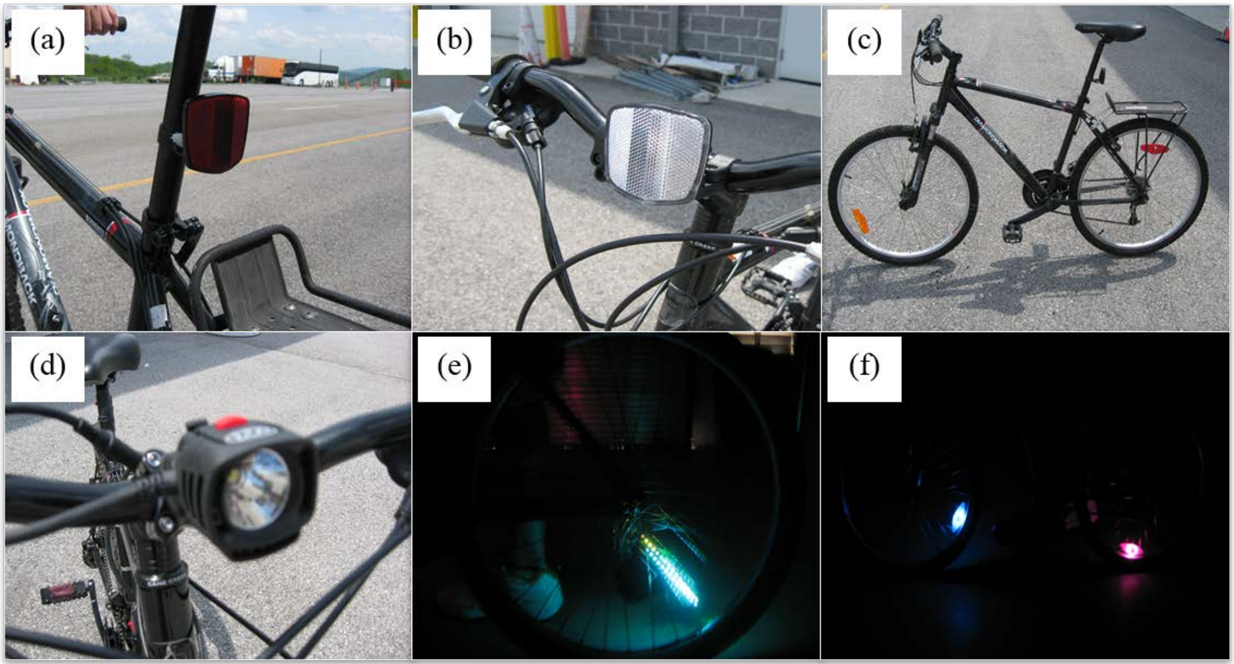

Figure 1. Photographs. Bicycle conspicuity treatments used in Preliminary Test Track Study – 1. (a), (b), and (c) are standard rear, front, and spoke reflectors; (d) headlamp (NiteRider); (e) Monkey Light®; and (f) SpokeLit®.

Experimental Procedure

Participants were recruited for a single session. Two participants were scheduled for a single experimental session that would last up to 2 hours. On arrival, participants provided informed consent and their visual acuity was measured using a Snellen Visual Acuity Test. Participants had to have a valid U.S. driver's license needed to have a visual acuity of at least 20/40. Participants who did not meet the requirements for the study were not used for data collection.

Once the participants completed the in-building paperwork, experimenters escorted them to an experimental vehicle parked in the VTTI parking lot. Each participant was assigned to one of two SUVs (Ford Explorer model years 1999 and 2000) to drive. Both SUVs were instrumented with a data acquisition system (DAS), which included cameras and digital video and audio equipment. The headlamps on both experimental vehicles were cleaned and aligned prior to each experimental session. One in-vehicle experimenter was present in each of the experimental vehicles each evening. These experimenters oriented the drivers to the basic vehicle controls (i.e., seat, steering wheel, and mirror adjustment), and ensured that participants' seat belts were fastened. The experimenters sat in the front passenger seat and prepared the data collection equipment.

Participants were then instructed to drive to the VTTI parking lot and look at a sign placed directly ahead of the vehicle. Only one participant at a time performed this task, while the other participant waited at the designated area out of sight of the test location. As participants looked at the sign, a bicyclist entered the forward view of the vehicle from the right (at approximately 10 mph, measured with a speedometer attached to the bicycle; see Figure 2). The bicyclist started behind a truck and was always moving at the predetermined speed (10 mph) when entering the field of view of the participant. The location at which the bicyclist emerged from behind the truck subtended an angle of 68 degrees to the vertical. Participants were asked to identify when the cyclist was visible in their peripheral vision. The cyclist utilized a different bicycle lighting system each time this task was performed. As soon as the cyclist was identified by the participant, the in-vehicle experimenter flashed the headlamps of the experimental vehicle and the bicyclist marked the spot by dropping a beanbag. The distance from the beanbag to the vehicle location was used as the detection distance (Figure 2), and the detection distance was used as the dependent variable. After identifying the cyclist, the participant entered the Smart Road and drove a predetermined route while the other participant completed the same task. After each participant completed all cyclist presentations, the in-vehicle experimenters instructed them to return to the VTTI building where they started. The in-vehicle experimenters then escorted the participants back to the conference room, where they were paid ($30 per hour) and thanked for their participation.

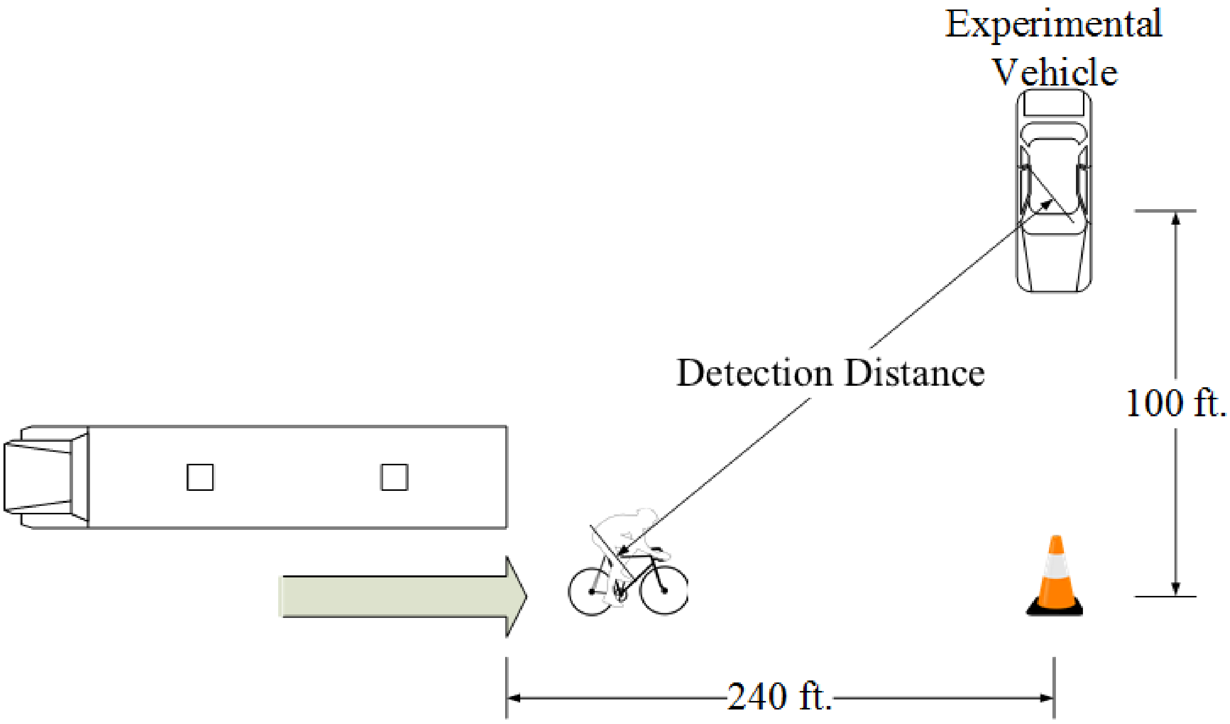

Figure 2. Diagram. Experimental protocol for the bicycle detection task.

Analysis

An analysis of variance (ANOVA) was used to assess the effect of the bicycle visibility-enhancement condition on detection distance with participant age group included as a blocking variable. Effects were considered significant at $p < 0.05$. Where required, post hoc analyses were performed using Tukey's honest significant difference (HSD) test.

RESULTS

The main effect of the bicycle visibility-enhancement condition was significant, $F(5,110) = 40.95$, $p < 0.0001$. The two-way interaction between the bicycle visibility-enhancement condition and age was also significant, $F(5, 110) = 5.43$, $p = 0.0002$.

Further analysis of the two-way interaction between bicycle visibility-enhancement condition and age indicated that the differences in detection distances between older and younger drivers were significant only for the headlamp bicycle visibility-enhancement condition, with older participants having longer detection distances by 24.2%. Active bicycle visibility-enhancement conditions had significantly longer (53.9%) detection distances than passive and control conditions (see Figure 3). Detection distances between the control (no light) and the passive (reflectors, RR biomotion) bicycle visibility-enhancement conditions were not significantly different (see Figure 3). Further, within each subcategory, the bicycle visibility-enhancement conditions were not significant. For instance, in the active subcategory, the detection distances between the headlamps, Monkey Lights, and Spoke Lights were not significantly different (Figure 3).

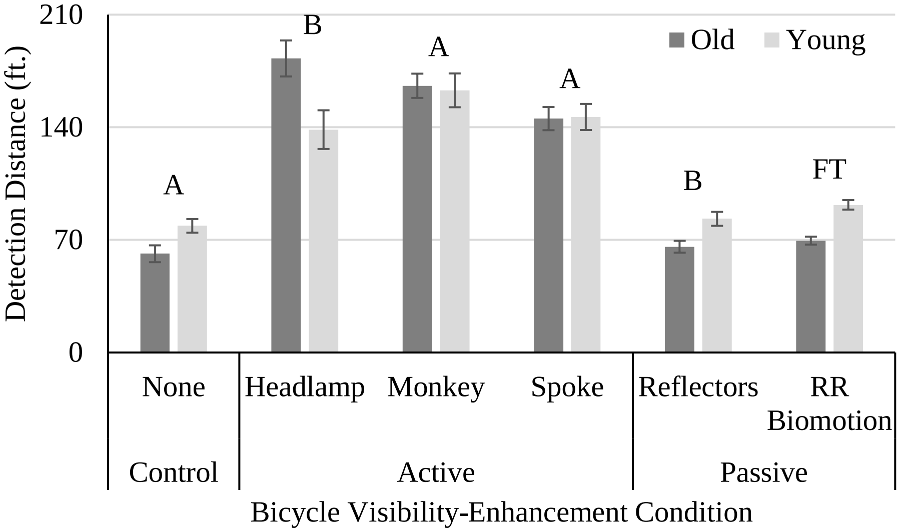

Figure 3. Bar graph. Interactive effect of bicycle visibility-enhancement conditions and age on detection distance. Values reported are means, and error bars represent standard errors. Upper case letters (A and B) indicate significant post hoc pairwise comparisons between bicycle visibility-enhancement conditions.

DISCUSSION

The goal of this study was to evaluate the conspicuity of commercially available bicycle visibility enhancements in a test-track environment. Four major findings were evident from the analysis. First, active bicycle visibility-enhancement conditions like headlamps, Monkey Lights, and Spoke Lights had longer detection distances than passive conditions like standard reflectors and RR biomotion bands. Second, within each subcategory, there were no differences in the detection distance of different bicycle visibility-enhancement conditions. Third, there were also no differences in detection distances of the control and the passive bicycle visibility-enhancement conditions. Finally, age-related differences in detection distance were only evident in the headlamp bicycle visibility-enhancement condition.

The finding of higher detection distances in active bicycle visibility-enhancement conditions is consistent with existing research, which states that flashing lights, tail lamps, and handheld lights result in increased detection distances (Kwan & Mapstone, 2009). The lack of difference between the no bicycle visibility-enhancement condition and the passive (standard reflectors and RR biomotion bands) bicycle visibility-enhancement condition is not in alignment with existing research, which clearly indicates that both reflectors and biomotion result in increased bicyclist conspicuity (Kwan & Mapstone, 2004; Kwan & Mapstone, 2009; Sayer & Medford, 2003; Tyrrell et al., 2009; Wood et al., 2012). This result could be due to the orientation in which the participants viewed the bicycle. The bicycle always approached the participant’s vehicle in an intersecting orientation, which may have rendered the standard front and rear reflectors ineffective since they were not illuminated by the vehicle headlamps. Furthermore, the surface area of the RR biomotion bands may have been smaller than in previous studies, and therefore could have affected detection. The surface area of RR biomotion bands was not altered in this study and they were 1 inch wide.

Future research should consider using larger surface areas for biomotion, such as a RR vest, which could result in increased detection distances. Further, the effect of different kinds of active bicycle conspicuity treatments, such as flashing head and tail lamps should also be evaluated in multiple orientations to assess their visibility at night.

CONCLUSION

This study evaluated the nighttime visibility of several commercially available bicycle conspicuity treatments in a test-track environment when the bicycle approached a vehicle in a perpendicular orientation. In such an orientation, active treatments like bicycle headlamps, Monkey Lights, and Spoke Lights resulted in longer detection distances than passive treatments, such as standard reflectors and RR biomotion bands. Interestingly, there was no difference between the passive conspicuity treatments and no treatment conditions.

CHAPTER 3. PRELIMINARY TEST TRACK STUDY – 2

INTRODUCTION

This study was a follow-up to the first preliminary test track study. The results of the first study drove the experimental design of this study. In the first study, bicycle conspicuity treatments were evaluated in only one vehicle-to-bicycle orientation. Further, only a small sample of bicycle conspicuity treatments were evaluated and did not include treatments like flashing headlamps and RR vests, which have a larger surface area. The purpose of this study was to address the questions raised in the first preliminary study in order to further assess the nighttime visibility of a wide range of commercially available bicycle conspicuity treatments in two vehicle-bicycle orientations and add to the body of knowledge on bicycle safety. The results of this study also served as inputs to the final phase of the project, in which bicycle visibility was evaluated on public roads.

METHODS

Participants

Thirty-two participants were recruited from the VTTI participant database to participate in this study. It should be noted that these participants were different from those of the first study. The participant sample was both age and gender balanced. Participants had to have a valid U.S. driver's license, a useful field of view (UFOV) score of two or lower, and a minimum visual acuity of 20/40. Participants were recruited for three sessions, one of which was a screening session and two of which were experimental data collection sessions. All procedures used were approved by the Virginia Tech Institutional Review Board.

Experimental Design

A mixed factorial design was used to analyze the effect of bicycle conspicuity treatments with regard to whether or not they led to the correct identification of a bicycle. Participants' responses were measured while they were exposed to several bicycle conspicuity treatments in two bicycle-to-vehicle orientations. The order of presentation of bicycle conspicuity treatments or visibility-enhancement conditions was randomized with blanks (no bicycle presentation) to minimize confounding effects related to order of presentation. Experimental sessions happened on clear nights after civil twilight. Independent variables and their levels used in the study are shown in Table 2.

Table 2. Independent variable levels used in Preliminary Test Track Study – 2.

Independent Variables	Subcategory	Level	Subcategory	Levels
Orientation	Passing Bicycle Parked and Vehicle Moving		Intersecting - Bicycle Moving and Vehicle Parked	
Age		Younger (18–34 years)		Younger (18–34 years)
		Older (65+ years)		Older (65+ years)
Bicycle Visibility-Enhancement Condition	Control	No TL	Control	No TL
	Active	TL	Active	Spoke Lights
	Passive	RR Vest		TL & HL Flash
		RR Biomotion		TL & HL Steady On
		RR Biomotion – Coast	Passive	RR Vest
		RR Vest, Biomotion		RR Biomotion
		RR Vest, Biomotion – Coast		RR Vest, Biomotion

Note. TL = tail lamp; HL = headlamp

Bicycle-to-Vehicle Orientations

Visibility was assessed in two orientations. In the first orientation, passing, a stationary bicycle on a trainer (device that clamps onto the rear wheel of a bicycle and adds resistance, so the bicycle can be ridden in place) was located on the left shoulder of the roadway facing in the same direction as the vehicle, but outside the lane the in which the participant vehicles were traveling (Figure 4a). In the second orientation, intersecting, the bicycle was ridden across the stationary participant’s field of view, as seen from within the vehicle (Figure 4b). In this orientation, the vehicle was stopped and the distance between the vehicle and bicycle was 300 ft.

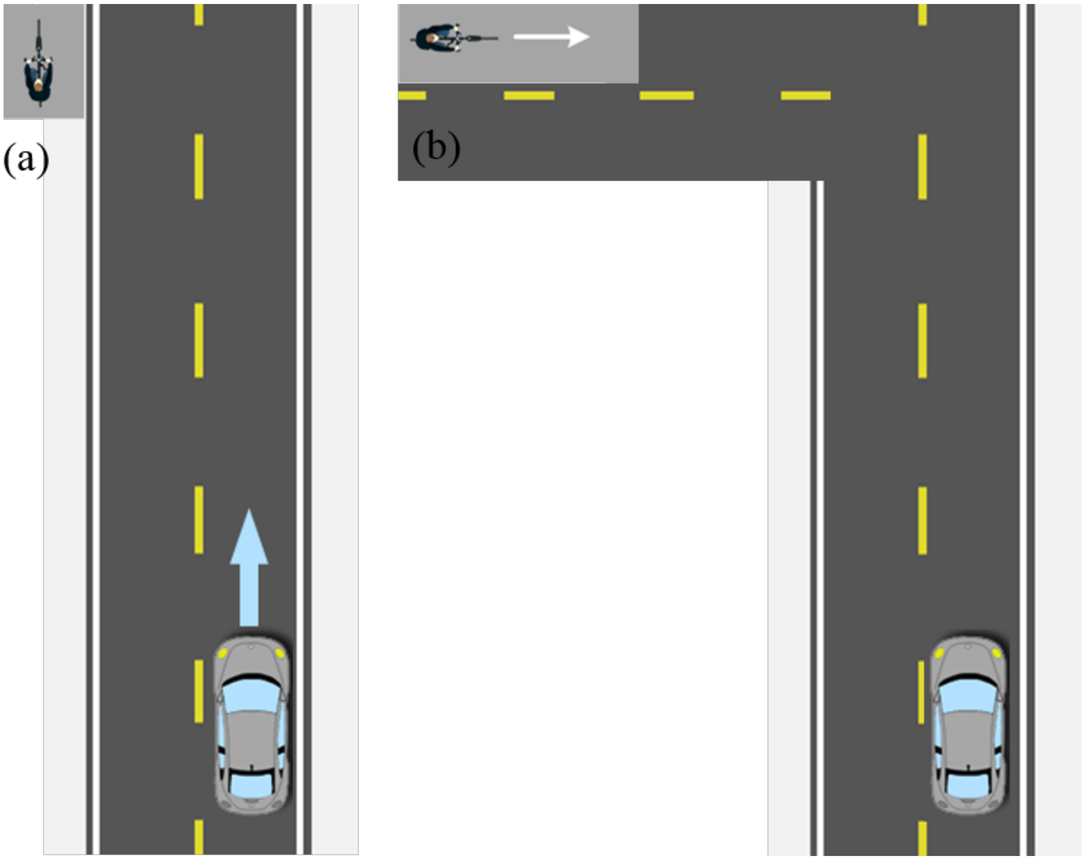

Figure 4. Diagrams. Two bicycle-to-vehicle orientations were used in the study: (a) passing, bicycle stationary and vehicle moving; (b) intersecting, bicycle moving and vehicle stationary.

Independent Variables

Age

Participants were divided into two age groups: younger (18–34 years) and older (65 and older). The participant sample was age and gender balanced. The two age groups were intended to encompass a broad range of visual capabilities and driving experiences.

Bicycle Visibility-Enhancement Condition

Several commercially available bicycle conspicuity treatments were selected to form multiple bicycle visibility-enhancement conditions. These were primarily classified into control, active, and passive conditions. The control condition did not have any additional treatments other than the standard reflectors (including pedal reflectors) that were already included on the bicycle (Figure 1a–c). The active condition included the following treatments, in which the light sources were installed on the bicycle: headlamps, tail lamps, and spoke lights. The passive condition consisted of the following RR treatments that were worn by the bicycle rider: vest, biomotion bands on the ankles, and a combination of vest and biomotion bands. To see if biomotion played a greater role in nighttime conspicuity when the bicyclists were actively biking or when there was “motion,” the two RR biomotion conditions were presented in two ways. In the first, the confederate experimenter was actively biking, and in the second, to signify coasting, the experimenters just sat on bike without moving their legs (but the wheels were moving as the bicycle was on a trainer). In the passive condition, the bike’s standard front, rear, and spoke reflectors were covered to minimize the confounding effects. In the passing orientation, the headlights and spoke lights were not included, as they could not be detected during the pilot testing.

Experimental Procedure

Upon initial contact, potential participants were given basic information about the study. Those who were interested in participating were asked to provide verbal consent to a telephone screening used to determine eligibility. Those who were eligible based on the telephone screening were scheduled to come to VTTI for the administration of the UFOV and other screening tests.

On arrival, participants reviewed and signed the informed consent form. Participants performed a UFOV and a basic visual acuity test. Those who did not meet the requirements were paid for the time they participated and were excluded.

Eligible participants were scheduled for a time to return to VTTI for the experimental sessions. The initial session lasted for approximately 30 minutes. The experimental sessions took place on two separate nights following the initial screening session.

Two participants were scheduled to arrive for each nighttime experimental session. Once the participants had read and initialed the informed consent and health questionnaire previously signed during their initial visit, they were asked to show the experimenter their valid driver's license. Following this, the experimenters escorted them to the experimental vehicles parked in the VTTI parking lot. Each participant was assigned to one of two SUVs (Ford Explorer model years 1999 and 2000) to drive for the night. Both SUVs were instrumented with a DAS, which included cameras and digital video and audio equipment. One in-vehicle experimenter was present in each of the experimental vehicles during each session. These experimenters oriented the drivers to the basic vehicle controls (i.e., seat, steering wheel, and mirror adjustment) and ensured that participants’ seat belts were fastened. The experimenters sat in the front passenger seat and prepared the data collection equipment.

The two participants were instructed to drive the two experimental vehicles to the Smart Road and to park at one of the turnarounds. While one vehicle was driving a section of the route, the other vehicle remained stationary while waiting for the moving vehicle to finish its lap. After the first vehicle finished its lap, the second vehicle began its lap. When both the participants were at the assigned turnarounds, confederate experimenters prepared the Smart Road by placing bicycles along the course in designated locations.

Once the lead on-road experimenter confirmed that all confederates were in position and ready, each in-vehicle experimenter instructed their respective participant to start driving the first practice lap. In-vehicle experimenters informed the participants that they should not exceed a speed of 35 mph while traveling on the Smart Road. Participants also performed a practice lap prior to the start of the data collection. During the practice lap, the participants were presented a bicyclist to identify. This also helped them become more comfortable with their vehicle and the route they would be driving for the study.

Bicyclists were presented at two locations. At the first location, a stationary bicycle was located on the left shoulder of the roadway, outside the lane the participant vehicles were traveling in. Participants were asked to identify what they saw as soon as they saw the object (pedestrian or bicyclist). When the object was identified, the in-vehicle experimenters noted the participants' responses. After participants identified the object, the participant vehicle moved to a second location, parked, and remained stationary until the next condition. For this next condition, the experimental vehicle was stopped and the bicycle was ridden across the stationary participant's field of view as seen from within the vehicle. Participants were asked to identify whether they saw a bicycle or a pedestrian. Once the participant identified the object as either a bicycle or a pedestrian, the in-vehicle experimenter again made a note of the participant's response. Following this condition, the bicycle moved to the shoulder of the roadway and remained stationary as the participant vehicle completed the rest of the lap. Both bicycle presentation locations utilized different bicycle visibility-enhancement conditions each time the task was performed. When all laps were completed, participants were instructed to return to VTTI, where they were escorted back into the conference room. The same procedure was repeated for the second session.

Dependent Variable

Participant response was measured as a categorical variable with two levels: "correct" or "wrong." Only presentations detected as "bicycle" were categorized as "correct"; any other response was categorized as "wrong." The frequency counts of the correct and wrong responses for each bicycle visibility-enhancement condition were used as dependent variables. Detection distance could not be measured in any of the orientations, as the sight distances were not long enough to yield meaningful differences between conditions, resulting in a floor effect.

Analysis

A chi-square test of independence was performed to examine the relation between the bicycle visibility-enhancement condition and participant response (correct vs. wrong) in each of the two bicycle-to-vehicle orientation conditions. The level of significance was established at $p < 0.05$. The percentage of correct responses for each bicycle visibility-enhancement condition is also reported for both bicycle-to-vehicle orientations.

RESULTS

In the passing orientation, the chi-square test indicated there was no relationship between the bicycle visibility-enhancement condition and participants' correctness of response. As Figure 5 indicates, there was very little variation in participants' correct identification percentages.

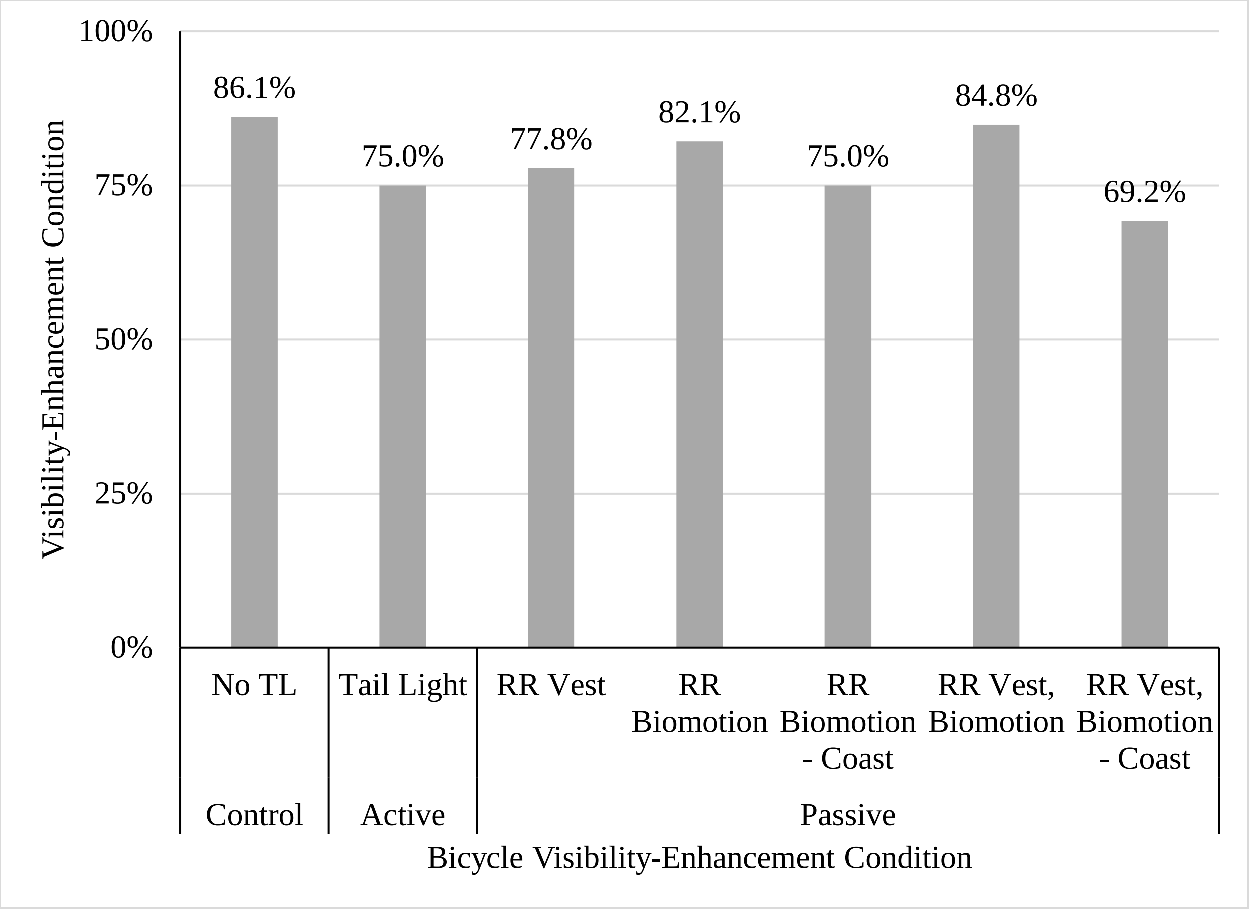

Figure 5. Bar graph. Percentage of correct identifications in evaluated bicycle visibility-enhancement condition in the passing orientation.

However, in the intersecting orientation (when the vehicle was stationary), the relationship between the bicycle visibility-enhancement condition and participants' correctness of response was found to be significant at χ^2 (6) = 40. 02, p < 0. 0001, with the RR vest having the highest correct percentage of identification (Figure 6).

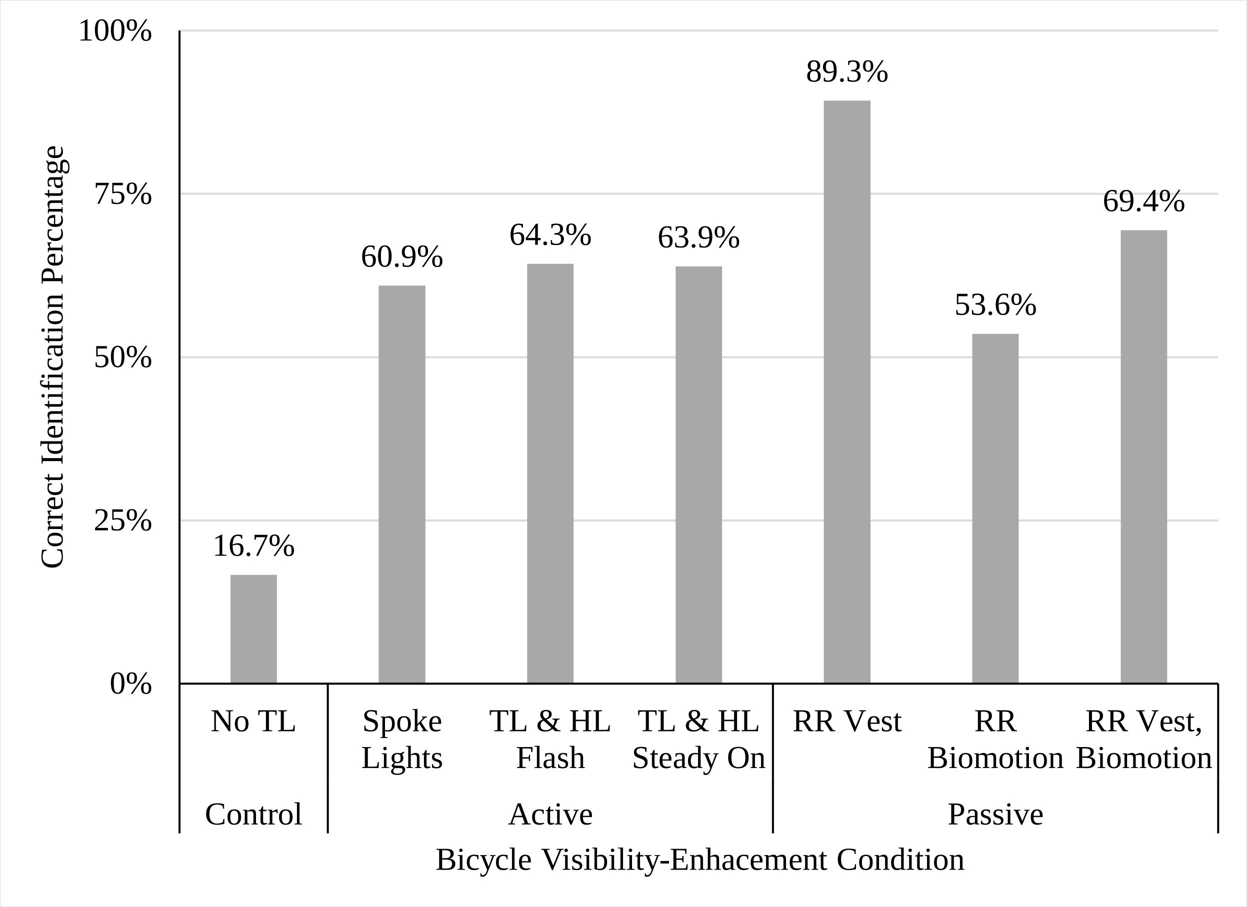

Figure 6. Bar graph. Percentage of correct identification in evaluated bicycle visibility-enhancement conditions in the intersecting orientation.

DISCUSSION

The goal of this study was to evaluate the visibility of commercially available bicycle conspicuity markings in two bicycle-vehicle orientations in a test-track environment and to contribute to the existing literature on bicycle visibility. Three major findings were evident. First, bicycle-to-vehicle orientation plays an important role in participants' ability to correctly identify a bicycle. Second, in the intersecting orientation, the RR vest had the highest correct identification percentage, higher even than the RR vest and biomotion combination. Third, correct identification percentages of bicycle visibility-enhancement conditions varied widely within each bicycle-to-vehicle orientation, with higher variation in the intersecting orientation than in the passing orientation.

The significance of the relationship between correct identification percentage and bicycle visibility-enhancement condition in both orientations indicates that the bicycle's motion plays an important role in increasing its conspicuity. There were also big differences in the identification percentages of the same bicycle conspicuity markings across the two orientations. For instance, the standard reflectors in the intersection orientation had the lowest correct identification percentage, whereas in the passing orientation they had the highest correct identification percentages.

In the intersecting orientation and the passing orientation, the RR vest had the highest and second highest correct identification percentages, respectively, which could be due to the larger RR material surface area, as suggested by Wood et al. (2012). Interestingly, the other passive treatments (RR biomotion bands and vest with biomotion bands) had lower correct identification percentages than the vest; these percentages were very similar to those of the active treatments.

Even though the relationship between bicycle visibility-enhancement condition and the ability to correctly identify the bicycle was not significant in the passing orientation, the correct identification percentages in both orientations showed important trends. The variation in the correct identification percentages in the passing orientation (69.2%–86.1%) was much smaller than the variation in the intersecting orientation (16.7%–89.3%). This suggests that, in general, participants had higher correct identification percentages in the passing orientation and their performance was more consistent.

Biomotion conditions (ankle bands and vest with ankle bands) with active biking had higher correct identification percentages than did coasting. This suggests that biomotion is conspicuous only when bicyclists are actively biking.

In the passing orientation, only one active treatment (tail lamps) could be evaluated, as the bicycle’s headlights could not be seen from the participant’s point of view. Future research should evaluate the visibility of conspicuity treatments in all three possible orientations (oncoming, passing, and intersecting) with both the vehicle and bicycle in motion. As research has also shown that high-conspicuity apparel and lights help increase visibility during the day, bicycle conspicuity treatments should also be evaluated during the daytime. Further, bicycle conspicuity treatments that utilize biomotion should be evaluated on real roadways to see if the effect of biomotion is lost in the visual clutter and to more accurately determine their effectiveness in making bicycles more conspicuous.

CONCLUSION

This study evaluated the visibility of different bicycle conspicuity treatments in two orientations in a test-track environment, finding that the type of bicycle conspicuity treatment influenced participants’ ability to correctly identify the bicycle. The effectiveness of a certain bicycle conspicuity treatment also depended on the orientation in which the bicycle was seen by the participant. The RR vest seemed to increase bicycle conspicuity when the bicycle was moving across the participants’ field of view. A bicycle’s standard rear reflectors and pedal reflectors, along with the RR vest and a combination of both the vest and biomotion bands, seemed to increase bicycle conspicuity when the participant’s vehicle was passing the bicycle. Biomotion increased conspicuity only when the bicyclist was pedaling actively and not when the bicyclist was coasting.

CHAPTER 4. PUBLIC ROAD STUDY

INTRODUCTION

The goal of this study was to evaluate the visibility of several commercially available bicycle conspicuity treatments in multiple bicycle-to-vehicle orientations in a naturalistic setting during both day and nighttime conditions. Such an evaluation in realistic environments will help provide high-validity recommendations for increasing bicyclist conspicuity.

METHODS

Public-Road Test Track

This experiment was conducted in downtown Blacksburg, Virginia, and on the Virginia Tech campus. A map of the route is included in Figure 7.

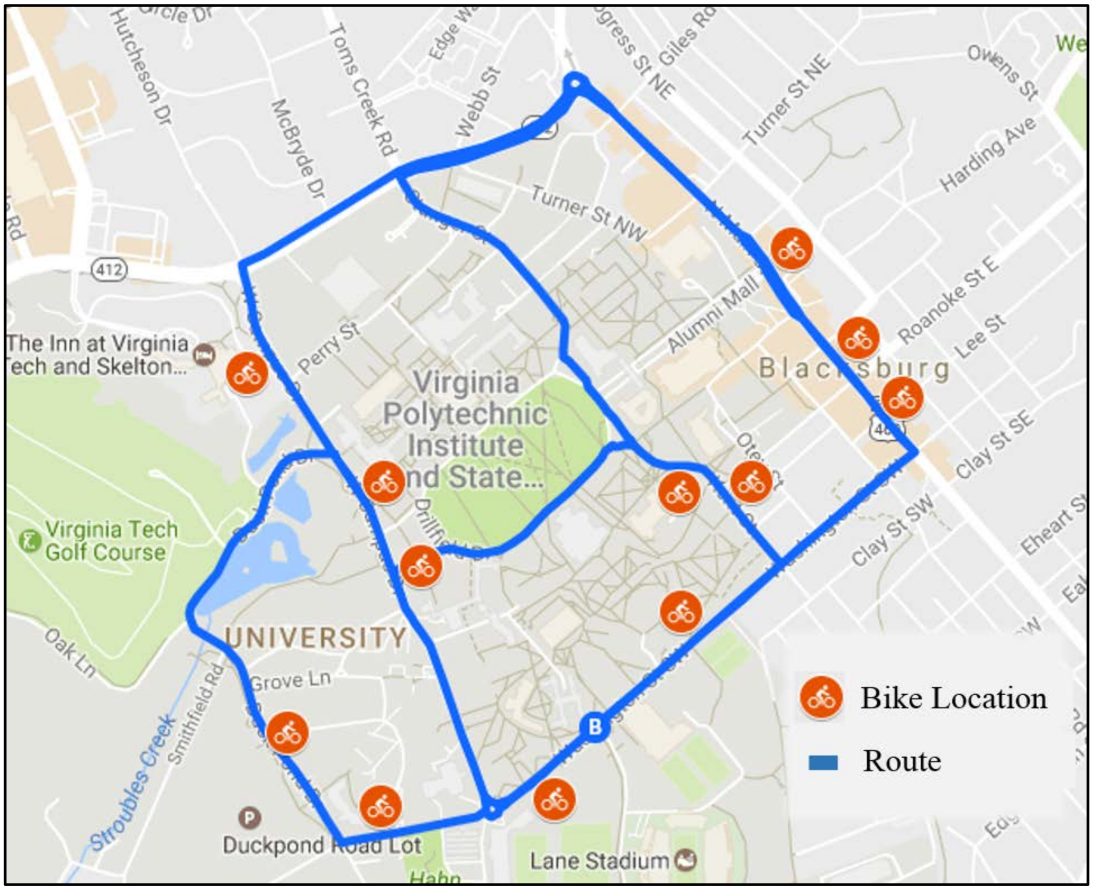

Figure 7. Map. Experimental route and bicycle location (Source: Google Maps).

Experimental Design

This experiment compared detection distances for seeing a cyclist under a number of different bicycle visibility-enhancement conditions. The experiment was performed for three different cyclist-to-vehicle orientations and was run both during the day and at night.

Participants

Twenty-four people were recruited from the VTTI participant database to participate. Participants had to have a valid U.S. driver’s license and a minimum visual acuity of 20/40 (measured by Snellen chart), and not be colorblind (measured by Ishihara Color Vision Test). Participants were recruited for a single session and all procedures were approved by the Virginia Tech Institutional Review Board. Participants were compensated $30 per hour for their time.

Experimental Conditions

Because different visibility treatments can be seen only from certain directions, three different approaches were chosen. Visibility treatments between approaches were not compared.

Similarly, as a visibility treatment’s effectiveness depends on ambient lighting, treatments were not compared between day and nighttime conditions.

Bicycle-to-Vehicle Orientation

Confederate cyclists approached the participant vehicle from three directions, as shown in Figure 8: (a) oncoming, (b) passing, and (c) intersecting. In the passing orientation, the cyclist was not in the middle of the travel lane but in the right shoulder. The three approach directions gave researchers discrete opportunities to evaluate headlamps, tail lamps, and a side-view of biomotion markings.

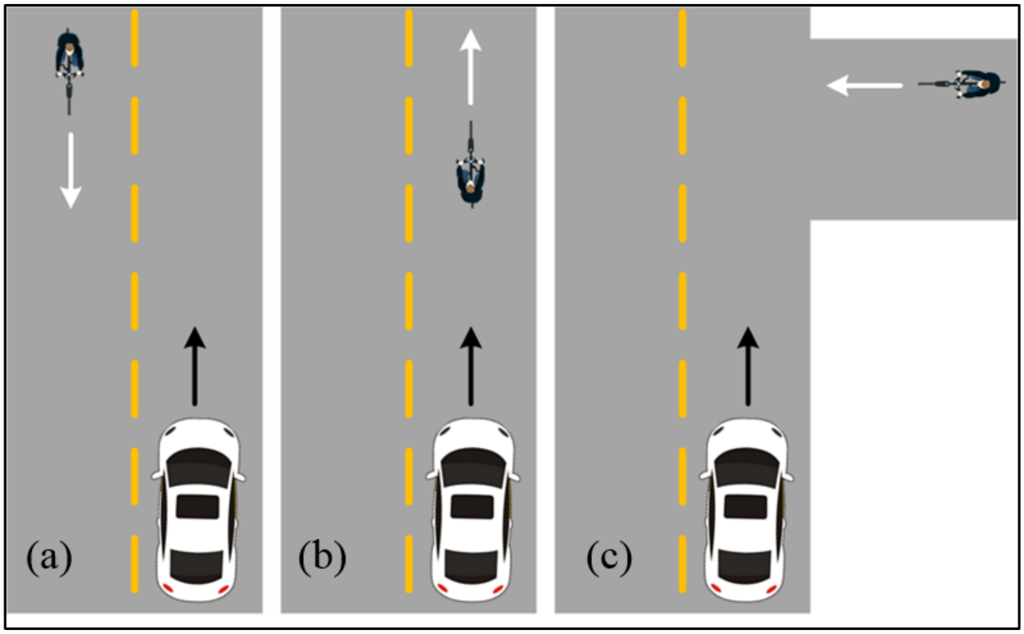

Figure 8. Diagram. Bicycle-to-vehicle orientations used in the Public Road Study.

Time of Day

Experiments were conducted either during the day or at night; no comparisons were made between the conditions since day- and night-visibility treatments cannot be meaningfully compared. Twelve participants drove during daytime conditions and 12 during nighttime conditions.

Independent Variables

Participant Age

Age affects drivers' ability to detect pedestrians while driving at night (Bhagavathula & Gibbons, 2012; Bhagavathula & Gibbons, 2013; Wood et al., 2005). Therefore, participants were recruited from two groups: younger (18–34 years old) and older (over 65 years old) to investigate age effects. The two groups were gender balanced.

Bicycle-Visibility Enhancements

Confederate cyclists wore gray clothing (see Figure 9) and no RR markings other than those included in the experimental design.

Three confederate researchers rode bicycles during the experiment. Two bicycles were equipped with active visibility-enhancement devices (headlamps and tail lamps); the riders wore no RR clothing. One bicycle was equipped with one active device (spoke lights) and all the passive devices, consisting of a variety of RR markers.

Because it is both dangerous and illegal to ride a bicycle on public roads at night with no lights or reflectors, the cyclist with the spoke lights and RR markers rode a bicycle with standard front, rear, and pedal reflectors.

Figure 9. Photo. Confederate experimenter with headlamp and tail lamp.

Headlamp Conditions (active): NiteRider Pro 700 Race headlamps were selected for the study, as researchers could program their intensity level.

Seven headlamp configurations were used for the study. Three were steady on, three were flashing, and one had the headlamp off. The steady-on headlamp had three levels of brightness: low intensity (100 lumens [lm]), medium intensity (350 lm), and high intensity (700 lm). Those intensity levels were chosen because they were similar to the intensities of off-the-shelf bicycle headlamps. The flashing headlamp oscillated at three different frequencies: slow flash (0.9 Hz), moderate flash (3.4 Hz), and fast flash (6.67 Hz). When the headlamp was not used, the bicycle was equipped with a standard front reflector.

Tail Lamp Conditions (active): NiteRider Cherrybomb tail lamps were used for the study. They were selected because they were similar to typical, low-end tail lamps on the market at the time of the study.

The tail lamp was either on, flashing, or off. When the tail lamp was off or not used, the bicycle was equipped with a standard rear reflector.

Spoke Lights (active): A Nite Ize SpokeLit was used for the study (see Figure 10). The bicycle had the spoke light either turned on or turned off.

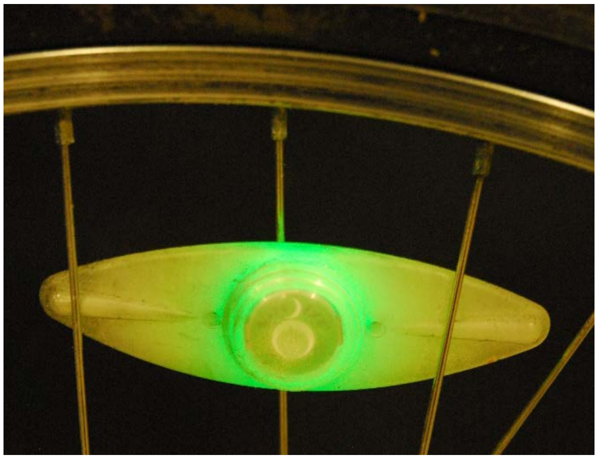

Figure 10. Photograph. Spoke light mounted on the spoke of the bicycle.

RR Markings and Biomotion (passive): The cyclist wore either (a) a RR vest, (b) RR bands on the limbs for biomotion, (c) both vest and bands (see Figure 11), or (d) no RR markings.

All experimental conditions calling for RR markings with no headlamp or tail lamp were performed on a bicycle with standard front and rear reflectors.

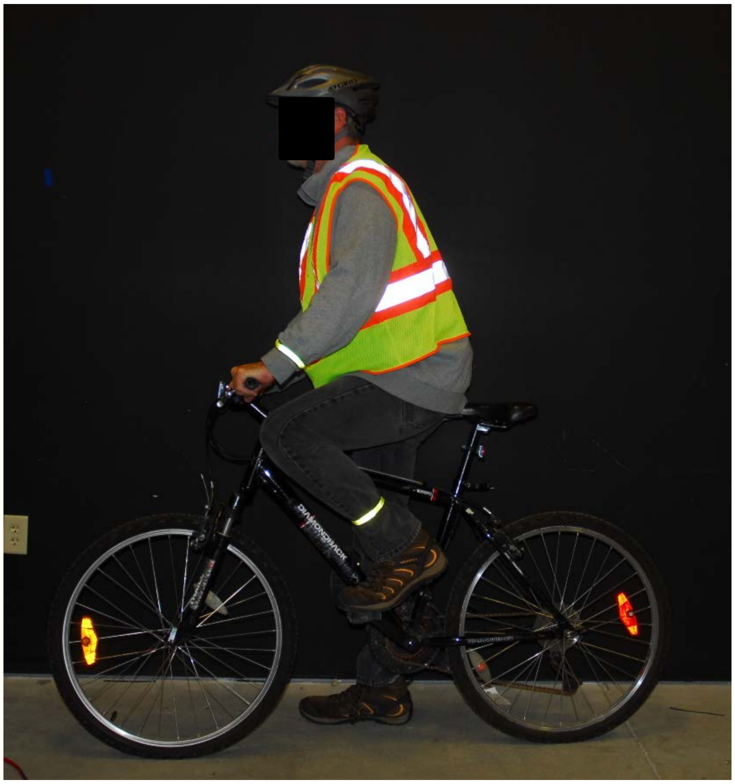
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Figure 11. Photo. Confederate researcher on bicycle wearing RR vest and biomotion bands.

Table 3. Independent variables and values.

Independent Variable	Values
Age (two levels)	Younger (18–25), Older (65+)
Headlamp* (seven levels)	Steady Low Intensity (100 lumens), Steady Medium Intensity (350 lumens), Steady High Intensity (700 lumens), Flashing Slow (0.9 Hz), Flashing Moderate (3.4 Hz), Flashing Fast (6.7 Hz), No Headlamp
Tail Lamp* (three levels)	On, Off, Flashing
Spoke Lights (two levels)	On, Off
RR Markings* (four conditions)	Vest, Biomotion, Vest and Biomotion, No Markings

* All conditions with no headlamp or tail lamp were run with standard front and rear reflectors.

Bicycle Visibility-Enhancement Combinations

Not all visibility-enhancement devices were visible from each approach, and different confederate cyclists had different treatments. Thus, not all combinations of all treatments were tested. Instead, for each approach, a combination of bicycle visibility-enhancement conditions was tested (see Table 4). Each condition was presented three times for each participant, excluding blanks.

Table 4. Combinations of bicycle visibility conditions presented in each orientation.

Bicycle Orientation	Front	Back
Oncoming	Headlamp OR RR Markings, not both	Nothing
Passing	Nothing	Tail Lamp OR RR Markings, not both
Intersecting	Headlamp OR RR Markings OR Spoke Lights (no combinations)	Tail Lamp

Covariates

The cyclist’s surrounding environment affects their visibility but was not controllable in the public-road setting where the experiment was performed. Therefore, video taken when the bicycle was detected was analyzed for visual clutter in the cyclist’s vicinity. Three covariates formed the visual clutter construct, as follows.

Traffic

Traffic was the number of vehicles traveling on the roadway when the cyclist was detected.

Parking

Parking was whether there were vehicles parked on either side of the road near the cyclist when they were detected.

Obstruction

Obstruction was whether the cyclist was obscured from the participant's view by a vehicle, tree, or other object or structure when they were detected.

Dependent Variables

Detection Distance

The detection distance was the distance where the participant driver was able to detect the cyclist. To measure this variable, both the test vehicle and cyclist were equipped with GPS receivers. The in-vehicle experimenter asked the participant driver to say "bike" when he or she saw a bicycle. The experimenter pressed a button, flagging the data stream (including the GPS data) at that point. The GPS data from the bicycle at that point in time was retrieved from the data stream and compared to that from the test vehicle. The linear distance between the two GPS coordinates was the detection distance.

Facilities and Equipment

Test Vehicles

Two SUVs were used in the study: a 1999 Ford Explorer and a 2000 Ford Explorer, with the same body style and internal layout. The headlamps were aligned prior to each experimental session according to manufacturer specifications. Both were instrumented with VTTI's DAS, which included digital audio and video recorders, and GPS receivers. The data collected included driving distance, vehicle speed, GPS location, and a user-input button used to calculate detection distance.

Bicycles

Hybrid bicycles, typical for Blacksburg's suburban environment, were used in this experiment.

The confederate cyclists carried smartphones with a mobile application (My Tracks®) that tracks and updates GPS coordinates. The application was accurate enough to calculate detection distance, but only collected data every 1 second (1 Hz), which was not frequently enough to accurately correlate with when the participant driver detected the cyclist. Thus, another program (TopoFusion Pro®) was used to interpolate between the GPS coordinates, resulting in a measurement frequency of 10 Hz.

PROCEDURE

Confederate researchers were issued bicycles, positioned at various points on the roadway, and assigned visibility treatments. Another group of researchers rode in the vehicles with the participants, guiding them through the test procedure while simultaneously coordinating the position of the confederate cyclists with respect to the vehicles and then recording participant responses.

Participant Recruitment, Consent, and Compensation

Recruitment was performed via the VTTI participant database. First, a general description of the study was provided to the participants so they could decide if they were willing to participate. If they were interested, participants completed questionnaires to determine their eligibility based on licensing, driving history, and health. Eligible participants were scheduled for a single experimental session.

When participants arrived at VTTI, they completed an informed consent form. Compensation was $30 per hour and participants were allowed to withdraw at any point in time, with compensation adjusted accordingly.

Experimental Procedure

On arrival, participants were provided the informed consent form, completed any other requisite paperwork, and completed vision and health screenings. After the forms were completed, experimenters escorted participants to the test vehicles where they were familiarized with its operation (i.e., seat, steering wheel, and mirror adjustment) and told about the experimental procedure. Participants were assigned to two SUVs to drive. Both SUVs were instrumented with a DAS, which included cameras and digital video and audio equipment. One in-vehicle experimenter was present in each of the experimental vehicles. They then proceeded to drive around the test route. To ensure the confederate cyclists' approaches were timed correctly with respect to the participant vehicle, the in-vehicle researcher informed the confederate cyclists, via radio, when they should start riding.

As an in-vehicle researcher directed participants through the test course, the confederate cyclists positioned themselves according to their order sheets and timed their approaches as directed by the in-vehicle researcher. All bicycle orientations and the bicycle visibility-enhancement conditions were presented at every location. The presentation of bicycle orientations and visibility-enhancement conditions was counterbalanced to minimize order-related confounding effects. The presentation also included blanks (no bicycle presentation). After a participant passed the bicycle and proceeded out of view, the confederate cyclists altered their visibility treatments for the next run, proceeded to the next specified location, and waited for the in-vehicle researcher's instructions to begin riding again. Each participant drove through the test course announcing when they saw a bicycle, and the in-vehicle researcher pressed a button marking the data at that point. When the experiment was complete, the in-vehicle researcher directed the participant back to VTTI.

DATA REDUCTION

Before data analysis, errors in the data were identified and corrected, and the data were reduced. Data with dropouts in GPS coordinates and DAS malfunctions were excluded from analysis. Of the 432 bicycle presentations, 35 had dropouts in the GPS data for the cyclist and were excluded from analysis, as detection distance could not be calculated.

Detection Distance

To validate data, data reductionists confirmed whether the in-vehicle researchers' button presses occurred at a time corresponding to when participants saw a cyclist and said, "bike." If the times did not correspond, the data reductionist noted the actual detection time. Once detection times were accurately identified, detection distances were calculated from the vehicle and cyclist's GPS coordinates.

Visual Clutter

After the detection times were correctly identified in the data stream, data reductionists viewed the video surrounding each bicycle detection and coded the video for presence of traffic (number of vehicles on the road), parking (number of vehicles parked on either side of the road), and obstruction (whether or not the cyclist was obscured from view).

Two data reductionists coded 25% of the data and compared their results. Any discrepancies in coding were discussed, reviewed, and an agreement reached with the guidance of the data reduction manager.

DATA ANALYSIS

The study employed a mixed (headlamp/tail lamp/combination of head and tail lamp/RR marking × age) factorial design.

The data were analyzed separately for day and night experiments since a visibility treatment's effectiveness depends largely on ambient light. The data were further separated by approach (oncoming, passing, and intersecting) because different treatments were visible from the different approaches, rendering them incomparable. For the oncoming approach, only the front of the bicycle was visible to the driver, so the tail lamp configurations were not analyzed. For the passing approach, only the rear of the bicycle was visible, so the headlamp configurations were not analyzed. For the intersecting approach, all independent variables were analyzed. Where there were no headlamps or tail lamps (or they were turned off), the bicycles had standard front and rear reflectors.

Detection Distance

For detection distance calculations, six linear mixed-model analyses were performed, one for each combination of time of day and approach, with detection distance as the dependent variable. If detection distance correlated with visual clutter covariates, it was also included in the mixed model to see if the slope of the covariate was significant. If the slope of the covariate was not significant, (slope is the same for all treatments), then the interaction term between the covariate and the treatment effect was removed and a linear mixed-effects model was run again.

If the linear mixed-model results showed a significant difference in detection distances, Tukey's HSD test was performed to determine which independent variables significantly differed from each other.

RESULTS

Oncoming Orientation

Day

The slopes of the covariate were the same across all conditions, indicating that the covariate affected all the conditions in the same manner. However, visual clutter was still included in the model to better account for variance. Bicycle visibility enhancement was not significant, *F*(9, 23.7) = 1.82, *p* = 0. 12. Bicycles with headlamps flashing fast had the highest mean detection distance (*M* = 862 ft), followed by headlamps steady at medium intensity (*M* = 740 ft) and low intensity (*M* = 629 ft) as shown in Figure 12.

Neither age nor the interaction between age and headlamp type was statistically significant. Obstruction was also not significant.

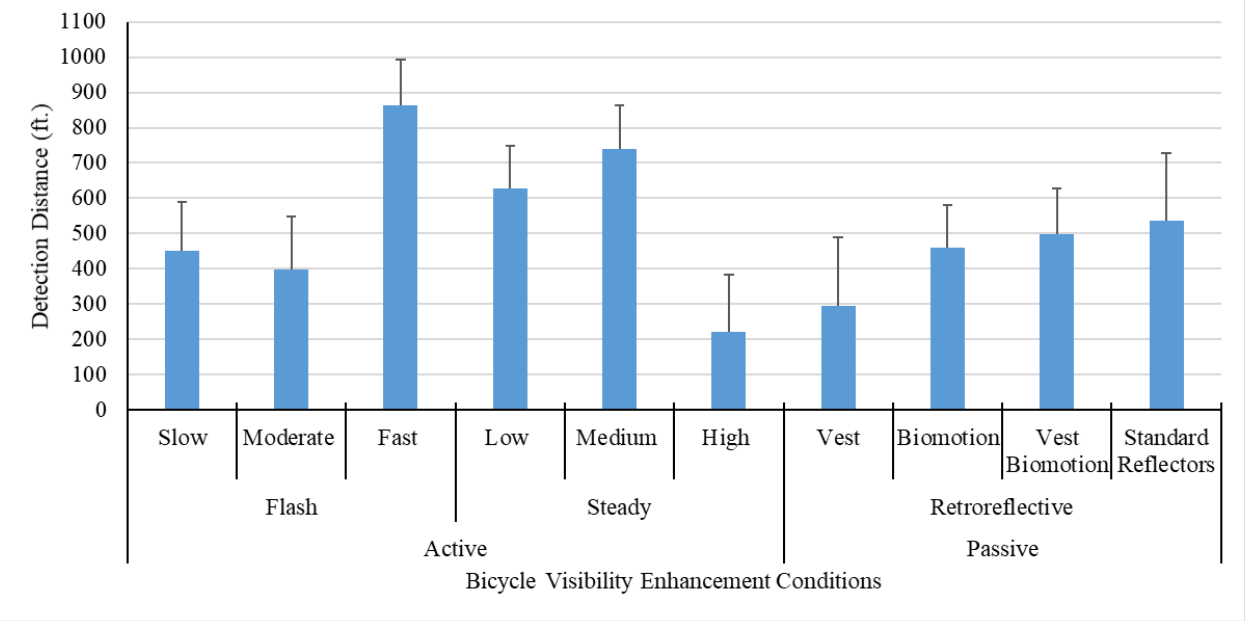

Figure 12. Bar Graph. Effect of bicycle visibility-enhancement condition on detection distance. Values are least square means of detection distances and error bars denote standard errors.

Night

The slopes of the covariate were the same across all conditions, indicating that the covariate affected all the conditions in the same manner. Only the main effect of bicycle visibility-enhancement condition was significant, *F*(9, 33.1) = 3.23, *p* = 0. 006. The average detection distances of all the bicycle visibility-enhancement conditions in this configuration are illustrated in Figure 13. Headlamps flashing moderate had the greatest mean detection distance (*M* = 455 ft) followed by the low-intensity steady headlamp (*M* = 350 ft) and slow-flash headlamp (*M* = 354 ft) conditions.

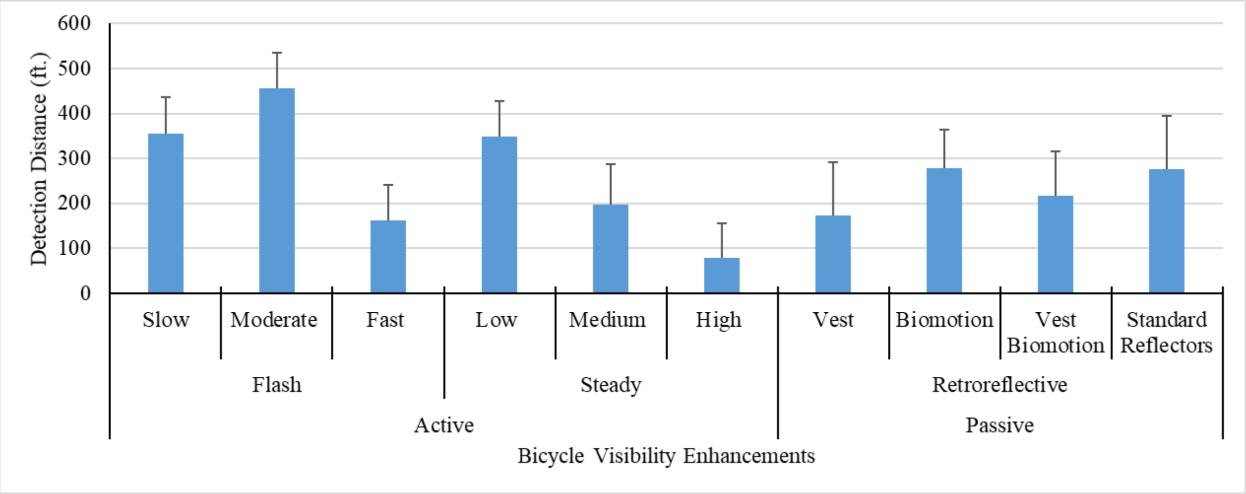

Figure 13. Bar Graph. Effect of bicycle visibility-enhancement condition on detection distance. Values are least square means of detection distances and error bars denote standard errors.

Passing Orientation

Day

The slopes of the covariate were the same across all conditions, indicating that the covariate affected all the conditions in the same manner. Bicycle visibility-enhancement condition and age did not significantly affect detection distance; their interaction was not significant as well. The means of detection distance are illustrated in Figure 14. RR vest on had the highest mean detection distance (M = 567 ft), closely followed by a combination of RR vest and biomotion (with rear reflector; M = 500 ft). Biomotion had the shortest detection distance (M = 180 ft).

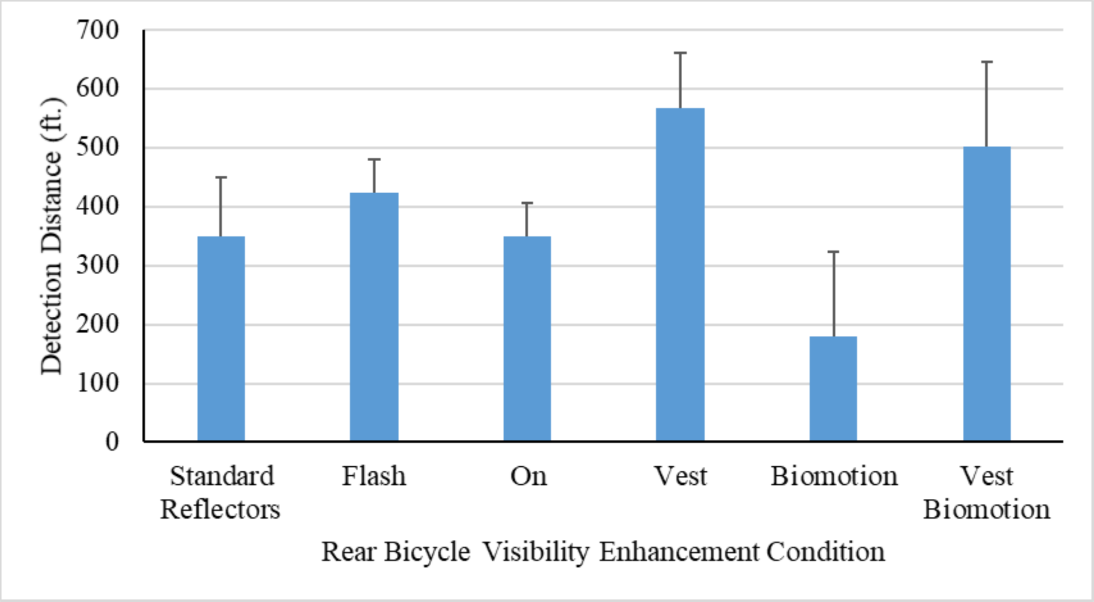

Figure 14. Bar Graph. Effect of bicycle visibility-enhancement condition on detection distance. Values are least square means of detection distances and error bars denote standard errors.

Night

The slopes of the covariate were the same across all conditions, indicating that the covariate affected all the conditions in the same manner. None of the main or interaction effects was significant. RR vest (*M* = 383 ft), tail lamp on (*M* = 375 ft), and flashing (*M* = 388 ft) had the longest detection distances (see Figure 15). Biomotion band alone had the shortest detection distance (*M* = 108 ft).

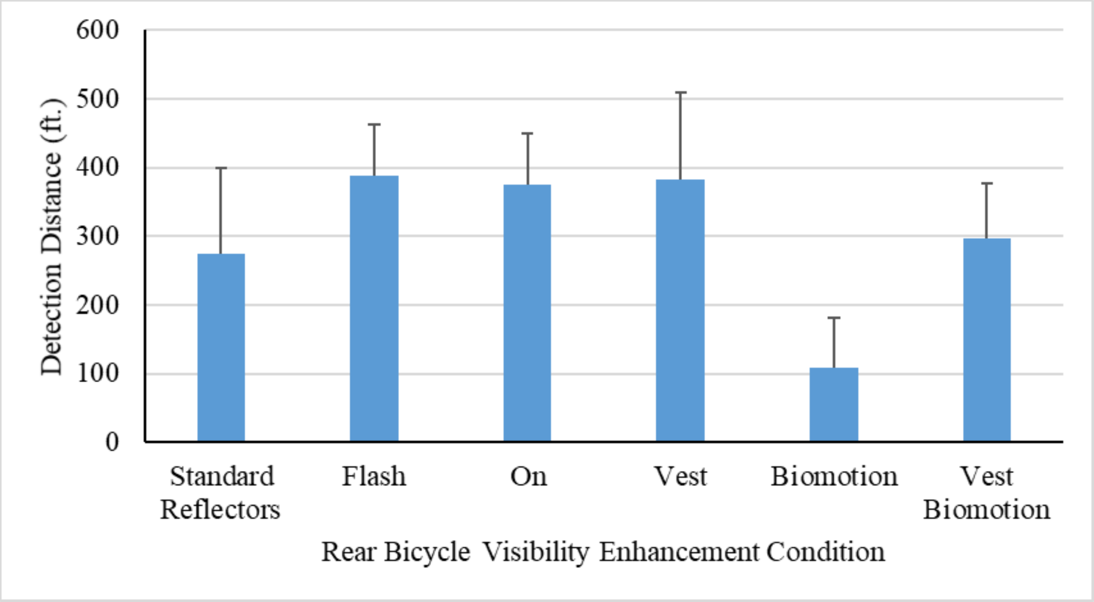

Figure 15. Bar Graph. Effect of bicycle visibility-enhancement condition on detection distance. Values are least square means of detection distances and error bars denote standard errors.

Intersecting Orientation

Detection Distance

The slopes of the covariate were the same across all conditions, indicating that the covariate affected all the conditions in the same manner. The main effect of the bicycle visibility-enhancement condition was significant, *F*(10, 42.1) = 3.17, *p* = 0. 0004. Age and interaction effects were not significant. The mean detection distances for the visibility treatments are shown in Figure 16. Post hoc pairwise comparisons showed that the spoke light had significantly longer detection distances than steady-on low- and high-intensity and moderate flashing headlamps. Steady-on medium brightness headlamps had significantly longer detection distances than steady-on low- and high-brightness and moderate flashing headlamps. Spoke lights (*M* = 346 ft) and steady-on medium-brightness headlamps (*M* = 332 ft) had the longest detection distances. The estimates for detection distances of RR vest and RR vest with biomotion bands were not statistically significant and were thus excluded.

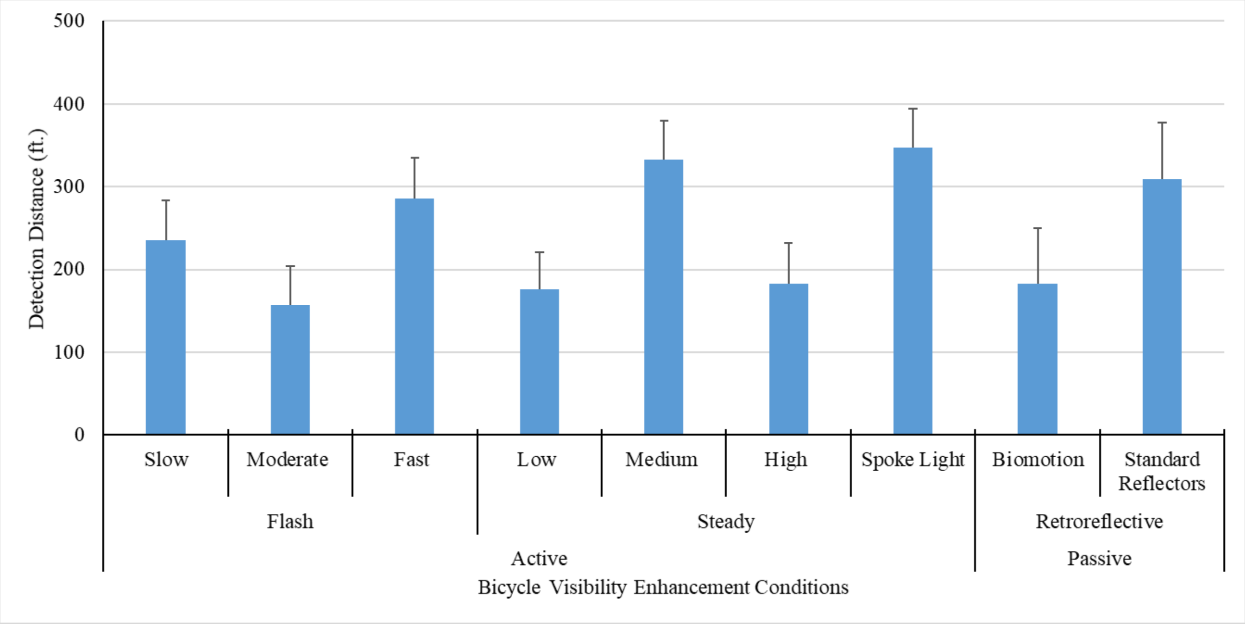

Figure 16. Bar Graph. Effect of bicycle visibility-enhancement condition on detection distance. Values are least square means of detection distances and error bars denote standard errors.

Night

The slopes of the covariate were the same across all conditions, indicating that the covariate affected all the conditions in the same manner. None of the main or interaction effects were significant. The mean detection distances for the visibility treatments are shown in Figure 17. Steady-on high (*M* = 250 ft) and medium-intensity (*M* = 231 ft) headlamps had the longest detection distances, followed by spoke lights (*M* = 158 ft). The estimates for detection distances of slow and moderate flash headlamps along with RR vest and biomotion bands were not statistically significant and were thus excluded.

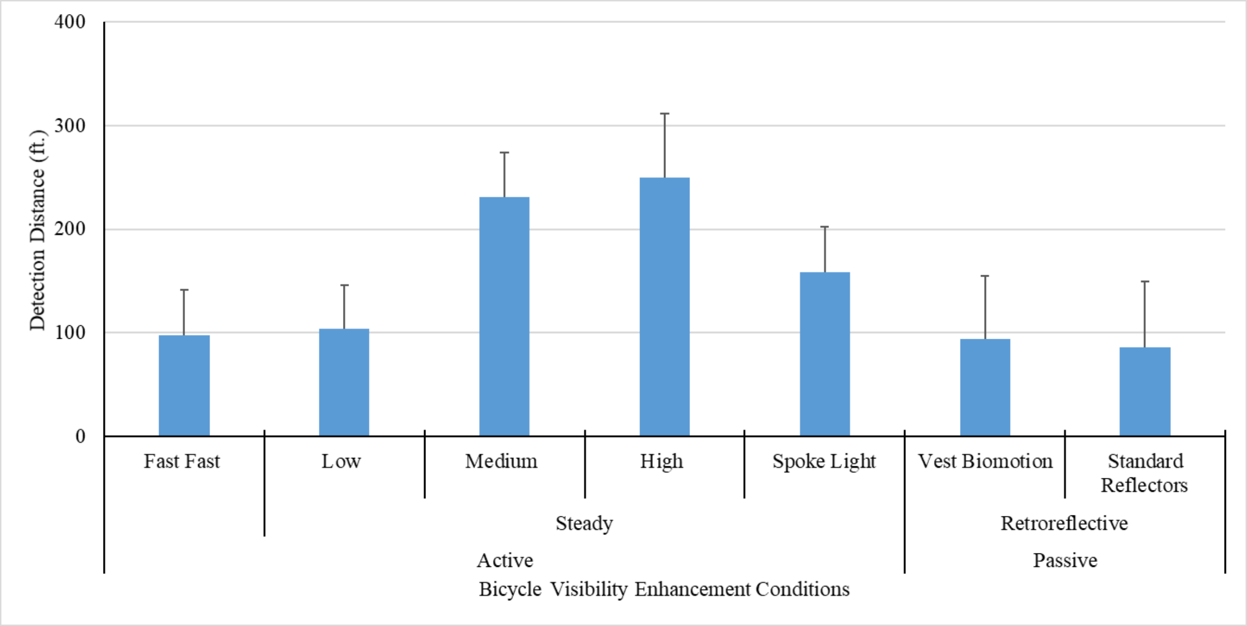

Figure 17. Bar Graph. Effect of bicycle visibility-enhancement condition on detection distance. Values are least square means of detection distances and error bars denote standard errors.

DISCUSSION

The goal of this study was to evaluate the conspicuity of commercially available bicycle visibility-enhancement systems in naturalistic settings, in order to make recommendations that could potentially increase bicycle safety both at night and during the day. The results of the study yielded two major findings. First, the conspicuity of the bicycle visibility-enhancement system depended on the orientation. Second, within each enhancement system (active vs. passive), there were major conspicuity differences.

In the oncoming orientation, statistically significant differences were observed only at night where active systems, like headlamps with moderate (3.4 Hz) and slow (0.9 Hz) flash frequency, and steady-on low-intensity (100 lumens), could be detected the farthest. These results support prior research in the area that flashing lights increase the detection distances of bicyclists and pedestrians (Kwan & Mapstone, 2004; Kwan & Mapstone, 2009). Active systems also had longer detection distances during the daytime, but the differences were not statistically significant. These results are also supported by existing work that showed that daytime running lights significantly increase bicycle visibility (Madsen et al., 2013).

In the oncoming orientation, there were also some differences within each active visibility-enhancement system, and these differed between night and day conditions. Most notably, during the day the fast flash (6.67 Hz) resulted in longer detection distances, whereas during the night moderate and slow flashes had longer detection distances. Similarly, during the day medium-intensity (350 lumens) headlamps had longer detection distances, whereas during the night lower-intensity headlamps had longer detection distances. The differences in the detection of intensities during both night and day conditions and lack of improvement in performance with increasing intensity at night was also reported in existing research (Flanagan et al., 2008).

In the passing orientation, there were no major differences between active and passive bicycle visibility enhancements. While statistically significant differences were not observed during both day and night conditions, these results show important trends in the data. The detection distances of active tail lamps were similar to those of passive systems like the RR vest and a combination of biomotion bands with the RR vest. One condition that had the shortest detection distance during both night and day is the condition with only biomotion bands. The differences in the performance of RR vest, RR vest and biomotion bands, and only biomotion bands shows that the size of the retroreflective area could play an important role in bicycle conspicuity during both night and day conditions. This result is also in agreement with existing research in the area, which shows that the size of the retroreflective area significantly affects visibility (Wood et al., 2012).

In the intersecting orientation, statistically significant differences between the visibility-enhancement conditions were only observed during the day. Similar to the oncoming orientation, there were differences within each of the active visibility-enhancement systems. Spoke lights had the longest detection distances closely followed by steady-on medium-intensity headlamps. Also in this orientation, detection distance estimates of multiple passive systems during the day and both active and passive systems were not statistically significant, indicating that the variance in those conditions was high. This high variance could be attributed to noise as result of visual clutter. Although adequate precautions were taken to account for visual clutter during data reduction, variables like glare and driver distraction could not be accurately modelled.

In general, poor performance of the passive visibility enhancement systems, like biomotion bands, could be attributed to their presence being occluded by the visual clutter of a naturalistic environment, as suggested by earlier research (Moberly & Langham, 2002). Further, biomotion bands work by using reflected light from the vehicles’ headlamps and are only activated when they are within the range of the headlamps. As such, this is a major disadvantage at night, especially at higher speeds when drivers need longer distances to come to a stop. Active systems like headlamps do not rely on the range of the vehicles’ headlamps to be conspicuous. Supplementing biomotion bands by increasing their surface area along with active visibility enhancement systems like headlamps could potentially increase the conspicuity of bicyclists at night.

Finally, older drivers had 25% shorter mean detection distances (*M* = 148 ft) than younger drivers (*M* = 199 ft). Those results are congruent with prior research on age and visual performance while driving (Bhagavathula & Gibbons, 2013; Wood et al., 2012).

This study has some limitations. It was the first of its kind conducted in naturalistic driving environments and as a result the data had a lot variance. While all possible covariates were considered during data reduction and analysis, it is possible that some of them could not be accounted for, like glare from opposing vehicles, driver distraction, driver fatigue, etc. The lack of statistical significance in most of the models could be a direct result of lack of power. It is also encouraging to see some statistically significant results indicating that the approach considered in this study is in the right direction. Future studies in the area should address these limitations.

CHAPTER 5. RECOMMENDATIONS AND CONCLUSIONS

RECOMMENDATIONS

An ideal bicycle conspicuity treatment should increase the bicyclist's visibility in all orientations in which a bicycle could be seen by motor vehicle drivers. Bicyclists should take every precaution to make themselves visible to traffic from all directions. Thus, taking the results of this study into consideration, the following recommendations are made.

- It is recommended that both active and passive conspicuity treatments be integrated in order to increase cyclists' conspicuity during both the day and at night. This includes using headlamps and tail lamps along with RR vests and biomotion bands.

- Headlamps should be either steady on or flashing and should have an intensity of at least 350 lumens. For daytime conditions, flashing headlamps should be used to increase cyclists' conspicuity. For nighttime conditions, steady-on headlamps are recommended to increase cyclists' conspicuity.

- Tail lamps should be either steady on or flashing. It is recommended that tail lamps be used during both during the day and at night to increase cyclists' conspicuity.

- Use of RR vests, along with biomotion bands on ankles and arms, is also recommended during both the day and at night to increase cyclists' conspicuity.

CONCLUSIONS

The results from this study indicate that, in general, active visibility treatments, such as bicycle-mounted lights, make cyclists more conspicuous than passive systems like RR vests and biomotion bands. Flashing headlamps and tail lamps were the most conspicuous treatments during both the day and at night; fast flashing headlamps (6.7 Hz) had higher detection distances and rates during the day, and moderately fast flashing headlamps (3.4 Hz) had higher detection distances and rates at night. Spoke lights and flashing tail lamps, along with RR vests, also aided cyclist visibility during the day and at night, especially for vehicles approaching intersecting cyclists. Passive RR visibility treatments were most effective only at night, when the vehicle was passing the cyclist from behind. However, that approach also used reflectors, so the discrete effect of passive RR treatments could not be determined.

This study also found that biomotion markers alone do not significantly increase cyclist conspicuity in visually complex natural environments. For most approaches, flashing lights had greater detection distances than biomotion markers, which in turn had higher detection rates than head and tail lamps.

Finally, a combination of both active and passive treatments could potentially increase bicyclist conspicuity both during the day and at night.

FUTURE RESEARCH

One of the major drawbacks of this study is the limited sample size. Future studies should increase the sample size to increase the power of the study and account for all possible covariates like glare from oncoming vehicles, driver distraction, etc.

The results of this study provide new avenues for future research. Because the comparative effectiveness of bicycle conspicuity markings seemed to depend on headlamp or tail lamp intensity, future studies should examine the size of RR markings and head and tail lamp size and intensity to identify their individual contributions to visibility.

The results also indicated that not all bicycle-mounted headlamps increase cyclist conspicuity. High-intensity headlamps had shorter mean detection distances than other headlamp settings for oncoming vehicles. That could be because participants saw the lamp but did not necessarily associate it with a cyclist. Getting data that are more detailed on how participants interpret what they see would help safety researchers find the optimum intensity for increasing cyclist visibility without confusing drivers.

Studies have shown that an increase in expectancy increases the distance at which objects are detected by drivers, especially at night (Bhagavathula & Gibbons, 2013). Expectancy might have played a role in detection distances, with participants detecting bicyclists from farther away than drivers who were not asked to look for bicyclists. Studies comparing methods for creating driver expectancy, such as relevant roadway signage, with detection distances and rates for various visibility markings should be performed to determine the optimal combination for increasing bicyclist visibility. One outcome could be that departments of transportation could increase bicyclist safety by placing signs telling drivers to actively look for bicyclists in places with high bicyclist density.

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