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The Nighttime Conspicuity Benefits of Static and Dynamic Bicycle Taillights

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THE NIGHTTIME CONSPICUITY BENEFITS OF STATIC AND DYNAMIC BICYCLE TAILLIGHTS

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ABSTRACT

The rear conspicuity of bicyclists riding with traffic at night is critical for preventing collisions with motor vehicles. Past research suggests that bicycle taillights can offer conspicuity benefits at night but the effects of the placement and operational mode of taillights has not been studied. This study investigates the conspicuity benefits of bicycle taillights at night. Specifically, the distances at which participants respond to bicyclists as they are driven along an open-road route at night were compared. The bicyclists used either a full-intensity taillight on their seat post (either flashing or steady) or a half-intensity taillight on each heel (while either pedaling or not). One bicyclist was stationed on a road segment with a long sight distance and another was stationed on a road segment with a sight distance that was limited by road curvature. For the cyclist positioned at the end of the long straight section of a roadway, conspicuity was maximal when the lights were placed on the heels while pedaling. The conspicuity of the cyclist positioned at the end of a 90 degree curve was maximized when the lights were placed on the heels while pedaling and when the lights were placed on the seat post of the bike (both flashing and static). However, conspicuity for both cyclists was minimized when the lights were placed on the cyclists' heels while not pedaling. These results confirm that highlighting biomotion enhances bicyclists' nighttime conspicuity.

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INTRODUCTION

A total of 729 cyclists' fatalities and approximately 50,000 cyclists' injuries were reported in the United States in 2014. Of the bicyclist fatalities, roughly 44% involved crashes that occurred at night, and 6% occurred at either dusk or dawn (NHTSA, 2016). While the percentage of cyclist fatalities that were reported from collisions that occurred at civil twilight and after dark was the same as the percentage reported from crashes occurring during the daytime, these percentages are misleading. When taking the injury rate per distance traveled into account, cyclists had a higher risk of being injured or killed when cycling on roadways at night than they did when cycling during the day (Twisk & Reurings, 2013).

Bil, Bilovaa, and Muller (2010) analyzed the patterns found in 5428 cyclists/motor vehicle collisions in the Czech Republic. They uncovered that cyclists that rode on roadways devoid of streetlights at night had the highest percentage of fatalities (35%) when compared to the percentages of cyclist fatalities from roadways with streetlights at night (16%), roadways with good daytime visibility (14%), and roadways with bad daytime visibility (21%) (Bil et al., 2010). Cycling on roadways without streetlights at night may be more dangerous because ambient light is limited, and cyclists therefore run the risk of not being seen by drivers with whom they are sharing the road.

There is empirical evidence that suggests that visual capabilities are degraded due to diminished ambient light, as daytime transitions into nighttime. There are two separate cortical pathways that process visual information. The focal (ventral – "What") pathway is responsible for object and pattern recognition, while the ambient (dorsal – "Where" or

“How”) pathway supports navigation and self-localization. Since the ventral pathway relies heavily on information provided by foveal cones, this pathway is selectively degraded at night. Therefore, it is difficult to recognize objects and discriminate patterns in dimly lit environments, such as roadways without street lights at night. However, the dorsal pathway primarily relies on the rods which are optimally sensitive in dimly-lit environments to contrast distinctions and motion. Unlike the ventral pathway, the dorsal pathway is still functional and conveys information supporting self-locomotion in situations with limited illumination. This is known as the selective degradation hypothesis, which is useful for understanding why drivers may fail to recognize a cyclist from safe distances at night (Leibowitz & Owens, 1977; Leibowitz, Owens, & Tyrrell, 1998; Owens & Andre, 1996).

Not only do nighttime cyclists need to overcome their own visual deficits in order to maneuver safely to their destinations, but they also face the threat that drivers will fail to see them. This could potentially lead to motor vehicle/cyclist collisions. While cyclists have the ability to control their own actions as they cycle in these dangerous settings, they possess little to no power to control the surrounding drivers’ behaviors. Therefore, cyclists need to invest their efforts into making themselves as conspicuous as possible to other road users.

Potential solutions to the problem of cyclist nighttime conspicuity reduction due to insufficient roadway illumination are the utilization of bike lights (headlights and taillights) and reflectors. By using active lighting and reflectors, a bicyclist can create visual contrast that can help draw drivers’ attention. Therefore, the NHTSA recommended that cyclists should use a head light and a rear reflector or flashing taillight to make themselves more noticeable when cycling on a roadway at night (NHTSA, 2015). Various governmental agencies have also passed laws that require bicyclists to mount a headlight to the handlebars and/or at least a standard red reflector to the seat posts of their bicycles (For instance SC laws - http://www.bikelaw.com/2010/08/09/south-carolina-bicycle-laws/).

In addition to obeying laws about lights and reflectors that were enacted in attempt to enhance cyclist safety, cyclists are also expected to abide by the same traffic laws as drivers. Thus, they are held accountable for riding in the same direction as traffic, as opposed to cycling against traffic patterns. Thus cyclists face the threat of being hit from behind or the side, and Kim et al. (2007) found that cyclists' fatalities in the United States resulting from accidents that occurred while the cyclists were riding with traffic were more common than those that resulted from head-on collisions with motor vehicles. By analyzing the 5428 cyclist/motor vehicle collision reports in the Czech Republic from 1995 – 2007, Bil et al. (2010) found that collisions that resulted from the cyclists getting hit by vehicles from behind had the highest percentage of cyclists' fatalities (28%) in comparison with the cyclist fatality percentages for lateral (13%), head-on (20%), and from side (15%) collisions.

An investigation of Australian bicycle/motor vehicle crashes that occurred between 1994 and 2006 also found that approximately 30% of cyclists' deaths resulted from collisions where the cyclists were riding in the same direction as traffic, and 64% of the cyclists' deaths that resulted from collisions while riding with the flow of traffic were the result of being hit from behind. Further, this investigation revealed that 86% of the cyclists' fatalities that were the product of motor vehicle collisions from behind occurred at night (Hutchinson & Lindsay, 2009). Because a large percentage of cyclist fatalities resulted from being hit from behind when cycling at night, it is critical that cyclists maximize their rear conspicuity to help drivers become aware of their presence from safer distances. Bil et al. (2010) also analyzed the 5428 cyclist/motor vehicle collisions with respect to roadway geometry. From this analysis, the highest percentages of cyclists' fatalities occurred on straight road segments (23%). Further, curved road segments had the second highest cyclist fatality percentage (16%), while intersections (13%) and roundabouts (4%) had the lowest cyclist fatality percentages (Bil et al., 2010). It is unclear how many of the 5428 cyclists involved in the crashes on the various road segments made use of conspicuity aids to alert drivers of their presence. The effects of conspicuity aid usage on drivers' ability to see a cyclist on straight vs. curved road segments has not yet been studied in daytime or nighttime contexts, and these effects may be more critical at night due to the inherent limited visibility.

Previous studies of cyclist visibility aids found that driver detection and recognition was enhanced when cyclists made use of lamps, flashing lights, and reflectors at night. For example, when comparing the conspicuity benefits of seat post-mounted lights versus reflectors, the use of a taillight while cycling in nighttime traffic environments may be more advantageous in helping a driver to recognize a cyclist than a standard rear reflector (Blomberg, Hale, & Preusser, 1986; Kwan & Mapstone, 2004; Matthews & Boothby, 1980; Watts, 1984). For instance, Watts (1984) found that bicyclists with taillights were detected by participant drivers from farther distances than bicyclists with rear reflectors on their bikes, both with and without glare present. This may be because the amount of reflected light that reaches the driver depends on the angling of the reflector relative to the emitted light (entrance angle), the distance between the source and the reflectors, and the angular separation between the observers' eyes and the light source (observation angle). Therefore, standard bike reflectors appear brighter to a driver when the driver's car is nearer to the reflectors and when the headlights are directly facing the reflectors. Burg and Beers (1978) found that the orientation of the bike relative to a car's headlights and the distance from a car to the bicycle were important factors contributing to the effectiveness of reflectors on a bicycle. These issues of bike orientation and distance from an approaching motor vehicle may not be as pronounced when taillights are used in place of reflectors.

In a laboratory study done by Matthews and Boothby (1980), red rear reflectors were compared to red taillights in terms of participant detection. Photographs of cyclists with a reflector or a taillight mounted to the back of their bikes were taken in visually cluttered and uncluttered environments. The cyclists were positioned at two different distances (60 and 120 meters), and photographs were taken of the roadways without cyclists as well to serve as control images. Participants were asked to respond to each of the 150 images with a "yes" or a "no" to indicate whether or not a cyclist was present in each photograph. The results suggested that participants' performance was better for the images featuring a cyclist with a taillight, in comparison with the images containing a cyclist with a rear reflector (Matthews & Boothby, 1980).

Based on the findings of the aforementioned studies, it may be more valuable for cyclists to utilize bicycle taillights when cycling at night, as opposed to standard rear reflectors. What remains unclear is whether there is an optimal taillight mode, such as flashing or steady (always-on), for enhancing a cyclist's nighttime conspicuity. Wood et al. (2012) conducted a study in which the conspicuity of flashing (2 Hz) versus steady handlebar-mounted headlights was assessed in terms of drivers' recognition distances. Participants were told to drive a test vehicle on a test track and respond to cyclists by pressing a touchpad on the vehicle's dashboard. At the moment that participants pressed the touchpad to indicate that they were confident that a cyclist was present, the distance between the driver and the cyclist was recorded. There was no significant difference between the recognition distances of flashing and steady headlights (Wood et al., 2012). However, this comparison has never been studied empirically using bicycle taillights (which are red), as opposed to headlights (which are white and more intense than taillights).

Another gap in the existing nighttime bicycle conspicuity literature pertains to the lack of studies specifically assessing whether there is an optimal place to mount taillights to the back of the cyclist/bicycle unit in order to enhance the cyclist's conspicuity. Blomberg et al. (1986) varied the placement of active and passive lights in an on-road nighttime study, in which participants were instructed to drive around a designated test route and respond to each of the confederate cyclists. Cyclists either had a standard reflector on the seat post of the bike, retroreflective spokes and crank, one light emitting band around the left ankle, or a fluorescent triangle with a retroreflective border worn on the rider's back and retroreflective bands around the ankles. The findings suggested that the cyclist with the light emitting left ankle band was detected by the drivers from significantly farther away than the other conditions. However, the recognition distances for this rider were not significantly farther than those for the cyclist with the fluorescent/retroreflective triangle on his or her back plus the retroreflective ankle bands (Blomberg et al., 1986). These results may have been obtained because the luminous ankle band rider only had one band on his or her left ankle. While the light emitted from the luminous ankle band can be detected from a farther distance than the reflective bands which need light from the car's headlights to be effective, the single band may not sufficiently supply enough perceptual information to emphasize the rider's biological motion (biomotion).

Indeed, another study conducted by Tyrrell, Fekety, and Edewaard (2016) investigated the conspicuity benefits of bicycle taillights in daylight. Participants rated the conspicuity of test bicyclists pedaling on stationary bicycles from a test vehicle parked at different fixed distances along a closed road. The results indicated that the bicyclist with a taillight mounted to each ankle was significantly more conspicuous (more easily recognized as a bicyclist) than bicyclists with taillights on the seat post or helmet. This was the case even though the luminance of the two lights on the bicyclist's ankles was halved by neutral density (ND) filters (Tyrrell et al., 2016). Therefore, a light mounted to each ankle of a bicyclist may be sufficient for highlighting biomotion. Humans are perceptually sensitive to discriminate human joint movement patterns (Balk, Tyrrell, Brooks, & Carpenter, 2008; Blomberg et al., 1986; Johansson, 1973; Owens, Antonoff, & Francis, 1994; Wood, Tyrrell, & Carberry, 2005). Studies focused on the conspicuity of pedestrians at night have consistently found that placing conspicuity aids (e.g. reflective or electroluminescent material) on a pedestrian's major joints (e.g., wrists, elbows, knees, and ankles) improves participant drivers' recognition distances (Balk, Graving, Chanko, & Tyrrell, 2007; Fekety, Edewaard, Stafford-Sewall, & Tyrrell, 2016; Wood et al., 2005; Wood, Tyrrell, Lacherez, & Black, 2017). Studies focused on bicyclist conspicuity at night have also found that highlighting the moving parts of a bicyclist's body (the knees and ankles) helped drivers to recognize the bio-motion cyclists from farther distances than the cyclists who wore all black clothing with or without a safety vest (Koo & Dunne, 2012; Koo & Huang 2015; Wood, Tyrrell, Marszalek, Lacherez, Carberry, Chu, & King, 2010; Wood et al., 2012; Wood, Tyrrell, Marszalek, Lacherez, & Carberry, 2013).

Matthews and Boothby (1980) included a condition within their study of active versus passive lighting in which amber reflectors were placed on the pedals of the bicycle. Even though this condition did not result in better detection from participants than the seat post-mounted taillight in this study, the amber pedal reflectors might have been more valuable had the researchers used videos or actual on-road methods in which the cyclist was physically moving. The up and down motion of the pedals as the cyclist moves is distinct to cyclists, and hence, the pedal reflectors might have emphasized the rider's biological motion had they been moving.

A nighttime pedestrian conspicuity study conducted by Balk et al. (2008) investigated whether pedestrians would be more conspicuous while walking in place or simply standing still on the right sidewalk of a roadway. The test pedestrians wore black garments with various retroreflective marking configurations, including biomotion configurations with retroreflective bands on the pedestrian's extremities. The results indicated that the pedestrians who walked in place elicited longer response distances than the pedestrians who stood still, especially when the retroreflective material was on the pedestrians' wrists, elbows, shoulders, waist, knees, and ankles. This provided empirical support that biomotion configurations offer more benefits for pedestrians when their extremities are in motion (Balk et al., 2008). However the parallel comparison for bicyclists (i.e., non-pedaling cyclist vs. pedaling cyclist) has never been empirically made.

The purpose of the present study is to investigate the nighttime conspicuity advantages of static and dynamic bicycle taillights. Specifically, seat post-mounted lights that were either flashing or always-on were compared in terms of their conspicuity values. In addition, the conspicuity value of placing taillights on the ankles of cyclists whom were either pedaling or not pedaling was compared. This was completed in order to determine the extent to which highlighting a cyclist's biological motion enhanced conspicuity. Participants were driven at night along a route that included two separate cyclists riding on bikes mounted to trainers. One cyclist was on a road segment that offered a long sight distance (a long straight-away) while the other was positioned on a road segment that offered a shorter sight distance due to road curvature. Using both a long, straight road segment and a curved road segment allowed the data to be generalized to road segments with varying lengths, curvatures, and speed limits. The two cyclists each displayed one of four taillight configurations. The participants' were asked to press a button each time they became confident that a bicyclist was present. The distances at which the participants responded were the primary dependent measure.

METHOD

Participants

Data were collected from 235 undergraduate students from Clemson University, and all participants received course credit for participating. This 235 tally does not include the participants who did not meet the vision screening criteria; these participants were dismissed without participating in the driving portion of the study. Only participants that had 20/40 binocular visual acuity or better with the Bailey-Lovie acuity chart and a log contrast sensitivity score of 1.65 or better with the Pelli-Robson Contrast Sensitivity chart, with presenting optical correction, were allowed to continue their participation in the study. The ages of the 235 participants ranged from 18 and 27 years old (*M* = 19) and all had a valid driver's license in order to participate. All participants were required to sign an informed consent document prior to taking part in the experiment.

Design

The study included four taillight configurations (see Table 1.1): Flashing Seat Post, Steady Seat Post, Pedaling Heels, and Non-pedaling Heels, and it followed a between-subjects design. There were two different iterations of sight distance leading up to the test cyclists: a short sight distance and a long sight distance. Specifically, participants encountered two test cyclists during each experimental session; Cyclist 1 was encountered on a long and straight road segment (long sight distance) and Cyclist 2 was encountered on a short curved road segment (short sight distance). Each cyclist displayed one of the four taillight conditions but never displayed the same condition. The dependent variable was response distance (the distance between the vehicle and the cyclist at the moment that the participant responded to the presence of the test cyclist). The test cyclists were male members of the research team, who wore all black clothing and pedaled on bicycles that were mounted to stationary trainers. Each test cyclist was positioned on a sidewalk (Cyclist 1) or a grassy shoulder to the right of the roadway (Cyclist 2).

Table 1.1: The Four Taillight Configurations

Taillight Configuration	**Description**
Flashing Seat Post	A single taillight operating in the Nighttime Flash mode was mounted to the seat post of the bicycle. The cyclist pedaled at a cadence of approximately 78 rpm.
Steady Seat Post	A single taillight operating in the Steady (always-on) mode was mounted to the seat post of the bicycle. The cyclist pedaled at a cadence of approximately 78 rpm.
Pedaling Heels	Two taillights (each filtered to half intensity with neutral density (ND) filters) operating in the Steady mode were mounted to the heels of the cyclist's shoes, facing the traffic approaching from behind. The cyclist pedaled at a cadence of approximately 78 rpm.
Non-pedaling Heels	Two taillights (each filtered to half intensity with ND filters) operating in the Steady mode were mounted to the heels of the cyclist's shoes, also facing the traffic approaching from behind. The cyclist did not pedal, but rather the cyclist's feet were positioned on the pedals such that they were both at the same height above the ground (i.e., at the 3 o'clock and 9 o'clock positions).

Materials

Both bicycles (Trek 7.3 FX 17.5; Model 1327010-2016) had black frames and were mounted to black trainers (CycleOps SuperMagneto Pro; Model 411852). Each bike included a cadence-monitoring bike computer (Bontrager Trip 300 and Duo Trap S). All taillights were Bontrager Flare RT taillights that are commercially available (see Figure 1.1 and 1.2). The Steady mode had a luminous intensity of 3.5 lumens. The Nighttime Flash mode presented 9 lumen flashes at frequency of 2.6 Hz or 156 RPM, and the third flash in the cycle, which had a frequency of 0.87 Hz, had a 56 lumen increase in intensity (65 total lumens) (see Figure 2.1 for flash details). The Nighttime Flash mode also had an "always-on" background light with a luminous intensity of 0.4 lumens. The measurements of the lumen output of the lights were specified by the taillight manufacturer (Bontrager). When the taillights were mounted to the heels of the riders' shoes, the steady 3.5 lumen output was reduced in half by 0.3 ND filters, which were mounted to each of the two lights. Both the Steady and Nighttime Flash modes had an average luminous intensity of approximately 3.5 lumens.

Figure 1.1: The Bontrager Flare RT taillight.

Figure 1.2: A Bontrager Flare RT inside a custom-made neutral density (ND) filter box mount, which holds the 0.3 ND filters in front of the light in order to reduce the luminance of the taillight in half. The circular frame on the box is the mechanism that holds the ND filter in place.

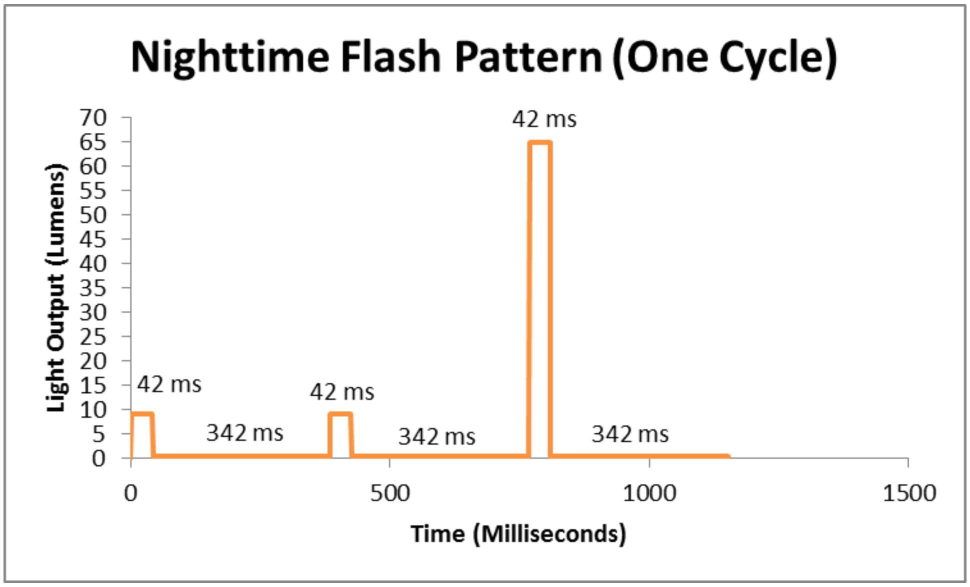

Figure 2.1: Specifications of one cycle of the Nighttime Flash mode, as determined by the manufacturer. The first two light pulses have a luminous intensity of 9 lumens with durations of 42 ms each. The third light pulse has a luminous intensity of 65 lumens with a duration of 42 ms. In between each light pulse (342 ms), the Flare R has an output of 0.4 lumens.

The test route consisted of a 6.4 km (4.0 miles) route that included both roads on and near Clemson University's campus (see Figure 3.1). One of the two test cyclists was positioned along a straight and level stretch of Highway 93 that offered a sight distance of 2034 ft (620 m) with a 40 mph (64.4 km/h) speed limit, and the other cyclist was positioned on a level stretch of a public roadway that offered a sight distance of 284 ft (86.5 m) due to road curvature with a 30 mph (48.3 km/h) speed limit. The sight distance of each road stretch was measured at night by measuring the stretch of roadway (not the driver's line of sight) from a bicycle set up at each cyclist position to the point at which the light from a taillight on the bicycles' seat posts were just visible. The long sight distance cyclist (Cyclist 1) was positioned on the sidewalk to the right of the northwest-bound side of the highway after the long, straight section of the roadway that included a bridge over a lake. Along this road, the test vehicle maintained a constant speed of 40 mph. The short sight distance cyclist (Cyclist 2) was positioned on the right shoulder of a nearby roadway positioned shortly after a 90 degree curve to the right. The test vehicle maintained a constant speed of 30 mph along this road. The cyclists were roughly 2 minutes from each other and in areas with negligible ambient illumination (e.g., mean vertical illumination < 0.1 lux). During the entire drive along the test route, the test vehicle uses low-beam headlights.

Figure 3.1: The positions of Cyclist 1 and Cyclist 2 along the designated test route, which started and finished at Brackett Hall with the turn-around point on McGregor Rd.

Procedure

All data collection sessions started at least one hour after sunset and only on nights when there was no precipitation or fog. Prior to each experimental session, the windshield and headlight casings of the test vehicle were cleaned. Up to two participants were tested during each session, and upon arriving at the lab, participants first provided demographic information and underwent the vision screening process. Following successful vision tests, the participants were escorted to the test vehicle (a 2016 Nissan Altima). The first participant was seated in the front passenger seat. The second participant, if present, was seated in the middle back seat. All participants' seat positions were noted.

Two researchers were in the test vehicle: one researcher drove the vehicle and the other was in the back seat operating the computer and interacted with the participants. Participants were given a numeric keypad that was connected to the computer, and they were instructed to press a designated button when they were certain that they saw a cyclist on or near the road. Once participants indicated that they understood the procedure, they were taken on a 15 – 20 minute drive. Participants first encountered Cyclist 1 approximately 5 minutes after the drive began, and approximately two minutes after passing the first cyclist, participants were driven past Cyclist 2.

Upon each press of the response button, a timer on the computer was activated. The researcher stopped the timer upon passing the relevant cyclist. The time between the participants recognizing a cyclist and the vehicle passing the cyclist was used to calculate each participant's response distance (Distance = Speed * Time). This particular technique has been used in numerous on-road pedestrian studies, and its accuracy has been verified (e.g., Fekety, Edewaard, Stafford-Sewall, & Tyrrell, 2016; Whetsel-Borzendowski, Stafford-Sewall, Rosopa, & Tyrrell, 2015; see Figure 4.1).

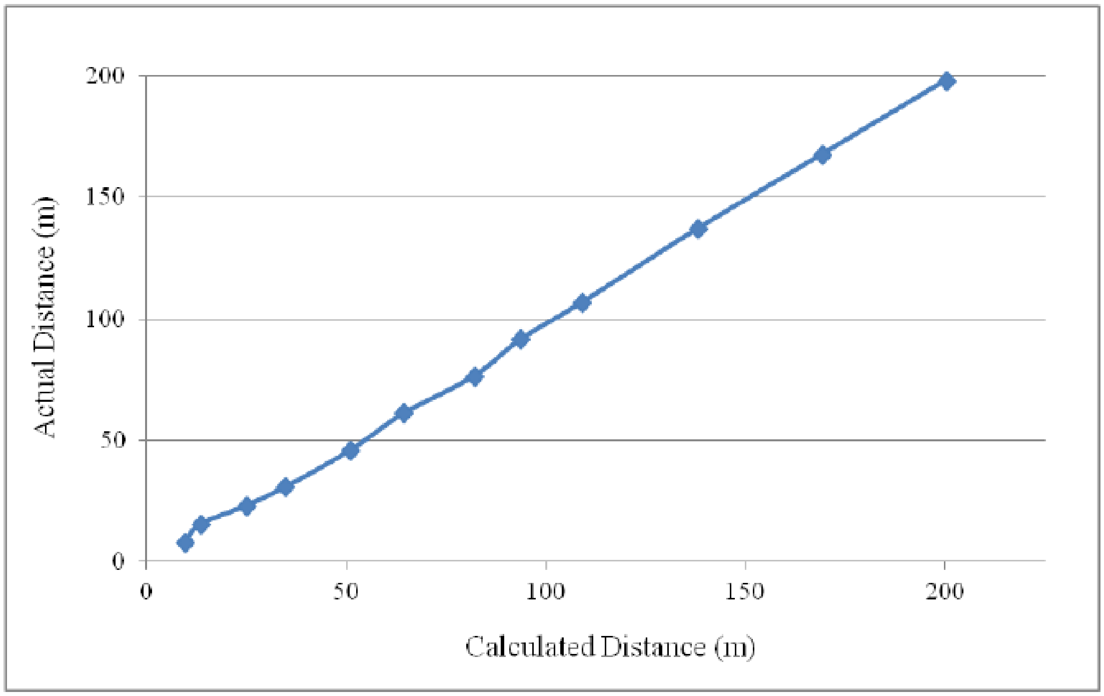

Figure 4.1: The Linear regression model depicts the relationship between the actual distance and the calculated distance, which demonstrates the accuracy of the distance calculation method (Whetsel-Borzendowski et al., 2015).

After passing both test cyclists, the participants were informed that the experimental session was finished and that they could terminate their search for cyclists. The participants were then debriefed and driven back to Brackett Hall where they were released. Each experimental session lasted approximately 30 minutes.

Only responses to the cyclists that were part of this study were included in the analyses; all other responses were ignored. Also, only response distances resulting from trials where glare from oncoming vehicles did not interfere with the participants' view of the bicyclists were included in analyses. If the moon was visible during any data collection sessions, its presence and phase were recorded. A response distance of 0 m was recorded whenever a participant failed to respond to a cyclist or when a participant responded after passing a cyclist.

To calibrate the measurement technique, the same technique was used to measure the distance between a pedestrian standing at 15 known distances (ranging from 100 feet – 2000 feet as measured by rolling a measuring wheel) from the rear of the test bicyclist's marked position on the sidewalk. This process confirmed that that the response distance measurements were accurate. The following linear model predicted the response distance (in feet) from the wheeled distance (also in feet):

$$ResponseDistance = 0.984 * WheelDistance - 3.785$$

Most of the variability was accounted for by this linear model (R2 = 1.00). This linear model was applied to the participants' raw response distances in order to correct the distances, before data analysis. This procedure was conducted so that the response distances measured in the data collection protocol closely matched the true distances (mean error of 0.21 feet or 0.11%).

RESULTS

Of the 235 participants that took part in this study, a total of 219 participants provided data for at least one of the two bicyclists. Data from 63 participants were excluded from the analyses for the response distances to the cyclist on the long straight roadway, and thus, data from 172 participants were included in the analysis for Cyclist 1. Of the 63 Cyclist 1 exclusions, 3 were due to rain or from smoke from forest fires being present during testing, 2 were due to traffic obstructing the participants' view during the approach toward Cyclist 1, 15 were due to participants admitting to having prior knowledge of the study, 4 were due to participants failing to follow instructions, 25 were due to various methodological problems (e.g., the test bicyclist was not ready when the test vehicle passed or the retroreflective dots on the back of the cyclists' leggings were not properly covered), and 14 participants were outliers in that their response distances were greater than two standard deviations above the mean. Meanwhile, 166 participants provided a usable data point for Cyclist 2. Of the 69 curve-cyclist exclusions, 3 were due to rain or from smoke from forest fires being present during testing, 3 were due to participants admitting to having prior knowledge of the study, 2 were due to participants failing to follow instructions, 60 were due to various methodological problems, and 1 participant was an outlier in that the response distance was greater than two standard deviations above the mean.

Each of the four taillight configurations' distributions for Cyclist 1 and Cyclist 2 were positively skewed (i.e., the distributions are asymmetrical due to a long tail protruding to the right of the curve), and the variances of the configurations for each cyclist were not consistent. It was found that the homogeneity of variance assumption in analysis of variance (ANOVA) was violated. To mitigate the biasing effects of heterogeneity of variance, weighted least squares (WLS) estimation was used (for a review, see Rosopa, Schaffer, & Schroeder, 2013). Specifically, the four configurations were given a weight that depended on the variability of their residuals (the inverse of the variance for each taillight configuration was calculated by dividing each configuration's degrees of freedom by each configurations' summed squared residuals). This method preserves the values for the response distances for each configuration, but it assigns more weight to configurations with less variability among the residuals and less weight to those with greater amounts of variability. In other words, the WLS transformation helps to even out the unequal variability among the configurations. It deserves noting that after using WLS estimation the homogeneity of variance assumption was no longer violated. Thus, estimated parameters and statistical tests can be interpreted as normal.

Separate one-way between-subjects ANOVAs were performed to quantify the effects of the four taillight configurations (Flashing Seat Post, Pedaling Heels, Steady Seat Post, and Non-pedaling Heels) for the response distances to each cyclist. It is important to note that the data from the two cyclists were not directly compared. Each dataset was analyzed separately because the cyclists were positioned on two distinct road segments, in an attempt to generalize the findings. The results of each ANOVA are described separately in the following sections.

Cyclist 1

From the ANOVA for the cyclist positioned on the long, straight section of roadway, the main effect of Taillight Configuration was statistically significant, $F(3,168) = 19.21$, $\eta^2 = .255$, $p < .001$. Bonferroni post hoc comparisons revealed that the bicyclist pedaling with the lights mounted to the heels of his shoes (Pedaling Heels: $M = 220.7$ m, $SD = 148.0$ m) yielded significantly longer response distances than any of the bicyclists in the other taillight configurations (all $p < .05$). In addition, the response distances to the bicyclist in the Flashing Seat Post Taillight Configuration ($M = 123.1$ m, $SD = 157.3$ m) were significantly greater than those for both the Steady Seat Post Taillight Configuration (*M* = 40.8 m, *SD* = 93.13 m) and the Non-pedaling Heel Lights (*M* = 37.3 m, *SD* = 71.6 m). All *p*-values were less than .05. Finally, the difference between the response distances from the bicyclists in the Steady Seat Post Taillight and the Non-pedaling Heel Lights Configurations was not statistically significant ($p = .84$) (see Figure 5.1 and Table 2.1).

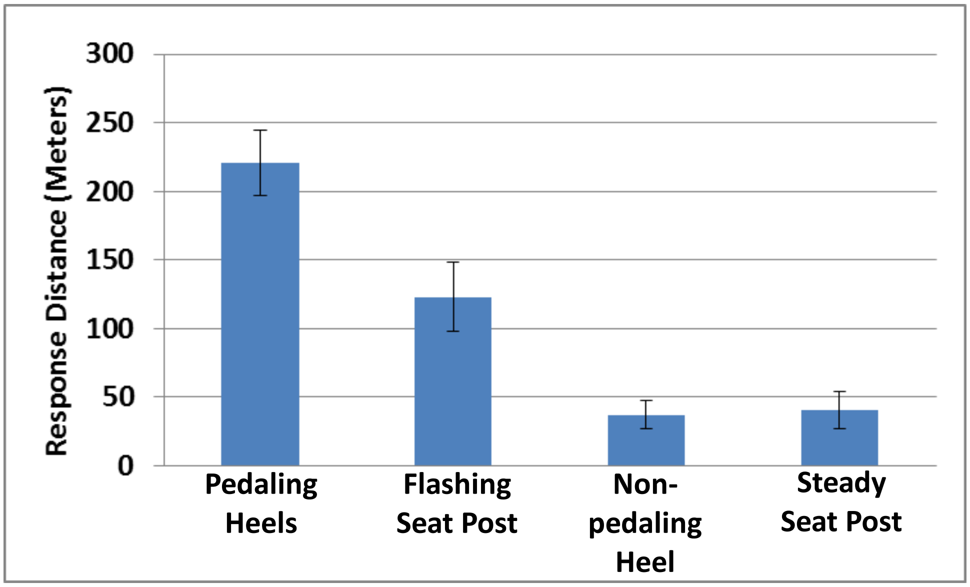

Figure 5.1: Mean response distances for the four taillight configurations of Cyclist 1, with error bars representing ±1 standard error of the mean. Farther response distances indicate earlier recognition and greater conspicuity.

Cyclist 2

From the ANOVA for the cyclist positioned at the end of a 90 degree curved road, the main effect of Taillight Configuration was statistically significant, $F(3,162) = 9.82$, $\eta^2 = .154$, $p < .001$. Bonferroni post hoc comparisons indicated that the response distances to the bicyclists in the Flashing Seat Post Taillight Configuration (*M* = 43.2 m, *SD* = 19.7 m), the Steady Seat Post Taillight Configuration (*M* = 45.5 m, *SD* = 19.2 m), and the Pedaling Heel Lights Configuration (*M* = 49.9 m, *SD* = 15.9 m) were not significantly different from each other ($p > .05$). However, the response distances for all three of these configurations were significantly greater than the response distances to the bicyclist in the Non-pedaling Heel Lights Configuration (*M* = 28.1 m, *SD* = 21.3 m) ($p < .001$). See Figure 6.1 and Table 2.1 for means and deviations.

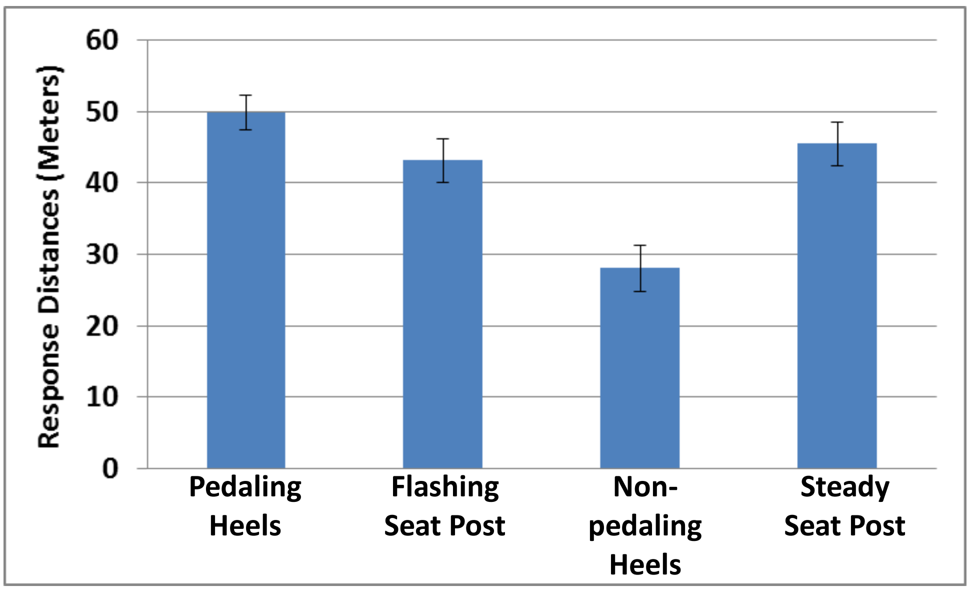

Figure 6.1: Mean response distances for the four taillight configurations for Cyclist 2, with error bars representing ±1 standard error of the mean. Farther response distances indicate earlier recognition and greater conspicuity.

Table 2.1: Descriptive Statistics for Cyclist 1 and Cyclist 2

Location		**Taillight Configuration**				
		Flashing Seat Post	*Steady Seat Post*	*Pedaling Heels*	*Non-pedaling Heels*	*TOTAL*
Straight (Cyclist 1)	*Mean (SD)*	123.1 m (157.3 m)	40.8 m (93.1 m)	220.7 m (148.0 m)	37.3 m (71.6 m)	63.1 m (139.0 m)
	N	38	48	38	48	172
Curve (Cyclist 2)	*Mean (SD)*	43.2 m (19.7 m)	45.5 m (19.2 m)	49.9 m (15.9 m)	28.1 m (21.3 m)	43.1 m (20.8 m)
	N	41	41	42	42	166

DISCUSSION

To maximize their safety, bicyclists must maximize their conspicuity. This study investigates the effectiveness of bicycle taillights as a way for bicyclists to enhance their own nighttime conspicuity to drivers approaching from the cyclist's rear. The present study was performed at night on an open-roadway route containing a road that offered a long, straight sight distance of 620 m and a road with a 90 degree curve offering a sight distance of 86 m. Visually healthy young observers were driven along this route and pressed a button each time they recognized that a bicyclist was present. Two test bicyclists who each displayed one of the four taillight configurations were positioned on an adjacent sidewalk or road shoulder. Data from 172 participants were reported for the bicyclist that was positioned at the end of the 620 m roadway (Cyclist 1), and data from 166 participants were reported for the bicyclist that was positioned on the roadway with the 90 degree curve (Cyclist 2).

The placement and type of signal (dynamic or static) of the bicycle taillights in this study were systematically varied to create four different taillight configurations that were assessed in each of the two roadway geometries. Two configurations featured taillights (flashing and static) positioned on the seat post of the bicycle, which is the conventional place for bicyclists to mount a taillight. The conspicuity value of lights mounted to the heels of the cyclist's shoes was also examined in the other two configurations. This was prompted due to findings from other studies on bicyclist conspicuity that highlighting the bicyclist's biological motion provided conspicuity benefits (Blomberg et al., 1986; Koo & Dunne, 2012; Koo & Huang, 2015; Tyrrell et al., 2016; Wood et al., 2010; Wood et al., 2012; Wood et al., 2013).

For Cyclist 1, the most important finding was that participants responded from significantly greater distances when the rider was pedaling with lights on the heels of his shoes. When the lights were mounted to the cyclist's pedaling heels (M = 220.7 m, N = 38), participants responded from a mean distance that was 1.7 times greater than for the flashing seat post light (M = 123.1 m, N = 38) and 5.5 times greater than for the static seat post light (M = 40.8 m, N = 48) and the for static lights on the heels of his shoes (M = 37.3 m, N = 48). In other words, the configuration with the lights mounted to the pedaling heels of the rider led to a powerful increase in response distances relative to the other three configurations.

It is important to note that, while the configurations with lights mounted to the heels of rider's shoes had two lights instead of the one light featured in the seat post configurations, the luminance of the lights mounted to the heels was halved by ND filters. While bicyclists would not naturally ride with lights covered by ND filters, this was done so that the total light output of the two heel lights would equal the light output of the one seat post light. Further, the cadence maintained by the cyclist in the pedaling heel lights condition was controlled to be 78 rpm. Being as that the two pedaling heel lights moved in phases that opposed each other, the pedaling heel lights configuration portrayed the unique pattern of movement created by a bicyclist and was a spatially and temporally powerful stimulus. Thus, it appears that the Pedaling Heels condition provided greater conspicuity benefits for Cyclist 1 due to highlighting the rider's biological motion. This is consistent with the existing literature that demonstrate the value of emphasizing a bicyclist's biological motion (Blomberg et al., 1986; Koo & Dunne, 2012; Koo & Huang, 2015; Tyrrell et al., 2016; Wood et al., 2010; Wood et al., 2012; Wood et al., 2013). Future research could assess the conspicuity benefits of the heel-mounted lights without the ND filters at night because, without the ND filters, it is likely that bicyclists pedaling with full intensity heel-mounted lights would be recognized from even farther away.

Another interesting finding that resulted from data for Cyclist 1 was that the mean response distance for the flashing seat post-mounted light configuration (M = 123.1 m, N = 38) was three times greater than the mean response distances to the static sea post-mounted lights (M = 40.8 m, N = 48) and 3.3 times greater than the non-pedaling heel-mounted lights (M = 37.3 m, N = 48). During the debriefing interview, many participants mentioned that this cyclist with the Steady Seat Post Light or the Non-pedaling Heel Lights looked like a motorcyclist or person riding a moped. This finding indicates that using a flashing seat post light while riding at night can also offer bicyclists conspicuity benefits relative to an unchanging light. The conspicuity advantages found for flashing taillights over static taillights is not consistent with the finding that flashing headlights were no more conspicuous than static headlights in the study conducted by Wood et al. (2012). This may be because drivers are more accustomed to seeing the rearview of bicyclists, and bicyclists are more frequently encountered with flashing taillights, especially at night. However taken together, the findings from the present study for Cyclist 1 positioned at the end of a long straight section of roadway suggest that lights that feature a dynamic quality (spatial or temporal) provide conspicuity advantages over lights with steady or nonmoving characteristics.

For the cyclist position at the end of a 90 degree curve, the average response distances to the Pedaling Heels (M = 49.9 m, N = 42), Flashing Seat Post (M = 43.2, N = 41), and Steady Seat Post (M = 45.5 m, N = 41) lights were not significantly different from one another. It appears that the relatively short sight distance (86 m) offered by the curved roadway allowed participants to recognize the cyclist in these three configurations from similar positions. However, these three configurations produced average response distances that were 1.6 times greater than for the Non-pedaling Heel Lights Configuration (M = 28.1 m, N = 42). This finding is particularly intriguing because this Non-pedaling Heel Lights Configuration had qualities that were similar to the other three configurations (e.g., the light placement was the same as the Pedaling Heel Lights Configuration, and the lights were on the same mode as the Steady Seat Post Light Configuration). Therefore, the nearer average response distance produced by the Steady Heel Lights Configuration may be due to the novelty of encountering a cyclist using this configuration. For instance, the static lights were placed on an unconventional location, and the cyclist was not pedaling while mounted on the bicycle, which also is less common.

For both Cyclist 1 and Cyclist 2, the mean response distances were the shortest for Non-pedaling Heel Lights Configuration. This is similar to the finding of Balk et al. (2008) in which pedestrians who stood still while wearing biomotion markings were recognized from significantly shorter distances than pedestrians who were moving with the same markings. In fact during the process of debriefing, it was not uncommon for participants who encountered a cyclist displaying the Non-pedaling Heel Lights Configuration to comment that they were confused by the two static lights and that they did not realize that the lights were on a bicyclist until the test vehicle was adjacent to or had already passed the cyclists. Some participants who saw this configuration and did not press their button disclosed that they thought this bicyclist was a person on a motorcycle or moped. However, it is important to note that, even though the mean distance from which participants *recognized* this bicyclist as being a bicyclist was shorter than those for the other three configurations, participants reported that they *detected* the lights on the non-pedaling heels from far away. This suggests that the drivers may not recognize that lights are mounted to a bicyclist's non-pedaling heels from far distances unless the cyclist begins to pedal, but the stationary lights may be detected by drivers from relatively far distances, which could provide some safety benefits.

In this study, the distances from the point at which participants *recognized* the presence of the test bicyclists to the bicyclists' locations were recorded and analyzed. This is different from *detection* distances, or the distances from which participants detect the presence of an ambiguous object that may (or may not) be a bicyclist. Participants were specifically told to only press their buttons when they were confident that they saw a bicyclist (as opposed to seeing lights that may be coming from bicyclists). This is because, when a driver recognizes that a bicyclist is present, the driver can better predict what courses of action may be necessary in order to avoid a future collision. In other words, when objects are simply detected, observers have more difficulty predicting the object's future actions. Therefore, it is important to assess observers' recognition distances in order to determine the conditions which afford drivers more time to plan maneuvers to avoid collisions. Further research, however, is needed to assess the differences between driver detection distances for bicycle taillights and their recognition distances to the bicyclists using the taillights in order to better understand the transition from detection to recognition.

In order to prevent biased responses, participants were not told that they would encounter an experimenter on a bicycle. This may have reduced the participants' expectation that they would encounter a bicyclist in a particular location. Cyclist 1 was always positioned at the same point of long, straight, and flat section of roadway. Cyclist 2 was always positioned at the same point at the end of a 90 degree curved section of roadway. Therefore, the conspicuity benefits of the four taillight configurations were only tested on two roadway geometries, and all of the data analyzed in this study was recorded on nights without precipitation, when the road environment was dry, and uncluttered by motor vehicle traffic. This maximized experimental control and prevented extraneous variables from confounding the taillight manipulation. However, it is important to keep in mind the effectiveness of these light configurations in other roadway conditions was not tested. Future research is required in order to assess the conspicuity benefits of bicycle taillights at different times of day, on roadways of different geometries (e.g., hills), and/or in the presence of traffic or precipitation.

Both bicyclists in this study were mounted on stationary bicycles held in place by bicycle trainers to ensure the safety of the riders and the accuracy of the measurements. This did not appear to influence participant's response distances. In fact during debriefing, many participants commented that they did not realize Cyclist 1 was not moving forward until after passing Cyclist 2. In addition, the bicyclists were always approached by the test vehicle from the rear, and therefore other orientations were not tested in this study. Future research could investigate the conspicuity benefits of bicycle taillights viewed from different orientations than just the rearview.

The comparison between the conspicuity benefits of active (e.g., taillights) and passive lighting (e.g., retroreflective material) was also not assessed in this study. While configurations involving passive lighting has been found to provide nighttime conspicuity benefits for cyclists (e.g., Wood et al., 2010; Wood et al., 2012; Wood et al., 2013), the conspicuity value of active lighting had not been heavily investigated in the context of bicyclists. Active lighting offers several advantages over passive lighting. For example, active lighting relies on its own light source, while passive lighting requires on an external light source (e.g., car headlights) to be effective. Also, they can have the ability to be detected from greater distances than passive lighting materials, which depend greatly on the intensity and distance of the external source for effectiveness. It is unclear how the response distances to the active lighting configurations used in this study would compare to response distances to similar configurations with passive lighting. However with the advancement of improvements in battery life and optics of bicycle lights, active light sources, such as taillights, have the potential to provide safety benefits for bicyclists who ride at night, especially when configured in ways that capitalize on drivers' perceptual sensitivity to biological motion.

It is important to note that a control condition (e.g., a configuration with no taillight) was not tested in the present study. Therefore, it is unclear how the response distances obtained for bicyclists with the four tested configurations compare to a bicyclist with no taillights or other configurations of taillights at night. Further, only red lights (taillights) were tested, and due to this reason, it is uncertain whether the results of this study can be generalized to lights of other colors or purposes (e.g., white bicycle headlights). The taillights used in this study also had special optical lensing to focus the beam and minimize light scattering. This allows the taillights to be seen from large distances when aimed properly. Since these taillights have different optical qualities than most other types of taillights on the market, the results of this study may not generalize to other taillights. In addition, these taillights were designed to be used in static locations such as the seat post of the bicycle so that the beam of light was always parallel to the ground and faced approaching drivers. However when the lights were mounted to the heels of a pedaling rider, the light beams were not always aimed directly at approaching drivers. The up and down motion of the cyclists' legs with lights attached made the lights appear dimmer on the up-stroke than on the down-stroke. This did not seem to be an issue, as the Pedaling Heels configuration was found to be the most conspicuous on the rider at the end of a long sight distance. Many participants who responded to the cyclists in this condition commented during debriefing that they quickly realized that the lights were on the cyclists' pedaling legs.

It is critical that bicyclists take responsibility for their safety while sharing the roadway with motor vehicles, and this means that they must make informed decisions about the gear with which they choose to ride. Bicyclists must also be informed that conspicuity aids are not effective 100% of the time, and therefore, they should always ride defensively. Still, the findings from this study suggest that the strategic use of bicycle taillights can provide substantial conspicuity benefits for bicyclists riding at night. Specifically, highlighting a bicyclist's movement by mounting lights on the rider's heels has been found to be effective for maximizing nighttime conspicuity.

CONCLUSION

This study provides insight into the distances from which drivers may recognize cyclists on roadways of varying lengths and curvatures. The findings indicate that there are conspicuity advantages of using lights with dynamic qualities (e.g., flashing or moving spatially), as opposed to static qualities when cycling at night. This study also empirically demonstrated that the strategic placement of active lighting devices can enhance a cyclist's conspicuity in various cycling environments. Specifically, the findings of this study highlight the conspicuity advantages of using active lighting to emphasize a cyclist's biomotion, as opposed to conventional uses of taillights (e.g. mounted to a seat post) in the context of on-road nighttime cycling. In the case of the cyclist who was positioned at the end of a long, straight section of roadway, participants responded to this bicyclist with taillights on the pedaling heels from a mean distance that was almost double the distance at which other participants responded to the rider who used a flashing taillight mounted to the seat post. The response distance to the rider with lights on the pedaling heels was also 5.5 times as large as the response distances when the rider had a static seat post light and lights on the non-pedaling heels. Since the heel lights have the ability to highlight the bicyclist's movement, the conspicuity benefits of lights mounted to a pedaling bicyclist's heels aligns with findings from the existing scientific literature that humans are perceptually sensitivity to biological motion. Therefore, the heel lights have the ability to capitalize on the perceptual sensitivity that approaching drivers' have for recognizing biological motion and provide a way for bicyclists to enhance their own conspicuity at night. For the bicyclist positioned at the end of a curved roadway, conspicuity was maximized when the lights were mounted to the rider's pedaling heels and mounted to the seat post of the bicycle in both flashing and static modes. The results of this study can be useful to designers of bicycle taillights, since these data offer valuable insights into how taillights can be used to maximize bicyclist conspicuity at night.

REFERENCES

Balk, S. A., Graving, J. S., Chanko, R. G., & Tyrrell, R. A. (2007). Effects of retroreflector placement on the nighttime conspicuity of pedestrians: An open-road study. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 51*(24), 1565-1568.

Balk, S.A., Tyrrell, R.A., Brooks, J.O., & Carpenter, T.L. (2008). Highlighting human form and motion information enhances the conspicuity of pedestrians at night. *Perception*, *37*(8), 1276.

Bíl, M., Bílováa, M., & Müller, I. (2010). Critical factors in fatal collisions of adult cyclists with automobiles. Accident Analysis and Prevention, 42, 1632-1636.

Blomberg, R.D., Hale, A., & Preusser, D.F. (1986). Experimental evaluation of alternative conspicuity-enhancement techniques for pedestrians and bicyclists. *Journal of Safety Research*, *17*, 1-12.

Burg, A., & Beers, J. (1978). Reflectorization for nighttime conspicuity of bicycles and motorcycles. *Journal of Safety Research, 10*(2), 69-77.

Fekety, D. K., Edewaard, D. E., Sewall, A. A. S., & Tyrrell, R. A. (2016). Electroluminescent materials can further enhance the nighttime conspicuity of pedestrians wearing retroreflective materials. *Human Factors: The Journal of the Human Factors and Ergonomics Society*.

Hutchinson, T.P. & Lindsay, V.L. (2009). *Pedestrian and cyclist crashes in the Adelaide Metropolitan Area (Report #CASR055)*. Adelaide, Australia: Centre for Automotive Safety Research.

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Attention, Perception, & Psychophysics, 14*(2), 201-211.

Kim, J., Kim, S., Ulfarsson, G. F., & Porrello, L.A. (2007). Bicyclist injury severities in bicycle-
motor vehicle accidents. *Accident Analysis and Prevention*, *39*, 238-251.

Koo, H., & Dunne, L. (2012, April). Enhancing visibility in bicycling apparel using integrated flashing LEDs. In *Smart Design: First International Conference Proceedings*, 41-47. Springer London.

Koo, H.S. & Huang, X. (2015). Visibility aid cycling clothing: flashing light-emitting diode (FLED) configurations. *International Journal of Clothing Science and Technology*, *27*, 460-471.

Kwan, I. & Mapstone, J. (2004). Visibility aids for pedestrians and cyclists: a systematic review of randomised controlled trials. *Accident Analysis and Prevention, 36*, 305-312.

Leibowitz, H. W., & Owens, D. A. (1977, July 29). Nighttime driving accidents and selective visual degradation. *Science, 197*,422-423.

Leibowitz, H. W., Owens, D. A., & Tyrrell, R. A. (1998). The assured clear distance ahead rule: implications for nighttime traffic safety and the law. *Accident Analysis & Prevention, 30*(1), 93-99.

Matthews, M.L., & Boothby, R.D. (1980, October). Visibility of cyclists at night: laboratory evaluation of three rear warning devices. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 24* (1), 129-133.

National Center for Statistics and Analysis. (2016). *Bicyclists and other cyclists: 2014 data*. (Traffic Safety Facts. Report No. DOT HS 812 282). Washington, DC: National Highway Traffic Safety Administration.

Owens, D. A., & Andre, J. T. (1996). Selective visual degradation and the older driver. IATSS research, 20(1), 57-66.

Owens, D.A., Antonoff, R.J., & Francis, E.L. (1994). Biological motion and nighttime pedestrian conspicuity. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *36*(4), 718-732.

Rosopa, P. J., Schaffer, M. M., & Schroeder, A. N. (2013). Managing heteroscedasticity in general linear models. Psychological Methods, 18(3), 335-351.

Twisk, D. A. M., & Reurings, M. (2013). An epidemiological study of the risk of cycling in the dark: The role of visual perception, conspicuity and alcohol use. *Accident Analysis & Prevention, 60*, 134-140.

Tyrrell, R.A., Fekety, D.K., & Edewaard, D.E. (2016). *The conspicuity benefits of bicycle taillights in daylight*. Technical Report delivered to Trek Bicycle Corp. on January 13, 2016.

Watts, G.R. (1984). Pedal cycle lamps and reflectors – Some visibility tests and surveys. *TRRL Report 1108*.

Whetsel-Borzendowski, S.A., Stafford-Sewall, A.A., Rosopa, P.J., & Tyrrell, R.A. (2015). Drivers' judgments of the effect of headlight glare on their ability to see pedestrians at night. *Journal of Safety Research*, *53*, 31-37.

Wood, J.M., Tyrrell, R.A., & Carberry, T.P. (2005). Limitations in drivers' ability to recognize pedestrians at night. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *47*(3), 644-653.

Wood, J. M., Tyrrell, R. A., Lacherez, P., & Black, A. A. (2017). Night-time pedestrian conspicuity: effects of clothing on drivers' eye movements. *Ophthalmic and Physiological Optics, 37*(2), 184-190.

Wood, J.M., Tyrrell, R.A., Marszalek, R.P., Lacherez, P.F., Carberry, T.P., Chu, B.S., & King, M.J. (2010) Cyclist visibility at night: perceptions of visibility do not necessarily match reality. *Journal of the Australasian College of Road Safety*, *21*(3), 56-60.

Wood, J.M., Tyrrell, R.A., Marszalek, R., Lacherez, P., Carberry, T., & Chu, B.S. (2012). Using reflective clothing to enhance the conspicuity of bicyclists at night. *Accident Analysis and Prevention*, *45,* 726-730.

Wood, J.M., Tyrrell, R.A., Marszalek, R., Lacherez, P., & Carberry, T. (2013). Bicyclists overestimate their own night-time conspicuity and underestimate the benefits of retroreflective markers on the moveable joints. *Accident Analysis and Prevention,* *55*, 48-53.